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Service Mode and Visitor Mode at Paranal
Rendezvous with ʻOumuamua
Massive Star Formation and Evolution in the Galactic Centre
Resolving the Interstellar Medium at the Peak of Cosmic Star Formation

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Should I stay, or should I go? Service and Visitor Mode at ESO's Paranal Observatory

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Since the beginning of Very Large Telescope (VLT) operations in 1998, ESO has been offering time in both Visitor Mode (VM) and Service Mode (SM). In this article we discuss the advantages and limitations of these two observing modes, explain the rationale behind the one-hour observation rule in SM, and provide some statistics comparing the usage in each mode. Community demand has been steadily growing for SM observations and is now above 80% for normal programmes (i.e., not Large or Guaranteed Time Observation programmes). Here, we highlight the benefits of VM and promote its usage to the community. We also emphasise the low demand for SM for observations in the most demanding seeing conditions.

Observing modes at Paranal

The VLT and its interferometer (VLTI) Science Operations Policy[1] defines the policies and procedures that form the basis of time allocation and operation of the VLT and its interferometer (VLTI). The document states that at least 50% of the scheduled observations will be implemented in SM in order to optimise the scientific return while adjusting the VLT/VLTI schedule to the prevailing atmospheric conditions, while at least 40% of the available time is reserved for VM. These percentages are subject to periodic adjustments, depending on the experience gained at ESO and the evolution of the community's demands.

In the 1990s SM was new territory for ESO, its user community, and ground-based observatories in general. SM at ESO, along with its supporting end-to-end data flow system (DFS), was envisaged to ensure that observations requiring the most challenging observing constraints were acquired during the right conditions, and that there was generally more flexibility to choose which observation best matched the current observing conditions. Furthermore, the observatory established calibration plans for instruments, ensuring that sets of measurements useful for both instrument health monitoring and calibration of scientific data were obtained while maximising the telescope time used for science (Hanuschik & Silva, 2002). In addition, the calibration plan was intended to be usable for a variety of scientific programmes, enabling the reuse of science data for archival research.

The DFS also included the development of tools for the definition of observations, and the provision of all necessary information and calibration files for data reduction and analysis. The ESO DFS has been flexible enough to accommodate new VLT/VLTI instruments, new programme and run types (for example, monitoring and calibration proposals, public surveys, target of opportunity and rapid response mode proposals) and a new observing mode, the designated Visitor Mode (Marteau et al., 2017). Designated VM, introduced in 2014, is limited to observing runs shorter than one night, when it is too inefficient for visiting astronomers to travel to Chile to observe. In those cases, the observer can connect from anywhere in the world via the Paranal Observatory Eavesdropping Mode (POEM) tool[2], which was introduced in 2017 and displays operational screens from the telescope in real time. See Hainaut et al. (2018) for further information about the evolution of the VLT/VLTI DFS.

At the very start of VLT operations, an effort was made to promote the then new SM, and several articles described its implementation, scheduling principles, tools and effectiveness (for example, Silva, 2001; Comerón et al., 2003). These articles, probably combined with the effective implementation of an operating model with satisfactory scientific return and the general satisfaction of SM users[3], resulted in a steadily increasing request for SM by the community. From an initial request of just under 50% in 1999, the SM request now exceeds 80% (see Figure 7 in Patat et al., 2017).

The scheduled (as opposed to requested) SM:VM ratio on the telescopes is more constant and has stayed at around 70:30 over the last decade, owing to the strong contribution of Large Programmes and Guaranteed Time Observation (GTO) proposals to VM (see Figure 1 from Primas et al., 2014). ESO schedules GTO observations in VM intentionally because operational procedures are fine-tuned during the early operation of new instruments, and there is transfer of knowledge from community experts who built the new instrument to the observatory staff. Additionally, ESO has scheduled all Spectroscopic Public Surveys in VM over the past six years.

Advantages of Visitor Mode

Visiting astronomers at ESO receive support that starts with the organisation of their travel to the telescope. ESO covers travel and accommodation expenses for one observer for each observing run allocated in VM[4]; this applies to observers affiliated to institutes in ESO Member States at the time of observing run. On Paranal, the visiting astronomers receive help from observatory staff astronomers with preparing their observing run, and they are assisted by a telescope and instrument operator and a support astronomer throughout the observing run.

The presence of visiting astronomers on Paranal is very important. It fosters a sense of ownership by the community, for whom the observatory and its suite of telescopes and instruments were built. By being present at the telescope, astronomers understand better how their data are taken and calibrated, and learn about their limitations. Visiting astronomers also have the opportunity to discuss their use of the instrument suite in Paranal face to face with ESO experts. By spending time travelling to remote observatory sites in Chile and by being present at the exciting moment when observations are appearing on the detector, an emotional link is established with the data. Indeed, this may be partly responsible for the fact that the VM publication productivity is higher than the average productivity of all normal SM programmes (Sterzik et al., 2015).

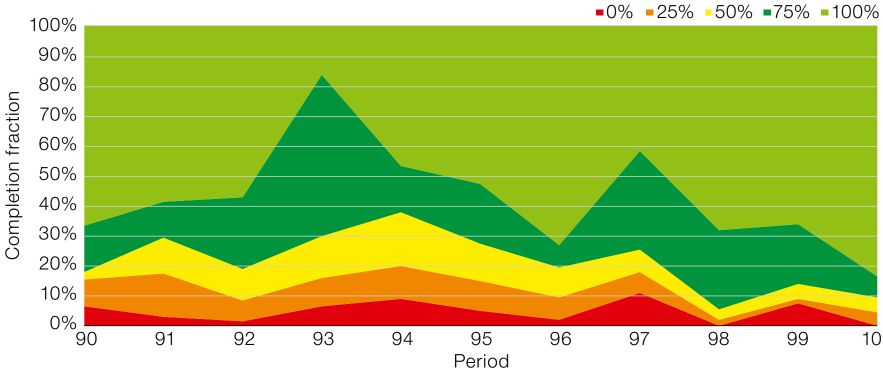


Figure 1. Visitor Mode run completion fraction.

VM is also an essential contribution to training the next generation of astronomers, who benefit significantly from an overview of the entire process involved in conducting their experiments. Astronomers with little or no observational experience, in particular graduate students and junior postdocs, are therefore encouraged to make use of VM. Observing is much more comfortable today and travelling to remote and beautiful observatory sites is something that every observational astronomer should experience at least once.

VM is not only important for the community, but also for ESO; visiting astronomers can provide direct feedback to the staff that run the operations. This feedback influences the evolution of the operational model and the services that ESO offers. Experienced observers can transfer their knowledge to the observatory staff, thereby enhancing the efficiency of the observatory for everybody. Also, seeing how the observations are run and meeting staff involved in operations facilitates later interactions when observing in SM. It provides a better understanding of the tools and communication channels at the observatory and helps observers to improve how they structure and convey their observing strategy for future observing runs.

In many cases, VM is the more efficient observing mode. Real-time decisions to optimise the observing strategy are possible only in VM. Typically, VM runs use very few different instrument setups, and there are no length restrictions for individual observation sequences. If the visitor has few targets, the overheads for telescope slew time, instrumental setup, and acquisition are minimised and the time spent integrating on the science targets is maximised.

Of course, the well-known disadvantage of VM is that the observer is at the mercy of the weather; in poor conditions, suboptimal or partial data (or none at all) may result from a VM run. The average weather downtime on Paranal is between 10% (summer) and 15% (winter), when conditions are so bad that telescopes must be closed or no useful observations can be taken. Yet the median conditions are excellent and most visitors go home happy with lots of data (Figure 1) and ready to quickly publish interesting results (Sterzik et al., 2015).

Preference for Service Mode

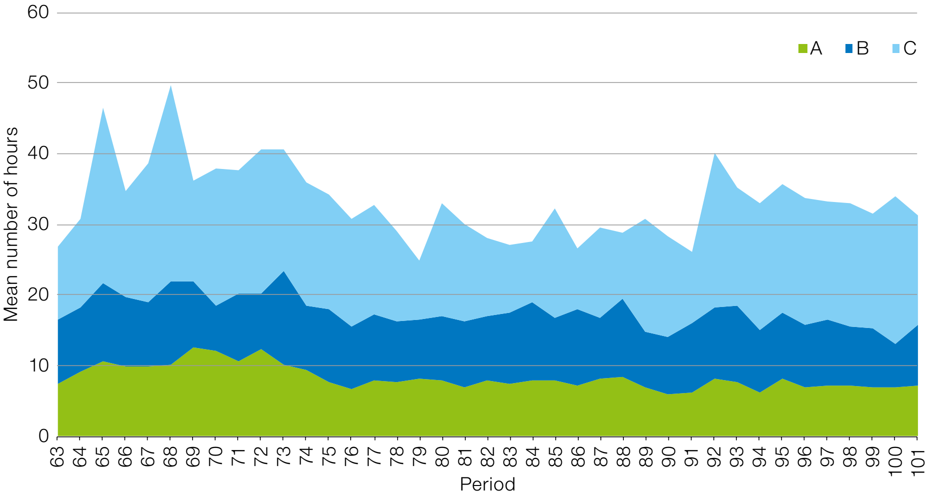
In the first decade after the year 2000 the SM *vs* VM request was stable, with about 70% of normal programmes requesting SM. Recently there has been an increase in SM requests: the VM fraction dropped from around 30% in 2012 to slightly below 20% in 2018 (Patat et al., 2017).

At around the same time, a new generation of Phase 2 observing preparation tools was released (Bierwirth et al., 2010). These tools allow the definition of complex observing strategies in SM, for example, via concatenations, groupings and time-links of observations. The tools were quickly adopted by users, and may have enhanced the perception that users do not need to be present at the telescope even if they require a more complex observing strategy.

Other possible explanations for the increasing preference for SM could be that observing programmes require less time (for example, because the second-generation instrumentation is more efficient and often offers a multiplexing capability), and/or that observing programmes request more demanding observing conditions that are most efficiently achieved in SM. Neither of these two suppositions is supported by data.

Figure 2 shows the evolution of the length of the mean SM observing run; no significant evolution for the lengths of A- or B-ranked runs has been observed since Period 75, i.e., since 2004. The C-rank class runs, are also called filler runs because they require most relaxed observing conditions. They are executed only

Figure 2. Evolution of the mean length (in hours) of allocated SM runs per rank class.



when there are no other higher-ranked SM observations, and show a larger scatter in their mean length per period, ranging between 9 and 27 hours. The mean length over all periods is 15 hours.

Figure 3 shows the evolution of the total execution time for scheduled SM runs in A and B ranks that requested 0.4- or 0.6-arcsecond seeing since the beginning of VLT operations on the four UTs and the VLTI. From this figure it is obvious that there is no difference between the A- and B-rank classes in terms of requested seeing and that 0.4-arcsecond seeing observations are almost never requested. Seeing conditions of 0.4 arcseconds are rare, occurring about 2—3% of the time. However, with sufficient SM allocation it is feasible to get such exceptionally good image quality (IQ). Moreover, 0.6-arcsecond seeing is fulfilled about 25% of the time, and the median seeing at Paranal is between 0.7 and 0.8 arcseconds. However, requests for observations with very good seeing have been dropping and now account for about 2 nights per telescope each semester. Primas et al. (2014) discuss the probability of the realisation and completion rate of demanding SM observations. Good seeing conditions, better than a median seeing of ~ 0.75 arcseconds, are undersubscribed, with most users requesting 0.8–1.0 arcseconds.

The success of SM could be attributed to an increasing confidence in the system. In addition, time requests are typically small, with the mean run length less than 2 nights, making travel to Chile inefficient (two observing nights typically require a trip lasting at least one week). Senior people may not want to go all the way to Chile regularly. It also seems that more junior people prefer to have experienced ESO staff take their observations in SM. By now, many users are accustomed to SM on Paranal and even rely on it.

In order to implement effective SM support, with about 1000 scheduled observing runs per year, ESO has developed tools and put in place well-defined procedures and rules to ensure that all users get appropriate support, enhancing the scientific return of their observations and treating everybody fairly. One of these is the so-called "Phase 1 constraint is binding" rule[5]. The targets, instrumental setup, and set of constraints requested at Phase 1 are used to define the schedule. Major changes with respect to the original plans may unbalance the schedule and cause conflicts between approved programmes. In particular, target and setup change requests are carefully evaluated and strictly controlled, because the Observatory needs to protect targets of approved programmes over later target change requests by other programmes.

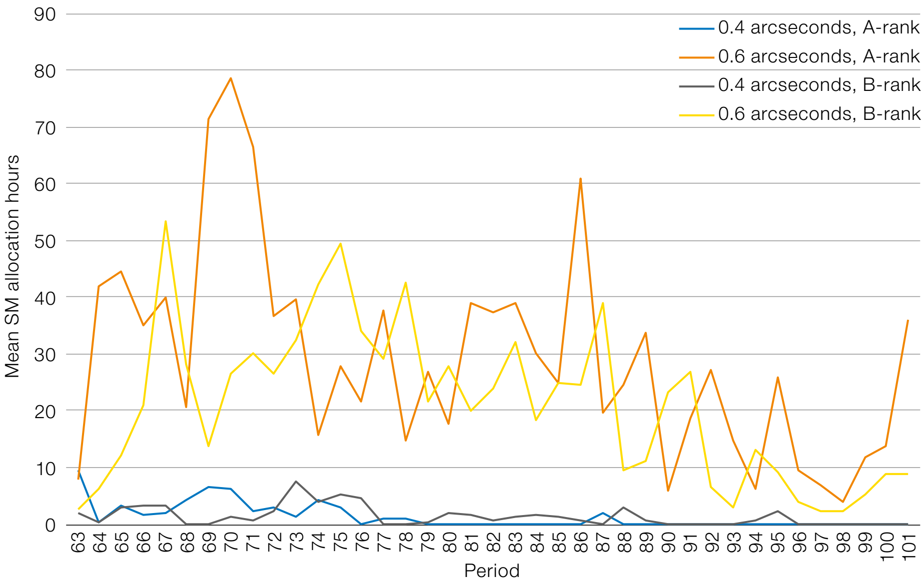


Figure 3. Mean SM allocation per telescope for best seeing runs.

Another rule that is sometimes less obvious to users, and in respect of which we frequently receive questions and waiver requests, is the "one-hour SM OB rule[5]". In the following, we summarise a recent analysis of stability in seeing, which is one of the reasons behind this rule. In so doing, we also highlight the fact that the good to very good observing conditions at Paranal are currently under-requested by the community. Strategies to improve the exploitation of these good conditions will be the topic of a forthcoming article.

Evaluation of the one-hour SM rule

At the onset of SM operations ESO introduced the rule that an SM observation block (OB), the smallest observational unit into which a given observing programme can be divided, should have a maximum length of one hour. This rule was introduced to ensure flexibility in short-term scheduling. Some users request longer OBs, and often the justification is that this will make their programme more efficient, because there will be fewer fractional overheads over the invested time. This may be correct for individual programmes and for a user who is not charged additional overheads in the case of a failed execution resulting from changing observing conditions, but it may not be correct for observatory-wide SM operations.

The efficient scheduling and execution of SM observations is a complex function that includes calculating the possibility of scheduling OBs given the target visibility, the duration of the observation, and the probability of the observing conditions staying within the specified constraints for the entire length of the OB. Furthermore, priority is given to completion of the most time-critical and highest-ranked SM programmes. After more than 17 years of SM observations we reviewed the merits of the "one-hour SM rule" in a study that focussed on seeing as the dominant meteorological factor dictating whether or not an OB can be successfully executed.

The analysis was based on seeing measurements taken at the zenith at 500 nm with the Differential Image Motion Monitor (DIMM) every minute during the night, over a period from 1 January 2000 to 11 December 2010. We used these seeing measurements as the first order

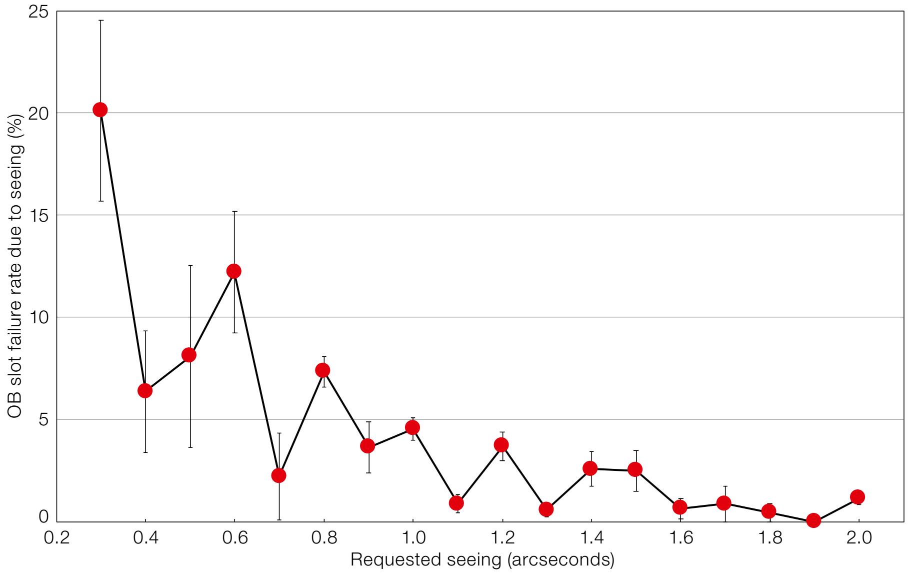


Figure 4. OB failure rate due to seeing as a function of requested seeing independent of OB length.

Requested seeing (arcseconds)	Percentage of intervals longer than one hour	Mean seeing (arcseconds) for all ~ one-hour intervals
0.6	57	0.66
0.8	63	0.87
1.0	70	1.06
1.2	76	1.29
1.4	82	1.52
1.6	82	1.70
1.8	83	1.89
2.0	87	2.11

Table 1. Results of seeing stability analysis based on DIMM data. The second column lists the percentage of time intervals that are longer than 1h for a requested seeing (column 1). The last column lists the statistically weighted mean seeing for all intervals that are 55–65 minutes long.

proxy for the resulting IQ of the science data[a] and we do not distinguish in the following between seeing requests for scheduling *vs* IQ requests in OBs.

We constructed a cumulative distribution of time interval lengths as a function of seeing. An interval starts after a waiting period of 30 minutes, during which seeing was at or below a target seeing value and ends after 10 consecutive seeing measurements above the requested value. This mimics a possible observational decision-making process at the telescope.

The results are presented in Table 1. In the case of typical seeing of 0.8 arcseconds, 63% of all intervals are longer than one hour. As expected, the fraction of time intervals longer than one hour increases as seeing gets more relaxed. Given our choice that the interval end after 10 consecutive non-compliant seeing measurements, there can be quite a range of seeing values for the one-hour-long intervals. The last column of Table 1 lists the mean seeing for all ~ one-hour intervals.

We then considered how this simulated one-hour duration OB success/failure rate estimate compares with what actually happens during SM observations on Paranal. The amount of time spent on observing OBs that are obtained during conditions outside of the specified constraints and that are considered for repetition varies from instrument to instrument. For example, AO instruments, and the VLTI have a higher fraction, on average, of unsuccessful executions. On UT1 and UT2 the fraction of observations executed out of the constraints is between 5 and 10%, while on UT3 and UT4 it is typically between 10 and 15%.

To assess the failure rate due to seeing alone, we analysed data from the night log database, where the fulfilment of all constraints, including seeing, is consistently recorded for each OB execution slot. As expected, the failure rate of OB executions due to unmet seeing constraints is higher for the most demanding OBs (Figure 4).

However, the overall failure rate is lower than implied by our analysis of seeing stability as reported in Table 1. Besides some scaling effects when converting the DIMM seeing values to IQ, these overall low failure rates suggest that OBs requiring close to median IQ (~ 0.8 arcseconds) are on average started under better initial seeing (0.6–0.7 arcseconds).

This would be a problem if the overall distribution of requested IQ were similar to or better than the statistical IQ distribution of Paranal. This would show itself if the IQ distribution of attempted OBs were skewed towards larger IQ with respect to the IQ distribution of scheduled OBs (and thus systematically resulted in unobserved requests with good IQ). However, this is not the case; the pool of available OBs binned by seeing and execution time is shown in Figure 5. We found it to be virtually indistinguishable from the distribution of attempted OBs that failed as a result of poor seeing (Figure 6). This indicates that the low failure fraction is not due to the systematic avoidance of demanding OBs, but the simple unavailability of such OBs, as already anticipated from the distribution of the requested seeing in the scheduled SM runs (Figures 3 and 5). The actual conditions on Paranal allow ESO to consistently fulfil IQ requests, since the distribution of requested IQ is more conservative than the real distribution. By implication, this also means that the fraction of failed observations is lower than the one estimated by the analysis of time intervals when seeing is stable at or below a given value.

Summarising the results of our study, an analysis of DIMM seeing stability anticipates that 37% of time intervals that started with a seeing of 0.8 arcseconds will be shorter than one hour in length. More generally, the length of time over which one can be assured of having seeing no worse than *S* is shorter for smaller values of *S*, or as shown in Table 1, the probability of successfully completing a one-hour-long OB is smaller for more demanding IQ. The one-hour limit appears to be a healthy compromise in this context, representative of the most requested values. In principle, OBs for more relaxed seeing requests could be longer, but this would have a knock-on effect penalising OBs of any length that require better seeing. In other words, two-arcsecond OBs can always be done under median or better conditions, but this is not the case for 0.6 arcseconds or even more demanding OBs.

In reality, the fraction of OB failure due to seeing constraints is about 5%. We show that this low failure rate compared to our statistical estimates of seeing stability has no negative impact on the execution of more demanding programmes. Rather, this happens because the IQ distribution of requested observations is more conservative than the average IQ distribution on Paranal. To take better advantage of the average site conditions, the community is encouraged to consider applying for slightly more stringent IQ constraints. The measures in place at Paranal to ensure the execution of more stringent observations such as these will be summarised in a forthcoming Messenger article (Anderson et al., in preparation).

References

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Comerón, F. et al. 2003, The Messenger, 113, 32
Hainaut, O. R. et al. 2018, The Messenger, 171, 8
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Patat, F. et al. 2017, The Messenger, 169, 5
Primas, F. et al. 2014, The Messenger, 158, 8
Sarazin, M. et al. 2008, The Messenger, 132, 11
Silva, D. 2001, The Messenger, 105, 18
Sterzik, M. et al. 2015, The Messenger, 162, 2

Links

[1] VLT/VLTI Science Operations Policy: http://www.eso.org/sci/observing/policies/Cou996-rev.pdf

[2] POEM instructions: http://www.eso.org/sci/facilities/paranal/sciops/POEM_instructions.html

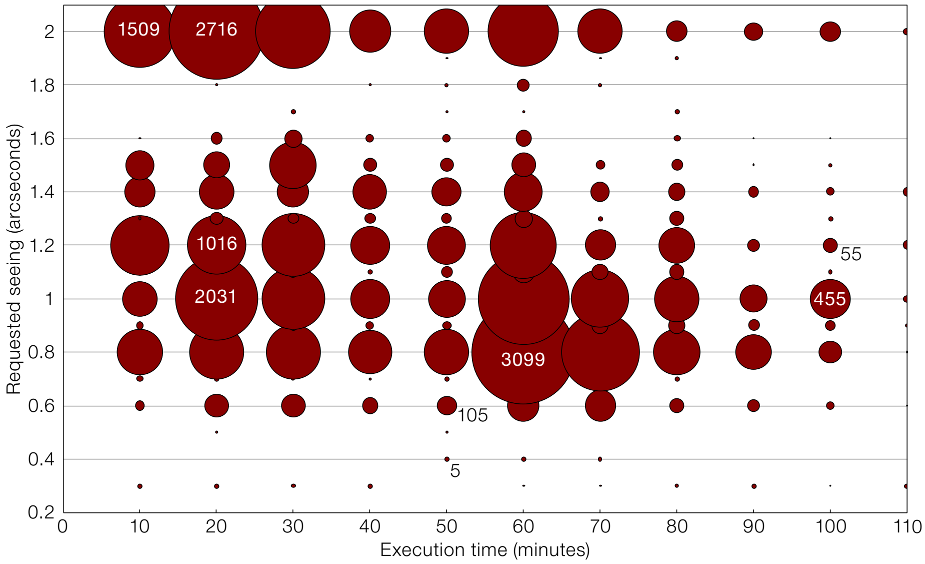

Figure 5. (Upper) Available OBs for Periods 90–97, binned as a function of execution time and requested seeing. The area of each dot is proportional to the number of OBs within the bin.

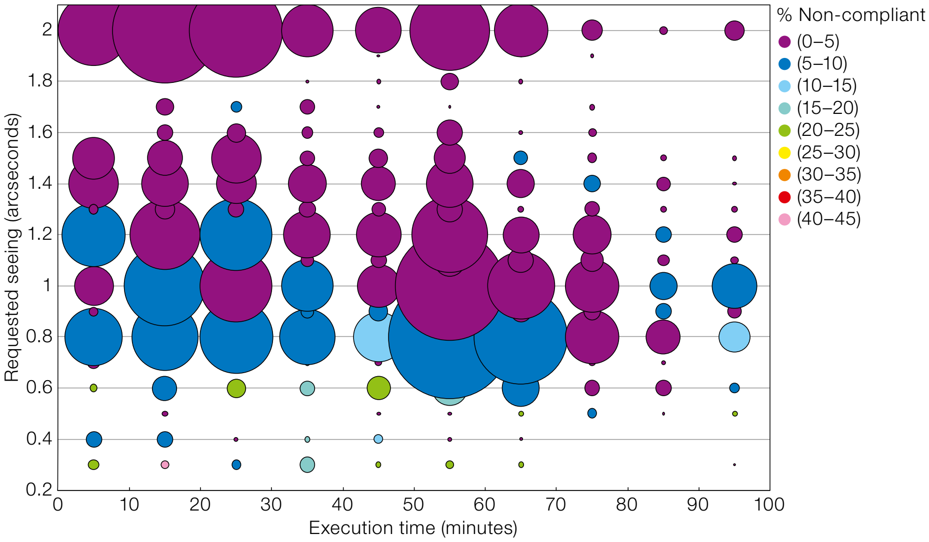

Figure 6. (Lower) OBs for Periods 90–97 binned as a function of execution time and requested seeing for which execution was not successful owing to non-compliant seeing. The area of each dot is proportional to the number of executed OBs, and the colour of the dot (see legend) indicates the percentage of the OBs with non-compliant seeing within that bin.

[3] Results from user surveys are presented to the Users Committee at its annual meeting. Since 2012, the SM user feedback on Phase 2 support and tools has been made available online: http://www.eso.org/sci/observing/phase2/PostObservation/UserFeedback.html

[4] For GTO runs, ESO fully supports one visiting astronomer every 8 nights of the total time allocation for each GTO programme per period: http://www.eso.org/sci/observing/travel/visas-instruc.html

[5] Service Mode Policies: http://www.eso.org/sci/observing/phase2/SMPolicies.html

Notes

[a] It can be shown that image quality dependence on wavelength and airmass roughly cancel out on average.

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The Time Allocation Working Group Report

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A Time Allocation Working Group was charged with the task of reviewing the telescope time allocation process at ESO. The working group submitted a report to the Director for Science, including a set of recommendations and suggestions for an implementation plan. This paper gives a general overview of the recommendations and a status report on their implementation.

The Time Allocation Working Group

The ESO 2020 prioritisation initiative prompted a series of actions (Primas et al., 2015). One of these was to constitute a Time Allocation Working Group (TAWG). The TAWG included experts in the field of scientific resource allocation and representatives from the Users Committee (UC) and the Scientific Technical Committee (STC): Almudena Alonso Herrero (STC delegate), Antonio Chrysostomou (SKA, Science Operations Planning), Stefan Janssen (Paul Scherrer Institute, User Office), Arvind Parmar (ESA, Science Operations), Rachel Mason (Gemini Observatory), Neill Reid (STScI, Science Mission Office), Stephen Smartt (UC representative), and Ferdinando Patat (ESO, Observing Programmes Office) — the Chair of the TAWG and author of this article.

The TAWG reviewed the entire time allocation process as currently implemented at ESO, examining the procedures and analysing a number of statistical indicators. The recommendations in the report[1] were formulated with the aim of achieving two goals:

1. to maximise the scientific return of ESO facilities by selecting proposals that promise to result in significant advancements;
2. to improve the level of feedback provided to the community by the Observing Programmes Committee (OPC).

Given the current workload placed on the panel members, the TAWG reached the conclusion that the most urgent measure ESO needs to take in order to achieve these goals is a drastic reduction in the number of proposals that each of the panel members have to review.

Although there is no clear indication from the literature of the optimal number of proposals per referee, the current number (over 70) is certainly above what is reasonable when trying to perform a thorough and consistent review. Most of the recommendations discussed in the TAWG report attempt to address this matter and aim at: a) reducing the total number of submitted proposals; b) increasing the average telescope time requested per proposal; and c) enhancing the quality of the review process and the feedback provided to the applicants — this last being the most recurrent complaint ESO receives about the whole process.

The TAWG considered possible radical changes to the way proposals are discussed at length, also considering substantial departures from the peer review schema. Notwithstanding the known limitations of this paradigm, the TAWG concluded that peer review still remains the most satisfactory way of selecting time applications. The choice of any time allocation committee is unavoidably subjective, and a different set of referees would provide a different list of top-ranked proposals, with only a fraction in common. However, in a scheme in which the community nominates panels, this type of selection still represents the priorities of the underlying population. Based on these considerations, the TAWG did not recommend changes in the overall process, although it advocated some substantial modifications. In general, the TAWG is in favour of deploying a distributed review, which is considered a valid means of sustaining the proposed fast-track channel (see below for more details on this channel). In this article, the main advantages and disadvantages seen by the TAWG for each recommendation are discussed, and suggestions for a possible implementation plan for the proposed recommendations are presented. The report is complemented by statistical studies probing various aspects of the process, some of which have already been published (Patat, 2016; 2017a; 2018).

The recommendations: an overview

The interested reader is encouraged to read the report; only a brief summary will be provided here. Perhaps not too surprisingly, some of the TAWG recommendations are very similar to those contained in the ESO OPC Working Group report (Brinks et al., 2012).

Recommendation 1: Decrease the frequency of the Call for Proposals to once per year

Given the artificial pressure that a semester-based call puts on the community, the typical time scales for publication return (see Patat et al., 2017) and the large number of resubmissions, there is no compelling scientific reason behind this frequency. A decreased frequency of regular calls could be compensated for by the creation of a new, fast submission and review channel (see next recommendation).

This change would bring a number of advantages; we mention only two of them here. The first is the increase of distinct referees who can be recruited within the same annual budget[a] which allows the panels to cover more scientific areas. The second is that the number of submitted proposals will be less than a factor of two larger than the current value (~ 900 proposals/period), simply because it will remove all the resubmissions generated by the artificial right ascension limitation introduced by a semester-based system. Obviously, an annual call would introduce some loss of flexibility and response time (but see Recommendation 2) and it would also increase the difficulty of adding or changing plans regarding technical activities. This could be mitigated by the creation of a devoted group in charge of more dynamic short-term scheduling, which would in any case be required if a fast-track channel (FTC) were introduced (see Recommendation 2).

Recommendation 2: Create a fast-track channel for the VLT

This new peer-reviewed channel would be in addition to the existing Director's Discretionary Time (DDT) and is not meant to replace it. It would rather provide a quick duty cycle — on a timescale of months — allowing users to obtain data for amounts of time below some threshold value. As in the case of similar channels that already exist (for example, the Fast Turnaround observing mode at Gemini[2]), specific criteria would be applied to eligible programmes to establish why they could not be submitted through the regular channel. To ease the review and scheduling processes, the deadline would be periodic (for example, once a month) and not continuous. ESO should also consider a maximum amount of time to be allocated to these programmes, which may be adjusted depending on how the community reacts to it.

The introduction of the FTC would have two beneficial effects: a) to improve the response time for science cases that do require a short duty-cycle; and b) to decrease the total number of proposals. The latter stems from the fact that applicants work to meet deadlines; the possibility of submitting short programmes at the next fast-track deadline will naturally lower the pressure, as users will not feel compelled to submit at every deadline.

While the FTC would have clear benefits for the community, it would also impact ESO operations. The review of FTC submissions would have to take place within a relatively short amount of time (depending on the final cadence of the FTC deadlines). In addition, it would require a strategy for dynamic scheduling in order to accommodate the newly approved programmes on top of those already allocated through the annual cycle described in Recommendation 1. The implementation plan proposed by the TAWG suggests ways to address these potential issues.

Recommendation 3: Radically change the proposal review procedure for the annual Call

In the current system, all proposals assigned to a panel are reviewed by all of the non-conflicted members of that panel. This results in 85% of the proposals being reviewed by 5 or 6 referees. The reviewers are required to read and grade all proposals; this corresponds to a load of more than 70 proposals per panel member and can reach up to about 100 proposals for each member of the "OPC proper". It is widely acknowledged that this number is too large to allow a thorough review and can adversely affect the quality of the feedback. This recommendation — which is in line with practices at other facilities (also outside astronomy) — is to stipulate that only a fraction of the panel should read and grade each proposal in the pre-meeting phase.

