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Astronomy in Poland
ESO2020+ community poll feedback
Earth transits from Jupiter and the Moon
Red supergiants as cosmic probes

Astronomy in Poland

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Polish post-war astronomy was built virtually from nothing. Currently, about 250 astronomers are employed in seven academic institutes and a few smaller units across Poland. Broad areas of astrophysics are covered and the level of astronomical research in Poland is higher than the world average. Joining ESO has created an atmosphere that is conducive to further improvements in the quality of Polish research, and it marks an important step towards the full integration of Polish astronomers into the international scientific community.

Figure 1. Mikołaj Kopernik pictured in his Frombork observatory. From the painting by Jan Matejko (1838–89).

Poland is a country with a long astronomical tradition: Mikołaj Kopernik (Nicolaus Copernicus, 1473–1543) with his great work on the heliocentric system, or Jan Heweliusz (Johannes Hevelius, 1611–1687), the author of *Selenographia* and inventor of several constellation names still in use, being two examples. However, starting from the end of the 18th century Poland entered a dark period in its history. The Polish state disappeared from the map of Europe for about 120 years and wars swept Polish soil during every generation. The last one, World War II, left Poland ruined, with a devastated intelligentsia and no scientific resources.

The very few professional astronomers who survived the war started to build scientific centres in some cities, literally from scratch. These were Włodzimierz Zonn, Stefan Piotrowski and Maciej Bielicki (in Warsaw); Władysław Dziewulski and Wilhelmina Iwanowska (in Toruń), Tadeusz Banachiewicz, Rozalia Szafraniec and Karol Kozieł (in Cracow); Eugeniusz Rybka, Antoni Opolski and Jan Mergentaler (in Wrocław); and Józef Witkowski and Hieronim Hurnik (Poznań). A modern approach to research and university courses meant that their first students rapidly reached a world-class level. Prominent examples are: Stanisław Gorgolewski (in radio astronomy), Stanisław Grzędzielski (interstellar and interplanetary matter), Jan Hanasz (radio astronomy, space research), Jerzy Jakimiec (in the field of Solar flares), Tadeusz Jarzębowski (photometry of variable stars), Andrzej Kruszewski (polarisation of starlight, variable stars and extragalactic astronomy), Wojciech Krzemiński (variable stars), Jan Kubikowski (stellar atmospheres), Józef Masłowski (radio astronomy), Andrzej Pacholczyk (magnetohydrodynamics and radio galaxies), Bogdan Rompolt (dynamics of the Solar atmosphere), Krzysztof Serkowski (polarisation of starlight and instrumentation), Grzegorz Sitarski (dynamics of comets and asteroids), Józef Smak (stellar evolution, cataclysmic variables and accretion discs), Jan Smoliński (luminous variable stars), Antoni Stawikowski (stellar spectroscopy), Jerzy Stodółkiewicz (magnetohydrodynamics and dynamics of globular clusters), Wiesław Wiśniewski (stellar photometry, comets) and Andrzej Woszczyk (planetary systems and variable stars).

In the mid-1950s, when the oppression of the communist system softened, the "old" professors renewed their pre-war contacts with foreign scientific institutions and recommended their best students as candidates to visit leading astronomical institutes. After returning home, the young astronomers continued to carry out world-class research and started to train the second generation of post-war astronomers. Unfortunately, the freedom to go abroad also has a dark side: Poland fell victim to a brain drain, as several brilliant Polish scientists decided to stay for good at different western academic institutions. Nonetheless, most of them preserved close ties with their Polish colleagues, e.g., by inviting them to visit abroad and carrying out collaborative research or providing support for scientific libraries. As soon as Poland achieved independence, the older emigrant astronomers frequently began to visit Poland for both shorter and longer stays. Nowadays young scientists almost always come back from abroad to their home institutions.