Once the pre-meeting grades were defined, a substantial triage (~ 30%) could be applied to the weakest proposals; triage is already standard practice in the current system. In the schema proposed by the TAWG, after triage was applied, the members of a given panel would subsequently have to read the non-triaged, surviving proposals that they had not read in the first round. The time freed by the load reduction would allow the referees to dedicate more time to assessing more meritorious proposals and providing feedback to all of the applicants.

This recommendation is based on the observed fact that the grade dispersion for higher-graded runs is lower than that for the lower-graded runs (Patat, 2018), so it is unlikely that a meritorious proposal would be triaged because of low number statistics. The TAWG did discuss the possibility of applying different selection criteria or figures of merit to select from the mid-range runs which have a higher dispersion, including semi-random selection, or schedule optimisation, but it did not make any specific recommendation in that direction. Obviously, having a reduced number N of reviewers increases the uncertainties related to the subjectivity of the process; however, the accuracy of the review increases only as $\sqrt{N}$. Therefore, from a statistical point of view, the difference between, $N = 6$ and $N = 3$ is not very significant (Patat, 2018).

Recommendation 4: VLT Large Programmes should have more massive allocations and shorter completion times

The current VLT Science policy includes a 30% upper limit for Large Programmes (LP) at the VLT. However, the time allocated to LPs is on average around 17%. LPs at the VLT can span up to four semesters. However, in a scheme in which LPs can only be requested on a yearly basis, there is no compelling reason that all the time should not be requested and allocated in one single cycle (barring time monitoring needs). As the statistics show (Sterzik et al., 2016), LPs are the most productive programmes (even when normalised by the allocated time), and should therefore be promoted and completed in the shortest amount of time compatible with their scientific requirements. Therefore, the TAWG recommended that LPs should normally span only one year, and larger time spans would have to be justified on scientific grounds. In addition, ESO should consider increasing/removing the 30% limit if the demand goes in that direction as a consequence of the proposed changes. This goes along the lines of encouraging the community to cluster around larger projects, which are expected to produce a higher scientific impact (as opposed to an increasing fragmentation into small programmes — see below).

Recommendation 5: Redistribute the time allocated in favour of larger programmes

The purpose behind this recommendation is to encourage the submission of larger, more comprehensive requests. At the same time, it aims to limit the number of submissions of short proposals during the annual cycle by increasing their rejection rate. One could argue that the community would react by artificially increasing the requested times in order to get above the threshold. However, this depends on the threshold — if it were set to 30 hours, about 25% of the current proposals would have to triple their requested time, at least, to elude the restriction. Although this is not impossible, it would require a well-substantiated scientific justification.

The distribution of the time request on the VLT for normal programmes submitted in the last five years (Periods 93–102) is shown in Figure 1; 50% of VLT normal programmes request less than 12 hours, 75% less than 20 hours, and 95% less than 41 hours. Although normal programmes are allowed to request up to 100 hours, there is a "desert" above 50 hours; in general, proposals for more than 30 hours are rare (11%).

In this respect, it is instructive to view the trend in requests since the start of VLT operations. The evolution of the distribution of the time request (per proposal) is presented in Figure 2, which shows different statistical indicators. This clearly demonstrates that there is a systematic and significant tendency to submit shorter (and more numerous) requests. Within a few semesters of the start of operations, the median VLT proposal stabilised at around 20 hours; since then it has steadily decreased to reach around 12 hours. The decrease is reflected in the entire distribution, which has shifted towards smaller time requests.

A closer look at the time evolution within time bins (Figure 3) reveals that the observed trend is related to a proliferation of programmes asking for < 10 hours; while in Period 70 (P70) this concerned only 18% of the proposals, in P101 the fraction reached 50%. There are likely to be various reasons behind this trend, relating to various demographic and sociological aspects. One factor may be linked to a general perception that it is easier to get small requests approved, and another factor is related to the conservative and risk-averse attitude of some reviewers who, for highly oversubscribed facilities, may prefer to allocate the same total amount of time to many small programmes rather than to fewer relatively large projects. These two factors lead to a negative feedback mechanism, which may explain the trends in Figures 2 and 3.

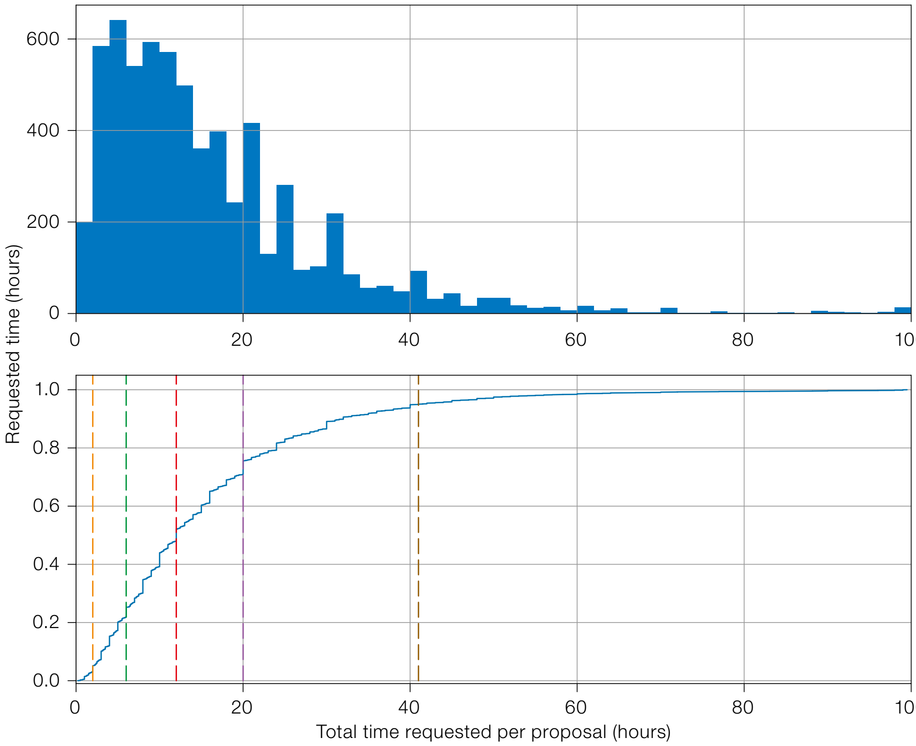
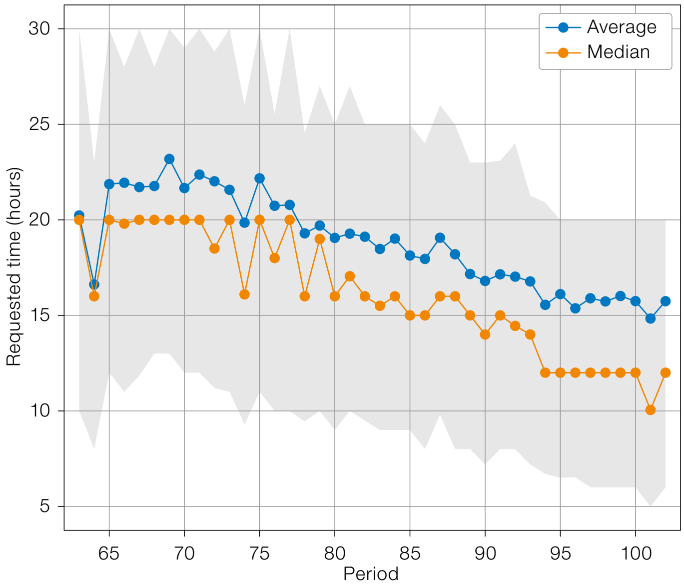
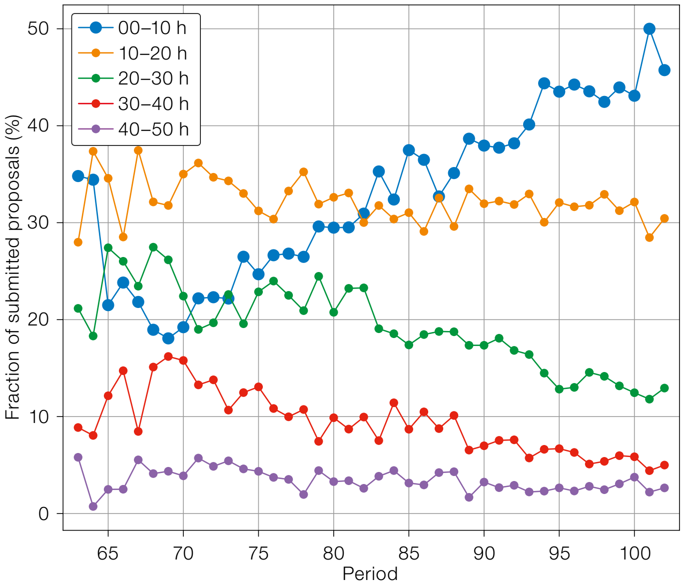


Figure 1. (Above) Distribution function (upper panel) and cumulative distribution function (lower panel) of the time request per proposal in the last five years (Periods 93 to 102; 6540 proposals). The vertical dashed lines in the bottom panel indicate the 5th, 25th, 50th, 75th and 95th percentiles. The peaks observed at 20, 24, 30–32 and 40 nights are generated by the visitor mode requests for 2, 3, 4 and 5 nights and their conversion to hours (8/10 hours per night in even/odd semesters). Only normal VLT proposals are included.

Figure 2. (Below left) Time evolution of the time request per proposal from the start of VLT operations (Periods 63 to 102; 22800 proposals). The grey-shaded area indicates the inter-quartile region of the time distributions in each semester. The connected symbols trace the average (blue) and the median (orange) of the distribution. Only normal VLT proposals are included.

Figure 3. (Below right) Fraction of submitted proposals for five time request bins. The time intervals (in hours) are shown in the legend. Only normal VLT proposals are included.





Although it is certainly true that ESO serves a wide community (about 3500 distinct scientists in the recent semesters; Patat et al., 2017a), time allocation is fragmented, and most proposals are comparatively small, both in terms of their time requests and their team sizes. The TAWG argues that, after twenty years of VLT operations, it is time to reconsider the way time is distributed. Setting a maximum fraction of accepted short programmes will encourage the community to propose larger, more ambitious projects. As shown by the ESO Survey of Non-Publishing Programmes (SNPP; Patat et al., 2017b), increasing the number of programmes requesting more than 20–25 hours would improve the scientific return of the VLT (at least in bibliometric terms). Also, applicants would be incentivised to complete their programmes more quickly (for example, completing samples with no right ascension limitations is easier with an annual cycle than with a semester-based cycle). Finally, since larger time requests require more thorough justifications and stronger teams, the total number of submitted proposals should decrease.

Recommendations 6–10

Whilst the first five recommendations affect the core of the time allocation process, the remaining five are more general and are discussed together here for the sake of conciseness.

Recommendation 6 is to create a proper filler channel. This is dedicated to proposals with loose observing constraints, which are allocated time at very low priority. Their review should be light, with a single, streamlined scientific evaluation that ensures a minimum standard, and a technical assessment to check that candidate projects conform to the filler criteria. Of course, nothing would prevent users submitting a proposal that required loose observing conditions through the regular channel for strong scientific cases. At the moment there is a deficiency in the request, leading to idle time, especially at some telescopes. The implementation of a filler channel should decrease the number of proposals requiring a full review and provide a sufficient number of reasonable projects to be executed under poor conditions.

Recommendation 7 encourages ESO to create a joint ALMA–VLT channel. In the current implementation, scientists applying for projects that require data from both facilities need to submit proposals to two different committees that are out of sync and are currently not coordinated. This can create discordant outcomes, with projects being judged very promising by one committee but rejected by the other.

Recommendation 8 proposes the introduction of a high-risk channel for the submission of high-risk/high-gain projects that require significant amounts of time. In the TAWG proposition, the high-risk channel would be kept separate from the DDT channel, and reviewed by an external board. Only large requests of time for very risky, but potentially highly rewarding proposals would be considered.

Recommendation 9 stems from the study of systematic effects in proposal selection carried out during the TAWG activities (Patat, 2016) and similar analyses performed at other large astronomical facilities (Reid, 2014; Lonsdale, Schwab & Hunt, 2016). Specifically, it is to consider limiting the level of information about the proposing team that is accessible to the reviewers (for example, the identity of the Principal Investigator [PI], the affiliation and the team composition). The TAWG acknowledges that this is potentially sensitive, and needs to be treated with care. Nevertheless, it recommends that ESO address this topic in coordination with other large scientific facilities worldwide.

The list of tasks assigned to the TAWG included the following item: "Examine the foreseeable evolution of the proposal selection and time allocation processes into the ELT era". The TAWG advised that it is too soon to be providing recommendations on this matter without more information on the strategy envisaged for VLT operations in the era of the ELT. The TAWG would like to see the impact of the proposed changes to the VLT model before making any recommendations. It therefore preferred that ESO consider the development of a strategic plan for the use of the various ESO facilities at the start of ELT operations. When this is ready, a new working group should be constituted and tasked with the review of the recommendations presented in the TAWG report, how they were implemented by ESO, and the lessons learnt, before looking at their application to the ELT.

Implementation status and outlook

The TAWG report was presented to the ESO Scientific Technical Committee and to the Users Committee, which both provided very detailed feedback about the implementation of the proposed changes. Following these discussions and after an internal analysis, ESO decided to take a gradual approach, in which each change is reversible and subject to revision. The first steps undertaken by ESO are as follows:

1. Move to a yearly cycle for the submission of LPs. This was announced in the Call for Proposals (CfP) for Period 102 and in science announcements issued in February, 2018[3,4]. From Period 104 onwards, LPs will be allowed in only even semesters. Starting from that period LPs are required to span the minimum number of cycles compatible with the science case.
2. Encourage the submission of larger requests to improve the project diversity. This was solicited in the CfP for Period 102[3]. While it will probably take some time before the community reacts in a significant way to this call, ESO will continue to work actively to ensure that the distribution of requested time remains unchanged after the allocation and scheduling processes, guaranteeing that proposals of all lengths will have equal chance of success. For the time being there are no plans to implement a quota for short programmes (Recommendation 5).
3. Reduce the number of reviewers from six to three in the pre-meeting phase. This was experimentally introduced in Period 102, and the lessons learnt are being considered for future semesters. A poll to the OPC and Panel members for Period 102 is being prepared.
4. The obfuscation of information about the proposing team (Recommendation 9) has been thoroughly discussed, and the deployment of initial measures within the current proposal submission system has begun. As of Period 103, all information about the PI and co-investigator (coI) affiliation (country,

institute, email address) will be removed from the version of the proposal distributed to the reviewers. The PI will be listed together with the coIs, and the list displayed in pure alphabetical order on the last page of the proposal. More sophisticated measures (for example, different obfuscation levels for different proposal review phases), or more radical measures — see the recent change introduced at HST[5] — will be considered for the new system.

The most substantial changes, i.e., the global move to a yearly cycle and the introduction of a fast-track channel (Recommendations 1 and 2) require structural modifications to the proposal handling software and underlying databases, and will therefore have to wait for the deployment of the new Phase 1 system. This particularly concerns the review of the FTC proposals, which involves automatic detection of conflicts and optimisation of the matching between proposals and reviewers. For the latter step — which will also be extended to the proposals in the regular cycle — a machine-learning approach is being investigated, along the lines described by Strolger et al. (2017).

The current implementation of proposal peer review at ESO involves a face-to-face meeting, which places strong constraints on the number of reviewers. Although there are certainly good reasons for having such a meeting, including educational and social aspects, the limitations and costs involved are sufficiently important to warrant changes[a]. Various approaches are being discussed, along lines that are also being considered for ALMA[6]. In the long term, other options are being considered, such as the abolishment of the panel meetings while keeping the OPC proper meeting for Large Programmes alone, and the deployment of distributed review for the remaining applications. Given the scale of proposal submissions at ESO (more than 700 distinct PIs in a semester), this would allow a very substantial increase in the statistical robustness of the review (by decreasing the effects of subjectivity; see Patat, 2018). This represents a major change, marking an epochal turning point in the 50+ years of the OPC tradition at ESO. It will therefore require thorough discussions with the governing bodies, the advisory committees and the community at large.

Acknowledgments

The author is grateful to all the members of the TAWG for their very constructive approach. The feedback provided by the Users Committee and the Science and Technical Committee is also acknowledged.

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Links

[1] The TAWG report to the ESO Users Committee: http://www.eso.org/public/about-eso/committees/uc/uc-41st/TAWG_REPORT.pdf

[2] The Fast Turnaround channel at Gemini Observatory: http://www.gemini.edu/sciops/observing-gemini/proposal-routes-and-observing-modes/fast-turnaround

[3] ESO science announcement for the P102 Call for Proposals: http://www.eso.org/sci/publications/announcements/sciann17098.html

[4] ESO P102 Call for Proposals document: http://www.eso.org/sci/observing/phase1/p102/CfP102.pdf

[5] HST Cycle 26 Anonymous Proposal Reviews: https://hst-docs.stsci.edu/display/HSP/HST+Cycle+26+Anonymous+Proposal+Reviews

[6] Report of the February 2018 ALMA ESAC F2F Meeting, 19 February 2018

Notes

[a] The current logistical cost of the OPC and Panel meetings is approximately 240 000 euros per year. This includes travel, accommodation and full board for all participants.

G. Hüdepohl (atacamaphoto.com)/ESO

The VLT at sunset.

Astronomical Science

ESO/A. Müller et al.

SPHERE image of a planet forming around the dwarf star PDS 70. Its detection is made possible by a coronagraph, which is used to block the light from the central star.

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Rendezvous with `Oumuamua

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On 19 October 2017 the Panoramic Survey Telescope And Rapid Response System (Pan-STARRS) discovered a rapidly moving object near the Earth. In itself this was nothing unusual but over the course of a few days astronomers realised that this was the first detection of an unbound object travelling through the Solar System. At the time of its discovery, the interstellar visitor, 1I/2017 U1 (`Oumuamua), was quite faint and already speeding away. In the ensuing days, thanks to the efforts of about 10 separate teams, over 100 hours on 2.5- to 10-metre telescopes were devoted to observing the object during the short, exhilarating and frantic period over which it was visible. This is an account of our observations and how they have contributed to the current view that 1I/2017 U1 is an elongated object in an excited rotation state with surface colours similar to those of Solar System comets and asteroids.

Models of the early Solar System suggest that the migration of forming giant planets ejected a large fraction of planetesimals into interstellar space. Most of these planetesimals are expected to be icy — i.e., comet-like — with only a small fraction of them being rocky objects. Depending on the model, the ice to rock planetesimal ratio varies between 400:1 and 10 000:1 (Meech et al., 2016). Assuming similar processes have been taking place elsewhere in the Galaxy, a large number of planetesimals should be wandering through interstellar space, some of them eventually crossing the Solar System.

These interstellar objects (ISOs) are icy planetesimals that are expected to behave like the long-period comets of the Solar System; volatile ices sublimate when the ISO approaches the Sun, developing a coma and a dust tail — features that should make them bright and therefore easy to spot. The rocky ISOs, on the other hand, only reflect sunlight. As their albedo is expected to be extremely low they become dark (after eons of bombardment by high-energy cosmic rays), they would be extremely faint and hard to detect. Overall, because of the overwhelming majority of icy over rocky objects, and thanks to the brighter aspect of the icy ones, the community expected that the first ISO signature would be a comet discovered on a hyperbolic orbit. The hyperbolic orbit would indicate an object not bound to the Sun. With various ongoing all-sky surveys hunting for transient and moving objects (for example, the Catalina Sky Survey, Pan-STARRS, the ESO Public Survey ATLAS, the All-Sky Automated Survey for Super Novae [ASAS-SN]), the time was ripe for such a discovery.

The discovery

We were nevertheless caught by surprise when object P10Ee5V was discovered by Pan-STARRS1 (PS1) at Mauna Kea on 19 October 2017 (Figure 1a). Immediate follow-up observations from the ESA Optical Ground Station discarded the data because of the “unrealistically large eccentricity of the orbit”. Fortunately, pre-discovery images from PS1 and follow-up observations on 20 and 22 October from the Catalina Sky Survey and the Canada-France-Hawaii Telescope (CFHT), respectively, pinned it down to a hyperbolic orbit with an eccentricity of 1.188 ± 0.016 (Figure 2). The IAU’s Minor Planet Center (MPC) registered the discovery under the cometary designation C/2017 U1 (Williams, 2017).

We immediately started a follow-up campaign via a series of Director’s Discretionary Time proposals — using the Very Large Telescope (VLT), Gemini South, the United Kingdom Infra-Red Telescope (UKIRT), the NASA/ESA Hubble Space Telescope (HST) — and additional time on the CFHT. Whilst we were reminded of the Rama spacecraft from the novel by Arthur C. Clarke (1973), our first surprise came from a deep stacked image, confirming what the discovery images indicated; the object does not display any cometary activity (Figure 1b). The deep limiting magnitude reached corresponds to an extremely low dust production limit, amounting to less than 1 kg of micron-sized dust within 750 km of the ISO. The object is therefore similar to asteroids, prompting the MPC to swiftly change its designation to A/2017 U1. However, as its origin from outside the Solar System had now been established without a doubt, the object received its final designation 1I/2017 U1, and a Hawaiian name in honour of the place of its first discovery, `Oumuamua. The number 1I reflects that this is the first interstellar object to be identified, and the Hawaiian name means scout or a messenger from our distant past reaching out to us from far away. We refer to the object as `Oumuamua for the rest of this article.

The measured colours from the object’s surface indicate a linear reflection spectrum with a fairly red slope (Figure 3), which is typical of cometary nuclei, D-type

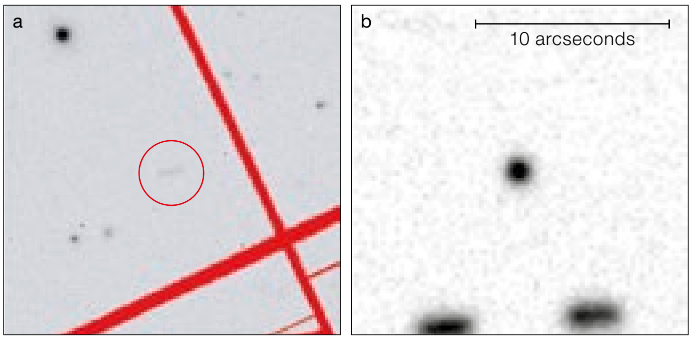

Figure 1. (a) The discovery image of `Oumuamua on 19 October 2017 with Pan-STARRS. The object is the faint trail in the centre of the circle. (b) A deep image, combining VLT and Gemini South *g*- and *r*-band data, illustrating the object’s asteroidal appearance. Reproduced from Meech et al. (2017).

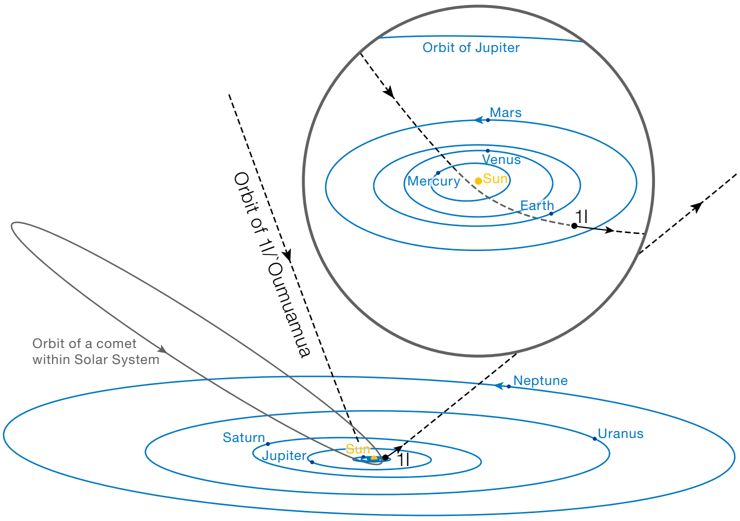

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Figure 2. The orbit of `Oumuamua, showing that it entered the Solar System from above the plane of the planets, passing inside Mercury's orbit at perihelion on 9 September 2017 and making its closest approach to Earth on 14 October 2017. `Oumuamua passed beyond the distance of Jupiter at 5.2 au in early May; while moving fast, it will still be inside the Solar System for the duration of our lifetimes. It will reach the outer edge of the Kuiper belt by the end of 2025, cross over the heliopause sometime in the late 2030s and won't even reach the innermost edge of the Oort cloud at 1000 au until nearly 2200.

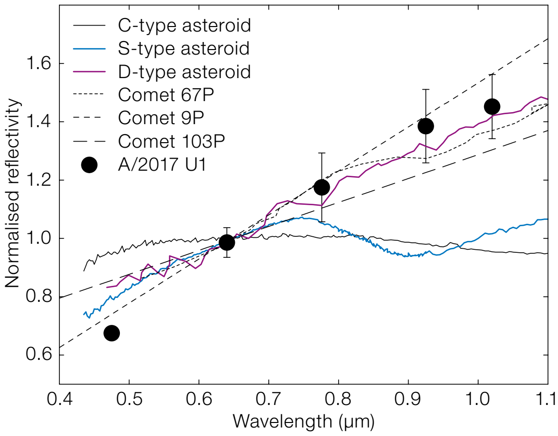

Figure 3. The reflectivity of the surface of `Oumuamua is consistent with D-type asteroids and comets (Meech et al., 2017).

asteroids from the outer asteroid belt, and some trans-Neptunian objects. In other words, `Oumuamua's surface seems similar to that of objects in the outer Solar System. This may suggest an organic-rich surface (as seen on comets) or a surface with iron-rich minerals. Another team observed the very faint `Oumuamua with the wide-band ultraviolet-infrared spectrograph, X-shooter, on the VLT (Fitzsimmons et al., 2018). This attempt resulted in a noisy spectrum that was in agreement with the reddish photometric colours, and the lack of emission lines set independent limits on the cometary activity.

`Oumuamua: cigar or pancake?

The second surprise was that the object displayed huge photometric variations; the flux changes by at least a factor of 10! Neglecting the effect of the solar phase illumination, this implies that the geometric cross-section of the object varies by a factor of 10, which indicates an elongation of 10. The fairly high solar phase angle at the time of the observations could make this elongation smaller, but the unknown geometry of the direction of the rotation axis makes the implied elongation a lower limit. Overall, the large-to-small axis ratio of the body is ~ 10:1.

The photometric light curve does not constrain the third dimension of `Oumuamua. For the rotation to be stable, the third axis should be small — similar to the short axis — which has given rise to the highly popular cigar-shaped artist's impression. However, collecting more data and combining ours with those of other teams, it became apparent that the light curve is not periodic (Figure 4), and that the object is in an excited state of complex rotation. Studying the rotation in detail, we found a spin state with two fundamental periods at 8.67 ± 0.34 hours and 3.74 ± 0.11 hours. The object could be spinning in a short-axis mode — where the short principal axis of the object circulates around the total angular momentum vector (TAMV) — or in a long-axis mode — where the long axis circulates around the TAMV. Interestingly, `Oumuamua could be either an elongated cigar-shaped object, in which case it would be in a state close to its lowest rotational energy, or an extremely oblate spheroid, pancake-shaped, close to its highest energy for its angular momentum (Figure 5).

Assuming the object has the standard dark albedo of distant Solar System objects, its brightness can be converted to a size. For the cigar shape, this leads to radii of 400 m and 40 m. Also, assuming that the object has a density typical of comets or asteroids in the Solar System (1000 to 3000 kg m^{-3}), its rotational periods indicate that it must have some modest, but non-zero, cohesive strength — otherwise the centrifugal forces would tear it apart. A pancake-shaped object could be held together by gravity only for densities above 1500 kg m^{-3}.

`Oumuamua: final glimpses and a last surprise

We continued to monitor `Oumuamua as it receded in order to improve the determination of its orbit, with the aim of extrapolating it back to its origin. The last datapoint was acquired with the HST on 2 January 2018, when the object was very close to its detection limit. The position of `Oumuamua was carefully measured on over 200 ground- and space-based images, including the recently published Gaia Data Release 2 (DR2) catalogue. This brought another surprise; the object was not following a purely gravitational orbit! A gravitational orbit accounts for the orbits of the eight planets, Pluto, Ceres, the largest asteroids and relativistic effects. Systematic residuals in the fit indicated an additional non-gravitational force non-gravitational force (see Figure 6). The best fit corresponds to a non-gravitational acceleration A/r^2, with A = (14.92 ± 0.16) 10^{-6} m s^{-2}, i.e., a ~ 30-σ detection. This detection of non-gravitational acceleration survived a series of tests; it is neither the result of an artefact caused by a subset of the data, nor the result of some unaccounted biases. The non-gravitational effect is also

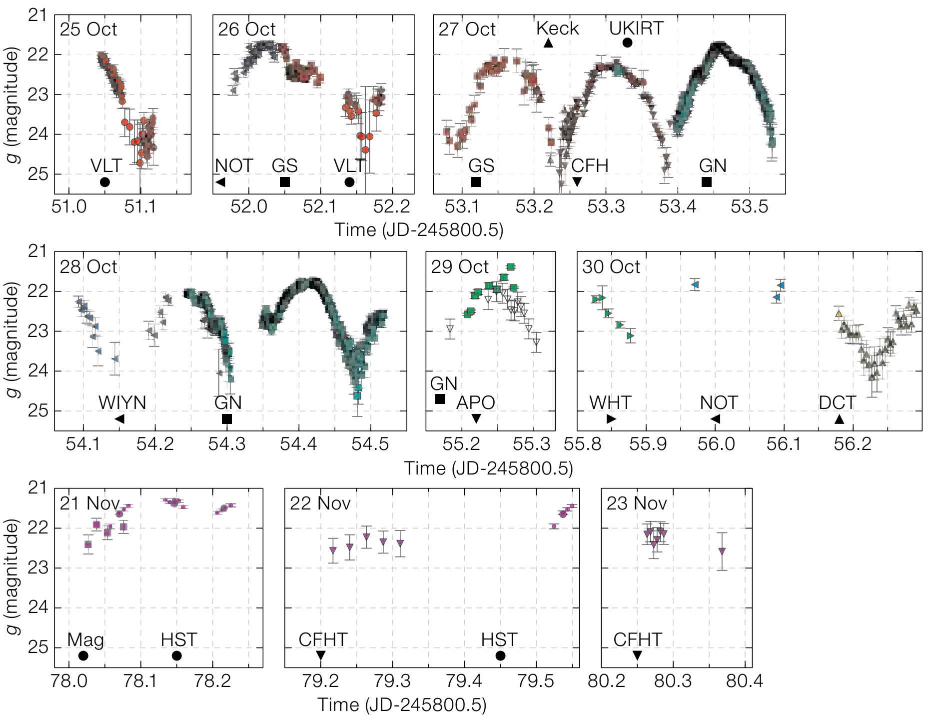

Figure 4. The 2017 lightcurve of `Oumuamua, converted to *g* band and corrected for geometry and light-time travel. The non-periodic variations indicate that the object is in a complex rotation state. These data are consolidated from observations at the VLT, Nordic Optical Telescope (NOT), Gemini South (GS), Keck Observatory, UKIRT, CFHT, Gemini North (GN), WIYN Observatory (WIYN), Apache Point Observatory (APO), William Herschel Telescope (WHT), Discovery Channel Telescope (DCT), Magellan (Mag) and HST (reproduced from Belton et al. 2018).

detectable when considering the ground-based data alone, or using the Hubble data complemented with a few of the first high-quality ground-based images.

We considered a series of hypotheses to explain the non-gravitational acceleration: the Yarkovsky effect — the anisotropic emission of thermal photons by a rotating body produces a small force; friction — drag opposite to the velocity vector; an impulsive force — for instance caused by a collision; a binary or fragmented object — causing a changing offset between the centre of light and the centre of mass; a magnetic effect — if `Oumuamua was strongly magnetised it would interact with the solar wind; and finally, either radiation pressure or cometary-type outgassing — each of which would produce a radial acceleration.

Except for the last two, all of these hypotheses have major flaws and cannot reproduce the observations; several are simply unrealistic in this case. Radiation pressure is observed to have an r^{-2} dependency and has been detected in the orbit of some asteroids, but the observed acceleration would imply an unrealistic bulk density. `Oumuamua would need to be very large and dark and with a density about three orders of magnitude lower than Solar System objects. Porosity of the body cannot account for this low density, and the alternative of a millimetre-thick hollow shell is unphysical.

To explore whether cometary activity could account for the acceleration, we modelled its thermal evolution using a 3D model, which suggested that any CO ice could have been sublimating over the whole volume of the body (at a temperature ~ 30 K or higher). CO_2 ice would have sublimated over a large fraction of the body (at 80 K or above), and water ice within 1 m of the surface (at 160 K or more). A detailed sublimation model was run to evaluate the gas and dust production rates and the corresponding acceleration. This was successful; the dust and gas production rate can reproduce the magnitude of the acceleration assuming a low-density object (450 kg m^{-3}), an ice-to-dust mass ratio of three and a CO-to-H_2O ratio of 0.25. While these values are at either the low or the high end of the ranges found in comets, they are still realistic. Assuming the dust released was composed of fairly large grains, they would have escaped detection in the deep images. The lack of detection of gas by any observer was also problematic.


ESO/M. Kornmesser

W. Hartmann

Figure 5. Left: Artist's impression of `Oumuamua in the case of a low energy rotation state. Right: Painting by William Hartmann, commissioned by Michael Belton, visualising `Oumuamua's shape for the high-energy rotation state (reproduced with the artist's permission).

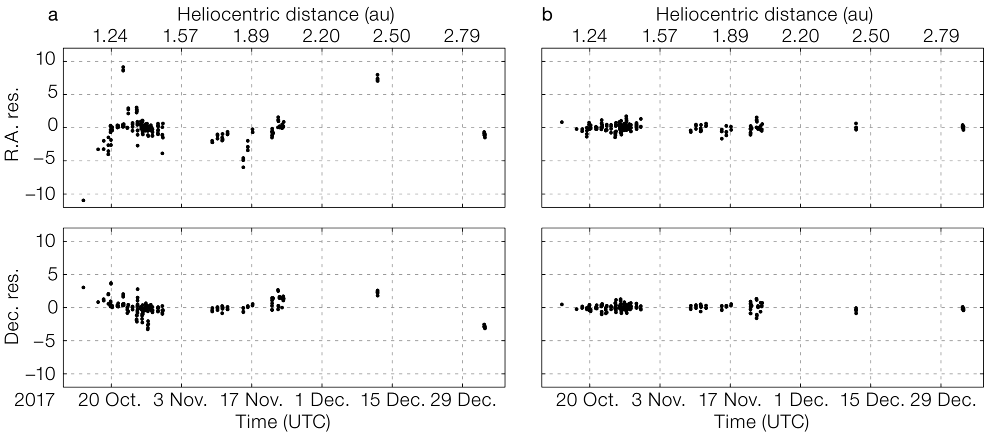

Figure 6. Residuals from the astrometry of `Oumuamua produced by comparing its measured position with the interpolation based on (a) the gravity-only best-fit solution, and (b) a solution including a radial non-gravitational acceleration scaling as r^{-2}. Each point has been scaled to its formal measurement error. Reproduced from Micheli et al. (2018).

If `Oumuamua had similar CN:H_2O abundance ratios to those seen in comets from the Solar System, CN emission should have been seen by spectroscopic observations (Ye, 2017; Fitzsimmons, 2017). While CN is a minor species seen in comets (typically < 1% the abundance of water), it fluoresces strongly in the blue and is often the first gas species detected in comets as they approach the Sun. This means that `Oumuamua as a comet is depleted in CN compared to comets in the Solar System. Overall, we found that cometary activity can account for the measured non-gravitational acceleration, indicating that `Oumuamua is a tiny comet, with unusual but not unrealistic characteristics.

The non-gravitational component of `Oumuamua's motion complicates the quest for its origin. While we can model it accurately over the observed arc, extrapolating it backward in time will require additional care as we do not know when or where the onset of sublimation took place. This results in larger uncertainties in the direction of the incoming asymptote of the orbit. Nevertheless, the search would have been fundamentally flawed if the non-gravitational acceleration had not been discovered. The asymptotic direction of the incoming orbit points towards the current position of Vega. However, to travel from that point would take about 600 000 years. Because of Vega's proper motion, it is not plausible that `Oumuamua was ejected from that system. The incoming velocity of `Oumuamua was very close to the mean motion of stars in the solar neighbourhood. As younger stars tend to have smaller velocity dispersions than older ones, this hints that `Oumuamua could have its origin in a nearby young stellar system. The recent release of Gaia's DR2 catalogue gives us the opportunity to search for it. It is, however, possible that `Oumuamua has been wandering the Galaxy for billions of years.

The discovery of `Oumuamua as an icy body confirms models of formation of our planetary system, and also suggests that similar objects are crossing the Solar System, awaiting discovery. While quantifying this population and predicting their discovery rate are not simple, we estimate that one interstellar object with a diameter of 250 m or more is present at any time within 1 au from the Sun; we caution that this is an order-of- magnitude estimate and assumes no visible cometary activity. The discovery of such objects will enable us to measure their composition, which in turn will make it possible to determine the elemental abundances in extrasolar planetary systems. While we are ready to observe these interstellar objects using ground based and space telescopes, it may be necessary to send a spacecraft after one of them, which comes with many attendant challenges.

Acknowledgements

The observations were made possible thanks to the prompt reaction and support of the directors of ESO, Gemini, CFHT, UKIRT and HST. The studies summarised here have resulted in over 30 papers; our observations have been published in Meech et al., 2017, Belton et al., 2018, and Micheli et al., 2018. Based on observations collected at ESO under Programme ID 2100.C-5008(A) and observations obtained at the Gemini Observatory under Programme GS-2017B-DD-7, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the NSF on behalf of the Gemini partnership.

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Notes

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The Accretion Discs in Hα with OmegaCAM (ADHOC) Survey

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We present the first results of the Accretion Discs in Hα with OmegaCAM (ADHOC) survey, which aims to perform a deep and homogeneous photometric study of pre-main sequence (PMS) stars in a number of nearby star-forming regions. We took advantage of the exquisite image quality and wide-field capabilities of OmegaCAM at the VLT Survey Telescope (VST) to perform multi-band (*ugri* and Hα), deep ($i_{SDSS} <$ 22 mag), homogeneous and wide-field (covering tens of parsecs) observations of eight star-forming regions: the Orion Nebula Cluster, Lupus, Sco-Cen, Haffner 18, Vela OB2, Eta Cha, Chamaeleon and Ophiuchus. Using a robust method to identify PMS stars through their photometric excess in the Hα band, we aim to measure physical parameters (including mass accretion rates) for over 10 000 PMS stars. Direct comparison with low-resolution spectroscopy confirms that the objects with Hα excess emission that are detected photometrically are bona-fide PMS stars. The first results from this study clearly demonstrate the validity of the observational approach to unveiling complex stellar populations in young clusters.

Discs around young stars

The way in which planets form is intimately connected with the properties of the circumstellar discs in which they are born. In particular, the timescale of disc survival sets an upper limit to the timescale of planet formation, becoming a stringent constraint for planet formation theories. It is generally accepted that nearby protoplanetary discs dissipate in a very short time (2–3 Myr; Fedele et al., 2010). This leaves a very narrow window of opportunity for planets to form. All proposed models of planet formation must predict rapid and very efficient formation of planetary systems within a few million years.

Interestingly, the first studies of PMS stars covering areas spanning tens of parsecs surrounding young stellar clusters in the Magellanic Clouds revealed the existence of a significant number of PMS objects with active circumstellar discs between the ages of 10–50 Myr (for example, De Marchi et al., 2013). Such old PMS accretors are only found sporadically in nearby star-forming regions (for example, Ingleby et al., 2014). However, the evidence is mounting that searches for PMS objects in nearby star-forming regions may be biased towards areas of a few square parsecs around regions of high stellar density. In such regions, disc disruption is driven by environmental effects like rapid disc erosion and dynamical interactions (for example, Vincke & Pfalzner, 2016). These conditions are unlikely to be representative of most star formation. It is therefore imperative to extend the studies of disc populations to include wide regions of diffuse star formation, covering several square parsecs.

In a pilot project (Beccari et al., 2015) we used the Wide Field Imager (WFI) at the MPG/ESO 2.2-metre telescope at the La Silla Observatory to study the population of PMS objects in a region of 15 × 15 arcminutes (corresponding to 17 square parsecs at a distance of 2.9 ± 0.3 kpc) around the young star cluster Trumpler 14 in the Carina Nebula. Using a combination of *V* and *I* broad-band photometry, together with Hα narrow-band images (ESO Programme ID 090.C-0647; Principal Investigator: G. Beccari), we identified PMS stars as Hα-excess emitters with photometrically measured Hα equivalent width EW(Hα) > 20 Å, which is a clear signature of accretion from the disc onto the central star (for example, Calvet et al., 2000).

By comparing the position of PMS objects in the colour-magnitude diagram (CMD) with PMS isochrones, we discovered that, in addition to a well-known young population, Trumpler 14 contains objects older than 10 Myr that are still unambiguously undergoing mass accretion and, therefore, must still have circumstellar discs. Moreover, by studying the cumulative radial distribution of PMS stars with respect to the centre of Tr 14, we demonstrate that PMS stars older than 10 Myr are more spatially dispersed than the young PMS objects in the same field, in agreement with their older ages and velocity dispersions of a few km s^{-1}.

All of these findings clearly question the simple picture in which discs dissipate on their own in less than 3 Myr, and hence challenge the common understanding of protoplanetary disc evolution, possibly implying a new scenario for the mechanism controlling planet formation. It is

Figure 1. True-colour image of the Orion Nebula Cluster obtained using OmegaCAM data, with a 59.95 × 46.56-arcminute field of view.

still an open question why these old accreting PMS stars are not yet systematically observed in nearby low-mass star-forming regions. Thus, we decided to perform a deep search for this population using the VST wide-field camera OmegaCAM.

OmegaCAM observations

We took advantage of the wide-field capabilities (1 square degree) of OmegaCAM to carry out a deep ($i_{SDSS} \leq 22$, corresponding to masses $> 0.1\ M_{\odot}$) wide-field study (up to 25 square degrees; > 10pc) of eight star-forming regions in the Galaxy. The observations were distributed over four ESO observing periods for a total of 355 hours using "filler conditions", i.e., exploiting the poorest observing conditions available at the VLT (ESO Programme IDs: 096.C-0730(A), 097.C-0749, 098.C-0850 and 099.C-0474). Most of the regions were observed with the SDSS *ugri* broad-band filters (hereafter referred to simply as *ugri*) and the NB659 (Hα) narrow-band filter. The observations were designed following the same observational strategy adopted by the ESO Public Survey VST Photometric Hα Survey of the Southern Galactic Plane (VPHAS+; Drew et al., 2014): each targeted region was sampled in groups of three overlapping fields, and in each group the fields are contiguous with a footprint close to 3 × 1 square degrees. For each position in the sky we acquired two exposures of 70 seconds in *u* and *g*, two exposures of 25 seconds in *r* and *i* and three images taken with the Hα filter using 150-second exposures.

The entire dataset was fully processed, from the bias, flatfield and linearity correction to the stellar photometry, at the Cambridge Astronomical Survey Unit (CASU). The magnitude for each star was extracted using aperture photometry, adopting an algorithm based on IMCORE[1] and the nightly photometric calibrations were also performed. The astrometrically and photometrically calibrated single-band catalogues are available for download from the VST archive at CASU[2]. Stars lying in the overlap region between adjacent fields were used to adjust residual photometric offsets. The photometric calibration of the final band-merged catalogues was performed against a catalogue of stars from the AAVSO Photometric All Sky Survey (APASS), used as a secondary standard catalogue.

With this new set of observations, we are now able to homogeneously sample the PMS stellar population of each target in an area of tens of square parsecs. As clarified in the previous section, this approach is critical in order to perform an unbiased study of the star formation in nearby regions, and to unveil the properties of the PMS stars showing ongoing accretion in order to eventually establish the existence of old circumstellar discs still feeding the central star. In the following section, we will present surprising and unexpected results obtained for two of the regions that we observed.

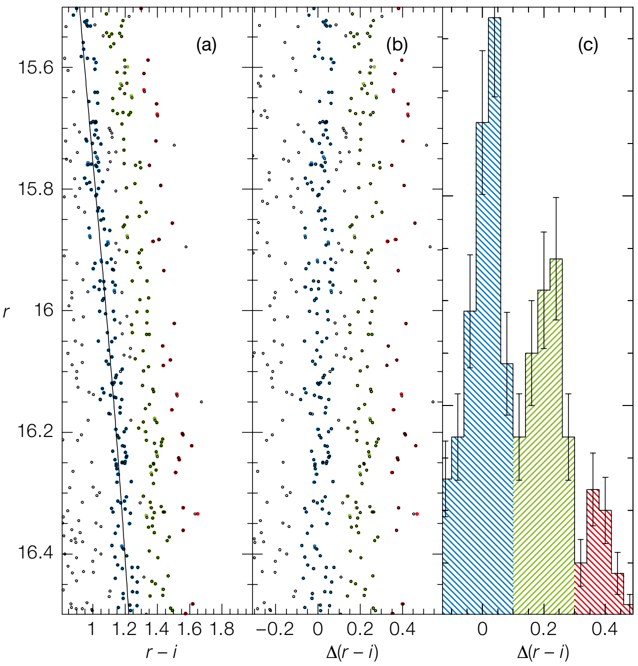

Figure 2. (Left) Colour distribution of the PMS stars in the colour magnitude diagram (CMD) of the central region of the ONC. The black line shows the mean ridge line of the blue population; b) rectification of the CMD shown in panel a); c) histogram of the distance in colour of the PMS stars from the mean ridge line of the bluest population.

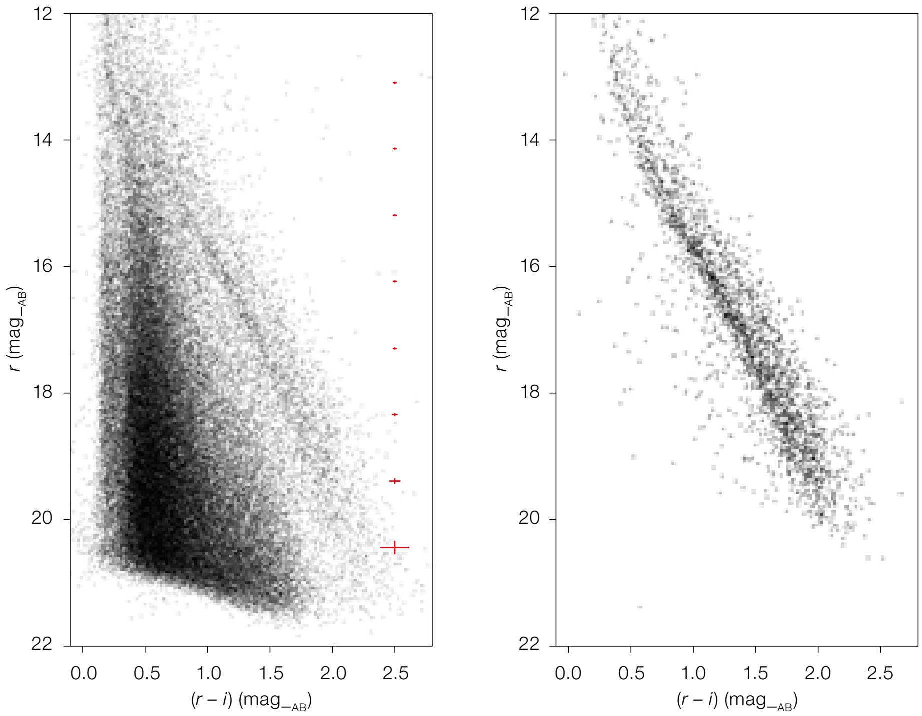

Figure 3. (Below) (Left) CMD of the entire stellar population in the ONC area; (right) stars selected using Gaia DR2 parallaxes around the ONC.

The complex stellar population in the Orion Nebula Cluster

The first results of our ADHOC survey were published in Beccari et al. (2017), and illustrated the potential of our proposed approach. In Figure 1 we show a true-colour image of the Orion Nebula Cluster (ONC) derived from OmegaCAM observations. In Figure 2a, we show a zoomed-in portion of a CMD of stars detected within a radius of 1.5 degrees (11.2 parsecs) from the centre of the ONC. The distance of each star from the mean ridgeline of the main population of PMS stars is shown in Figure 2b. Panel c of Figure 2 shows the histogram of the colour ($r - i$) displacement, and reveals three distinct PMS populations which are well separated in the colour-magnitude diagram.

There are two possible explanations of this feature: a population of unresolved binaries and triple systems with an exotic distribution of mass ratios; or three different age populations. Independent high-resolution spectroscopy supports the scenario of discrete star formation episodes, separated from each other by about one million years. Thanks to the unprecedented precision of available parallax and proper motion measurements thanks to the publication of the catalogue from Gaia Data Release 2 (Gaia DR2; Gaia Collaboration et al., 2018), we now have an exciting new opportunity to characterise the PMS population in the ONC. In the left panel of Figure 3 we show the colour-magnitude diagram of the entire stellar population sampled within a radius of 1.5 degrees around the ONC; in the right panel of the same figure we show the stellar population selected at the distance of the ONC (~ 400 pc) using parallax. The ONC stellar population is identified with unprecedented accuracy. The data confirm the presence of at least two well-separated populations whose spatial distribution (in α and δ space of parallax) and kinematical properties would be hard to explain if the multiple sequences in the colour-magnitude diagram were populated solely by multiple systems (Jerabkova et al., 2018).

The Hα filter provides the ability to identify PMS stars that still host gaseous protoplanetary discs from which accretion is still ongoing. Accretion in PMS objects can be identified by searching for excess Hα emission. In Figure 4, we show the dereddened $(r - i)_0$ *vs.* $(r - \mathrm{H}\alpha)_0$ colour-colour diagram of the stars whose membership of the ONC has been verified using Gaia DR2 (grey circles). We use the median $(r - \mathrm{H}\alpha)_{\mathrm{ref}}$ de-reddened colours of stars with a small combined photometric uncertainty of less than 0.05 magnitudes in the *r*, *i*, and Hα bands as a function of $r - i$ to define the reference template with respect to which excess Hα emission can be identified (solid line).

We selected a first sample of stars with excess Hα emission by considering all those with $\Delta(\mathrm{H}\alpha) = (r - \mathrm{H}\alpha)_{\mathrm{star}} - (r - \mathrm{H}\alpha)_{\mathrm{ref}}$ at least four times larger than the photometric uncertainty on the $(r - \mathrm{H}\alpha)_{\mathrm{star}}$ colour. Then we calculated the equivalent width of the Hα emission line, EW(Hα), from the measured colour excess using Equation 4 of De Marchi et al. (2010). We finally considered those objects with EW(Hα) > 20 Å (black stars in Figure 4) as bona fide accreting PMS stars. This allows us to safely remove possible contaminants from our sample, such as older stars with chromospheric activity and Ae/Be stars (White & Basri, 2003). Figure 4 shows the spectra of three stars identified as Hα-excess emitters via our photometry (shown as red, blue and black circles on the colour-colour diagram). The spectra were acquired with the ESO Faint Object Spectrograph and Camera 2 (EFOSC2) at the New Technology Telescope during the second ESO/NEON (Network of European Observatories in the North) La Silla Observing School (Selman et al., 2018). The three spectra show a prominent Hα emission line. Despite differences in the values of the spectroscopically measured EW(Hα) (indicated on the side of each spectrum) and the photometrically measured ones (horizontal dashed lines indicate different values of EW(Hα) in the colour-colour diagram) — mostly due to intrinsic Hα variability — this comparison proves the ability of our photometric approach to identify stars with Hα emission (also see Barentsen et al., 2011).

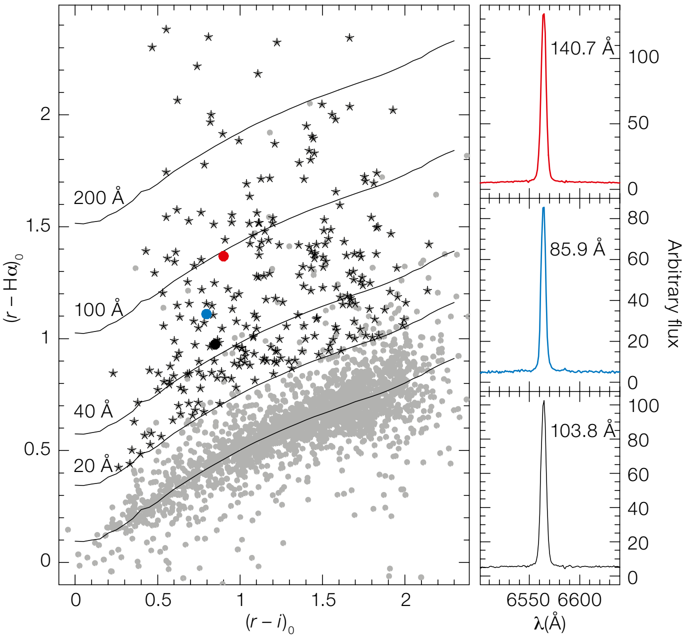

Figure 4. Reddening-corrected colour-colour diagram of the ONC members (grey open circles). The solid line represents the median $(r - \mathrm{H}\alpha)_0$ colour of stars and is defined as the locus of stars without Hα excess emission. The stars with Hα excess emission are shown with black stars. The spectra zoomed on the Hα line for three stars showing Hα in emission are shown on the right.

The Vela OB2 region

Following the successful ONC study, we also investigated the stellar population in the Vela OB2 region. Recently, Jeffries et al. (2014), using radial velocity measurements from the Gaia-ESO Survey (GES; Gilmore et al., 2012), found that the ~ 10 Myr cluster of stars around the Wolf-Rayet star γ^2 Vel (known as the γ Vel cluster) is in fact composed of two coeval but kinematically distinct populations, A and B. Notably, Sacco et al. (2015) performed a similar study of the stellar population around NGC 2547; a ~ 35 Myr star cluster located two degrees to the south of γ Vel. Using the radial velocity distribution of the sampled stars they could identify the main cluster together with a kinematically distinct population whose radial velocity distribution closely resembles the population B discovered in γ Vel.

Together, these results imply that the stars observed by Jeffries et al. (2014) in γ Vel B and Sacco et al. (2015) in NGC 2547 B belong to the same young, low-mass stellar population spread over at least several square degrees in the Vela OB2 complex. In order to investigate the stellar population of the region, we used a 12 × 5 square degree photometric catalogue in the *r*, *i* and Hα filters (obtained as part of the ADHOC survey), combined these with accurate radial velocities from GES, and astrometric information available from Gaia DR2. We first selected the stars in parallax, in the range $2.2 < \varpi < 3.9$ milliarcseconds; i.e., around the location of γ^2 Vel. We only considered stars that have a relative parallax uncertainty smaller than 10%. We then applied the data-clustering algorithm, Density-Based Spatial Clustering of Applications with Noise (DBSCAN; Ester et al., 1996), in order to simultaneously identify clusters in right ascension (α) and declination (δ), and in proper motions μ_α and μ_δ. The result is shown in Figure 5 and is, once again, surprising — revealing six clusters in the region! Two of the clusters were known — γ Vel and NGC 2547 (marked as Cl4 and Cl3, respectively in Figure 5) — while the other four clusters were previously unknown. Using accurate OmegaCAM photometry and the precise parallaxes from the Gaia DR2 catalogue, we conclude that the stellar "B" populations originally discovered in γ Vel and NGC 2547 (Jeffries et al., 2014; Sacco et al., 2015) actually belong to a complex set of clusters, well separated into two coeval groups of 10 and 30 Myr respectively, and overlapping in space over an area of almost 100 square parsecs.

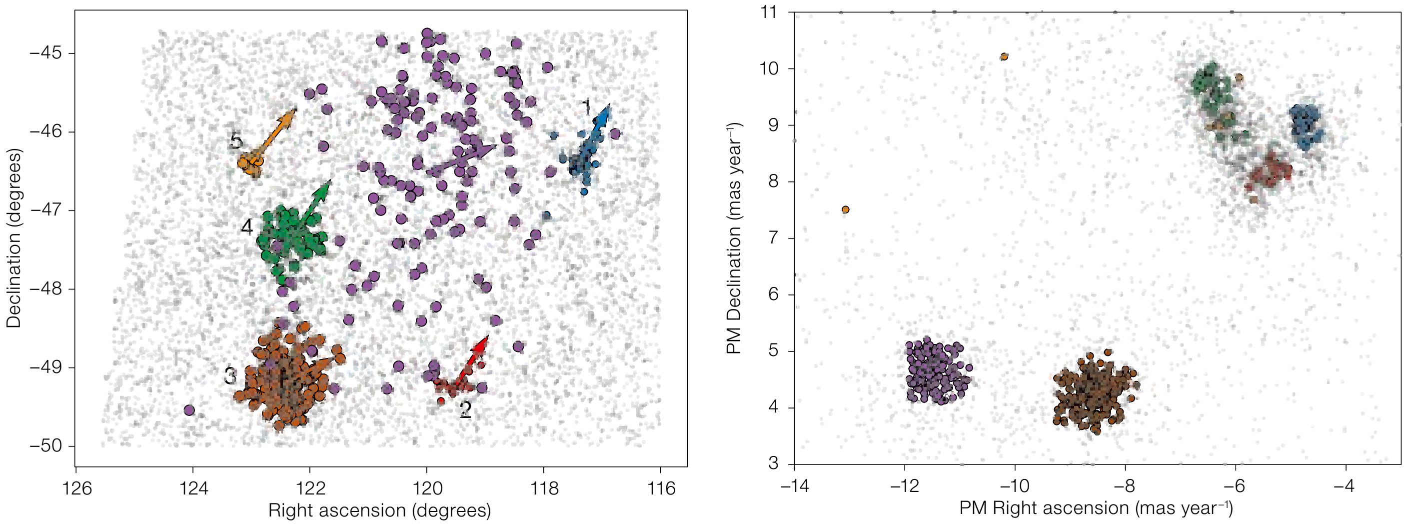

Figure 5. (Above left) identification of clusters in right ascension and declination. Cluster 1 is shown in blue, 2 in red, 3 in brown, 4 in green, 5 in orange and 6 in violet. (Above right) identification of clusters in proper-motion space.

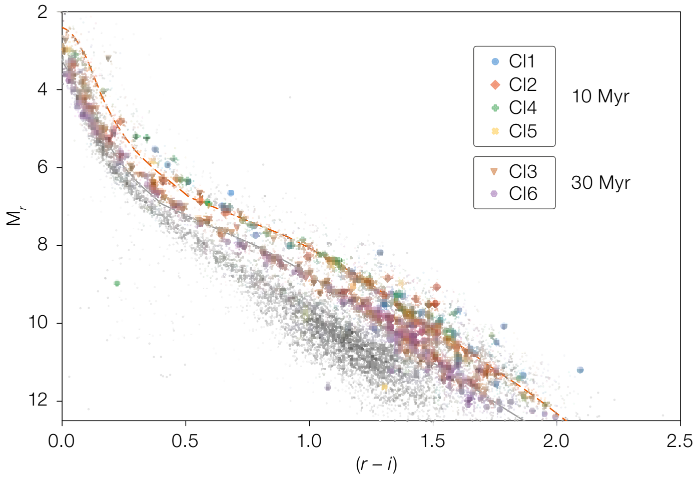

Figure 6. (Left) The colour-magnitude $(r - i) - M_r$ diagram for all stars in the OB2 Vela complex with $2.2 < v < 3.9$ and $\sigma v/v < 0.1$ (black dots) together with the stars of the clusters.

Conclusions

The first results obtained using the ADHOC data clearly demonstrate the importance of wide-field multiband homogeneous data sets covering tens of parsecs, in order to unveil the hidden secrets of the complex stellar populations in young star clusters. While the ADHOC survey offers the opportunity to identify PMS stars through the Hα filter, it is clear that the availability of accurate astrometric data from Gaia DR2 can be efficiently combined to disentangle the stellar populations in 3D. Hence, the primary goal of the ADHOC survey remains the identification of candidate long-lived accreting discs in nearby star-forming regions, which implies that planet formation could proceed on much longer timescales than previously thought. At the same time, we have also proved that the use of wide-field facilities is critical to unveiling the existence of multiple events of star formation in massive and extended star-forming regions. Establishing whether age spreads in the PMS population of clusters are common will have profound implications for theories of star cluster formation, for the meaning and determination of the initial mass function, and for the general assumption that clusters are simple stellar populations.

Acknowledgements

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Sacco, G. G. et al. 2015, A&A, 574, L7
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Links

[1] Software publicly available at CASU: http://casu.ast.cam.ac.uk

[2] VST archive at CASU: http://casu.ast.cam.ac.uk/vstsp/

[3] Gaia Data Processing and Analysis Consortium: https://www.cosmos.esa.int/web/gaia/dpac/consortium)

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Life at the Extremes — Massive Star Formation and Evolution in the Galactic Centre

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Many galaxies host pronounced (circum)nuclear starbursts, fuelled by infalling gas. Such activity drives the secular evolution of the nucleus and may also generate super winds which enrich the interstellar and intergalactic medium. Given the intense radiation fields and extreme gas densities present within these nuclear regions, star formation may not occur in the same manner as it does in more "quiescent" regions of the galactic disc. To address this uncertainty, we are driven to investigate the only circumnuclear starburst where individual stars and star clusters may be resolved. Its proximity permitting dissection at resolutions a hundred times better than available for M31, the Galactic Centre provides us with a unique laboratory to study both stellar and galactic evolution.

The circumnuclear starburst of the Milky Way

The central few hundred parsecs of the Milky Way host the most vigorous ongoing star formation activity within the Galaxy and, with a rich population of young massive stars and clusters, it appears that this activity has been under way for at least several Myr (see, for example, Figure 1). Raw material for star formation is abundant, with up to 10% of the Galaxy's molecular gas ($2–6 \times 10^7\ M_\odot$; e.g. Bally et al. 2010) found within the Central Molecular Zone (CMZ), spanning -1 to $+1.5$ degrees of Sgr A*. Somewhat counter-intuitively, and despite these extensive molecular reserves, the star formation rate within the CMZ is actually lower than expected based on the analysis of nearby star-forming regions in the quiescent galactic disc. A common assumption is that this is a result of the extreme conditions within the CMZ, where the density, pressure, temperature, velocity dispersion and radiation field are all significantly greater than elsewhere in the Milky Way (Barnes et al., 2017 and references therein).

Revealing the underlying physical reasons for this discrepancy has implications for a number of fields, not least because the conditions present within the CMZ potentially replicate those in starburst galaxies out to redshifts, $z \sim 1–3$, as well as in the circumnuclear regions of local, quiescent systems. As a consequence, the CMZ has been the subject of numerous millimetre- and radio-wavelength studies aimed at constraining the properties of the stellar nurseries hosting the earliest phases of

Figure 1. False-colour montage of Hubble Space Telescope (NICMOS) and Spitzer (IRAC) observations of the centre of the Galaxy, spanning ~ 47 pc × 22 pc. Sgr A* and the nuclear star cluster are at the centre of the bright spiral of ionised gas to the bottom right, the Arches cluster is the bright compact source located within the eponymous arcs of emission to the top left and the Quintuplet cluster is centred within the wind-blown bubble to the bottom left, directly adjacent to the compact rectangular ejection nebula associated with the Pistol star (V4647 Sgr).

star formation (for example, Barnes et al., 2017 and Ginsburg et al., 2018). However, such an approach yields an incomplete picture of star formation in the CMZ, since it is not sensitive to the products of this physical process. In particular, one would want to determine the recent star formation history of the CMZ, and whether the initial mass function (IMF) that results from the mode(s) of star formation favoured within the region is consistent with that of the Galactic disc, or alternatively requires a top-heavy IMF biased towards massive stars. These are important questions since massive stars and supernovae play a disproportionate role in secular galactic evolution via the deposition of chemically processed material, and both mechanical and radiative feedback. This, in turn, seeds and initiates the next generation of star formation as well as driving large-scale super winds that enrich the intergalactic medium.

As a consequence, a parallel observational effort to construct a stellar census for the CMZ has been undertaken at infrared wavelengths in order to overcome the significant interstellar extinction towards the Galactic Centre. These efforts have distinguished four components in the population of massive stars within the CMZ (Figure 1). The circumnuclear cluster associated with Sgr A* is the most well studied of these and comprises an extended stellar cusp of predominantly low-mass stars (integrated mass of ~ 3 × 10^7 $M_\odot$ within a half light radius of 3–5 pc) within which is a compact cluster comprising massive OB supergiants and hydrogen-depleted Wolf-Rayet (WR) stars. Extensive observations suggest an age of approximately 4–8 Myr and an integrated mass of > 10^4 $M_\odot$ for this stellar aggregate. Critically, this raises the possibility of a top-heavy or "flat" IMF (for example, Bartko et al., 2011 and references therein).

Two further young massive clusters — the Arches and Quintuplet — are found within the CMZ (Figures 1 and 2). Infrared spectroscopy of the cluster members (see Martins et al., 2008 and Liermann et al., 2009) suggests both aggregates are young (2–5 Myr) and massive (> 10^4 $M_\odot$), with potentially top-heavy IMFs. A final population of apparently isolated massive stars has also been identified throughout the CMZ (for example, Dong et al., 2011), although the properties of this cohort are less well characterised than those of the clusters and it is likely that the current census is highly incomplete.