There are currently about 250 professional astronomers (with 155 International Astronomical Union members among them) in Poland, most of them working in six separate university institutes and two institutes of the Polish Academy of Sciences. A few individual astronomers hold positions in other institutions, mostly within institutes of physics. According to data from Science Watch — a newsletter published by the Thomson Institute — 1777 papers on space science were published in the years 2009–2013 with at least one author affiliated in Poland (2.66 % of world production). These papers were cited 11.83 times on average, as compared to 9.61 for the world average, showing that the quality of Polish research in astronomy is high. In the Astronomical Data System (ADS) database, we found six papers cited over 1000 times and nine more papers cited between 800 and 1000 times with Polish astronomers as authors/coauthors (but not necessarily affiliated in Poland at the time of writing).

Figure 2. Two (of four) automatic telescopes from the Solaris telescope located at the South African Astronomical Observatory (SAAO), South Africa.

Figure 3. The Warsaw Observatory's 1.3-metre telescope in Las Campanas, equipped with the 32-chip CCD camera built in Warsaw, one of the largest in the world, and used for the OGLE survey.

We describe the six astronomy institutes, their staff complements and areas of expertise in the following sections.

Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences

The Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences (NCAC PAS[1]) is the largest astronomical institute in Poland. It is located in Poland's capital Warsaw, with a branch in the city of Nicolaus Copernicus's birth, Toruń.

The history of NCAC PAS started in the 1950s, when the idea of building a national astronomical observatory was first formulated. The failure of the first idea led Bohdan Paczyński and J. Smak to suggest that a theoretical astrophysical research institute should be established instead. This idea gained important support from the American National Academy of Sciences, as a result of preparations for the celebrations of the Nicolaus Copernicus Quincentennial (1973). The USA provided financial support for the creation of the institute. The Centre was finally opened in 1978 and immediately started vigorous research activity across a broad range of subjects in astrophysics. Currently these include: observational and theoretical aspects of stellar astrophysics (e.g., astroseismology), stellar systems (globular clusters, dwarf galaxies), nuclear matter, physical processes around compact objects (accretion discs, jets and outflows), circumstellar matter, structure and evolution of active galaxies, cosmology and extrasolar planetary systems.

NCAC PAS employs more than 40 full-time scientific staff (including postdocs), and runs a postgraduate programme for about 25 students. Each year there are openings (on a competitive basis) for three- and five-year positions at NCAC. The positions for three years are open to young researchers who have just completed their PhDs. Positions for five years may lead to a permanent position.

The most important contributions of NCAC scientists to modern astronomy and astrophysics include papers on stellar evolution and accretion disc theory by B. Paczyński and J. Smak. The other important topics are helio- and astroseismology (led by Wojciech Dziembowski), variable stars (Janusz Kałużny, Joanna Mikołajewska and Romuald Tylenda), nuclear matter physics and high energy astrophysics (Paweł Haensel and Andrzej Zdziarski).

The researchers are involved in a number of large international projects and collaborations.

Projects involving international cooperation are concentrated around the Cherenkov Telescope Array (CTA) and the High Energy Stereoscopic System (H.E.S.S.) working in the high-energy gamma-ray domain, and the South African Large Telescope (SALT), with a diameter of ten metres. NCAC astronomers are also members of teams involved in cosmic experiments, such as INTEGRAL, Herschel or BRITE-PL (a project for the observation of stellar pulsations with six photometric nano-satellites). The centre operates the ground communication station for the constellation of astroseismology satellites BRITE — a joint project involving Austria, Canada and Poland and headed by Aleksander Schwarzenberg-Czerny. The new programme Solaris (involving Maciej Konacki), aimed at accurate spectroscopic observations of binaries with four small (50-centimetre) automated telescopes distributed around the world, is also worth mentioning (see Figure 2). This programme aims to determine accurate parameters of binary stars, and to search for planets around them.

Astronomers from NCAC are active in collaborations with scientists at several institutes and universities around the world, such as: Stanford University, Harvard University, the University of Durham, the Institute d'astrophysique (Paris), the Institute of Space and Astronautical Science (Japan) and the Ioffe Institute (St. Petersburg). NCAC is an active participant in The European Laboratory "Astronomie Pologne–France", a collaborative programme formed by the Centre national de la recherche scientifique (CNRS) in France and the Ministry of Science and Higher Education in Poland.

Warsaw University Observatory

The Warsaw University Observatory[2] is a part of the Faculty of Physics. It offers astronomical study programmes at undergraduate and graduate levels and has the right to award PhD degrees in astronomy and the degree of doctor *habilitatus*.

Recent research in observational astronomy concentrates on two large photometric surveys: the Optical Gravitational Lensing Experiment (OGLE) and the All Sky Automated Survey (ASAS). Both were initiated by B. Paczyński, who was the first to point out the importance of microlensing as a new tool for stellar astronomy investigations. OGLE has been in operation since 1992 and is currently led by Andrzej Udalski. First observations were obtained with the Swope 1-metre telescope at the Las Campanas Observatory (LCO). Since 1996, the OGLE survey has used dedicated 1.3-metre telescope, owned by the Warsaw University Observatory, and located at the LCO (Figure 3). Presently, it is equipped with a large CCD camera containing 32 chips with 268 million pixels. The total sky coverage of OGLE is about 3000 square degrees and 1.3 billion sources are monitored every night. OGLE has been, and remains, a real mine of important discoveries. The first microlensing event was observed in 1993. Since then, over 15 000 of these events have been recorded. About 500 000 new variable stars were detected by OGLE. Fifty exoplanets have been discovered so far using transit and microlensing techniques and several new Kuiper Belt objects have been identified. The programme continues and we hope for many exciting new discoveries.

The other survey, ASAS, uses four small telescopes placed in two stations: in the north in Hawaii, and for the south at the LCO. ASAS is led by Grzegorz Pojmański. Over 20 million stars over the range 8–14 magnitudes are being monitored. Several hundred observations per star have already been collected. More than 40 000 new variable stars have been detected (in addition to the ~10 000 already known). All data from both the OGLE and ASAS programmes are publicly available and are continuously used by astronomers from all over the world.

Several astronomers led by Grzegorz Pietrzyński are involved in the large international observational programme Araucaria. Its principal aim is to provide an improved calibration of the local extragalactic distance scale. So far, the distance modulus to the Large Magellanic Cloud (LMC) of 18.493 magnitudes has been determined with an unprecedented accuracy of less than 2 %. Warsaw University astronomers are involved in a number of other international projects: H.E.S.S., the CTA, the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the VIRGO interferometer, Planck and Gaia.

Theoretical research is also conducted and is concentrated on Solar and stellar oscillations, and evolutionary models of binary stars.

Astronomical Observatory of the Jagiellonian University

The Astronomical Observatory of the Jagiellonian University[3] is a part of the Faculty of Physics, Astronomy and Applied Computer Science. A number of small radio and optical telescopes are located at the Fort Skała Observatory on the outskirts of Cracow. The main scientific programmes include high-energy astrophysics, the investigation of active galactic nuclei, galactic magnetic fields and radio astronomy (led by Marek Urbanik, Michał Ostrowski and collaborators). The observatory is involved in exploiting the large facilities H.E.S.S., the CTA, the LOw Freqeuncy ARray (LOFAR) and SALT.

There is another small group of astronomers in Cracow, employed in the group associated with the Chair of Astronomy within the Institute of Physics at the Pedagogical University, and led by Jerzy Kreiner. They have a small observing station with a 60-centimetre optical telescope located in the Western Carpathian Mountains, 1000 metres above sea level. The main research activities concentrate on observing variable stars (pulsating and eclipsing binaries).

Centre for Astronomy of the Nicolaus Copernicus University

The Centre for Astronomy of the Nicolaus Copernicus University[4] is a part of the Faculty of Physics, Astronomy and Informatics. It is located in Piwnice village, 15 kilometres north of Toruń. The site contains a 32-metre radio telescope, and a few optical instruments, among them a 90-centimetre Schmidt–Cassegrain telescope and 60-centimetre photometric telescope. The optical telescopes are used mainly for student training and modest research projects. The centre is involved in international collaborations such as the Very Long Baseline Interferometry (VLBI) network, H.E.S.S. and SALT.