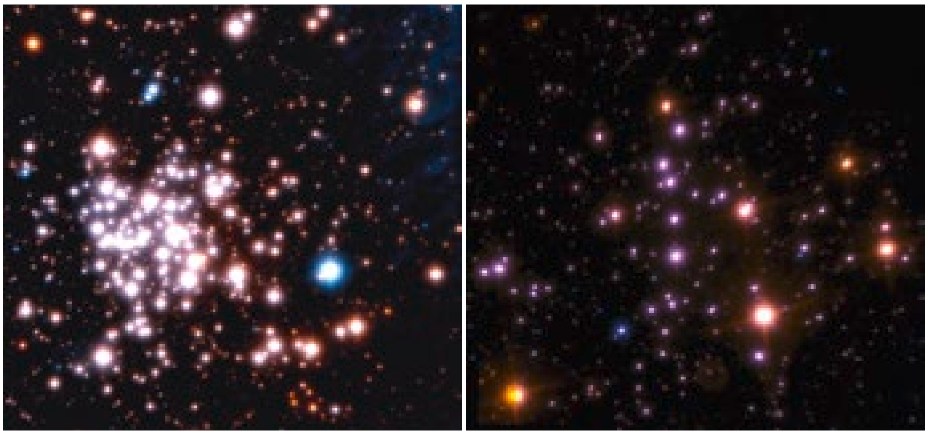

Figure 2. Near-infrared (*H*- and *K*-band) false-colour images of the Arches (left) and Quintuplet (right) clusters. Reproduced here by courtesy of Andrea Stolte.

However, it has recently become apparent that there may be systematic problems with the current estimates of cluster properties. Existing quantitative studies of both clusters are prone to uncertainties in the extinction law, whereby alternative formulations result in differences in the bolometric luminosities of cluster members of up to ~ 0.6 dex. When combined with the effects of differential reddening, this casts considerable doubt on current ages derived from isochrone fitting as well as the construction of mass-luminosity functions from which IMFs are derived (Clark et al., 2018a,b). Secondly, studies to date have been based on single-star evolutionary models, but a combination of observational and theoretical studies over recent years has highlighted the importance of a binary channel. Indeed, motivated by the suggestion of non-coevality for the Arches and Quintuplet, a reinterpretation of existing data by Schneider et al. (2014) suggests that both clusters may host a binary fraction approaching unity and that they are considerably older than has been assumed.

Resolving these issues is important, since the Arches and Quintuplet are (potentially) young and massive enough to have formed stars of >> 100 $M_\odot$ that have not yet undergone core-collapse; Groh et al. (2013) suggest that non-rotating 120 $M_\odot$ stars will experience SNe after 3 Myr. Determining the properties and the formation or evolutionary channels of these stars is vital to understanding the progenitors of both electromagnetic and gravitational-wave transients, as well as quantifying the radiative and mechanical feedback from young massive clusters. Such massive stars must also be the precursors of the black holes inferred to be present within the population of accreting X-ray binaries recently identified within the CMZ by Hailey et al. (2018) as well as the young, highly magnetised neutron star (or magnetar) SGR J1745-29 (Kennea et al., 2013). Moreover, they may provide an explanation for the high-energy emission (> 100 GeV) coincident with the inner 200 pc of the Galactic centre (Aharonian et al., 2006). Whilst exotic explanations such as the annihilation of dark matter have been proposed, a more prosaic explanation in which the emission arises as a result of the production of cosmic rays via either supernovae and/or the collision of the winds of very massive stars may also be viable (for example, Aharonian et al., 2018), assuming there are sufficient stars to support such physical mechanisms.

A VLT and HST survey of the CMZ

Central to these questions is the production of a reliable census of massive stars within the CMZ and the subsequent quantitative characterisation of their physical properties (for example, luminosity, mass-loss rates and initial mass). To achieve this goal we have undertaken multi-epoch near-infrared *H*+*K*-band spectroscopic observations of the Arches, Quintuplet and diffuse massive stellar population of the

CMZ with the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) and the *K*-band Multi-Object Spectrograph (KMOS) on the Very Large Telescope (VLT). The multi-epoch component of our survey, initially focussed on the Arches cluster, serves two purposes: allowing for the identification and characterisation of binary systems; and permitting us to reach deeper into the fainter, lower-mass cohort via the stacking of multiple individual exposures.

Additional spectroscopic data from the ESO archive expanded the temporal baseline of observations, increasing the sensitivity to long period systems, while multi-epoch photometric observations of the Arches cluster with NACO permitted a search for eclipsing systems from which dynamical stellar masses could be extracted. Observations from the NICMOS and WFC3 instruments on the Hubble Space Telescope (HST) enabled the construction of a near-infrared spectral energy distribution for the stars in question which, when combined with spectroscopic data, permits their physical properties to be determined via comparison to synthetic spectra derived from non-local thermal equilibrium model atmospheres. Further details of all observational datasets, reduction techniques and quantitative analysis may be found in Clark et al. (2018 a,b) and Lohr et al. (2018). In this article, we present some of our preliminary results and outline the new questions and consequent future research goals that they inspire.

The Arches cluster

The motivations for studying the Arches are compelling; as the youngest, densest and most massive young massive cluster in the CMZ it provides a unique test of theories of star and cluster formation under extreme physical conditions as well as our understanding of the physics of the most massive stars in our Galaxy. Martins et al. (2008) provided single-epoch VLT/SINFONI spectra of 28 cluster members, which comprise both very luminous H- and N-rich WRs (WN7-9ha) and mid-O supergiants. The analysis suggested that the cluster might not be coeval, although Schneider et al. (2014) found that this conclusion could be avoided if an extreme binary fraction was assumed, with the most luminous objects being the rejuvenated products of binary-driven mass transfer and/or mergers. However neither study fully accounted for the effects of an uncertain reddening law and significant differential extinction across the cluster. Once these are incorporated, the uncertainties in the stellar luminosities become so great that isochrone fitting becomes challenging, as do quantitative conclusions regarding coevality (cf. Martins et al., 2008).

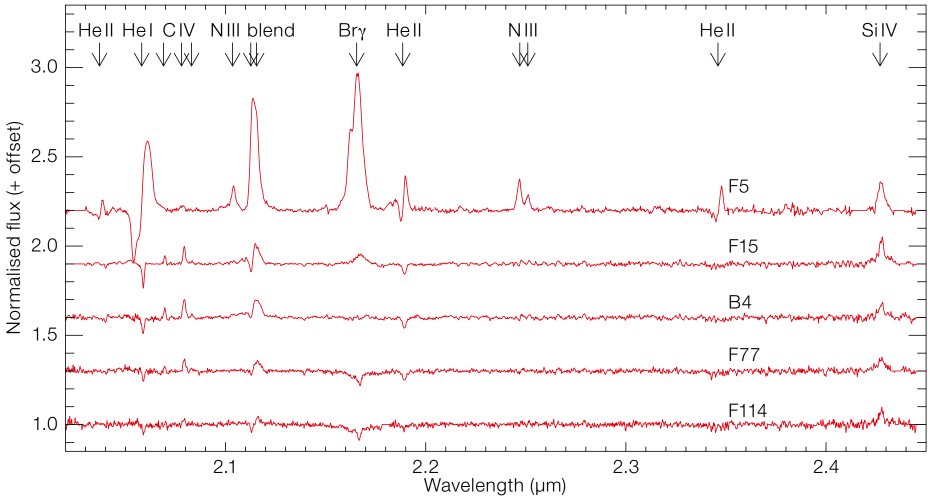

Figure 3. Montage of spectra of Arches cluster members, ranging from WNLha stars (F5) through mid-O hypergiants and supergiants (F15 and B4) and finally to mid-O giants and main sequence stars (F77 and F114); this is the first time such stars have been identified within the cluster.

Our SINFONI and KMOS spectroscopy has enabled us to classify 88 stars within the Arches cluster. This unprecedented census has revealed eight luminous O-type hypergiants — a substantial increase on the two previously identified by Martins et al. (2008) — suggesting a smooth evolutionary progression from the O supergiants through to the H- and N-rich WRs; see Figure 3. WNLh and WNLha are Wolf Rayet stars with spectra dominated by comparatively low excitation lines of H, He and N. The a in WNLha denotes the presence of absorption lines. We do not have to invoke binary interaction to explain the production of WNLh or WNLha stars (cf. Schneider et al., 2014), although some of these stars may still have formed via this route.

Secondly, our stacked observations were sufficiently sensitive to spectroscopically identify both giants and main sequence stars within the cluster for the first time. In particular, the apparent absence of stars earlier than spectral type O5-6 suggests a conservative estimate for the main sequence turnoff mass of ~ 40 $M_{\odot}$ and a likely age of ~ 2–3 Myr for the Arches — a conclusion bolstered by the lack of H-depleted WRs within the cluster (Clark et al., 2018a). This is an important finding since it is not expected that supernovae will have occurred in a cluster of this age (cf. Groh et al., 2013) and hence the most massive stars that formed initially should still be present.

Is this assertion borne out by observations? VLT NACO observations suggest that one of the most intrinsically luminous cluster members — the W8-9ha star F2 — is an eclipsing binary with a period of 10.483 ± 0.002 d (Lohr et al., 2018). Moreover, the light curve reveals the orbit to be slightly eccentric with a pre-contact morphology, indicating that substantive interaction/mass-transfer has yet to occur. Close inspection of the spectra reveals it to be a double-lined system with a O5-6 hypergiant secondary component. Simultaneously modelling both the light-curves and the radial velocity curves (Figure 4) yields current dynamical masses of 82 ± 12 $M_{\odot}$ and 60 ± 8 $M_{\odot}$, respectively. However, given the age that we infer for the Arches, both components will have lost a large quantity of mass via their powerful stellar winds. Comparison with theoretical predictions suggests an initial mass of >> 120 $M_{\odot}$ for the primary, implying that it was originally one of the

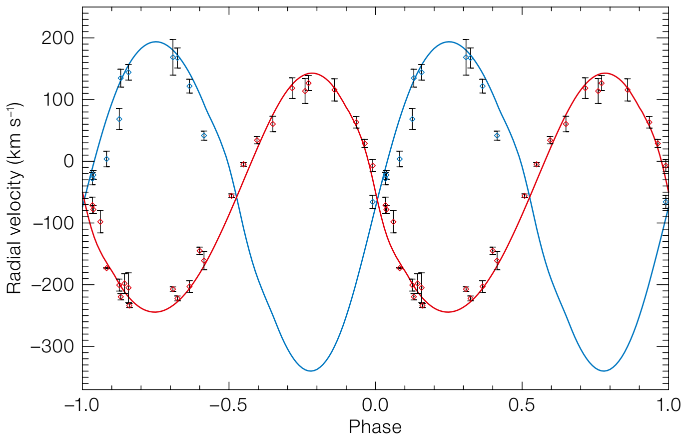

Figure 4. Radial velocity curves for the massive eclipsing binary F2 (WN8-9ha [primary] + O5-6Ia^{+} [secondary]) phased on the 10.483 ± 0.002 day orbital period. The red and blue points — and best fit lines — correspond to the primary and secondary, respectively.

most massive stars yet identified within the Galaxy, if not the most (Lohr et al., 2018).

Critically, stars with such high initial masses appear mandated by the properties of the coalescing black hole binaries detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO). This immediately begs the question of how many similarly massive binaries are present within the Arches. Prior detections of hard, bright X-ray emission from the eclipsing binary F2 and three further cluster WNLha stars suggests that they may be common, since the most natural explanation for this phenomenon is that all four systems are colliding-wind binaries, whereby the X-rays arise in shocks generated in the wind collision zone (Wang et al., 2006). We can test this assertion via the multi-epoch component of our spectroscopic survey, which is ongoing (ESO Programme ID 0101.D-0141). Preliminary results are suggestive of radial velocity variability in the remaining three X-ray bright sources (F6, F7 and F9), while a number of other objects exhibit substantial radial velocity modulation that is probably induced by binary motion (for example, F15 [O6-7Ia^{+}], F25 [O4-5Ia] and F35 [O4-5Ia]; Lohr et al., in preparation).

The Quintuplet cluster

Results from our Arches survey clearly show that conditions within the CMZ are amenable to the production of very massive binaries that may serve as the progenitors of coalescing black holes. However, this would rely on the retention of sufficient mass at the point of core collapse, and the Arches is too young for stars to have reached this point. Could the Quintuplet serve as an appropriate testbed for this hypothesis, since the literature consensus is that it appears older than the Arches? Once again, uncertain differential reddening casts doubt upon current age estimates, while an additional complication is the possibility of non-coevality, as suggested by the highly diverse nature of possible members (Liermann et al., 2009; Schneider et al., 2014).

In order to address the issue of coevallty we combined our new KMOS spectroscopic dataset with a re-analysis of archival SINFONI data (Liermann et al., 2009); together they yield classifications for 71 stars (Clark et al., 2018b). The most striking finding was that the cluster appears far more homogeneous than previously assumed, dominated by late-O supergiants and the richest population of early-B hypergiants, Luminous Blue Variables (LBVs) and cool N-rich WN9-11h stars within the Galaxy (Figure 5). The presence of H-free and C-rich (WC8-9) WR stars, which are not observed in the Arches cluster, clearly indicates that the Quintuplet is older.

Comparing the properties of the post-main sequence cluster members that retain hydrogen in their atmospheres to the simulations of Groh et al. (2014) reveals a spectacular consistency, suggesting that the progenitors of this subpopulation are coeval and likely derive from stars with initial masses of ~ 60 $M_{\odot}$. This would then imply that the H-free WR cohort result from yet more massive stars (>> 80 $M_{\odot}$), although mass-loss due to stellar winds will have rendered the current masses of both cohorts significantly below these values. A cluster age of 3–3.6 Myr is inferred for the Quintuplet and is of considerable interest, since the first supernovae are expected to occur at this time (Groh et al., 2013); as a consequence, their immediate progenitors, derived from the most massive stars

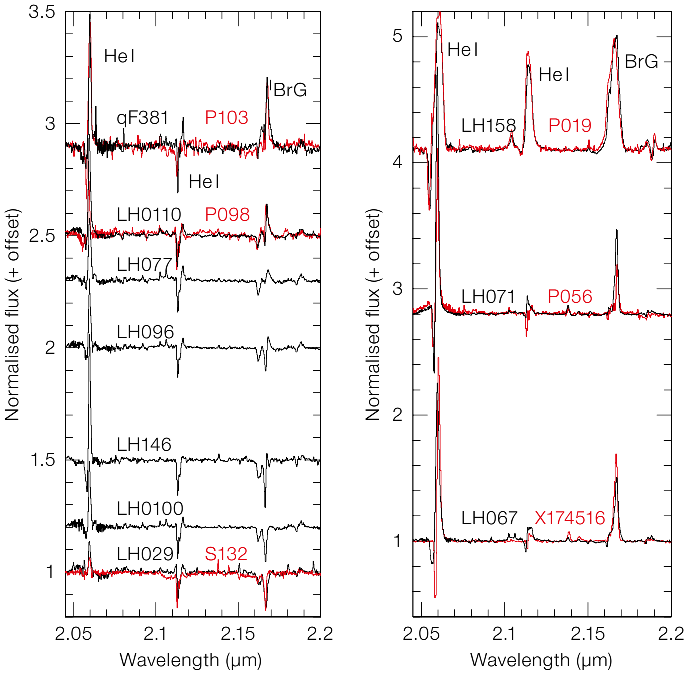

Figure 5. Montage of spectra of early-B hypergiants (left panel) and WN9-11h stars (right panel) with prominent lines indicated. Spectra of members of the Quintuplet cluster are presented in black, while those of the isolated diffuse population of the Galactic centre are in red.

present, should also be identifiable and amenable to analysis.

However, there are two stellar cohorts that do not initially appear to be accommodated by this hypothesis. The first comprises five stars that appear directly comparable to the younger O-type hypergiants and WNLha stars found within the Arches (Figure 6). This doesn't necessarily imply non-coevality for the Quintuplet, as this population could have evolved via a binary channel, whereby they are either secondaries that have been rejuvenated by mass-transfer from the primaries (c.f. Schneider et al., 2014), or else they are the post-interaction primaries viewed after substantial mass loss (cf. Clark et al., 2014). Unfortunately, we currently lack the multi-epoch data to test this hypothesis.

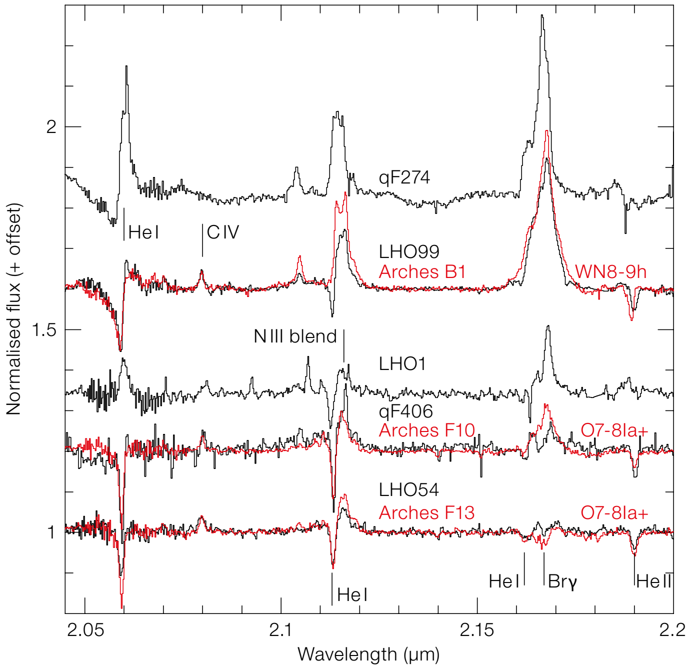

Figure 6. Montage of spectra of WN8-9ha and mid-late O hypergiant stars within the Quintuplet cluster (black) and direct comparators located within the Arches (red).

The second, and more challenging, finding is that the properties of the H-free WRs within the cluster are very different from the predictions of Groh et al. (2014, private communication), who suggest they should be comparatively luminous and massive stars with high-excitation spectral features (i.e., WNE, WCE and WO stars). WNE, WCE and WO stars belong to WR spectral subtypes, with spectra dominated by nitrogen, carbon and oxygen, respectively. Our current observations should be sensitive to such WNE and WCE stars, yet none are observed, with WCL WR stars dominating instead. Moreover, modelling one such WCL star suggests that it is substantially less massive than predicted (~ 10–12 *vs* ~ 19–31 $M_{\odot}$; Najarro et al., 2017, Clark et al., 2018b). Given that such stars and their short-lived WO descendants are expected to be the immediate progenitors of supernovae, these observations appear to challenge our understanding of the final phases of massive star evolution, and with it our predictions for the properties of the post-core collapse relativistic remnant.

The diffuse stellar population of the CMZ

The final CMZ stellar cohort we observed with KMOS was the population of apparently isolated stars. These are important for two reasons: firstly they appear numerous and so any stellar census compiled to quantify the total mechanical and radiative feedback from massive stars in the CMZ must account for them; secondly their origin is highly uncertain — did they form in isolation or were they instead located within a cluster before either being ejected (via a supernova kick or dynamical interaction) or having their natal aggregate dissolve into the field owing to tidal forces? In this regard the 2.8 × 2.8 arcsecond field of view of the KMOS IFUs is invaluable, since it allows us to search for nearby massive companions that might be the remnants of such primordial clusters (c.f. the infrared source GCIRS 13E within the nuclear star cluster).

Analysis of these data is currently underway, but it is already striking that no such remnant aggregates have been detected. A number of new isolated massive stars have been identified with diverse spectral classifications. However, it is notable that a significant proportion have spectral properties entirely consistent with membership of either the Arches or Quintuplet; this is exemplified by comparison of field B hypergiant and WN9-11h stars to those within the Quintuplet (Figure 5). In conjunction with radial velocities determined from these data, proper motions derived from multi-epoch HST observations (Principal Investigator: Lennon, Programme IDs: 13771 and 12915) will help constrain the ultimate origins of these stars and consequently improve our understanding of star and cluster formation (and dissolution) within the extreme environment of the Galactic Centre.

A synthesis of observations and future prospects

In combination with HST photometry, the unique spectroscopic capabilities afforded by SINFONI and KMOS on the VLT have allowed us to make substantial progress in understanding the properties of the massive stars found within the CMZ. The observations outlined here have answered, or are primed to resolve, many of the questions we initially asked, but have also posed many more. At the most fundamental level, a synthesis of spectroscopic and photometric data will allow the quantitative determination of the properties of a statistically significant (> 200) population of very massive (from about 40 to over 120 $M_{\odot}$) stars at every stage of their post-main-sequence evolution.

Critically, this includes the largest ever sample of short-lived hypergiant, LBV and WN9-11h stars — evolutionary phases that have been implicated in transient mass-loss episodes which are so extreme that they define their subsequent evolution. Moreover, the discovery of a rich binary population within the Arches and possible products of interaction within the Quintuplet together emphasise the importance of such an evolutionary channel. Clearly, constraining the binary population of the Quintuplet is a key observational goal in order to facilitate an understanding of the interaction.

Better defining both single and binary star evolutionary channels is also central to understanding the nature of the final post-core-collapse end points of massive stars. This is especially important given the apparent discrepancy between theoretical predictions and observations of the Quintuplet regarding the nature of supernova progenitors. Specifically, if all of the most evolved stars within the cluster, which must have evolved from very massive (>> 100 $M_\odot$) progenitors, are of masses similar to that of Q3 (10–12 $M_\odot$; Najarro et al., 2017) then it is difficult to see how black holes of masses comparable to those implicated in GW150914 (35 + 30 $M_\odot$) could form in high-metallicity conditions such as those inferred for the CMZ.

Finally, considering the CMZ as a coherent physical entity, the completion of our census and subsequent modelling will quantify feedback from the massive star cohort and hence determine whether it could be responsible for the high energy (> 100 GeV) emission associated with the CMZ (Aharonian et al. 2006), amongst other phenomena. We will determine cluster ages and IMFs (and the location of a high-mass cut-off to the IMF if present), and consequently ascertain whether star formation in such extreme conditions is biased to the formation of high-mass rather than low-mass stars. When combined with data on the isolated stellar component, we will be able to build a detailed picture of the mode(s) and results of star formation in the CMZ over the recent past; an unobtainable goal for any other circumnuclear starburst.

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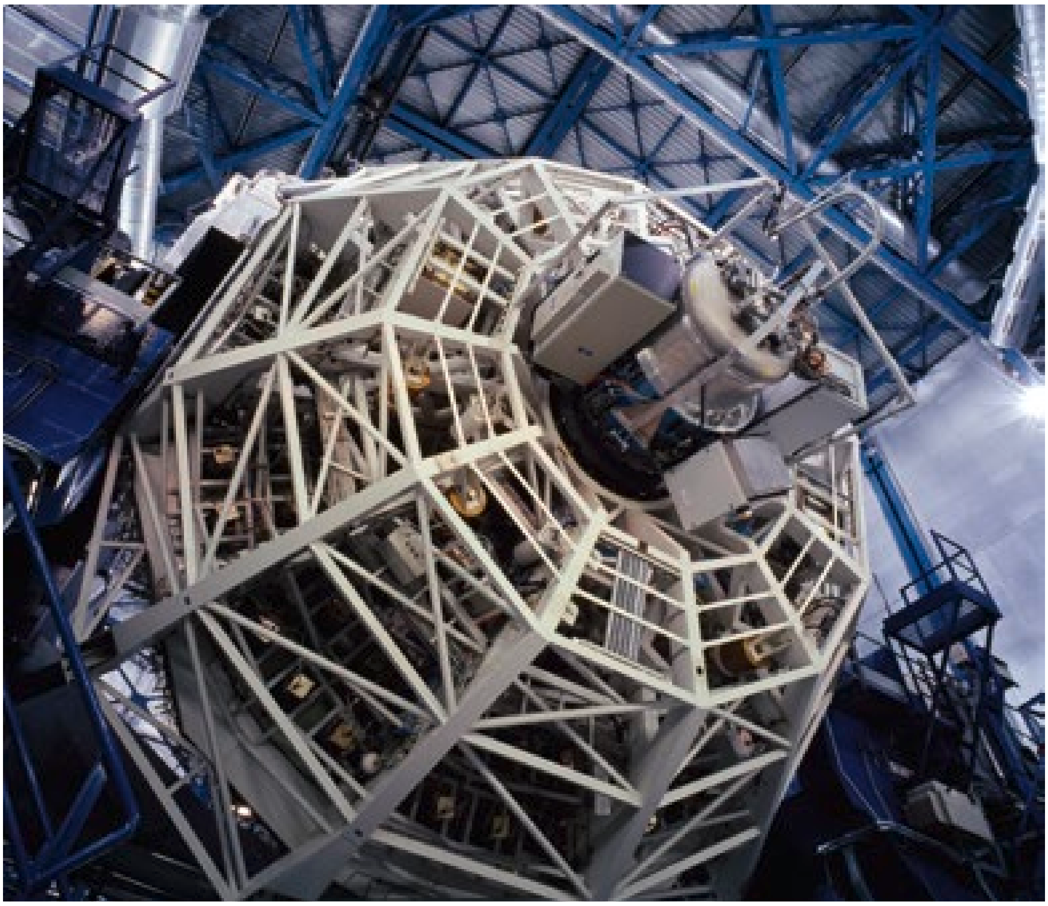

The SINFONI integral-field telescope is mounted on Yepun, the fourth VLT Unit Telescope.

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Investigating the Formation and Evolution of Massive Disc Galaxies with the MUSE TIMER Project

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The Time Inference with MUSE in Extragalactic Rings (TIMER) project is a survey using the integral-field spectrograph Multi Unit Spectroscopic Explorer (MUSE) on the VLT to study 24 nearby barred galaxies with prominent central structures, such as nuclear rings or inner discs. One of our main goals is to estimate the cosmic epoch when galaxy discs settle, leading to the formation of bars. This is also the onset of a phase in the history of the Universe during which secular evolution processes in galaxies become important. We illustrate the quality of the data with some first results and describe the legacy potential of the survey.

Timing a phase transition in galaxy evolution

In the nearby Universe, discs of massive spiral and lenticular galaxies show orderly dynamics, dominated by differential rotation and a relatively smooth rotation curve. However, this has not always been the case. At earlier cosmic epochs, at redshifts $z \sim 1–2$, discs were characterised by turbulent dynamics and a clumpy, irregular structure (for example, Förster Schreiber et al., 2006; Law et al., 2009). When and how did this transition happen? When and how do galaxy discs settle dynamically? The main goal of the TIMER project is to answer these questions.

We look for answers by investigating the archaeological evidence in nearby barred galaxies. Theoretical work suggests that bars can only form after the dynamical settling of the disc, or at least part of it. In addition, the formation of the bar will often happen a few hundred million years after the disc settles. Furthermore, on a similar timescale after the formation of the bar, the non-axisymmetric potential introduced by the bar produces tangential forces across the disc, which cause the cold gas in the interstellar medium (ISM) to shock, lose angular momentum and funnel down into the central region. The final fate of the gas is to form central stellar structures, such as nuclear rings, nuclear spiral arms, inner discs and inner bars. This is corroborated by both theoretical and observational work (for example, Buta & Combes, 1996).

The oldest stars in such bar-built stellar structures hold fossil evidence of the time at which the bar first brought gas to the centre; the ages of these oldest stars tell us directly how long ago the first bar-driven gas accretion event took place. This, in turn, gives us an estimate of the time of both bar formation (i.e., the age of the bar) and disc settling.

MUSE is perfectly suited to addressing these questions; its relatively large field of view, combined with the fine spatial sampling and large spectral coverage, allows a detailed derivation of the stellar population properties and kinematics across all stellar structures in the central region.

A proof of concept

We provided a proof of concept for the methodology outlined above during the first MUSE Science Verification campaign in 2014, when we collected data on the central region of NGC 4371, a nearby barred galaxy with a bar-built nuclear ring and inner disc (see Gadotti et al., 2015). We showed that these structures are dominated by stars that are older than 10 Gyr, with an uncertainty of about 0.8 Gyr based on Monte Carlo realisations. This sets a lower limit to the redshift at which the disc in NGC 4371 settled dynamically and developed a bar, in the range $1.4 \leq z \leq 2.3$.

At first sight, this is a surprisingly old bar, given the earlier difficulties with finding barred galaxies in the distant universe. However, while the fraction of disc galaxies with bars drops from about 70% at $z \sim 0$ to about 20% at $z \sim 1$, Simmons et al. (2014) present evidence suggesting that at least 10% of disc galaxies at $z \sim 2$ are strongly barred.

In addition, in the downsizing framework of galaxy evolution, more massive discs are expected to settle first and form bars first (Sheth et al., 2012), and the fact that NGC 4371 is a massive disc galaxy — at $6.3 \times 10^{10}\ M_{\odot}$ it is more massive than the Milky Way — is consistent with this picture. Incidentally, our results show that bars can be long lived (also see Seidel et al., 2015 for further evidence of long-standing bars).

The TIMER project

The Time Inference with MUSE in Extragalactic Rings (TIMER) project[1] is the fully-fledged version of our Science Verification programme, targeting 24 nearby galaxies ($d < 40$ Mpc) with a range of physical properties (Gadotti et al., 2018). Most importantly, the TIMER sample spans one order of magnitude in stellar mass, which allows us to test the downsizing picture in which more massive discs settle first. All 24 galaxies are barred, with different degrees of bar strength, and all host prominent bar-built central stellar structures, such as nuclear rings, nuclear spiral arms, inner discs and inner bars. Table 1 presents the full TIMER galaxy sample with some of their fundamental properties.

Galaxy	Type	Inclination degrees	Mass 10^{10} $M_\odot$	Distance Mpc
IC 1438	(R$_1$)SAB$_\mathrm{a}$(r’l,nl)0/a	24	3.1	33.8
NGC 613	SB(rs,bl,nr)b	39	12.2	25.1
NGC 1097	(R’)SB(rs,bl,nr)ab pec	51	17.4	20.0
NGC 1291	(R)SAB(l,bl,nb)0$^+$	11	5.8	8.6
NGC 1300	(R’)SB(s,bl,nrl)b	26	3.8	18.0
NGC 1365	(R’)SB(rs,nr)bc	52	9.5	17.9
NGC 1433	(R’$_1$)SB(r,p,nrl,nb)a	34	2.0	10.0
NGC 1512*	(RL)SB(r,bl,nr)a	43	2.2	12.3
NGC 2903*	(R’)SB(rs,nr)b	61	4.6	9.1
NGC 3351	(R’)SB(r,bl,nr)a	42	3.1	10.1
NGC 4303	SAB(rs,nl)bc	34	7.2	16.5
NGC 4371	(L)SB$_\mathrm{a}$(r,bl,nr)0$^{0/+}$	59	3.2	16.8
NGC 4394*	(RL)SB(rs,bl,nl)0/a	30	2.8	16.8
NGC 4643	(L)SB(rs,bl,nl)0$^{0/+}$	44	10.7	25.7
NGC 4981	SAB(s,nl)bc	54	2.8	24.7
NGC 4984	(R’R)SAB$_\mathrm{a}$(l,bl,nl)0/a	53	4.9	21.3
NGC 5236	SAB(s,nr)c	21	10.9	7.0
NGC 5248	(R’)SAB(s,nr)bc	41	4.7	16.9
NGC 5728	(R$_1$)SB(r’l,bl,nr,nb)0/a	44	7.1	30.6
NGC 5850	(R’)SB(r,bl,nr,nb)ab	39	6.0	23.1
NGC 6902	(R’)SAB(rs,nl)ab	37	6.4	38.5
NGC 7140	(R’)SAB$_\mathrm{x}$(rs,nrl)ab	51	5.1	37.4
NGC 7552	(R’$_1$)SB(rs,bl,nr)a	14	3.3	17.1
NGC 7755	(R’)SAB(rs,nrl)bc	52	4.0	31.5

Table 1. Some fundamental properties of the full TIMER sample: morphological classification, inclination with respect to the plane of the sky, stellar mass, and redshift-independent distance. See Gadotti et al. (2018) for details. Galaxies marked with * are still to be observed.