The major research activities are concentrated on radio astronomy (led by Andrzej Kus), interstellar matter (Jacek Krełowski), stellar astrophysics, exoplanets and celestial mechanics. Among the most significant achievements of recent years are the spectroscopic observations of red giants conducted by Andrzej Niedzielski and Aleksander Wolszczan with the Hobby–Eberly Telescope in Texas, within the Pennsylvania–Toruń Planet Search, which has led to the detection of 20 exoplanets. Theoretical investigations by Krzysztof Goździewski and his collaborators have enabled the determination of the orbital parameters and masses of several exoplanets.

Astronomical Observatory of the Adam Mickiewicz University

The Astronomical Observatory of the Adam Mickiewicz University[5] is a part of the Faculty of Physics of the university. The main areas of work include the dynamics of artificial satellites and small bodies in the Solar System, including non-gravitational effects (work of Sławomir Breiter and Agnieszka Kryszczyńska), as well as the investigation of the physical properties of asteroids (under Tadeusz Michałowski).

Not long ago, observational astrophysical research was started at the Observatory. Recently, a new, small robotic telescope went into operation at the University of Arizona. It is equipped with a spectrograph and it supplements a small double telescope located near Poznań. Together they make up the Global Astrophysical Telescope System project.

Astronomical Institute of Wrocław University

The Astronomical Institute of Wrocław University[6] is a part of the Faculty of Physics and Astronomy. Research is concentrated on two main subjects: investigation of Solar activity (by J. Jakimiec and his group) and of pulsating stars (led by Mikołaj Jerzykiewicz and Andrzej Pigulski). Heliophysicists carry out observations of dynamical phenomena in the Solar atmosphere using a coronagraph located near Wrocław, but they also extensively use satellite observations. Observations and pulsation modelling of β Cephei-type variables (among them DD Lac, which has been investigated in Wrocław for the last 50 years) and δ Scuti-type variables have resulted in an accurate determination of the basic parameters of several of these stars.

Institute of Astronomy of the Zielona Góra University

The Institute of Astronomy of the Zielona Góra University[7] is a young institute, founded in the year 2000, and is part of the Faculty of Physics and Astronomy. Research is concentrated on the magnetospheres of pulsars, neutron stars, high-energy astrophysics and celestial mechanics. The physical parameters of neutron stars, their magnetic fields and internal structure are modelled, based on the analysis of radio emission of pulsars (started by the late founder of the institute, Janusz Gil, and continued by Giorgi Melikidze). The properties of binary compact objects and the dynamics of planetary systems are also investigated.

Space Research Centre of the Polish Academy of Sciences

The main body of the Space Research Centre (SRC) of the Polish Academy of Sciences[8] is located in Warsaw and its two divisions in Poznań and Wrocław. Some of the research areas cover astronomical targets: the dynamics and physics of planets and the small bodies of the Solar System (Marek Banaszkiewicz and Hans Rickman with their collaborators), interplanetary space and the heliosphere (S. Grzędzielski and his colleagues) and Solar physics (Janusz Sylwester and his group). All the Polish instruments that have flown on a variety of space missions, e.g., Cassini, Herschel, Integral, Rosetta and Solar Orbiter, were built at the SRC and Polish scientists coauthored the papers describing the achieved results. The first two Polish scientific satellites, Lem and Hevelius, which are part of the international programme BRITE, have also been built there. The SRC will face important new tasks in instrumentation resulting from Poland's recent entry into the European Space Agency (ESA).

As Poland joins ESO we are very optimistic about the future of Polish astronomy. The talents and competence of the young generation of astronomers, supplemented by access to modern instrumentation and the wide range of possibilities that have opened up for international collaboration, will certainly soon result in numerous exciting discoveries, deepening our understanding of nature.

Acknowledgements

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Links

[1] Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences: http://www.camk.edu.pl

[2] Warsaw University Observatory: http://www.astrouw.edu.pl

[3] Astronomical Observatory of the Jagiellonian University: http://www.oa.uj.edu.pl

[4] Centre for Astronomy of the Nicolaus Copernicus University: http://www.ca.umk.pl

[5] Astronomical Observatory of the Adam Mickiewicz University: http://www.astro.amu.edu.pl

[6] Astronomical Institute of Wrocław University: http://www.astro.uni.wroc.pl

[7] Institute of Astronomy of the Zielona Góra University: http://astro.ia.uz.zgora.pl

[8] Space Research Centre of the Polish Academy of Sciences: http://www.cbk.waw.pl

Shaping ESO2020+ Together: Feedback from the Community Poll

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A thorough evaluation and prioritisation of the ESO science programme into the 2020+ timeframe took place under the auspices of a working group, comprising astronomers drawn from ESO's advisory structure and from within ESO. This group reported to ESO's Scientific Technical Committee, and to ESO Council, concluding the exercise with the publication of a report, "Science Priorities at ESO". A community poll and a dedicated workshop, held in January 2015, formed part of the information gathering process. The community poll was designed to probe the demographics of the user community, its scientific interests, use of observing facilities and plans for use of future telescopes and instruments, its views on types of observing programmes and on the provision of data processing and archiving. A total of 1775 full responses to the poll were received and an analysis of the results is presented here. Foremost is the importance of regular observing programmes on all ESO observing facilities, in addition to Large Programmes and Public Surveys. There was also a strong community requirement for ESO to process and archive data obtained at ESO facilities. Other aspects, especially those related to future facilities, are more challenging to interpret because of biases related to the distribution of science expertise and favoured wavelength regime amongst the targeted audience. The results of the poll formed a fundamental component of the report and provide useful data to guide the evolution of ESO's science programme.

In mid-2014, ESO embarked on a challenging exercise — evaluating and prioritising ESO's programme for the 2020–2030 timeframe on scientific grounds. A working group was formed, which included representatives of ESO's Scientific and Technical Committee (STC), Users Committee (UC) and Visiting Committee (VC), as well as the Very Large Telescope (VLT), VLT Interferometer (VLTI), Atacama Large Millimeter/submillimeter Array (ALMA) and European Extremely Large Telescope (E-ELT) Programme Scientists, plus a few representatives of the ESO Faculty with knowledge of ESO Operations. The composition of the working group is reflected in the author list of this article.

During its regular meetings (from May 2014 to April 2015), the working group discussed a variety of topics based on their main domains of expertise and devised a plan on how to proceed with the overall scientific prioritisation of ESO's programme. It recognised the importance of involving the community at large, as well as exploiting in-house expertise. Community involvement was in the form of a users' questionnaire and of a dedicated workshop. All these components were then taken into account in the final report, "Science Priorities at ESO", which was presented to the STC and to ESO Council. This report is now publicly available[1].

This article concerns the user poll, which was launched at the end of 2014 with the aim of discerning the scientific priorities of the ESO user community. The poll was designed to elicit clear guidelines from the community and to provide context for the ESO Workshop, ESO in the 2020s (held in January 2015, at ESO Headquarters), where preliminary results from the poll were first presented. Of the 9350 users who were invited to participate in the poll, 20% completed the survey in its entirety. Here, we present the complete survey and highlight its main outcomes.

The poll: Basic facts

The poll was launched on 19 December 2014 with an initial deadline of 9 January 2015 in order to be able to report some preliminary results at the ESO2020+ workshop (19–23 January 2015). The poll remained open longer and was officially closed on 18 February 2015.

Professional astronomers (students, postdocs and tenured astronomers) registered in the ESO User Portal and in the ALMA Science Portal were invited to participate and share their scientific views. The poll was anonymous and contained four sections:

I. Tell us about yourself and your scientific interests (7 questions)
II. Present and future observing facilities (5 questions)
III. Time scheduling and observing modes (2 questions)
IV. Data management and services (5 questions)

Table 1. Questions from Section I of the ESO2020+ Users' Poll.