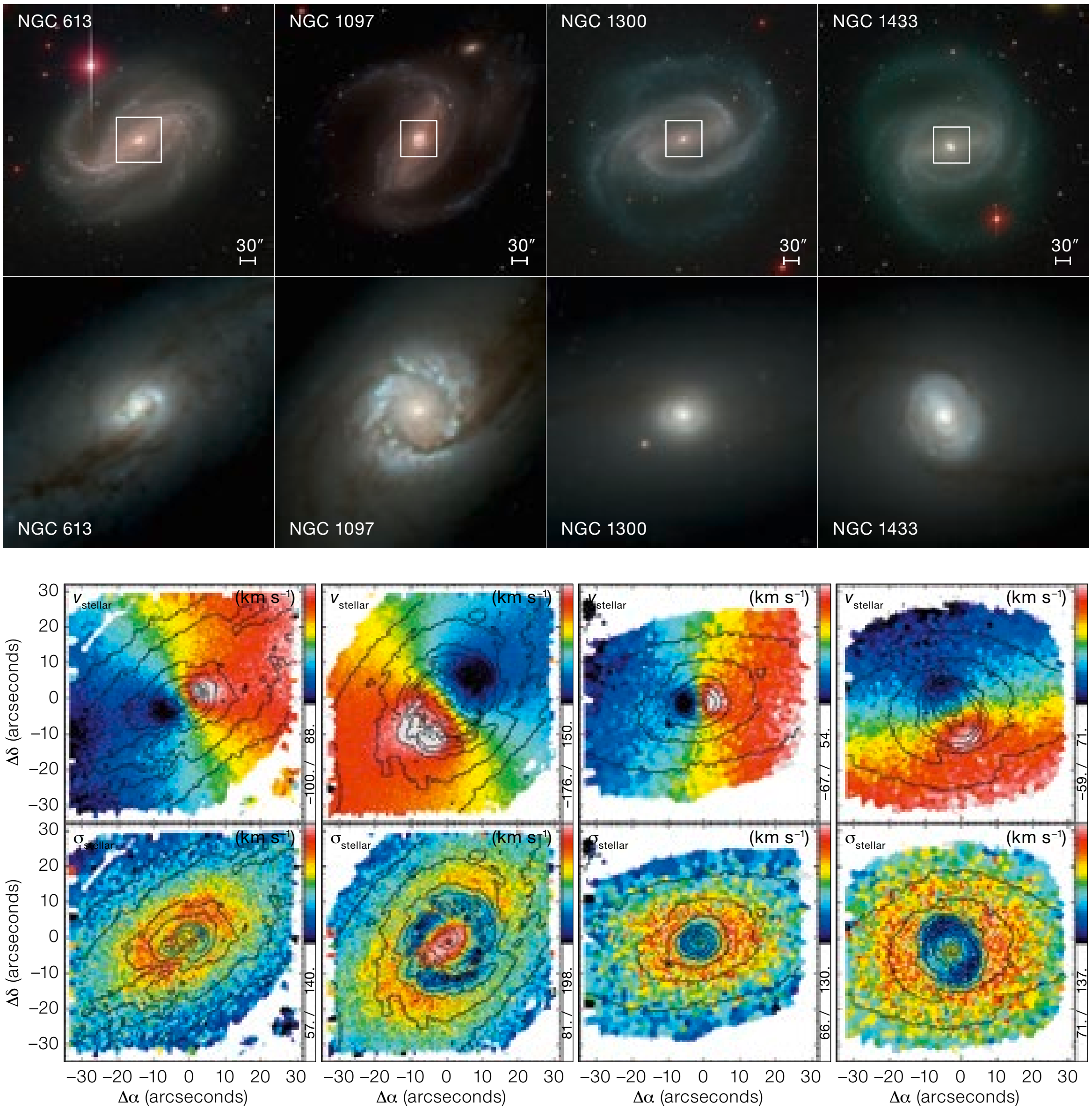

Figure 1. Various properties of four galaxies in the TIMER sample are shown here. Upper row: large-scale colour-composites from the Carnegie-Irvine Galaxy Survey[2] (Ho et al., 2011) — the white squares indicate our MUSE fields. Second row from top: colour composites derived from our MUSE data cubes of the inner one square arcminute. Third row from top: maps of the stellar radial velocity. Lower row: maps of the stellar velocity dispersion (units are km s^{-1}). The isophotes shown are derived from the MUSE data cube reconstructed intensities and are equally spaced in steps of about 0.5 magnitudes.

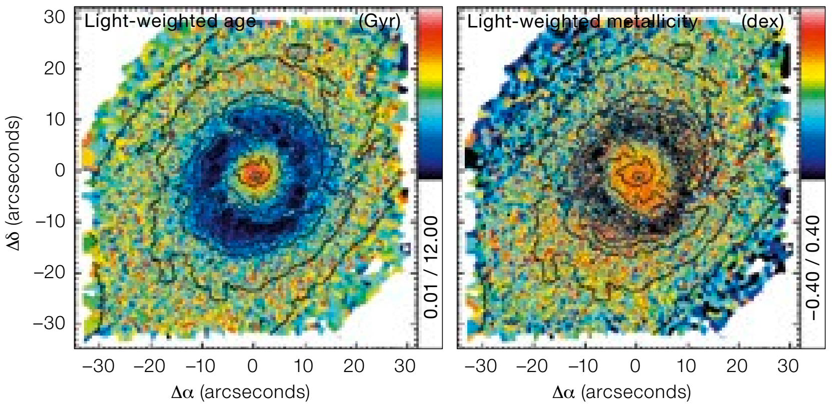

Figure 2. Maps of light-weighted mean stellar age and (left) metallicity (right) for the central square arcminute of NGC 1097.

The top row of Figure 1 shows four examples of galaxies in the TIMER sample. We targeted the central 1 × 1 square arcminute of each galaxy (typically 6 × 6 kpc), with dedicated background exposures and a total integration time of typically one hour on source. The typical image quality of the data is between 0.8 and 0.9 arcseconds, and most of the data were taken during ESO Period 97. After employing the ESO data reduction pipeline to remove instrumental and background features, and to calibrate the raw data, we used a method based on principal component analysis to further remove residual background emission. Colour composites built directly from the MUSE data cubes are shown in Figure 1 (second row from top). These composites attest to the superb imaging quality of the instrument.

Stellar kinematics and dynamics

In order to study the stellar kinematics and dynamics, the fully reduced cubes were Voronoi binned[a] to ensure a minimum signal-to-noise ratio per spatial bin of forty. However, the TIMER cubes contain so much signal that many spaxels remain unbinned, and each of the cubes still contains tens of thousands of spatial bins. In Figure 1 we show maps of velocity and velocity dispersion, illustrating the fine spatial sampling of the data and the richness of detail and information that can be derived.

The velocity maps show that the central stellar structures identified photometrically as bar-built components are indeed dominated by stars in near-circular orbits, as expected, with line of sight velocities higher than those of stars in the underlying disc. This is also reflected in the low values of velocity dispersion shown in these structures (bottom row in Figure 1), and implies that the photometric and kinematic pictures are consistent.

We made an unexpected discovery when examining in detail the line of sight velocity distributions (LOSVDs) in the inner bar of the face-on double-barred galaxy NGC 1291. In Méndez-Abreu et al. (2018) we show that the changes in the kurtosis of the LOSVDs along the major axis of the inner bar are such that they can only be explained if the inner bar has buckled. Bar buckling is a process commonly seen in large-scale bars but this is the first time it is seen in an inner bar. This is remarkable, as it shows that inner bars are essentially governed by the same dynamical processes as large-scale bars, despite being substantially shorter.

Stellar ages and metallicities

Full spectral fitting allows us to derive spatially resolved star formation histories of all stellar structures seen in our MUSE fields. As described above, the star formation histories of the bar-built structures give an indication of the cosmic epoch in which discs settle dynamically and bars form. While this is a challenging enterprise, the first step — deriving mean stellar ages and metallicities — is more robust.

In Figure 2 we show the light-weighted maps of mean stellar age and metallicity for NGC 1097. They show an old, metal-rich nuclear component within a few arcseconds of the centre, and the much younger, metal-poor nuclear ring. The fact that the metallicity inside the ring radius is substantially higher than that in the ring itself, shows that nuclear rings can very efficiently halt the inflow of gas from the bar. In Gadotti et al. (2015, 2018) we show that bar-built central structures can display a wide range of stellar ages and metallicities. This is an important result since it means that not necessarily all stellar structures built via bar-driven secular evolution processes are young, as initially thought. The case of NGC 4371 is clear; the bar formed at $z \sim 1.8$ and then swiftly formed the nuclear ring and inner disc that only passively evolved afterwards, since the gaseous content within the bar radius was depleted by the bar and not replenished further. The absence of further gas infall to the galaxy is likely to be a result of environmental effects in the core of the Virgo cluster, where the galaxy is.

Spatially resolved star formation histories

One of the most powerful aspects of integral-field spectroscopy is the combination of photometric and spectroscopic information. We are currently performing sophisticated structural decompositions using deep ancillary imaging data from the Spitzer Space Telescope, including a number of structural components beyond bulge, disc and bar (for example, inner discs, inner bars, lenses, and disc breaks) and carefully masking structures that are not modelled, such as rings. This allows us to determine which spaxels in our MUSE data are dominated by each stellar structure, which in turn helps to more accurately determine the stellar population content and the star formation history of each stellar structure separately. This is undoubtedly a powerful tool for shedding light on the assembly history of massive disc galaxies.

Following this approach, in de Lorenzo-Cáceres et al. (2018) we study the formation of the inner bars, inner discs and other central structures in the double-barred galaxies NGC 1291 and NGC 5850. We find evidence suggesting that these inner bars are long-lived and formed at least ~ 6 and ~ 4 Gyr ago, respectively. The TIMER data also indicate that the inner bars are formed from a dynamical instability in the inner disc, just like their outer bars but at a smaller spatial scale.

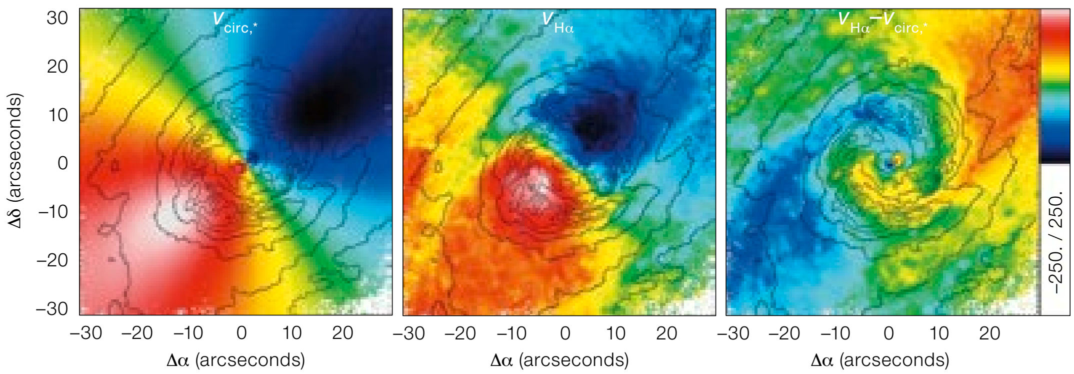

Figure 3. Jeans stellar dynamical model circular velocity field (left), unbinned Hα velocity field (centre), and the difference between both (right) for NGC 1097. The colour scale units are km s^{-1}.

Ionised gas properties, kinematics and dynamics

In all TIMER galaxies we detect a number of optical emission lines from ionised gas, which can be used to assess which processes are causing the ionisation of the interstellar medium (ISM), as well as a number of other physical properties, such as electron density and temperature, and gas metal content. Only one galaxy has ionised gas produced exclusively by star formation; most galaxies have their centres dominated by ionisation similar to that seen in low-ionisation nuclear emission-line regions (LINERs), and two are broad-line, type 1 active galactic nuclei (AGN).

We can also use the emission lines to study the kinematics of the warm, ionised gas, and physical processes other than gravity affecting its dynamics. Figure 3 illustrates how we detect and measure the inflow of gas along the leading edges of bars, where the gas shocks and loses angular momentum. The left panel shows the circular velocity field derived from modelling the stellar dynamics in NGC 1097 (after correcting for asymmetric drift), while the middle panel shows the observed velocity field of the gas. The right panel is produced by subtracting the dynamical model from the gas velocity field, and thus shows deviations from circular speed in the motions of the gas. Such deviations are associated with non-gravitational motion, and, in this case, clearly show the inflow of gas via the bar, feeding star formation in the nuclear ring.

AGN and stellar feedback

The central region of a disc galaxy is home to a number of physical processes that are fundamental to galaxy evolution. It is there that supermassive black holes reside and trigger AGN, which in turn may cause AGN feedback, having a strong effect on the physical properties of the ISM in the galaxy and the circumgalactic medium in its immediate surroundings. AGN feedback may alter star formation histories, the building of central stellar structures and patterns of chemical abundance in and outside galaxies.

Additionally, nuclear rings are often sites of elevated star formation rates and this is seen also in some of the galaxies in the TIMER sample. These sites host young massive stars and are the locations of supernova explosions, both at the root of the stellar version of feedback processes into the ISM.

It is no surprise then that the TIMER data can help shed light on AGN and stellar feedback, as well as other astrophysical problems beyond the main scope of the project. In fact, the top panels of Figure 4 show the powerful bi-conic outflow seen in [O III] produced by the AGN in NGC 5728. MUSE provides a view of this system in unprecedented detail.

The bottom panels of Figure 4 illustrate our serendipitous discovery of stellar feedback from the star-bursting nuclear ring in NGC 3351. Our data show expanding bubbles of warm gas (emitting in Hα) emerging from the nuclear ring, which in some places has a star formation rate surface density reaching 20 $M_{\odot}$ yr^{-1} kpc^{-2}. With ancillary ALMA data (from Principal Investigator Karin Sandstrom, see Figure 5), we see that the Hα is confined within a dense molecular gas shell perpendicular to the bar major axis, which is also a region with elevated dust content. The neighbouring warm gas shows high velocity dispersion (up to 150 km s^{-1}), and with dynamical models we show that it is expanding radially away from the ring at speeds of up to 70 km s^{-1} just inside the molecular gas feature (Figure 5).

Such a strong gas and dust shell perpendicular to the bar major axis is not reproduced by hydrodynamical simulations of barred galaxies without feedback. Given the observed properties described above, we propose in Leaman et al. (2018) the idea that the molecular band was pushed outwards from the region of the nuclear ring by stellar feedback processes. Consistent with this picture, the ALMA data show that the molecular shell has peculiar dynamics and a relatively high velocity dispersion.

A strong legacy

TIMER's rich dataset is allowing us to explore a number of other astrophysical problems, including:

1. star formation and stellar populations in primary bars;
2. the star formation desert in barred galaxies;
3. the connection between box/peanuts and barlenses;
4. stellar migration in disc galaxies;
5. the location of nuclear rings with respect to the inner Lindblad resonance;
6. gas shear and shocks along bars;
7. the excitation states of the ionised gas in the ISM;
8. the initial mass function across disc galaxies.

Furthermore, forthcoming observations of TIMER galaxies with the MUSE Narrow-Field Mode will help us understand how

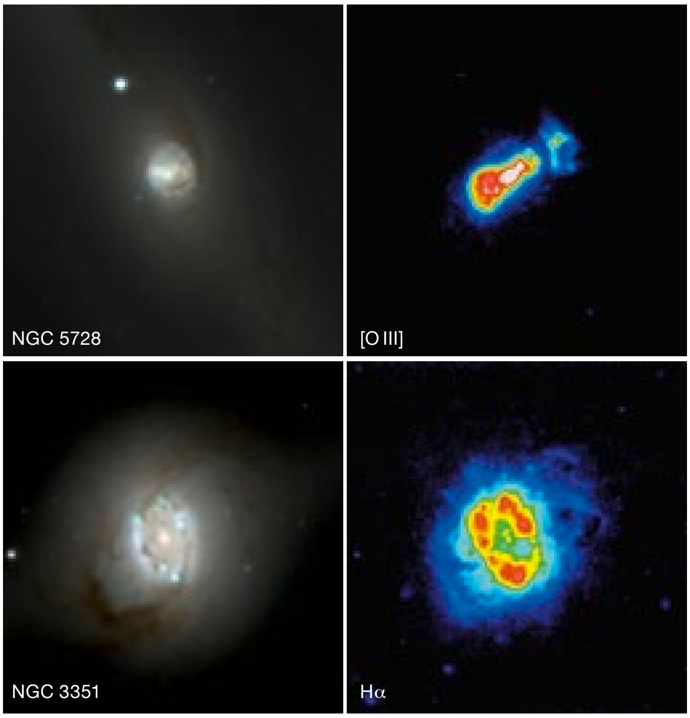

Figure 4. (Left) Colour-composites images from the TIMER MUSE data cubes for NGC 5728 and NGC 3351, as indicated. (Right) Continuum-subtracted images of [O III] emission (upper: NGC 5728) and Hα emission (lower: NGC 3351).

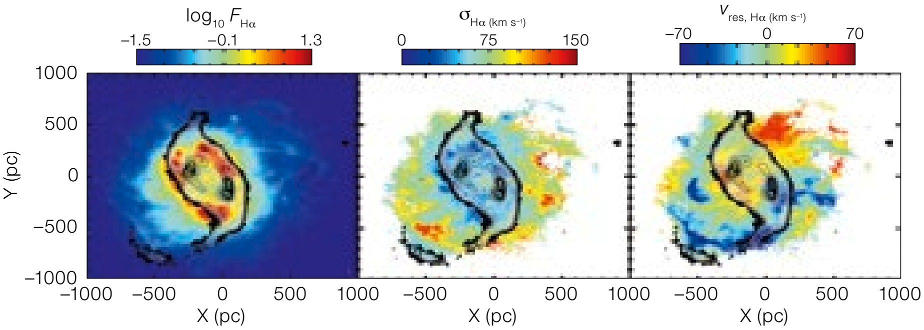

Figure 5. Hα flux (left), velocity dispersion (middle) and residual velocity (right) fields of NGC 3351 are shown in the colour scale. The velocity fields are built by subtracting a dynamical model of the circular speeds from the Hα velocity field. The ALMA CO(1–0) intensity map is overlaid as contours, and clearly encloses the ionised outflows to the south-west of the nuclear ring.

the inflow of gas via primary and inner bars proceeds from kiloparsec scales down to parsec scales, approaching the supermassive black hole.

Another exciting window that opens up with TIMER is the possibility to work in tandem with other revolutionary facilities such as ALMA, as has already been demonstrated above. By combining MUSE and ALMA observations of nearby galaxies, it is now possible to connect, at high angular resolution, the cause and effect of star formation (including molecular gas and young stellar populations), as well as monitoring their interplay in the form of stellar feedback. Moreover, we can probe that connection spatially and kinematically at the same time, which can help to understand the cycling of ISM phases and their associated timescales. AGN feedback can also be explored simultaneously at these different phases of the ISM, bridging the gap between ionised and molecular outflows. These observables are crucial to inform galaxy-scale hydrodynamical simulations, which often assume simple analytic prescriptions for the conversion of gas into stars and for the various forms of feedback.

The policies governing the project are such that collaborations with experts outside the team are encouraged, and interested parties should contact the Principal Investigator, Dimitri Gadotti.

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Links

[1] TIMER Project: https://www.muse-timer.org/
[2] The Carnegie-Irvine Galaxy Survey (CGS): https://cgs.obs.carnegiescience.edu/CGS/Home.html

Notes

[a] Voronoi binning is an an algorithm that bins two-dimensional data in such a way as to ensure a constant signal-to-noise ratio per bin, optimally preserving the spatial resolution of the data.

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Resolving the Interstellar Medium at the Peak of Cosmic Star Formation

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The interstellar medium feeds both the formation of stars and the growth of black holes, making it a key ingredient in the evolution of galaxies. With the advent of the Atacama Large Millimeter/submillimeter Array (ALMA), we can now probe the interstellar medium within high-redshift galaxies in increasingly exquisite detail. Our recent ALMA observations map the molecular gas and dust continuum emission in submillimetre-selected galaxies on 1–5 kpc scales, revealing significant differences in how the gas, dust continuum, and existing stellar emission are distributed within the galaxies. This study demonstrates the power of ALMA to shed new light on the structure and kinematics of the interstellar medium in the early Universe, suggesting that the interpretation of such observations is more complex than typically assumed.

The interstellar medium in the early Universe

The growth of a galaxy, through the formation of new stars, is deeply connected to its interstellar medium. Characterising the interstellar medium within galaxies thus sheds light on the physical conditions around the process of star formation. The submillimetre and far-infrared regimes play a prominent role in this characterisation, since both the line and continuum emission are largely related to the star formation process in galaxies. Indeed, the emission lines in this regime trace the cold molecular gas phase most closely related to the feeding mechanism of star formation (for example, Narayanan et al. 2011). At the same time, the peak of the dust continuum emission in galaxies is considered to be one of the most reliable tracers of recent star formation episodes, since it is the optical and ultraviolet emission from newly-born stars that heat the dust to produce the far-infrared continuum emission.

Among the molecular gas emission lines, carbon monoxide (CO) is the most strongly emitting molecule and thus the most commonly used molecular gas tracer. However, it is only the second most abundant molecule in the interstellar medium after molecular hydrogen, H_2, which dominates by mass. Since H_2 is not easily observable, most studies use CO emission as a tracer of the molecular mass. This, however, requires a CO-to-H_2 conversion factor (α_{CO}). Numerous observational and theoretical efforts suggest that this factor has strong dependencies on galaxy properties such as gas density, temperature and metallicity, although these relationships are not well understood, particularly in the high-redshift Universe (for example, Bolatto et al. 2013). Although this conversion factor plays a key role in molecular gas measurements, it represents one of the biggest uncertainties in high-redshift molecular gas studies.

Since detecting the CO emission from distant galaxies can still require long exposure times, another way to indirectly probe the cold interstellar medium is through observations of the cold Rayleigh-Jeans tail of the dust continuum emission. Efforts to study the evolution of the cold gas content of galaxies have increasingly relied on such unresolved dust continuum measurements to construct statistically significant samples (see, for example, Scoville et al. 2015). These studies carry their own assumptions, including that the ratio of gas to dust is constant, and that these components are well-mixed and co-located within galaxies.

To test the validity of these assumptions, detailed observations of both gas and dust continuum emission within galaxies at similar spatial resolutions are required. Galaxies selected on the basis of their bright emission in the submillimetre continuum (known as submillimetre galaxies, or SMGs) are excellent laboratories in which to carry out these observations due to their large molecular reservoirs and bright dust continuum emission. In addition, SMGs contribute around 20% of the total star formation rate density at $z \sim 2–3$ (Swinbank et al., 2014), making them an important population to study in order to characterise the peak epoch of galaxy assembly.

A spatially resolved study of the molecular gas and dust in submillimetre galaxies

The long baselines and large collecting area provided by ALMA make deep, high-resolution observations of multiple tracers of the interstellar medium increasingly possible for distant galaxies and, most crucially, in a fraction of the time required by other facilities. We therefore exploited the capabilities of ALMA to resolve the molecular gas emission — through CO — and dust continuum emission in a sample of bright submillimetre galaxies at redshift $z \sim 2.5$.

The SMGs in our study are part of the ALMA LABOCA ECDFS Submillimeter Survey (ALESS; Hodge et al., 2013). This is an ALMA Cycle 0 study of ~ 100 luminous and ultra-luminous infrared galaxies in the Extended Chandra Deep Field (ECDFS) originally selected based on the Atacama Pathfinder Experiment (APEX) LArge APEX BOlometer Camera (LABOCA). The galaxies in the ALESS survey constitute the most extensively studied submillimetre galaxies to date in terms of multi-wavelength and spectroscopic follow-up observations, including accurate spectroscopic redshifts, radio to X-ray photometric characterisation, and now high-resolution ALMA follow-up (Hodge et al., 2016; Chen et al., 2017; Calistro Rivera et al., 2018).

In Calistro Rivera et al. (2018), we present the latest high-resolution (subarcsecond) molecular gas observations of the CO(J = 3–2) transition in four ALESS SMGs: ALESS 49.1, 57.1, 67.1 and 122.1 (Project ID 2013.1.00470; PI: Hodge). With only 30 minutes of exposure time per source with ALMA's Band 3, we detect and resolve the CO(3–2) emission in these high-redshift galaxies (Figure 1). The measured positions are coincident with the ALMA dust continuum emission, and the measured frequencies confirm the expected spectroscopic redshifts ($z \sim 2–3$). Figure 1 shows the CO(3–2) emission overlaid on the stellar emission as traced by the Wide Field Camera 3 (WFC3) and/or Advanced Camera for Surveys (ACS) imaging from the Hubble Space Telescope (HST). With the exception of ALESS 122.1, the CO gas overlaps the existing stellar distributions.

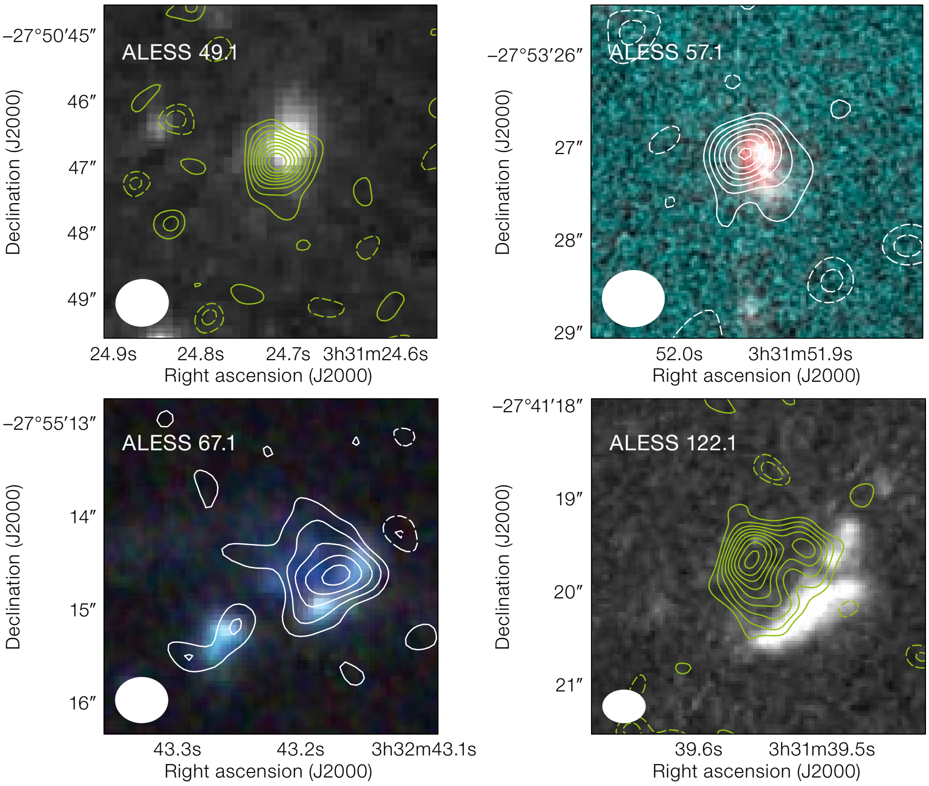

Figure 1. The molecular gas emission, as traced by the velocity-averaged CO(3–2) emission (Calistro Rivera et al., 2018), is shown as contours overlaid on the stellar emission, traced by the Hubble Space Telescope imaging. We see that our 30-minute-per-source ALMA observations can strongly detect and resolve the CO emission in these four SMGs on scales of around four kiloparsecs (beam sizes are shown in the lower-left corners), showing a diversity of morphologies in both CO and stellar emission. The accurate astrometry, as calibrated using Gaia data, reveals offsets among the gas and stellar emission distributions.

High-resolution 870-micron continuum observations for 16 ALESS galaxies were previously presented by Hodge et al. (2016). Figure 2 shows that the dust continuum emission in these galaxies is distributed over scales of only a few kiloparsecs and appears to have a smooth and disk-like morphology at the sensitivity and resolution of the observations. In Chen et al. (2017), we presented a detailed comparison of the dust continuum and CO for one source. Here, we use all of the high-resolution gas and dust continuum data now available for the ALESS sources to learn about the resolved properties of the interstellar medium in the early Universe.

A census of gas masses using galaxy kinematics

The CO(3–2) data obtained in these observations have the potential to reveal the total mass of molecular gas in these SMGs. However, the derivation of total masses from CO data depends on several unknown factors, which can now be inferred from our observations.

The total mass of a galaxy within a given radius can be estimated from the dynamics of the contained matter according to the virial theorem. These kinematic properties are reflected in the CO line emission and can be extracted by applying kinematic modelling to the velocity field observed in the line (or in cases where the resolution or signal-to-noise ratio is not enough, they can be approximated simply by the observed line-widths). In Figure 3, we use a model of a rotating exponential disk galaxy (Galpak3D; Bouché et al., 2016) in order to fit the CO(3–2) emission of the source of highest signal-to-noise ratio in our sample, ALESS 122.1. We infer the relevant kinematic parameters that produce the best fit, such as the inclination angle and

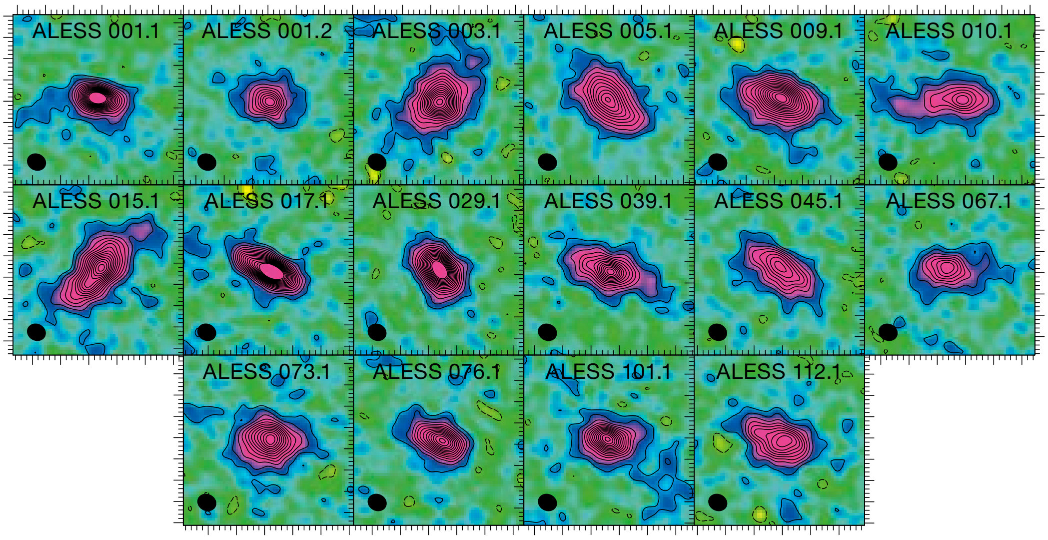

Figure 2. The 870-μm dust continuum emission at around one kiloparsec resolution in 16 submillimetre galaxies from the ALESS survey (Hodge et al., 2016). The dust continuum emission is distributed over scales of only a few kiloparsecs and appears to have a smooth and disc-like morphology at the sensitivity and resolution observed.

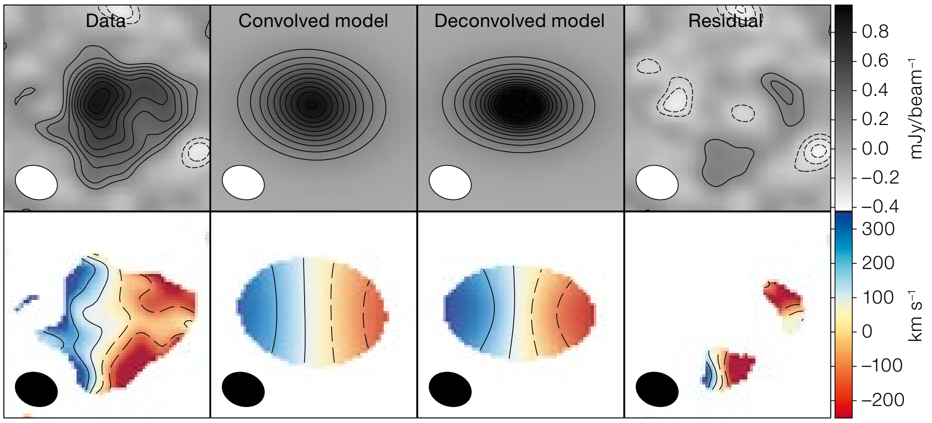

Figure 3. Kinematic modelling of the CO emission in ALESS 122.1 using the code Galpak3D. The top row shows the integrated intensity maps. The bottom row shows the intensity-weighted velocity maps. The field of view of each image is ~ 1 square arcminute. The columns correspond to the observed data, the best-fit model convolved with the beam, the deconvolved best-fit model and the residual. The cool molecular gas emission in this source, as traced by the CO(3–2) emission, can be well described by a rotating disk. Given the clumpy stellar emission in the source, this result suggests that an ordered rotating molecular gas disk could have been quickly reformed after a merger event.

maximum rotational velocity of the gas. These parameters allow us to estimate the total dynamical mass of the galaxy.

The mass of a galaxy is essentially composed of dark matter, stars and the gas that constitutes its interstellar medium. A census of the various components contributing to the mass of a galaxy can shed light on unknown parameters needed in molecular gas studies, such as the CO-to-H_2 conversion factor, α_{CO}, mentioned above. Through our estimated total dynamical masses — as well as further knowledge and assumptions about the dark matter and stellar mass components — we can then estimate the remaining mass which is in the form of gas. Since the total gas mass is predominantly molecular hydrogen at these redshifts, it provides a fair estimate of the hydrogen mass content in the ISM of the galaxy. Relating this estimate of the total molecular hydrogen mass to the measured CO luminosity, we can finally infer the conversion factor α_{CO}.