Section I – Tell us about yourself and your scientific interests		
1.1	What best describes your current position?	See Figure 1a
1.2	My home institution is located in	List of countries provided
1.3	My home institution is best described as	See Figure 1b
1.4	My primary focus is	See Figure 1c
1.5	I use data from these wavelength regimes	See Figure 1d
1.6	Your science: What are your main areas of scientific research? (check all that apply)	See Figure 2
1.7	Overall science vision: what are the top three research areas that in your opinion should dominate the astrophysical scene in 2020–2030?	See Figure 2

Section I was meant to collect basic demographic and professional aspects of the targeted audience: current position, country of present affiliation, type of home institution, main research interests (scientific area and wavelength domain), science vision for the 2020–2030 period. Section II followed up on the research interests and paired them to facilities, inside and outside ESO. Sections III and IV focused mostly on ESO science policy aspects and their implementation in terms of observing, data processing and data archive capabilities. The results presented here follow the structure of the poll. The following sections are devoted to sections I, II, III and IV of the user poll. Each section reports the lists of questions that were asked under that specific part of the poll (see Tables 1 to 4) and comments on the results. Graphical representations of as many responses as possible are included. The final section of this article adds some concluding remarks on the poll and indicates possible ways forward.

Out of the 9350 astronomers invited, a total of 1775 complete responses were received, representing close to a 20 % response rate. In addition we received almost 400 incomplete responses, analysis of which is not included here.

We are aware of the weaknesses that polls often suffer in terms of biases and caveats, but we believe that the final numbers provide a relatively solid basis for our analysis of the results. Whenever applicable, we will spell out possible biases and caveats affecting the interpretation of the data.

Section I — Tell us about yourself and your scientific interests

The poll did very well in sampling the targeted audience, both in terms of geographical and professional distribution of the respondents. We received, on average, of the order of 20–25 % response rates from all ESO Member States.

Figure 1 provides an overview on all the demographic aspects of the poll. Of the 1775 complete responses, slightly more than half come from tenured professionals, a third from young astronomers at

Figure 1. Overview of the main characteristics of the pool of poll respondents, in terms of career stage, home institution, main areas of research and wavelength domains.

Figure 1a.

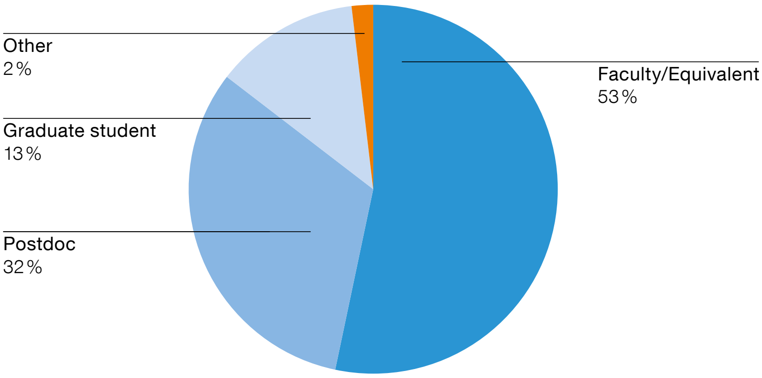


Figure 1b.

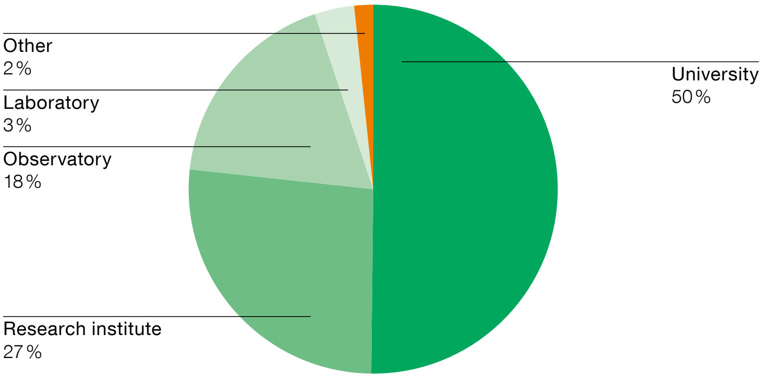


Figure 1c.