In applying this method in our study, we put particular emphasis on recovering robust uncertainties in the estimation of α_{CO}. These uncertainties arise from assumptions made about the dark matter fraction and stellar mass component, in particular. We use a Bayesian method in order to sample the probability density functions of all of the unknown parameters contributing to these uncertainties, such as the mass-to-light ratio of the stellar component and the unknown dark matter fraction. Taking advantage of our high-resolution imaging, we are able to recover a mean value of $\alpha_{CO} = 0.9 \pm 0.6$ ($M_\odot$/[K km s^{-1} pc^2]$^{-1}$). This value is consistent with the value generally assumed for luminous and ultra-luminous infrared galaxies in the local Universe, but is considerably smaller than the Milky Way value ($\alpha_{CO} \sim 4$). We also investigate the covariance between α_{CO} and the stellar mass-to-light ratio, showing that they are strongly correlated. Although we are limited here by a small sample of four SMGs, we suggest that this method holds great potential for robustly recovering these unknown parameters when better statistics are available.

Offset distributions of stars, gas and dust

The availability of high-resolution, subarcsecond imaging at different wavelengths, such as the optical/near-infrared imaging of the Hubble Space Telescope and the far-infrared dust continuum emission mapped by ALMA, allows us to make a detailed image of the different physical components within a high-redshift galaxy. In Figure 4, we explore the case of the offset distribution of the CO gas (green region) relative to the stellar emission (blue region) in ALESS 122.1, now including the dust continuum emission (red region) corresponding to the rest-frame 1 mm emission. The emission from the cold dust appears to be colocated with the gas, as expected since both trace the interstellar medium.

However, the emission from the dust does not overlap with the existing stellar emission, suggesting that they may not be produced in the same regions. This finding has important implications for methods commonly used at high redshift to fit panchromatic spectral energy distributions — particularly energy balance techniques that attempt to self-consistently

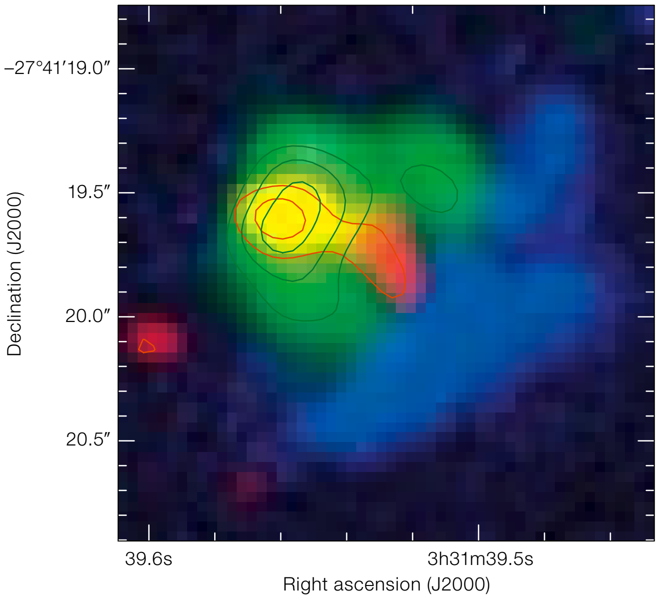

Figure 4. Image of the cool molecular gas emission (green), dust continuum emission (red) and stellar emission (blue) components in the submillimetre galaxy ALESS 122.1. The physical components in this galaxy appear clearly misaligned. This galaxy is one example of a large number of similar cases within high-resolution submillimetre surveys of extreme sources such as SMGs (Hodge et al., 2016). These observations may have important implications for energy-balance assumptions between the integrated dust and stellar emission of extreme sources.

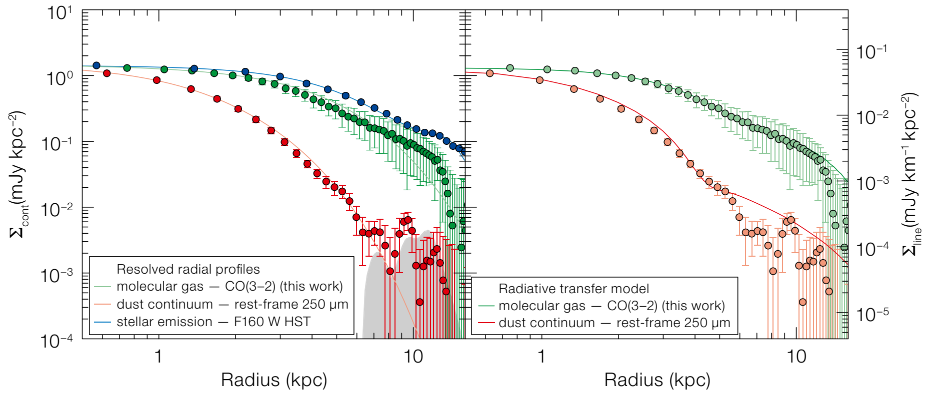

Figure 5. Stacked radial profiles of the gas (green), dust (red) and stellar (blue) emission in ALESS submillimetre galaxies, showing the average intensity as a function of radius. The solid lines in the left panel show the best fit exponential profiles, which have been convolved with Gaussian functions of the size of the ALMA beam to account for the effect of the different resolutions. We note that the data contaminated by the beam side lobes (grey shaded area) have been removed for the fit. This plot shows that the dust continuum emission is more than twice as compact as the stellar and molecular gas emission, which have similar extents. In the right panel, we use radiative transfer to consistently model the gas and dust phase of the interstellar medium in these sources (Weiss et al., 2007). The model shows that the apparent difference between the dust and gas emission sizes does not necessarily imply different intrinsic physical distributions, but rather can arise from temperature and optical depth gradients alone.

model the observed optical and infrared emission by coupling the dust and stellar emission. The increasing number of multi-wavelength, high-resolution observations at high redshift with similar findings are indeed challenging this picture, especially for extreme sources such as SMGs (Hodge et al., 2016).

A statistical study of the distribution of the gas and dust emission

Although not all SMGs show an offset between their dust and stellar distributions, a growing number of studies find a contrast between the apparent sizes of the compact dust and extended gas and stellar components, suggesting that this difference in physical scale is a general feature. In order to investigate this observation in a statistical manner, in Figure 5 we apply a stacking analysis to all ALESS submillimetre galaxies with high-resolution dust, gas and stellar emission imaging. To produce the average gas radial profile (green points), we stack the profiles of the four ALESS galaxies in Figure 1 presented by Calistro Rivera et al. (2018). The average radial profiles of the dust (red points) and stellar emission (blue points) are produced through stacking 16 ALESS galaxies presented in Figure 2 and by Hodge et al. (2016). Through the stacking method, we not only investigate the average properties of the population, but also achieve a higher sensitivity since the signal-to-noise ratio improves in the final stacked image.

Our statistical approach reveals that the (observed-frame) 870 μm dust continuum extends over less than half of the gas emission, while the gas and the stellar emission distributions appear to have similar spatial extents. This finding raises several questions regarding the physical nature and relationship of the emitting components. In particular, is the compact dust distribution an observational effect due to the lack of sensitivity? Despite the higher sensitivity achieved through the stacking, we do not recover a significant low-surface-brightness component to the dust emission. Is the dust continuum then physically present only in a central compact region, while the gas is more spread out? This would mean that gas and dust are not well-mixed in the interstellar medium as is commonly assumed. To answer this last question, we apply radiative transfer modelling to our observations in order to recover the physics that may produce these different distributions.

We use an updated version of the radiative transfer model of Weiß et al. (2007) to simulate the stacked radial profiles of the gas and dust as presented in the right panel of Figure 5. In this method, we consistently relate the gas and the dust emission through radiative transfer by assuming that gas and dust are well mixed and equally distributed throughout the galaxy. As initial conditions, we apply a radially decreasing temperature and optical depth gradient to the system, as commonly expected in centrally located starbursts. The right panel of Figure 5 shows the best-fit model to the data, demonstrating that the different apparent extents of dust and gas can be well reproduced by the proposed model.

These results indicate that the apparent difference in size observed between the compact dust continuum and extended gas emission does not necessarily imply different physical distributions for these components. Rather, this apparent size difference can be a consequence of a combination of temperature and optical depth gradients, which can be extreme in galaxies such as SMGs, but also non-negligible in normal star-forming galaxies. Such a scenario has important implications for methods that adopt dust continuum sizes as an approximation to molecular gas sizes, especially for the calculation of dynamical masses. These results demonstrate the potential of high-resolution campaigns with ALMA to reveal observational challenges and solve open questions in the study of the interstellar medium in the early Universe.

Acknowledgements

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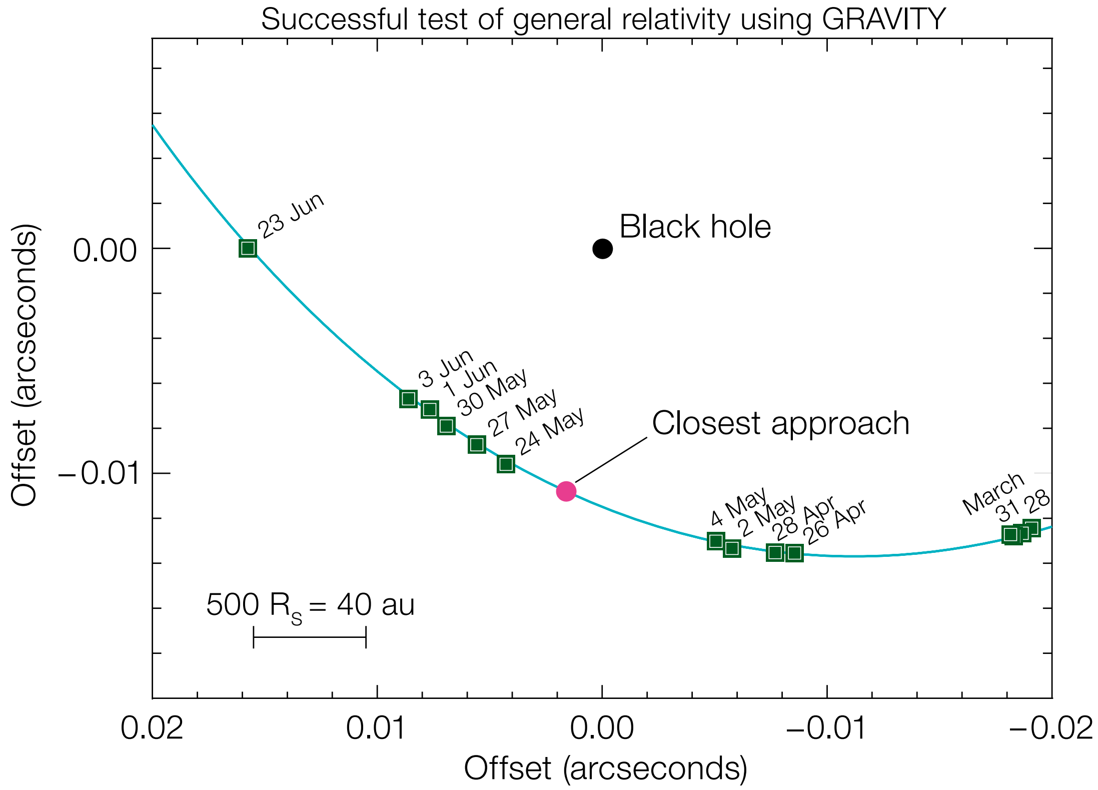
ESO/G. Hüdepohl (atacamaphoto.com)

Upper image: Construction proceeding at the site of ESO's ELT.

Lower image: The orbital motion of the star S2 as it passes close to the supermassive black hole at the centre of the Milky Way was monitored with high levels of precision using GRAVITY. These 2018 observations were used to confirm gravitational redshift as predicted by general relativity. Note that the relative sizes of the star and the black hole are not to scale.

ESO/MPE/GRAVITY Collaboration



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The ESO Digital Object Identifier Service

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Digital Object Identifiers (DOIs) are persistent identifiers in a global registry that assist in the citation, identification, and discoverability of research information. The ESO library has created a service to provide DOIs to departments within ESO. DOIs have been in use for articles in The Messenger since March 2017, and plans are underway to begin creating DOIs for datasets in the ESO Science Archive.

Digital Object Identifiers

Scholars have long cited the literature they used when defining a piece of work or study, both as a way of giving due credit, and as a way of bolstering the credibility of the study itself. In the hypertext era, such citations can be enhanced with direct links to the cited resources — including both literature and data. Data citation is especially important for the reproducibility of science. However, nearly three decades since the invention of the World Wide Web, we have seen that not all web addresses (or Uniform Resource Locators — URLs) are permanent. Digital Object Identifiers (DOIs) have entered the scene to address this problem.

DOIs are persistent, globally unique identifiers for publications, datasets, and other research products. They are used to refer to information resources in an unambiguous way, for example when citing a paper. They can also be used as URLs, preceded by “https://doi.org/”, to conveniently retrieve the resource in question. Typically, this URL brings the user to a “landing page” that describes the resource, and provides a link via which it can be downloaded.

DOIs were conceived in the 1990s by associations of publishers, and the first DOIs were created in 2000[1]. At the time of writing, approximately 148 million DOIs had been created, and there are over five billion DOI lookups per year[2].

The global DOI registry is administered by the non-profit International DOI Foundation. DOIs are specified in a syntax defined by the standard ISO 26324:2012 format. They have become standard components of scholarly publishing, as major journals create a DOI for every article they publish.

A DOI consists of an identifier string (aka DOI name), and some information (metadata) about the resource to which it is assigned. An example of a DOI name is: “10.18727/docs/2”. Every DOI name begins with “10.”, followed by a number representing the data centre that registered the DOI, a forward slash, and then an arbitrary string (“docs/2”, in the example shown in Figure 1). In this way, there is no risk of two data centres trying to register the same DOI name, and each data centre also has control over how it names its DOIs. The particular DOI given in Figure 1 resolves to the landing page for the 2017 ESO Annual Report[3].

The benefits of the DOI system include:
- unambiguous citation — traditional citations can contain confusing abbreviations and are sometimes incomplete;
- convenient and machine-readable retrieval — every DOI is easily turned into a URL, and the DOI name format is easily detected by computers;
- reducing (ideally entirely eliminating) the number of links that “break” after publication.

Publishers and data centres that register DOIs are making a pledge to maintain their records in the DOI registry, so that a requested DOI always resolves, even if the resource itself moves to a different URL. Furthermore, since DOIs give all stakeholders a simple and standard way to refer to the same resource, the DOI system enables the creation of a network of scholarly services and tools.

The ESO DOI service

The ESO Library began investigating the adoption of DOIs in 2015. The two use cases under consideration at the time were publications, such as The Messenger, and datasets in the Science Archive. Although DOIs have typically been used for text publications, they can also be applied to datasets, which should enable easier and higher-quality data citation and tracking. This use is not yet widespread, but data centres in various disciplines are increasingly interested in deploying DOIs for datasets. Furthermore, there is a trend in public funding agencies (for example, the European Commission and the German Research Foundation [Deutsche Forschungsgemeinschaft, DFG]) demanding that data be Open Access; it follows that they should also be citeable.

ESO negotiated an agreement with the Technische Informationsbibliothek (TIB) in Hanover, a national library that provides DOI registry access to academic institutions in Germany, in association with DataCite, one of the foremost DOI registration agencies. Once this agreement was in place, the ESO Library developed the software needed to manage interactions with DataCite. DataCite offers an HTTP[a] application programming interface (API) for registering DOIs.

The resulting software, called the ESO DOI Service, acts as a hub for ESO departments (or “clients”) wishing to create DOIs (Figure 1). Several steps are required when a client wants to create a DOI:
1) The client sends a request to the DOI Service with the necessary resource metadata.
2) The DOI Service stores a record and attempts to register it with DataCite.
3) The DOI Service receives DataCite’s response and notifies the client.
4) The DOI Service also renders a landing page for every DOI that it registers, so that when someone resolves the DOI, they arrive at a page provided by the DOI Service. Clients can also supply their own landing pages if desired. Figure 2 depicts the architecture of the ESO DOI Service.

In developing the ESO DOI Service, the Library had to take several factors into account. Since more than one type of information resource was involved,

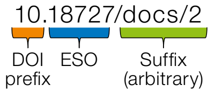


Figure 1. The composition of a DOI name.

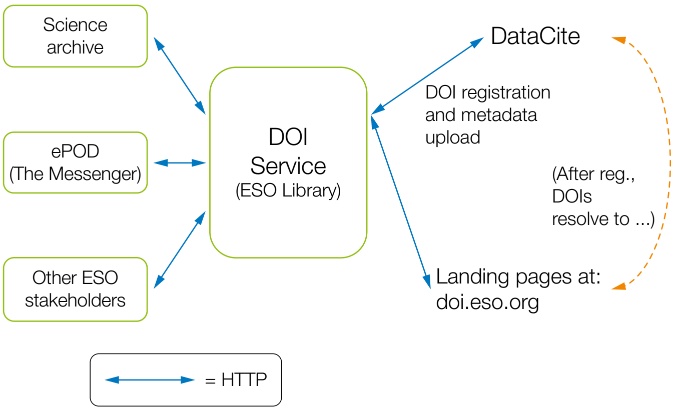
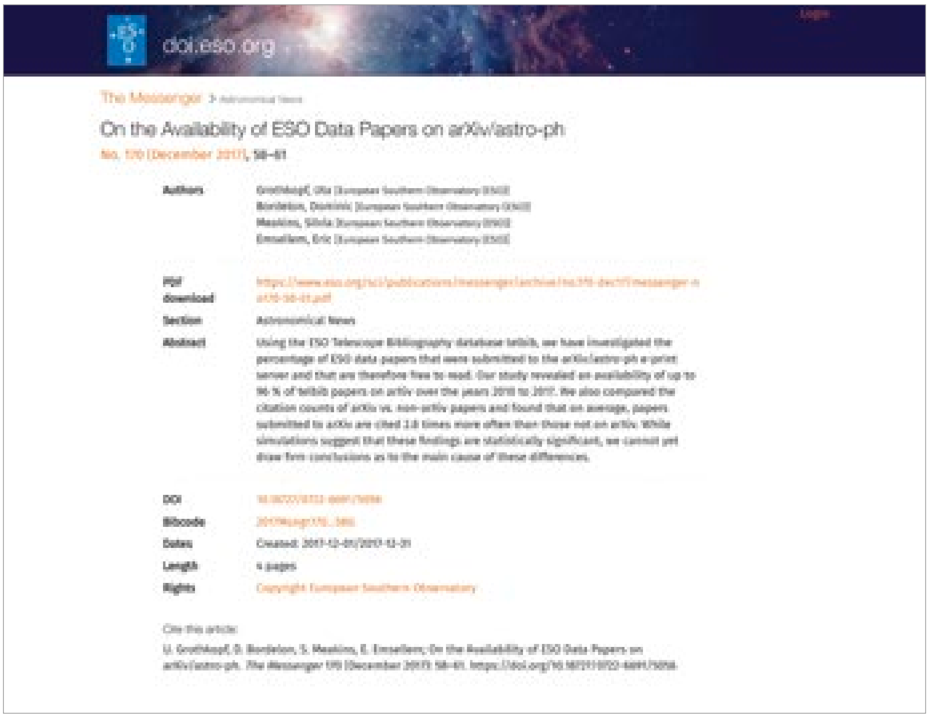


Figure 2. Architecture of the ESO DOI service, showing how the DOI service is used by the main stakeholders. Currently, the main users of the DOI service are the science archive and the education and Public Outreach Department (ePOD).



doi.eso.org

The Messenger

On the Availability of ESO Data Papers on arXiv/astro-ph

No. 170 (December 2017), 58–61

Figure 3. A screenshot of the landing page for an article in The Messenger.

a common data model which would accommodate multiple types of resources was needed. Since more than one department — potentially using different programming languages or database systems — would be served by the software, the solution needed to provide an “agnostic” and universal API to clients via HTTP. The software also needed to handle failure states in case DataCite is unavailable.

With these requirements in mind, development began in the autumn of 2016, and the service was launched in March 2017. The first DOIs minted were for articles of volume 167 of The Messenger (see Figure 3). In the meantime, ESO has created 67 DOIs, and feature developments for the ESO DOI Service have continued. The most important addition is a monitor that checks each record weekly to ensure that the link still works, greatly helping to keep the promise of persistence that is made when participating in the global DOI registry.

Future developments

Plans are under way for the Science Archive to use DOIs for raw datasets, data products, and ad hoc collections that have been assembled by Archive users. The eventual goal is for authors to cite DOIs of the datasets that they used in writing a paper, which would improve scientific reproducibility and greatly assist ESO in tracking the use of its data. DOIs are an excellent tool for continuing and extending the scholarly practice of citation in a way that is accessible, persistent, and situated in a network of resources. The rising trend of data citation not only complies with funding agency demands, but also facilitates further scientific analysis. With the ESO DOI Service, ESO is ready to fully participate in future developments.

Acknowledgements

We would like to thank ESO’s Legal Services for their work on the agreement with the Technische Informationsbibliothek.

References

ISO 26324:2012: Information and documentation — Digital object identifier system. International Organization for Standardization, Geneva, Switzerland.

Links

[1] The DOI Handbook: https://doi.org/10.1000/182
[2] Key Facts on the Digital Object Identifier System: http://www.doi.org/factsheets/DOIKeyFacts.html
[3] Landing page for the 2017 ESO Annual Report: https://www.eso.org/public/products/annualreports/ar_2017/

Notes

[a] Hypertext Transfer Protocol (HTTP) is the protocol used for the World Wide Web.

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Report on the ESO Workshop

Diversis mundi: The Solar System in an Exoplanetary context (OPS-III)

held at ESO Vitacura, Santiago, Chile, 5–9 March 2018

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Inspired by the previous two Observing Planetary Systems (OPS) workshops held in ESO-Chile and by the rapid evolution of exoplanet studies and Solar System exploration, we organised the *Diversis Mundi* workshop. The focus of this conference was to bring together the Solar System and exoplanet communities to put the Solar System into the context of the current knowledge of planetary systems and to understand all the known components of extrasolar systems. Around 100 researchers from both communities met and discussed these topics in a very collaborative and inspiring environment, and in a workshop format that enhanced the interaction between the two communities.

Motivations

After centuries of wondering, we now know that planets abound in the Universe. Indeed, according to recent work based on results of the Kepler mission and ground-based surveys, at least one planet inhabits each FGKM star in our Milky Way. The exponential increase in the number of known extrasolar planets in the last 30 years has brought with it a variety of unexpected environments and architectures where planets can grow. The absence of these configurations in the Solar System (like the presence of super-Earths or hot Jupiters) is still puzzling and shows that many factors influence the shaping of a planetary system, making them very different in structure and composition. However, the Solar System is one of the key pieces of this jigsaw puzzle. It is our test laboratory, a place where we can directly explore the result of the processes that give rise to the formation of an environment suitable to host life as we know it, and the only place where we can collect in-situ information (at least over human time scales). Moreover, the new results from the Solar System exploration probes in recent years have shown that our celestial home is still a mystery. Questions about how Earth became a water world, why Mars became a desert, what the origin is of the diverse orbital properties of Jupiter trojans or how moons are formed, are just some of the large crop of unknowns that remain open.

On the positive side, several instances of exocomets have been identified (for example, in β Pic) and since 1984, thanks to the InfraRed Astronomical Satellite (IRAS), we are also aware of Kuiper-belt-like structures around other stars and we are already looking for exomoons and exotrojans. This suggests that at least some of the components present in the Solar System are also present elsewhere as outgrowths of the planet formation process. In addition, the plethora of exoplanets found so far at different stages of their lives can provide a complete picture of how these bodies form and evolve, as well as external feedback to our theories of Solar System structure.

Exploring the synergies between the Solar System and exoplanet communities and investigating how each of these fields can feed or contrast the theories of the other is critical to understanding the big picture of planetary systems and to unveiling our own history. We proposed the *Diversis Mundi* (OPS-III) workshop — with the invaluable help of the exoplanet and Solar System experts from ESO, both in Chile and Garching — with the main motivation of bringing together researchers from both communities to discuss the current status of the two fields and build bridges to connect them. The workshop focussed on two main topics: (1) thinking about extrasolar systems as extra Solar Systems, with all their components, and (2) putting the Solar System in context with the wide variety of extrasolar system properties found so far.

In order to achieve these goals, we designed a workshop format specifically intended to merge both fields and to enhance the interaction between the two communities. We identified four main topics that are key to understanding the big puzzle of planetary systems: (a) the formation of planetary systems and their components; (b) the architecture and evolution of planetary systems; (c) small components of planetary systems; and (d) planetary atmospheres and biomarkers. The meeting was then divided into four sessions corresponding to these four main topics, with one day devoted to each. Finding the synergies between both communities in these four main areas is crucial to understanding our own environment and for the search for life outside the Solar System. Joining together people from both fields is an opportunity for them to learn, test their ideas, and trigger inter-disciplinary collaborations. The last day of the meeting was devoted to the "Present and future facilities for the exploration of planetary systems". The full programme and presentations are available online[1,2].

In order to succeed, a workshop aimed at two communities requires both a broad audience with expertise in the two fields, and a format designed to encourage interaction, discussion, and collaboration between them. To achieve these two key requirements, a particular effort was made in selecting the invited and contributed speakers, and in designing the format of the invited talks and the hands-on activities. We chose to have a one-hour session each day to open the topic with a broad view of the theme, chaired by an international expert from each community in what we called "bridge talks". Total freedom was given to the two speakers in designing their combined talk to encourage their interaction before the conference. An invited talk focussed on a particularly relevant topic was scheduled after the lunch break on each day. This kept the focus of the session and encouraged digging into a particular science case. The schedule was filled with contributed talks on the topic of the day. At the end of each day, sessions with different goals were organised. In particular, in the Tuesday session we organised round tables on seven big topics where the audience from both communities split to discuss and bring up new ideas. A "blackboard session" to present short results with only the support of chalk was organised on Thursday afternoon. Finally, a poster session was scheduled on Thursday to give an opportunity to the poster presenters to explain their work and leave some time for free discussion.

In the coming paragraphs, we present summaries of some particularly interesting talks and highlights from each session.

Figure 1. Conference photo at the ESO premises in Vitacura.

Formation of planetary systems and their components

The bridge talk of the first session of the workshop was given by Jürgen Blum & Joan Najita, who discussed the formation of planetesimals and planets. They summarised our understanding of planetesimals and planet formation, from the evolution of dust in protoplanetary discs, to pathways towards planetesimals, and finally planet formation. They also discussed what we can learn about planet formation from the observations of discs using mainly ground-based facilities.

The other talks of that session were mainly dedicated to the study of protoplanetary discs. The use of new facilities/instruments has revealed a whole diversity of features (for example, gaps, vortices, rings, asymmetries) in young planetary discs and revolutionised our view of their structure. Findings from large surveys of discs with ALMA were presented by, amongst others, François Ménard, Laura Pérez and Nienke van der Marel. Several results from observations of proto-planetary discs with the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) were presented too. Even though a planet forming inside a disc has not been directly observed yet, such observations are essential to constrain planet formation models.

Architecture and evolution of planetary systems

The first talk of this session was again a bridge talk, this time focussed on the dynamical evolution and architecture of Solar and extrasolar systems. Aurélien Crida and Pedro Figueira discussed the link between planet formation and evolution mechanisms and the observed demographics of exoplanets as well as the structure of the Solar System. They reviewed how mechanisms such as core accretion, gravitational instability, and planet migration shape planetary systems, and how those can be linked to the observed structure of our own Solar System and the diversity of exoplanet systems we have observed so far.

Very interesting contributions about various aspects of the architecture and evolution of planetary systems followed this bridge talk. The results of a survey aimed at detecting Solar System twins was presented by Jorge Meléndez, who showed that such systems might be very rare. Later, Dino Mesa and Alice Zurlo presented the first results from the SpHere INfrared survey for Exoplanets (SHINE), the purpose of which is to provide the best statistical constraints to date on the population of giant exoplanets. Solar System architecture and evolution were not left out of the discussion, and an invited talk by Matija Çuk in the afternoon was devoted to theories of the formation of the Moon, and highlighted the necessity of moving on from the Giant Impact theory. A lot of work still needs to be done before reaching a clear picture on how planetary systems, including our own, evolve.

Small components of planetary systems

This session started with a bridge talk on water in small bodies of the Solar System and in planetary systems in the formation stage. In the first part of the talk, Karen Meech reviewed what we know about water in our Solar System, and how evidence of water-driven activity is found in unexpected places, such as the main asteroid belt. Studying the isotopic signature of water, in combination with other chemical fingerprints, is key to establishing connections with early stages of planet formation, and understanding how, when, and from where Earth got its large water content. In the second part of the talk, Edwin Bergin made the link between the history of water in the Solar System and our current understanding of how the water is formed and transported from clouds to discs, and to planetesimals. Observations with the space-based telescopes Spitzer and Herschel allow the emission of water molecules to be traced, from before stellar birth to the disc stage. This in turn allows the initial conditions of water distribution (as gas and ice) available at the time of planet formation to be established.

During the rest of this session, several talks were devoted to the detection of small bodies outside the Solar System. Alex Teachey presented an overview of the search for exomoons in Kepler data and the latest updates about the exomoon candidate Kepler-1625b I. Isabel Rebollido-Vázquez and Daniela Iglesias discussed the search for exocomets, and Siyi Xu the study of a transiting extrasolar asteroid. Even though we have now begun detecting small bodies in extrasolar systems, we still do not fully understand the origin and formation of small bodies in our own system. In the afternoon, Silvia Protopapa gave a summary of the results of the New Horizons mission, which flew by Pluto in July 2015, allowing us to gather critical information on the surface composition, geology, and atmosphere of Pluto and its satellites.

Planetary atmospheres and biomarkers

The bridge talk of this fourth session was given by Patrick Irwin and Nikole Lewis and was focussed on the atmospheres of giant planets in the Solar System and beyond. In the past 40 years, our understanding of the composition, structure, atmospheric circulation, photochemistry, and cloud formation in the atmospheres of the Solar System giant planets has markedly improved, thanks to a combination of several space missions and ground-based observations. However, numerous questions still remain, despite the ability to study those planets in much more detail than is possible for exoplanets. Much progress has been made during the past 10 years in observation techniques and methodologies as well as in specialised atmospheric and circulation models, many of which have their roots in Solar System studies. This has allowed us to begin probing the atmospheres of exoplanets, especially those of hot Jupiters, which are extremely different from what we observe in Solar System planets.

Later that day, Elyar Sedaghati and Monika Lendl presented very interesting results from transmission spectroscopy of the atmospheres of hot Jupiters using the FOcal Reducer/low dispersion Spectrograph (FORS2) on the Very Large Telescope (VLT). Among these was the first discovery of a metal oxide in the atmosphere of an exoplanet by Sedaghati and collaborators. In the afternoon, Máté Ádámkovics presented an overview of the dense, nitrogen-dominated atmosphere of Titan, which could serve as an example for exoplanet atmospheres with haze and clouds.

Present and future facilities for the exploration of planetary systems

The first talk of the last session was given by Bin Yang and Claudio Melo, on behalf of Luca Pasquini, presenting the variety of ESO instruments used to study Solar System objects, planets in extrasolar systems, and protoplanetary discs. The emphasis was on second-generation instruments such as the Multi Unit Spectroscopic Explorer (MUSE), SPHERE and the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO), and the new capabilities that will soon be available were presented. This was followed by John Carpenter who discussed the wide range of planetary science observations that can be performed with the Atacama Large Millimeter/submillimeter Array (ALMA). Finally, the last talk of the conference was about the James Webb Space Telescope (JWST), and its capabilities to observe Solar System objects and exoplanets.

In addition to the five regular sessions, round-table sessions provided an excellent environment for more detailed discussions about critical open questions regarding planetary systems and their formation. As an example, one of the round tables, chaired by Jürgen Blum, was devoted to discussing the formation of planetesimals. During this round table, the need to develop new ways to test the different planetesimal formation models was emphasised. Those would concern both the Solar System small body population, and the structure and composition of protoplanetary discs outside the Solar System. In any case, the visit to the Kuiper belt object 2014 MU69 by the New Horizon mission in late 2018 could provide an essential test for planetesimal formation models. Another round table was chaired by Karen Meech and dedicated to the interstellar interloper `Oumuamua. The first part of the discussion focussed on what additional observations could have been made if the observability of the target had been better, and what further properties could be investigated for the next interstellar object detected crossing the Solar System, such as making a size estimate. The strange shape of `Oumuamua and the implications for its formation mechanism were also discussed.

This third Observing Planetary Systems workshop was a real success, thanks to a combination of a careful choice of invited speakers and the specific format of the workshop. It allowed the synergies between the Solar System and exoplanet communities to be explored, and numerous ideas were exchanged and discussions started. The bridge talks, featuring two speakers discussing complementary subjects from each community, were particularly fruitful and the blackboard presentation proved a very efficient means to present short scientific results to a wide audience. Gathering the Solar System and exoplanet communities together to foster and encourage collaboration is essential to reaching a better understanding of the structure, formation, and evolution of exoplanetary systems as well as why the Solar System is so peculiar and how life appeared on Earth. Such workshops are of great value in ensuring progress in that direction. We hope that future OPS workshops, as well as others in this area, continue to promote collaborations between the two communities.

Demographics

For a workshop that covered two areas with the main aim of building bridges between them and that was held in Chile (far from the usual European or US venues but in a country where astronomy is growing fast), the selection of the invited speakers and contributed talks was crucial to attracting researchers from all over the globe and from the two communities. To that end, we composed a Scientific Organising Committee (SOC) with the following criteria: world-wide expertise in their field; gender balance; topic balance; and origin balance. The final SOC was composed of: Jorge Lillo-Box (ESO, co-chair); Cyrielle Opitiom (ESO, co-chair); Monika Lendl (Austrian Academy of Sciences); Eric Ford (PennState); Nuria Huélamo (Astrobiology Center, CAB); David Kipping (Columbia University;, Christophe Mordasini (Bern University); Colin Snodgrass (The Open University); Karen Meech (University of Hawai'i); Imke de Patter (University of California); and Emmanuel Lellouch (LESIA, Observatoire de Paris). This included six men and five women, with five experts in different exoplanet fields and their five counterparts in Solar System studies, plus one expert in planetary system dynamics (with influence in both communities). Seven of them were from European institutions and four from US institutions.

The ESO proposing team presented a proposal for the workshop format, previously discussed in internal meetings, focussed on bridging the two communities. This proposal was discussed by the SOC and some modifications were introduced to accommodate the different suggestions. The SOC proposed a list of invited speakers, focusing on researchers with broad topic knowledge for the bridge talks. In the end 57% of the invited speakers were from the Solar System community and 43% from the exoplanet community (with a 56:44 male:female ratio). The submitted contributed talks were split into four panels matching the four topics of the conference. The expert from each field then gave a score to each abstract and the final decision was taken based on their scores by the two chairs of the workshop. We received 58 abstracts, of which 40 could be scheduled. The male:female ratio of the submitted abstracts was 60:40, as was the ratio of scheduled talks. Interestingly, we found a clear gender imbalance per topic: while men submitted many more abstracts for planet formation and evolution topics (the first two sessions of the workshop) leading to a 68:32 male:female ratio, women submitted more abstracts for the small components and atmospheres topics, with a 40:60 male:female ratio. Regarding the two broad communities, however, the imbalance was very strong, with 28% of the talks related to the Solar System and 72% related to exoplanet studies.

As to the participants, we hosted 95 attendees during the week, filling the venue. The male:female ratio was 67:33, proportional to the ratio of submitted abstracts although still far from gender balanced. This highlights once more the still unequal scientific society and showing that much more needs to be done, at a higher level, in this regard. We had a reasonably balanced participation from the different stages of the scientific career: 36% of attendees were PhD students, 28% postdocs and 36% tenured/senior astronomers. These percentages were also broadly reflected among the speakers and poster presentations. The attendees came from four continents with the following distribution: South America (49%); Europe (33%); North and Central America (17%, including Mexico, US and Canada); and Asia (1%). The lack of attendees from Africa (sadly typical of international conferences held in Europe and America) also points to the challenges of doing science in this continent and the relative lack of resources, another challenge to our goal of a modern and global scientific society.

In summary, the *Diversis Mundi* workshop hosted a wide variety of expertise within the two main topics of the conference and brought together people from many different nationalities and backgrounds. The high level of participation with a full conference room on all five days of the workshop demonstrated the interest in this kind of mixed workshop.

Acknowledgements

We thank ESO for the financial support that made the organisation of this workshop possible. We would also like to thank the ESO staff from the exoplanet and Solar System fields who supported the proposal of this workshop, provided feedback and participated in the discussions to define the workshop proposal — Bin Yang, Zahed Wahaj, Claudio Melo, Anna Burcalassi, Valentin Ivanov, Bill Dent, Henri Boffin, Daniela Iglesias, Michael Sterzik, Julien Milli, Florian Rodler, Hans-Ulrich Käufl, Markus Kasper, Olivier Hainaut and Matias Jones. We also want to thank the Scientific Organising Committee of the workshop for their invaluable help in selecting the speakers and topics for the invited talks, and for helping with the definition of the workshop format — Karen Meech, Emmanuel Lellouch, Nuria Huélamo, David Kipping, Monika Lendl, Eric Ford, Imke de Pater, Colin Snodgrass and Christoph Mordasini. Finally, we also acknowledge the invaluable help of Maria Eugenia Gómez and Paulina Jirón with the logistics aspects of the workshop.

Links

[1] Link to the workshop programme: http://www.eso.org/sci/meetings/2018/ops2018/program.html

[2] Presentations are available via Zenodo: https://www.zenodo.org/communities/diversismundi2018

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Report on the ESO Workshop

Proposal Submission Tools

held at ESO Headquarters, Garching, Germany, 4–6 June 2018

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The Atacama Large Millimeter/submillimeter Array (ALMA) Observing Tool is a desktop Java application which has been used very successfully since the beginning of science operations to submit requests for time during the annual Call for Proposals, as well as to prepare observing materials such as Scheduling Blocks. An ALMA upgrade study is currently looking at ways in which the OT might be modernised. As part of this study, a workshop was held at ESO Garching in order to bring together groups working on similar systems at observatories around the world.

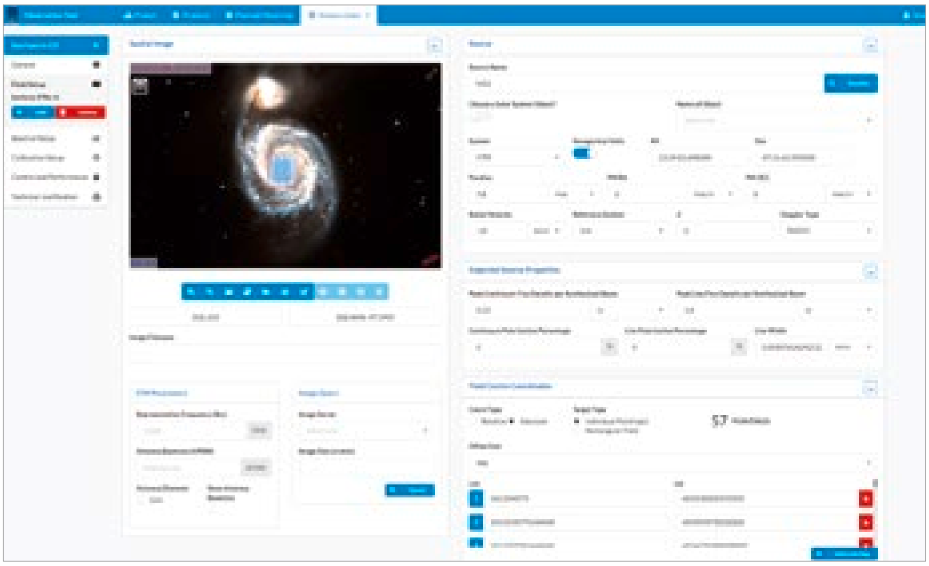
As is the case for most astronomical observatories, it is necessary for ALMA to provide a way for astronomers to submit their observing proposals. As mundane and obvious as this may sound, proposal submission tools have evolved into complex systems which can carry out a number of tasks. As well as collecting the essential scientific parameters (pointing position, frequency or wavelength coverage, desired sensitivity, etc.), modern submission systems should be easily operable by astronomers working in any band of the electromagnetic spectrum, and incorporate tools and visualisation capabilities, enabling the performance of technical feasibility checks. They must also be capable of dealing with a large volume of traffic due to increased rates of submission close to the deadline. In addition, the software should interface with other software systems in operation at the observatory. Software developers, on the other hand, require code that is easily maintainable and which is not in danger of becoming deprecated or obsolete.

The solution adopted by ALMA is the Observing Tool (OT), a Java desktop application which was released to the ALMA community in time for Cycle 0 of ALMA operations in 2011 (Bridger et al., 2008). The OT has been a great success and was used to submit over 1800 proposals in the most recent deadline in April 2018 (Cycle 6). However, the OT is beginning to show its age. Its development was begun in 2002, and the original technologies have been overtaken by increasingly rapid developments in the available software. In addition, certain toolsets used by the OT have become deprecated, for example, the toolset used to display the OT's main GUI and Java Web Start; the latter will be removed from Java 11 (due to be released later this year). At the same time, desktop installations such as those used by the OT have generally given way to web-based solutions.

With this in mind, an ALMA upgrade study was launched in September 2017, with the goal of investigating alternatives to the current implementation, which could subsequently form the basis of an upgraded OT. It was quickly realised that a huge amount of expertise is in place across various observatories around the world, each of which tends to develop its own proposal submission system independently. In order to allow the ALMA OT team to benefit from the knowledge and experience embedded at each observatory and, perhaps more importantly, to allow all observatories to benefit, a short workshop was organised at ESO with the aim of bringing together staff working on these systems all over the world.

The workshop brought together representatives from 11 observatories. In alphabetical order, these were ALMA, the Netherlands institute for Radio Astronomy (ASTRON), the Cherenkov Telescope Array (CTA), ESO, Gemini, the Giant Metrewave Radio Telescope (GMRT), Institut de Radioastronomie Millimétrique (IRAM, France), the National Astronomical Observatory Japan (NAOJ), the National Optical Astronomical Observatories (NOAO, USA), National Radio Astronomy Observatory (NRAO, USA), and the Square Kilometre Array (SKA). As well as covering the entire electromagnetic spectrum (radio, millimetre, infrared, optical and high energy), these observatories represent different levels of sophistication in how proposals are collected from their community. Two of them, SKA and CTA, are still deciding what their proposal submission systems will look like when they issue their first Call for Proposals. ASTRON is notable as

Figure 1. A screenshot from a prototype of the ALMA Observing Tool showing the spatial visual editor.



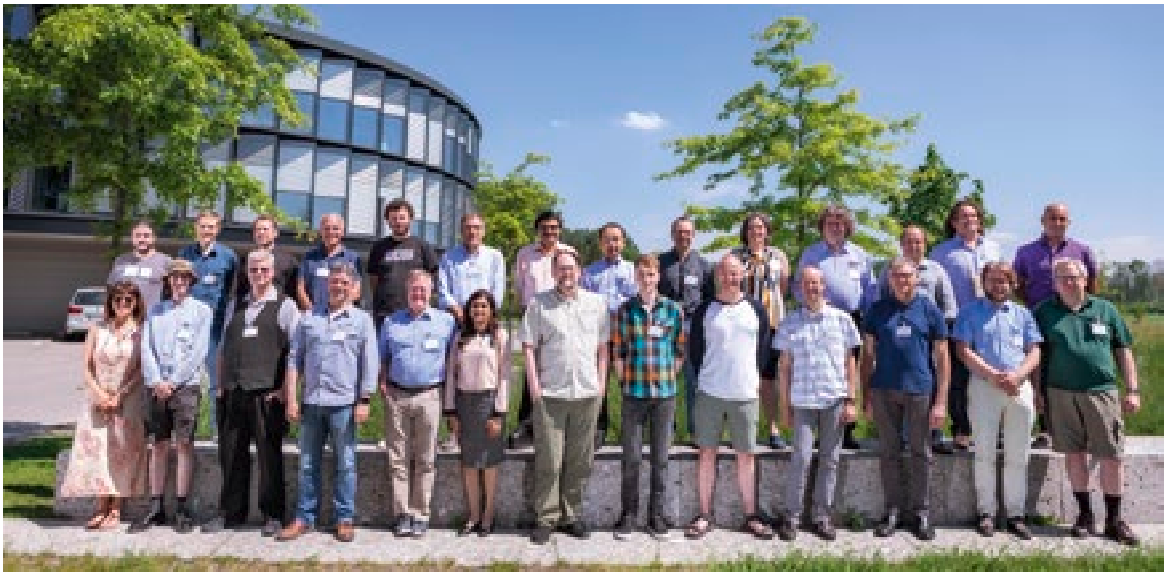


Figure 2. Workshop photo.

their Northstar system has been used by multiple observatories, both radio and optical, and they are experts in building common-user software.

The first part of the meeting was devoted to short presentations from each observatory giving an overview of their current proposal submission system, including their specific challenges and plans for the future. All talks given at the workshop have been published on Zenodo and are accessible from the workshop web pages[1]. The talks were followed by a demonstration of new tools and functionality by four of the observatories, ALMA (see Figure 1), ESO, Gemini and GMRT. The ESO proposal submission system is currently undergoing a major overhaul, and it was very interesting to see the new system in action. The discussions then began in earnest, covering a large array of topics and including two parallel sessions devoted to technical and policy issues, respectively.

One area that was given special attention during the workshop was that of Authentication, Authorisation and Accounting (AAA). All observatories currently maintain their own user databases and thus each astronomer must create a separate account with their own username and password. Federated Identities, whereby users can log onto multiple internet sites using their user credentials for another, have become familiar to us all through, for example, Facebook and Google, and the question now arises as to whether such an approach could also be used within astronomy. To familiarise the workshop participants with what is a relatively new field, we invited Davide Vaghetti, an expert from Consortium GARR[2] — the Italian national network for universities and research — to give a general talk introducing this area. ESO's Maurizio Chavan gave an introduction from a purely astronomical perspective.

At the conclusion of the meeting, it became clear that all participants were very interested in staying in touch and building on the discussions and the contacts that had been made during these three days. In order to facilitate this, a Slack workspace called "Astro Observatories Collaboration" has been set up to allow observatories to easily communicate with each other. Another decision was made to set up a working group to investigate what progress can be made in the area of AAA/Federated Identities. Given the success of the meeting, there was also agreement that having a similar meeting in a few years would be beneficial.

Demographics

The workshop was relatively small — with too many participants it would have been difficult to efficiently manage the discussion sessions that formed the bulk of the proceedings. Attendance was by invitation only and individual observatories were contacted by the Scientific Organising Committee and asked to nominate the members of staff that they would like to attend.

In total, we had 34 participants from observatories in Australia, Chile, Europe, India, Japan, South Africa and the US (Figure 2). The gender balance was unfortunately poor, with only four female attendees. With hindsight, the SOC should have encouraged observatories to think about gender balance in their invitations to participate. However, given the small numbers of people working on these systems, it is unclear if this would have brought about a more positive gender balance.

Acknowledgements

We are very grateful to Elena Zuffanelli for her help in organising and running this workshop, as well as to Rein Warmels for his sterling work in putting together and updating the workshop web pages.

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Report on the ESO–INAF Workshop

VST in the Era of the Large Sky Surveys

held at INAF–Astronomical Observatory of Capodimonte, Naples, Italy, 5–8 June 2018

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This workshop focussed on science programmes carried out with the INAF–ESO VLT Survey Telescope (VST) several years into its operation. The aim of the conference was to review the latest results and ongoing programmes, and to look ahead to future science cases, as well as potential synergies and collaborations with other projects and facilities.

The VST is an INAF facility operated by ESO under a 10-year agreement. It was developed to enable optical imaging surveys from Paranal. Equipped with a 1 × 1 degree field of view, the VST provides one of the best quality optical wide-field imaging capabilities to date. After seven years of operation, there was a need to discuss the present successes and to start organising the future of the VST. The Science Organising Committee included ESO and INAF representatives, the Principal Investigators (PIs) of the three ESO Public Surveys — ATLAS, the Kilo-Degree Survey (KiDS), and the VST Photometric Hα Survey of the Southern Galactic Plane (VPHAS+) — along with other scientific experts. The Science Organising Committee welcomed talks on ESO Public Surveys, Guaranteed Time Observation (GTO) programmes from both the VST and OmegaCAM consortia, and programmes carried out in Chilean and ESO time. Talks from other facilities were also encouraged in order to explore synergies and new scientific ideas, as well as proposals for technical upgrades. The programme comprised 51 talks, the full details of which can be found via the conference web page[1].

The first part of the conference was dedicated to managerial and operational aspects, and reviewing the landscape of the current ESO Public Surveys. The domain covered by these ongoing surveys encompasses a range of research areas across multiple wavelengths and using different telescopes. The surveys have demonstrated an increasingly high level of scientific productivity and, as with large programmes, have generally had a high impact. The operational aspects underpinning these programmes were also discussed. The efforts of ESO's quality control group were presented, as well as the night and day operations at the telescope; these help to ensure stable operation with negligible technical downtime. There were also talks on the publication of science data products via the ESO Archive, in order to ensure that they can be used for further scientific analysis by the community at large.

ESO VST Public Surveys

The ATLAS survey, which covers 4700 square degrees, was presented and its legacy value discussed, in particular its use in X-ray surveys with the extended ROentgen Survey with an Imaging Telescope Array (eROSITA), and follow-up with the 4-metre Multi-Object Spectrograph Telescope (4MOST). The ATLAS survey focusses on a range of topics including: quasar redshift surveys in the redshift range $0.5 < z < 6.5$; quadruply lensed quasars; investigations of the enigmatic Cosmic Microwave Background (CMB) Cold Spot (a region that appears unusually cold relative to the background radiation levels of the CMB); the discovery of dwarf Milky Way satellite galaxies (including the Crater 2 dwarf galaxy); and new catalogues of thousands of white dwarf stars in the Milky Way. An extension to the ATLAS survey in the *u* band is being conducted in Chilean time and the latest results from these efforts were also presented.

The application of the galactic plane survey VST OmegaCAM Photometric Hα Survey (VPHAS+) in uncovering the fainter ($r > 13$) massive O and early-B type stars of the Milky Way disc was also described. One session was dedicated to contributions from the KiDS survey, which is designed to take the maximum possible advantage of the wide field and the outstanding image quality of VST and OmegaCAM. Its science focusses on weak gravitational lensing by galaxies, groups and large-scale structure. Recent results were presented that demonstrated how cosmological constraints can be derived from KiDS lensing measurements. The high image quality and deep photometry of KiDS are ideal for galaxy evolution studies and for hunting peculiar and rare objects, such as massive compact galaxies and gravitational lenses. Methods and techniques to find Quasi-Stellar Objects (QSO) and arcs were addressed, as were the first spectroscopic follow-ups and specific science cases (for example, the Fornax dwarf spheroidal galaxy). Synergies between KiDS and other projects (both current and future) were also discussed. Many aspects of the approach to data handling for the Astronomical Wide-field Imaging System for Europe (Astro-WISE) will also be applied to data processing from the ESA Euclid mission. The overlap with the Galaxy And Mass Assembly (GAMA) project galaxy spectra allows for the measurements of the central velocity dispersions. Synergies between the strong gravitational lensing studies with Herschel and the VST observations were explored. We also explored the incorporation of VST data into the HELP-IDIA Panchromatic PrOject (HIPPO); HELP is the Herschel Extragalactic Legacy Project and IDIA is the Inter University Institute for Data Intensive Astronomy. This combines multi-wavelength datasets and tools in a cloud infrastructure.

Galactic astronomy

After an introductory talk about how data from multiple instruments can be combined to enable pulsating stars to be used as stellar population tracers, several stellar programmes were presented, ranging from the STRucture and Evolution of the GAlaxy (STREGA), which aims to investigate the formation and evolution of the galactic halo, to the SMC in Time: Evolution of a Prototype interacting late-type dwarf galaxy (STEP); and the study "Yes, Magellanic Clouds Again" (YMCA) — this focusses on the Magellanic system stellar populations. Galactic globular-cluster studies were also discussed, including photometric and astrometric studies of Omega Centauri, and the tidal tails of a selected sample of clusters. Finally, there was a talk on a survey called Accretion

Figure 1. Workshop participants at the Capodimonte Astronomical Observatory; Mount Vesuvius is in the background.

Figure 2. The conference tie: bringing together the ESO look with Italian style.

Discs in $H\alpha$ with OmegaCAM (ADHOC), which studies the population of pre-main sequence (PMS) objects in close-by star forming regions (also see p. 17).

Extra-galactic astronomy

There were many contributions addressing extragalactic science. The KiDS ATLAS Bridging Survey (KABS) is characterising many objects in fields not targeted by ATLAS or KiDS and will build on the strengths of the two Public Surveys in preparation for follow up with eROSITA and 4MOST. The Shapley Supercluster Survey conducted with VST, the Visible and Infrared Survey Telescope for Astronomy (VISTA) and the Australian Astronomical Observatory spectrograph AAOmega has observed the transformations of galaxies in a stormy environment. The survey called Galaxy Assembly as a function of Mass and Environment (VST-GAME) targets massive galaxy clusters in order to understand how different cluster assembly processes can drive the evolution of galaxies as a function of mass and environment. It is part of a larger effort that also uses VISTA and VLT data.

The Wide-field Imaging Nearby Galaxy clusters Survey with OmegaCAM (WINGS and OmegaWINGS) studies nearby galaxy clusters. In another talk results were presented from the the GAs Stripping Phenomena in galaxies (GASP) programme, which is a follow-up study using the Multi Unit Spectroscopic Explorer (MUSE). A set of coordinated contributions were presented from the VST survey of Early-type GAlaxies in the Southern hemisphere (VEGAS) and the Fornax Deep Survey (FDS) teams in a dedicated session. A survey of early-type galaxies which is using a deep photometric analysis to study stellar halos and faint structures was presented. Globular clusters within the same fields are also being studied, as well as NGC 1533 in the Dorado group and the post-merger evolution of early-type galaxies. The evolution of dwarf galaxies was analysed using FDS data. Other FDS contributions concerned automated searches for low-surface-brightness galaxies and surface photometry of late type galaxies inside the virial radius of the Fornax cluster.

Time-domain astronomy

Several talks focussed on time-domain astronomy. These included the study of the evolution of the supernova rate with cosmic time with the SUpernova Diversity And Rate Evolution (SUDARE) project, which targets the Chandra Deep Field South (CDFS) and the Cosmic Evolution Survey (COSMOS) field in a joint effort, including Italian and Chilean time, and the programme VST Optical Imaging of the CDFS and ES1 fields (VOICE). In addition, the multi-epoch survey of the COSMOS field allowed optical variability to be used as a tool to identify Active Galactic Nuclei (AGN).

Talks and discussions addressed the nascent field of gravitational wave astronomy, and the fundamental role played by the VST in the GRAvitational Wave INAF TeAm (GRAWITA), which searches for electromagnetic counterparts of gravitational wave events in rapid response to LIGO–Virgo alerts. The discovery of the kilonova, the optical counterpart of the GW170817 event, was showcased during this discussion. Time-domain astronomy and monitoring campaigns targeting variable phenomena are set to increase, thanks to the availability of science products in the ESO archive, the improved capabilities of the recently launched ESO Archive Science Portal[2], and the anticipated capability of the Large Synoptic Survey Telescope (LSST).

Synergies and future ideas

Building on the many synergies discussed by speakers between the VST and both ongoing and future facilities — including ongoing INAF projects in the optical and near-infrared — this conference began the necessary process of looking to the future. The astronomy landscape is continuously changing as new facilities start operating.

What is the VST's place amongst these future developments? Several major facilities were described, including the ESA Gaia satellite, for which the VST Ground Based Optical Tracking (GBOT) campaign has been essential to improve the astrometric precision, and which has also discovered lots of new asteroids. In addition, there is the Cherenkov Telescope Array (CTA), whose southern site will be close to Paranal and which will require the identification of optical counterparts. The ESA Euclid mission already incorporates lessons learnt with the VST and will require complementary ground-based data; the NASA Wide Field InfraRed Survey Telescope (WFIRST) space observatory may require a future exoplanet ground-based microlensing survey; and the 4MOST project will have wide-field multi-object spectroscopic capabilities.

New ideas were presented for cosmology experiments over the next decade, such as high-cadence monitoring of strongly lensed quasars for time-delay cosmography and a slitless spectroscopic survey to provide accurate redshifts for the synergy between the LSST and the ESA Euclid mission. The latter requires the implementation of a slitless spectroscopy unit working in combination with the existing imaging camera. A proposal to upgrade the system to make the VST the first large survey telescope for optical polarimetry, retaining the camera, was also discussed. Scientific cases include mapping the Milky Way, Magellanic cloud magnetic fields, surveys of quasar polarisation, identification and variability of polarised brown dwarfs, etc.

After this intense four-day workshop, we can state that the VST user community is addressing a wide range of scientific topics. The telescope and camera are in their best shape, regularly delivering seeing-limited images of outstanding image quality across the one-square-degree field of view, with a technical downtime that was recently determined to be smaller than that of ESO's VLT unit telescopes. The telescope is clearly delivering exciting science at the moment; the future is what we want to build! It is now important to define future science cases that are optimally designed to play a vital role in the astronomical developments of the next decade, with the participation of the INAF and ESO communities.

Proceedings based on the conference contributions are available through Zenodo[3]; they are fully searchable via the SAO/NASA Astrophysics Data System (ADS) and linked from the programme webpage.

Acknowledgements

This event received funding and sponsorship material from INAF and ESO, that are gratefully acknowledged. We are also grateful to Ugo Cilento for dedicating an artistic tie to our conference, as well as to our helpers. We especially thank the Science and Local Organising Committees for their hard work before and during the conference in putting together an interesting and vibrant event.

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This stunning VST image encompasses three star forming complexes. From left to right these are the Omega Nebula (Messier 17), the iconic Eagle Nebula (Messier 16) and Sharpless 2-54.

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Report on the ESO–European Interferometry Initiative School

The 9th Very Large Telescope Interferometer School

held at University of Lisbon, Portugal, 9–14 July 2018

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The 9th Very Large Telescope Interferometer (VLTI) school guided participants through the process of acquiring and analysing VLTI observations from end to end, encompassing a range of steps, from scientific programme design to data reduction and exploration. This school was jointly funded by OPTICON (through the European Interferometry Initiative [EII]) and ESO. In total, 37 students participated and 15 lecturers were involved, ensuring broad coverage of topics. Continuous feedback was gathered throughout the school and the lecturers worked hard to fine-tune the programme using input from the students.

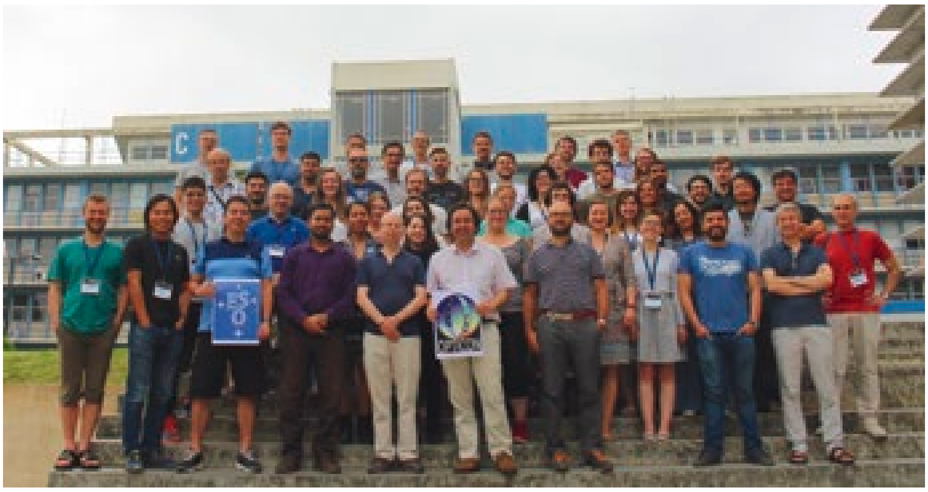

Figure 1. Group photo of the participants and lecturers of the 9th VLTI School at the Physics Department of the Faculty of Sciences, University of Lisbon.

Long baseline interferometry in the optical-to-infrared is in its infancy when compared with interferometry in the radio and (sub-)millimetre wavelengths. At the much higher frequencies of the optical-to-infrared, atmospheric turbulence dominates and this precludes detecting the oscillating electric field with an individual telescope. After several successful experiments worldwide, ESO's VLTI achieved first light in 2001, combining two telescopes. Closure phase, combining three telescopes, was obtained in 2004. The VLTI is unique as it is a common-user facility serving a very broad community and also allows the simultaneous combination of four 8-metre-class telescopes. Very early in its history, it was recognised that training on using the VLTI was essential — particularly as expertise in long baseline optical interferometry had been confined to only a few groups in France and Germany, and in the early years the UK was not yet an ESO member state. The first VLTI school took place in 2002 at Les Houches in France, and VLTI schools have since been held in several countries including France, Germany, Hungary, Poland and Portugal.

In July 2018, the Portuguese VLTI Expertise Centre organised the 9th VLTI Summer School[1], which was aimed at postgraduate students and postdocs wishing to learn the theory and practicalities of infrared interferometry. The school had 37 students, 28 of whom were MSc or PhD students originating from 15 different countries: Brasil, Bulgaria, China, Denmark, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Norway, Poland, the Netherlands, the UK as well as ESO. Roughly half of them were from France, Germany and the UK. The interferometric expertise of the students was varied, which allowed them to learn from each other as well. The gender balance among the participants was 38% female and 62% male.

The school was designed to be practical, introducing students to many tools that are commonly used to prepare VLTI observations and to facilitate data reduction. A computer room with more than 20 computers was made available to run the requisite software. An open source virtual machine[2] with all the required software was installed. Students also brought their own laptops, and could run the virtual machine on these computers. The main focus of the school was on the new adaptive-optics assisted, two-object multiple beam combiner, GRAVITY (Gravity Collaboration, 2017), but there were plenty of references to the other VLTI instruments including the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE; Lopez et al., 2014).

The school started on Sunday evening with a welcome dinner, registration and practical briefings. Classes started on Monday morning with a theoretical introduction by David Busher (Cambridge University, UK). Then Astronomical Software to PRepare Observations (ASPRO), from the Jean-Marie Mariotti Centre (JMMC) in France, was introduced in a practical session. Initially it was used to plot the visibilities using simple models and the *uv*-coverage of several array configurations. This same software was used to test for the observability of astronomical targets using the VLTI. These activities were guided by Gilles Duvert, Guillaume Mella and Laurent Bourgès (from the Institut de Planétologie et d'Astrophysique de Grenoble [IPAG], France).

A historical perspective on the VLTI was given by Antoine Mérand (ESO), after which the second-generation VLTI instruments were introduced, including MATISSE (Alexis Matter, Observatoire de la Côte d'Azur [OCA]) and GRAVITY (Oliver Pfuhl, Max Planck Institute for Extraterrestrial Physics [MPE]). Finally, Andres Pino (ESO) explained the importance of considering VLTI operations when preparing observations.

Figure 2. Oliver Pfuhl explains the GRAVITY pipeline to the students.

Figure 3. Joel Sanchez presents the solution to the image reconstruction exercise.

Figure 4. Eric Thiebaut explains the intricacies of image reconstruction to student Dominika Itrich, from Nicolaus Copernicus University in Torun, Poland.

An introduction to fitting models to interferometric data was carried out, followed by a practical session using the JMMC tool LitPro. These lectures and practical sessions were given by Michel Tallon and Eric Thiébaut (from the Centre de Recherche Astrophysique de Lyon [CRAL]). Eric Thiébaut, Joel Sanchez (ESO) and John Young (Cambridge) introduced image reconstruction theory and guided students through a practical application using several software packages, including BSMEM, MiRA and SQUEEZE. This allowed students to confirm that image reconstruction is possible and that results are consistent across different packages. Oliver Pfuhl and Gilles Duvert presented the GRAVITY pipeline and then led a practical activity illustrating its usage.

Finally, a lecture on the preparation of observations was given by Claudia Paladini (ESO); this very important lecture detailed how to submit a proposal to ESO, and afterwards the students created their own ESO proposal, submitting it to a mock Observing Programmes Committee (OPC). This exercise was carried out in groups over a specified amount of time. On the last day of the school (Saturday morning!) the groups presented their proposals orally and received feedback from the mock OPC, which consisted of Antoine Mérand, Claudia Paladini, Gilles Duvert, Oliver Pfuhl and Paulo Garcia. The proposals were considered to be of high quality, with subjects ranging from the Solar System to extragalactic science. In addition to the formal lectures and practical exercises, the programme also included time for students to give short talks on their own research.

Continuous feedback

The lecturers were very impressed with the professionalism shown by the students during this intensive school — the only social break was on Saturday afternoon!

Anonymous feedback from the students was collected daily. This allowed the collection of valuable information and enabled the lectures to be fine-tuned. The feedback was mostly very positive. One student stated, “Very good introduction lecture. I really appreciate that we start with hands-on exercises already on the first day.” The availability of several lecturers to answer questions was received positively by several students, with one remarking: “There were a lot of people around to answer questions during the practice session, it was very good.” Several students appreciated the practical aspects, which included fitting models and preparing observations — and in particular, the pause after each exercise to ensure everyone was on track. The lectures on GRAVITY also rated very highly amongst the students.

All students were housed in a large hostel, which maximised student interaction. On the first day, one student wrote that “The atmosphere” was the aspect that he most liked. Perhaps unsurprisingly, given that the school was held in Portugal, the organisers also received very positive comments on the food.

Several possibilities for future improvement were also identified over the course of this school. In their feedback, students requested, “more practice, fewer lectures” and “having slides before the lectures”. Some lectures could be improved further, in particular where “The tempo (…) was too fast or formulas weren’t explained enough.” “I know there were a lot of formulas and only a little time.” The organisers also plan to improve the gender balance of lecturers in future schools.

Acknowledgements

This school was one of deliverables of the OPTICON “VLTI Expertise Centres Network”, which included specific funding for its implementation; complementary funding was obtained via the Fizeau Exchange Programme and ESO. The total budget was around 37 000 euros; this covered full board for all participants, including lodging for 32 students and travel support for 17 students and for all of the lecturers. The VLTI school was organised by the Portuguese VLTI Expertise Centre and held at the Physics Department of the FCUL at the University of Lisbon. The organisers wish to express their gratitude to the Scientific Organising Committee, the Physics Department, and all administrative and support staff who made this school a reality.

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The First ESO Astronomy Research Training — Ghana 2018

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Designed by ESO astronomers, the Astronomy Research Training (ART) provides an intensive introductory course in astronomy to university-level students with no prior education in astronomy. The aim is to expand the astronomical community by empowering the participants to conduct research projects with open-source data. The first ESO ART was successfully conducted in Ghana in April 2018. We provide an overview of this new initiative here.

Motivation

One of ESO's missions is to foster cooperation in astronomical research. In an era of globalisation of knowledge and resources, ESO — with its ambitious telescopes and instrumentation, together with its multinational nature — is uniquely positioned to facilitate the dissemination of astronomical research worldwide. Currently, there are countries which are under-represented within the astronomical community despite their strong interest in developing the field, mainly due to a lack of available opportunities and resources. The ESO Astronomy Research Training (ART) aims at bridging this gap: it is conducted with the hope to encourage the growth not only of astronomy, but also to inspire youth to develop careers in science, technology, engineering, and mathematics.

Figure 1. Group photo of the ESO ART instructors together with the students of the undergraduate group and our hosts, Nana Ama Browne Kluste and Francis Kudjoe (front), and the head of the Physics Department at UCC, Benjamin Anderson (center, white shirt).

Figure 2. The Galaxies course: after exploring the Virgo cluster of galaxies using the GOLDMine database, the students discuss together with the facilitators the importance of galaxy morphological changes. In the background a slide on the future scenario of a Milky Way–Andromeda collision is visible.

Figure 3. The facilitators of the ESO ART together with the head of the Physics Department at UCC, Benjamin Anderson, and the head of the Mathematics and Statistics Department at UCC, Nathaniel K. Howard (front row) during the closing ceremony of the ESO ART.

The Astronomy Research training

The first ESO ART was conducted at the University of Cape Coast (UCC) in Ghana, in collaboration with the Ghana Space Science and Technology Institute[1] (GSSTI). Founded in 1962, the UCC is among the largest universities of the country with over 70 000 students. Despite this, the UCC does not currently offer astronomy classes. ESO ART has thus been a great opportunity for UCC and GSSTI to assess the interest for astronomy among its students and local communities. Our course was attended by about 40 highly motivated participants, split in two groups: undergraduate students, and graduate students enrolled in Masters and PhD programmes.

For each group, we designed a two-day workshop centred on "Stars" and "Galaxies". The courses followed an enquiry-based approach as used by the West African International Summer School for Young Astronomers[2], where Allison and Wolfgang had previously taught. Students learn by observing a particular image, posing questions, and discussing their ideas in groups. This approach is similar to the way we conduct research, by promoting critical thinking and knowledge-sharing.

The Stars course comprised basic knowledge about stars: their composition, structure and evolution. Furthermore, it introduced spectroscopy and how it is used to extract stellar properties. The lectures were interspersed with hands-on exercises. Using Jupyter Notebooks Online[3] written in Python[4], the students made back-of-the-envelope calculations addressing questions such as: how long would the Sun burn if it was made of coal? The course concluded with an introduction to the ESO archive, providing the students with Jupyter notebooks to analyse archival stellar data.

The Galaxies course began with a brainstorming exercise on what galaxies are made of, linking each component to its portion of the electromagnetic spectrum. We then introduced basic notions of observational astronomy such as celestial coordinates, distances, and our position within the Local Supercluster. Students then zipped through the Virgo Cluster using the interactive galaxy database GOLDMine[5], discovering variations in galaxy properties. They compared and discussed the differences seen in their images and spectra. By referring to the Stars course, we discussed how to identify spectral features and how to use them in deriving properties of the stellar populations in galaxies.

Figure 4. Sharing astronomical knowledge at a fishing village. Wolfgang was drawing the Solar System on the soil, and explaining the relevant sizes and distances to a very attentive audience of fishermen.

Figure 5. Group photo of the ESO ART instructors together with the director Jacob Ashong (centre), staff and volunteers of the Ghana Planetarium.

Figure 6. The "crater factory". Children at the Ghana Planetarium learnt about the moon and its craters together with Lisa.

A flexible teaching method with adaptive teachers

ART teaching is centred on frequent interactions with the students, to ensure they stay motivated and engaged. We encouraged students to be curious, to raise questions and to think critically. As the approach differs from traditional teaching methods, the students were initially quite shy. Eventually they eased into an open, collaborative atmosphere where any idea, doubt or thought was shared, and lively discussions took place.

The overall flow of ESO ART was also dictated by unforeseen events — a limited number of computers, power outages, bad internet connectivity, and other delays. These circumstances obliged us to improvise. One example was the set up of a parallax experiment in the classroom. A student questioned how astronomers could measure distances to objects that we cannot travel to. We hung a poster of a galaxy on the other side of the classroom and asked the students — divided into small groups — to measure its distance. Eventually, all groups used parallax and learnt how it can be applied to distance measurements in astronomy. Overall, the use of a flexible and adaptive teaching approach, together with help from our hosts and the enthusiastic students — "we don't need breaks!" — contributed to the success of the first ESO ART.

Connecting and expanding the astronomical community

ESO ART fostered communication between European and Ghanaian scientists. During the ART programme, our host Nana Ama Browne Klutse (GSSTI), and her PhD student Theophilus Ansah-Narh gave an overview of astronomy development and education opportunities in Ghana. She presented the Ghana Radio Astronomy Observatory in Kuntunse with its capability in Very Long Baseline Interferometry[6], as well as Ghanaian involvement in projects like the Square Kilometre Array.

In addition, ESO astronomers — Jason Spyromilio and Xavier Barcons — connected via Skype from Garching and the ALMA Operations Support Facility to give brief lectures, which engaged the participants and led to numerous questions about supernovae, black holes, ESO facilities, and the connection between astronomical findings and our daily life on Earth.

Local engagements and outreach activities

Aside from the ART programme, we presented astronomy to locals on two occasions. Nana prepared an excursion to a fishing village near Cape Coast, close to where she grew up. Thanks to her translating for us, we learnt how the fishermen use the stars to navigate and to find different types of fish. In return, we explained our understanding of stars and how the Sun is one of them. We described the Solar System by drawing on the soil, clarifying that the brightest objects in the night sky — like Venus and Jupiter — are actually planets and not stars.

Finally, we conducted an outreach event at the Ghana Planetarium[7] in Accra. This educational centre allows children to learn science through dedicated experiments. We designed hands-on activities for 40 participants, including young children and their parents. They assembled a puzzle of the Moon, learned about its phases, and observed how craters form by launching small stones into sand. Using hand-made CD-spectrographs, they learned that light is made up of different colours and discovered absorption and emission lines by looking at the Sun or artificial lights. In addition, the participants were introduced to ESO science releases by matching pairs of cards in a memory game designed by us. Two talks about colliding galaxies and exploding stars and a quiz based on the day's activities concluded the event. The latter was led by the volunteer Sarah Abotsi-Masters and the children competed to win ESO souvenirs.

Prospects of the ESO ART programme

This pilot programme demonstrated that ESO can contribute to developing research skills and encouraging interest in the sciences amongst young people all over the world. The various elements of the ART programme include:

1) engaging with students in countries that are under-represented in astronomy, disseminating astronomical knowledge;
2) connecting ESO with educational institutions globally and promoting collaborations, and promoting visibility for ESO and its member states;
3) facilitating the establishment of astronomy education in universities;
4) encouraging motivated students to pursue an education in astronomy and introducing them to research;
5) providing mentorship opportunities from ESO astronomers;
6) providing ESO astronomers the opportunity to develop teaching skills through instructing a diverse audience;
7) encouraging and increasing the use of ESO archival data, potentially enhancing the science return of ESO facilities.

In light of these benefits, and the strong demand for such a programme, we hope that the ESO ART will continue annually with support from the astronomical community in Europe and beyond.

Acknowledgements

The success of the ESO ART programme would not have been possible without the help and support from our hosts Bernard Duah Asabere (Ghana Radio Astronomy Observatory), Nana Ama Klutse and Kofi Asare (GSSTI). Fundamental to the success of the course has also been the role of the local hosts from the Physics department at the UCC, its head Benjamin Anderson, Francis Kudjoe and their team. We profoundly thank all of them for their enormous effort in providing us with the best possible organisational support and venue for the ESO ART.

We also thank the Ghana Planetarium staff and volunteers for helping us to organise the outreach event.

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We are grateful to Paolo Franzetti and Peppo Gavazzi for providing us with a local copy of the server GOLDMine. The creation of this local copy has been made possible thanks to the SDSS HiPS maps generously shared by the CDS team.

Links

[1] Ghana Space Science and Technology Institute (GSSTI): https://gssti.gaecgh.org

[2] West African International Summer School for Young Astronomers (WAISSYA): www.astrowestafrica.org/

[3] Project Jupyter: jupyter.org

[4] Python is an open-source programming language: https://www.python.org/

[5] Goldmine: http://goldmine.mib.infn.it

[6] African Very Long Baseline Interferometry Network: http://www.ska.ac.za/science-engineering/avn/

[7] The Ghana Planetarium: http://www.ghanascience-project.net/

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Fellows at ESO

Bruno Dias

Bruno Dias

I am far from being a philosopher, but I have learned something from my experience on Earth so far. Some of it is shared here and I hope it can be useful for someone.

"Life gives you opportunities. Be prepared for them."
It was the morning of 3 November 1994, my ninth birthday, and I could only think about being ready to see my first total solar eclipse from home. This event made me wonder about the Universe very early on in my life. This did not come as a surprise. My mother gave priority to high-level education for my siblings and me, even if it meant an economic sacrifice. My father always made me question everything and encouraged my interest in how things work in the Universe. Some special teachers guided me through the front door of my future career: the Olympiads of maths, physics and astronomy, as well as science clubs and fairs. All of this happened in the technological city of São José dos Campos, Brazil, where I also had the chance to visit inspiring places such as the National Institute for Space Research (INPE), where Brazilian satellites and rockets were developed, and Embraer which builds aeroplanes used for domestic flights in Europe.

"Work hard and be committed."
My formal studies started at the University of São Paulo in Brazil, the best in South America, where I received my bachelor's degree in Physics, master's and PhD in Astrophysics (with a prize for the best thesis) under the supervision of Beatriz Barbuy, who was vice-president of the International Astronomical Union (IAU) at that time. During my PhD, I was selected for an ESO studentship for one year in Chile with Ivo Saviane, who was the instrument scientist of the FOcal Reducer and low dispersion Spectrograph 2 (FORS2) at that time, and is currently the site manager of La Silla observatory.

My first postdoc position was at Durham University in collaboration with Ray Sharples, the Principal Investigator (PI) of the *K*-band Multi-Object Spectrograph (KMOS). I came back to ESO as a fellow after that. In fact, given my previous experience with FORS2, I volunteered to be its instrument scientist for six months, as there was no staff member available to fill this position. I learned a lot while contributing to ESO. One contribution was the analysis of the virtual slit — a way of elongating the shape of a star along the FORS2 slit to avoid saturation of bright stars when simultaneously observing faint stars using a multi-object spectrograph (MOS). Another contribution was to help a PI with the investigation of systematic errors in the wavelength calibration of blue spectra without strong sky lines. There were also numerous other contributions that eased operations, such as a script to decide which mask should be inserted into FORS2 before a given night.

Over the past decade I developed skills in the photometry and spectroscopy of star clusters in the Milky Way and Magellanic Clouds using FORS2, the Fibre Large Array Multi Element Spectrograph (FLAMES), the UV-Visual Echelle Spectrograph (UVES), the Multi Unit Spectroscopic Explorer (MUSE) at Paranal, and the ESO Faint Object Spectrograph and Camera 2 (EFOSC2) at La Silla. In addition I used several non-ESO facilities, such as the Southern Astrophysical Research (SOAR) Telescope and the Gemini telescopes.

My two major contributions to the field so far are: (i) the definition of a new metallicity scale for Milky Way globular clusters with a significant improvement for bulge metal-rich clusters — this is important to correctly and fully model the chemical enrichment history of the cluster population in our Galaxy, which is still incomplete; and (ii) the discovery of a Small Magellanic Cloud (SMC) region called the west halo, which is being tidally stripped away from the main body of the SMC — this is important because recent proper motion studies have shown that the Magellanic Clouds are on their first close passage towards the Milky Way, and not orbiting it as previously thought. Therefore, a detailed study of all structures in the SMC and Large Magellanic Cloud (LMC) are needed to fully understand their history. My ESO Fellowship has been the perfect period to develop my research, as I have total autonomy and leadership on my science projects.

"List priorities. Make choices. Follow them."
Discarding bad options is easy but what happens when you do not have time for all of the remaining good options? How you use your time shapes you as a person and determines the type of astronomer you will be. This is not the full story because you only have control over a few aspects of your life — most of your life

does not depend on you. It is not easy. I had two crises during my career. The first one made me doubt whether I should be a professional astronomer, but ended up making my choice even stronger. The second crisis concerned the balance between work and my personal life, and moving from one country to another. Now, I have the happiest family. These crises were very important in making me think hard about what I really wanted from my life. Now I have made my peace with my choices, and am more determined than ever.

During my ESO fellowship, I dedicate 50% of my time to operating NACO (which is made up of the Nasmyth Adaptive Optics System [NAOS] and high-resolution near-infrared camera [CONICA]), KMOS, and FORS2 at UT1 in Paranal, as well as developing some technical projects on FORS2. The other 50% of my time is spent on science projects (which is why I do astronomy), invited classes at local universities, and some outreach. I think it is our duty to communicate what we do to the general public, because science is not only for scientists. In addition, our salary comes from public funds, and so we should “pay it forward”.

“Nobody works alone.”
I learned very early on that being an astronomer means collaboration, so I have attended many conferences, talking to people wherever I am. On many occasions, a cup of coffee in a sunny garden has been much more efficient than a few hours in front of a computer. Working hard is only effective if I know where to direct my efforts. Working in Paranal is also good for my science. The shifts give me no choice but to finish my contribution to a particular project more quickly and to a higher standard before going up to Paranal. When I come back from Paranal my collaborators have delivered their part and I can resume working. We never stop until a paper comes out. Time management and coordination with my network of collaborators are both key to finishing projects and to continue publishing papers.

Life at Paranal is great for getting people to work as a group, joining forces with astronomers, telescope operators and all specialities of engineers, all with the common goal of offering state-of-the art facilities to the astronomical community. During my fellowship, I also organised a local workshop on stellar populations, the ESO python boot camp, and an international ESO conference on the Galactic bulge, and helped as a tutor at the first Network of European Observatories in the North (NEON) school held at La Silla and Vitacura. These events were only possible with the help of many collaborators, mostly based in Chile.

Another perspective is provided by the many prestigious astronomers, scientists and engineers who come to ESO as visitors to observe with our telescopes, many of whom possess the knowledge and/or skills that I am looking for. I have had the chance to discuss science and even start collaborations while I was their support astronomer. I have also organised the science talks in Vitacura for over a year, which also led to many interesting meetings.

“What makes you happy? This should be your ultimate goal.”
I am happy if I manage to accomplish the personal guidelines detailed above. In other words, serving the astronomical community at Paranal, while finishing scientific papers with my collaborators. In addition, organising scientific meetings to answer big questions on astrophysics while sharing the news with the general public. Finally, playing music to relax with friends and spending time with my family. All of my choices are perfectly suited to my personal goals. Now I plan to keep developing myself and producing results as I am sure I am on the right track. 247 nights and days in Paranal so far and counting!

Anita Zanella

The path that brought me to astronomy has been curved and made up of coincidences and chance.

I have always loved reading and when I was a child I wanted to become a writer. Even my first contact with astronomy happened thanks to literature. During middle school, we were asked by our literature teacher to read a book during the holidays. He brought us a great collection of titles, spanning the most diverse topics and asked each student to choose one. I remember that I was very undecided. I loved novels, poetry and art. However, that day, I discovered a small volume about black holes in the pile of books. I do not really know why, but curiosity made me choose that book. It turned out to be extremely complicated — not at all appropriate for my young age — but this did not stop me. On the contrary, I went through it several times trying to understand as much as I could and I was completely fascinated.

At the same time, this discovery did not change my conviction of becoming a writer at all, and when the moment came to choose high school, I registered — with no hesitation — at a literature school. What excited me most at that time was the possibility to study Latin, ancient Greek, philosophy, and art. My love for literature kept increasing and my dislike for maths became a deep hatred. It was not unusual to catch me trying to solve equations with tears in my eyes from exasperation, and I used to conduct a personal war against maths, saying that it was totally dry and useless, like searching in a dark room for a black cat that is not there.

However, at 17, I started a chemistry class. The teacher was a researcher who had just left academia. She would sometimes describe the life of researchers. The idea that there were people working all their lives to satisfy their curiosity, studying and discovering the world, fascinated me completely. At that point, I started to think that I would like to become a researcher. But what to research? That book on black holes that I had read so many years before came back to my mind. Astrophysics!

When it came time to choose a university, it was a bit hard to decide to abandon the study of ancient Greek and literature, but the curiosity of the unknown, and a few nights spent with amateur astronomers staring at the sky, made me finally pick astronomy. Needless to say, everybody around me was astonished by my choice and kept telling me that astronomy is full of maths. But I had a goal — studying the Universe — and even equations seemed no obstacle to me.

Anita Zanella

I got both my bachelor's and master's degrees in Astronomy at the University of Padova in Italy. The start was extremely difficult, and I felt quite out of place until I started a class about the formation and evolution of galaxies. I found the topic charming, intriguing, and much closer to my taste. I decided to follow beauty and focus my studies on the formation and evolution of galaxies. I did my master's thesis, partly at the University of Padova and partly at the University of Minnesota (Minneapolis, USA), on passive galaxies and the relationship between their mass and size.

I also continued to investigate galaxies during my PhD, which I carried out in Paris, at CEA Saclay. There, I studied how distant high-redshift galaxies form stars in complexes called clumps. I was particularly interested in understanding how these star-forming regions are assembled, how long they can survive, and whether they can affect the morphological transformation of the host galaxy as time passes (for example, by contributing to the formation of the central galaxy nucleus, called the bulge). I mainly worked with images and spectra taken with the Hubble Space Telescope and ESO's Very Large Telescope (VLT). The beauty of those images always gave me the energy to keep working even during moments of frustration, and I always found it thrilling that we are studying light that has travelled for billions of years before reaching us, our telescopes, our computers and ultimately our eyes.

During my ESO fellowship, I am pursuing the study of galaxy formation and evolution in both passive and star-forming galaxies. Furthermore, I decided to carry out my "functional duties" at the VLT in Paranal, as I had always worked with observations but had never actually observed at the telescope myself. Great choice! Once again, I have encountered beauty and curiosity; I am always amazed by the night sky that is visible from the desert, and excited when I see the images of the Universe appearing "live" on screen. It is from that same desert that I write this now. The night is finishing, so it is time to go out and watch one of the wonderful sunrises that Paranal offers up.

Remco van der Burg

The new ESO Supernova Planetarium & Visitor Centre has just opened its doors, and it has been fantastic to see the amazement on the faces of all those school kids after their visit. It takes me back about 25 years, when my own curiosity about space exploration and the Universe was sparked. I have never watched Star Wars, nor have I ever owned a telescope myself, so I do not fit the typical cliché image that people may have of astronomers. However, on the occasional cloudless night in the Netherlands — my birthplace — I used to look up at the sky and have long conversations with my father about the vastness of space, and the finite speed of light and its implications. Frankly, we actually talked about other worlds and aliens.

At school, I had a knack for mathematics and physics, at least compared to other subjects such as languages, culture or history. While I often read popular articles about astrophysics, the first time I heard about the possibility of studying astronomy as a major at university was from Arjen van der Wel, my childhood piano teacher. He comes from the same tiny village I grew up in, made a career in astronomy himself, and is now a tenured professor at Ghent University in Belgium. Having lived a stone's throw away from Leiden, it was an easy choice for me to move there in 2004 to study astrophysics. At that point, I did not imagine that I would become an astronomer by profession a decade later. It really happened step by step, but the journey has been a great adventure so far!

I remember in particular that during my second year of undergraduate studies, I was invited to join an observing trip to the 2.5-metre Isaac Newton Telescope on La Palma with a dozen other students. This mind-blowing experience really awakened the observational astronomer in me. Little did I know at that moment that I would return to this telescope many times during my PhD. Every time I went back there, I made observing more of a sport to push the limits of the telescope. I remember the times that I tried to suppress the dome seeing by switching off the heater in the adjacent control room and operate the telescope wearing my winter coat, 10 nights in a row!

During my undergraduate studies, I worked on many different research projects. In my third year, I hunted for transit events that were potentially caused by extrasolar planets in the large photometric dataset from the Optical

Remco van der Burg

Gravitational Lensing Experiment (OGLE) survey. We actually discovered and confirmed an exoplanet by means of radial velocity measurements using the Ultraviolet and Visual Echelle Spectrograph (UVES) on the Fibre Large Array Multi Element Spectrograph (FLAMES) instrument; this was my first time using ESO instrumentation!

As a fourth-year undergraduate, I studied the thermal dust emission and molecular gas transitions in planet-forming regions around several young stellar systems. During that time, I had my first solo observing run, with the James Clerk Maxwell Telescope (JCMT) on Mauna Kea in Hawaii. This was just three years before the spectacular revolution that the Atacama Large Millimeter/submillimeter Array (ALMA) started to bring to this field. In the final year of my master's degree, I moved to extragalactic astronomy, performing a statistical study of Lyman-break galaxies found in a large dataset taken with the Canada France Hawaii Telescope (CFHT), and investigating the associated star formation in the early Universe.

Around that time, Henk Hoekstra, an expert in weak gravitational lensing, accepted a staff position at Leiden Observatory. His broad field of research was very exciting to me, and I decided to start a PhD project in his group. While the initial plan was that I would work on projects related to weak lensing, I also gradually became interested in the physical processes affecting star formation in galaxies, in particular in galaxy clusters. I published most of my thesis papers on this broad topic, collaborating with both Henk and Adam Muzzin, who was a postdoc in Leiden at the time.

After my PhD, given my expertise in galaxy clusters, I was offered a postdoctoral research position at the Saclay Nuclear Research Centre (CEA Saclay) in France; this was funded by Monique Arnaud's European Research Council (ERC) Advanced Grant. I worked with her team on the study of galaxy clusters detected in the Planck mission. The multidisciplinary aspect of this ambitious project appealed to me; I got to work with experts in both X-ray studies of galaxy clusters and large hydrodynamical simulations. In turn, I brought my own complementary experience to the analysis of these structures in the optical and near-infrared. I took advantage of our privileged access to the CFHT, but also undertook a number of visitor runs at the William Herschel Telescope at La Palma.

I most recently became interested in the study of large low-surface-brightness galaxies, now dubbed Ultra-Diffuse Galaxies (UDGs). The real mystery about these galaxies is that they appear to be over-abundant in clusters, where you may naïvely expect them to be short-lived as a result of frequent interactions and the large tidal forces. UDGs are a particularly hot topic at the moment; even with recent progress (including a number of papers that I have authored and co-authored), much is still unknown about the formation mechanisms of these strange galaxies.

I am grateful that I was able to work in so many different areas during these first years of my career, and I hope to continue doing so at ESO in Garching, where I started a new position as an ESO Fellow at the end of last year. Apart from my research, my functional duty at ESO is to help prepare for ESO's Extremely Large Telescope (ELT), the construction of which will be one of ESO's biggest and most exciting challenges over the next 10 years.

I am spending much of my free time in the nearby Bavarian mountains, which continuously amaze the Dutch "flatlander" in me. I'm also always excited to cook for a selected company of friends, and thus put our friendship to the ultimate test. To take care of the calories accumulated thereby, I minimise my time in the *U-Bahn* and commute between ESO and the city centre of Munich either running or by bike.

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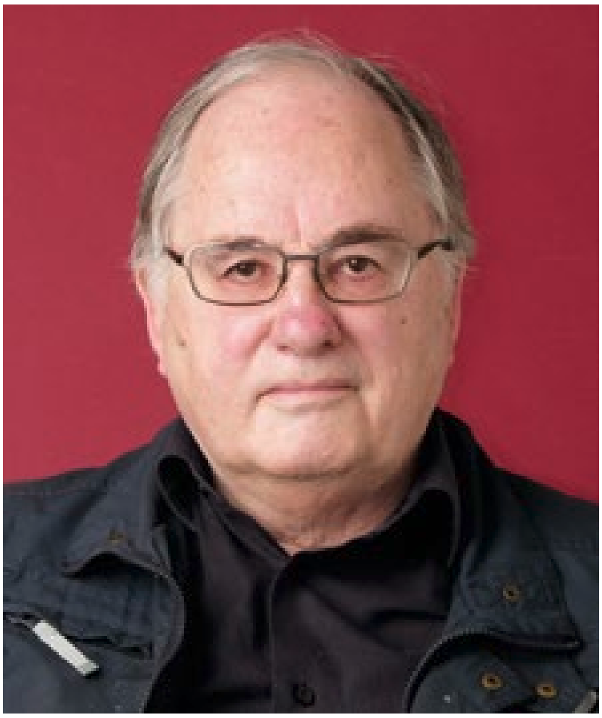
Leon B. Lucy, 1938–2018

Dietrich Baade[1]
John Danziger[2]
Richard Hook[1]
Jeremy Walsh[1]

[1] ESO
[2] Astronomical Observatory of Trieste, Italy



In March this year, Leon Lucy passed away unexpectedly. Leon was one of the most highly respected stellar astrophysicists of his generation. He was a student of Franz Kahn at the University of Manchester, where he received his doctoral degree in 1962. After postdoctoral positions at Princeton, Goddard Institute for Space Studies in New York and the Max Planck Institute for Physics and Astrophysics in Munich, he spent 20 years (from 1965 to 1986) at the Department of Astronomy at Columbia University, where he served as chair from 1979 to 1982. For a decade at Columbia, he was co-editor of the Astronomical Journal, initially alongside Lodewijk Woltjer, and later with Norman Baker. From 1998, Leon was a visiting professor at Imperial College London.

Leon started his career at a time when computers became capable of simulating complex physical processes. He realised early their power as tools to develop physical understanding beyond analytical techniques. His scientific vision and mathematical skills resulted in creativity in three different areas, namely: the invention of smoothed-particle dynamics; a method to combine radiative transfer calculations in expanding atmospheres using Monte Carlo methods; and the independent development of an iterative restoration technique, which is known as the Richardson-Lucy deconvolution algorithm. These three methods are still very broadly and successfully used in many scientific areas, and beyond. Leon continued to develop and apply these three methods in a large variety of contexts. Later, he also worked on algorithms to infer the validity of Bayesian models. Leon’s, mostly first-author, papers set the standard for the combination of elegance and clarity.

In 1976, Leon visited ESO, which was in Geneva at that time, for half a year, and he worked at ESO in Garching from 1984 to 1998 — initially in the Science Division and from 1991 in the Space Telescope-European Coordinating Facility (ST-ECF). Three important events occurred during the time of Leon’s stay at ESO, though in none of them was Leon’s participation initially foreseen. His emphatic offers to engage in providing support on these occasions demonstrated Leon’s strong motivation to accept responsibility when he saw the possibility to make a significant contribution, which he impressively achieved in all three cases.

The first opportunity arose completely unpredictably in 1987 with the supernova explosion SN 1987A in the Large Magellanic Cloud. The brightest naked eye supernova since the 17th century, this event meant that scientific analysis methods for observations of unprecedented detail had to be developed largely from scratch. Leon wrote two computer codes to model the spectra of the early photospheric and the subsequent nebular phases. The first results were presented as early as the summer of 1987. In August 1988, a subtle change was observed in the optical emission lines of SN1987A. Leon realised that this effect was due to obscuration by dust, which was the earliest recognition of the formation of dust in any supernova. A quantitative model provided many characteristics of the dust including its mass and type. It was supplemented by concurrent infrared observations from ESO. This methodology of using optical spectra as a diagnostic of dust formation has stood the test of time and has not been surpassed.

In 1989, the New Technology Telescope (NTT) at La Silla saw first light. The intrinsic optical quality of the NTT and the behaviour of the atmosphere were so excellent that the images of stars looked very pixellated when viewed at full resolution with the imagers available at the time. This was not only aesthetically unsatisfactory, but also scientifically detrimental, and it inspired Leon to enhance his deconvolution algorithm developed in 1974 to decrease the size of the output pixels so that the processed images would be sharper and look much smoother.

Only one year later, shortly after the launch of the Hubble Space Telescope (HST), it was discovered that the curvatures of the primary and secondary mirrors of the HST did not match. As a result, HST images of stars had a sharp core but very extended halos. Until the problem was fixed in 1993 by astronauts who installed some corrective optics, advanced versions of Leon's method were eagerly employed to make the best possible use of the early HST images. While at the ST-ECF, Leon continued to develop and refine these restoration techniques, applying them to both imaging and spectroscopic data.

Leon laid the foundations for the explanation, through radiation pressure and multiple scattering, of the flat-bottomed absorption troughs in the stellar-wind spectral lines of hot massive stars when these mass-loss indicators were discovered with the Copernicus satellite. His explanation of shocks producing X-rays from the same stars solved the riddle of the co-existence of hot and cool gas. A topic that excited Leon from the beginning to the end of his career was the mutual effects exerted by the components of close and common-envelope binaries. A strong focus of his was the reliability with which system parameters can be extracted from the observations, including astrometry by Gaia. Curiosity to understand how to best interpret observational data was a thread running through Leon's scientific life. In the year 2000, the Royal Astronomical Society honoured him with the Society's Gold Medal for Astronomy.

While in Garching, Leon attended almost every astrophysics seminar, regardless of the topic. His outstanding broad knowledge and deep understanding of physics became impressively clear in his contributions to discussions, in which he engaged nearly without exception. He enriched the scientific life of the entire local astronomy community, and he generously shared his vast font of expertise with everyone requesting it. He could deliver incisive critique but wrapped in his inimitable sense of humour.

If a single word could ever adequately describe a person, in Leon's case it would be unpretentiousness. Leon is survived by his wife, Ren Wen Wan, and their daughter.

Personnel Movements

Arrivals (1 September–31 December 2018)

Europe

Araujo Hauck, Constanza (CL)	Optical Engineer
Beneš, Nicolas (DE)	Software Engineer
Bergamo, Kevin (IT)	IT Specialist-Network
Bittner, Adrian (DE)	Student IMPRS
Cosentino, Giuliana (IT)	Student
Facchini, Stefano (IT)	Fellow
Fahrion, Katja (DE)	Student
Rubin, Adam (IL)	Fellow
Sqalli Houssini, Omar (AT)	Project Manager

Chile

Flores, Rumy Boris (CL)	Facilities Management Supervisor
Gil, Juan Pablo (CL)	Software Engineer
Olivares, Juan Carlos (CL)	Telescope Instruments Operator
Ribas, Alvaro (ES)	Fellow
Ritter, Florian (CL)	Procurement Officer

Departures (1 September–31 December 2018)

Europe

Agnello, Adriano (IT)	Fellow
Augustin, Ramona (DE)	Student
Cikota, Aleksandar (HR)	Student
Hashiba, Natsuki (JP)	Student
Hook, Richard (UK)	Public Information Officer
Janssen, Edmund (NL)	Graphic Designer
Stroe, Andra (RO)	Fellow
Surot Madrid, Francisco (CL)	Student
Vera Sequeiros, Ignacio (ES)	Software Engineer
Warmels, Rein (NL)	Astronomer (Web Publication Manager)
Yen, Hsi-Wei (TW)	Fellow

Chile

Asmus, Daniel (DE)	Fellow
Bolmer, Jan (DE)	Student
Guerra, Juan Carlos (ES)	Instrumentation Engineer
Leftley, James (UK)	Student
Meilland, Anthony (FR)	User Support Astronomer

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Front cover: The Atacama Large Millimeter/submillimeter Array (ALMA) antennas withstand harsh conditions at Chajnantor in Chile (5100 metres above sea level), to transform our understanding of the cold Universe.
Credit: S. Otarola/ESO