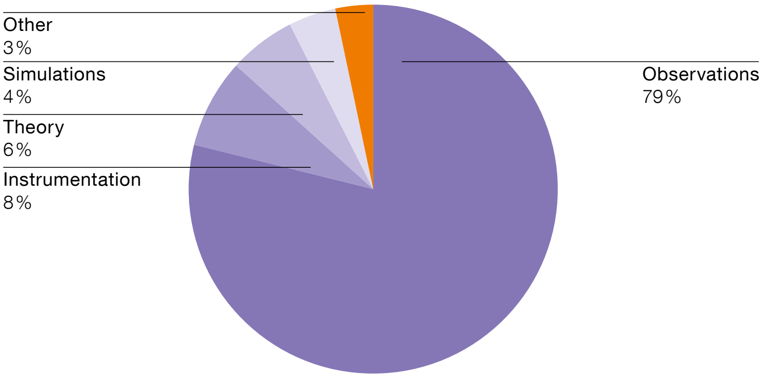
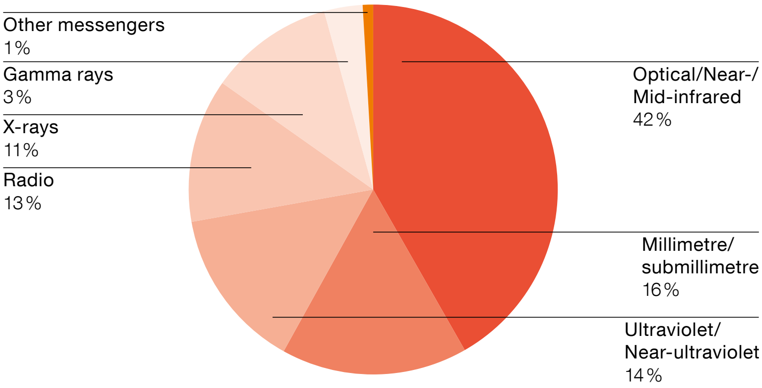


Figure 1d.



postdoctoral level and the remainder from students. Not surprisingly, the majority of the respondents work in observation-related research fields (79 %). Half of the respondents work in an academic environment and most of them use optical/near-infrared/mid-infrared data. Part of this may be implicit in how the targeted audience of the poll was selected, with the ALMA Science Portal registered users contributing only a small fraction of the total (10 % or 20 %, respectively, depending whether one considers only the unique ALMA Science Portal registered users or also those who are registered on both portals). Moreover, it is important to note here that of the four pie-charts shown in Figure 1, the first three required a unique answer, whereas for the fourth — relating to wavelength domains — users were allowed to select several domains that apply to their research work.

Section I also aimed to collect the main scientific drivers of the community, now and in the future. The users were presented with two similar lists of research topics and asked to select first those that best describe their current research interests and then their science vision in the 2020–2030 timeframe (i.e., not so much about what they will be doing scientifically, rather what they think would be the research topics dominating in 2020–2030).

Figure 2 shows a direct comparison between the view of individual researchers on their research areas today and their science vision for the 2020–2030 decade, in terms of absolute numbers of preferences. While the topics structure/evolution of galaxies, stars and planetary systems dominate the pool today, planetary systems, cosmology/fundamental physics, search for life and structure/evolution of galaxies are foreseen to dominate the 2020+ astrophysical scene.

There exist some noticeable differences between the current areas of research and those fields expected to dominate the astrophysical landscape. Among the top four fields that will dominate the future (Figure 2), three are expected to increase significantly in popularity, the most affected one being the search for life. Two other areas of research are also expected to double their significance, but overall they represent a smaller fraction of respondents (extreme states of matter, pre-biotic chemistry).

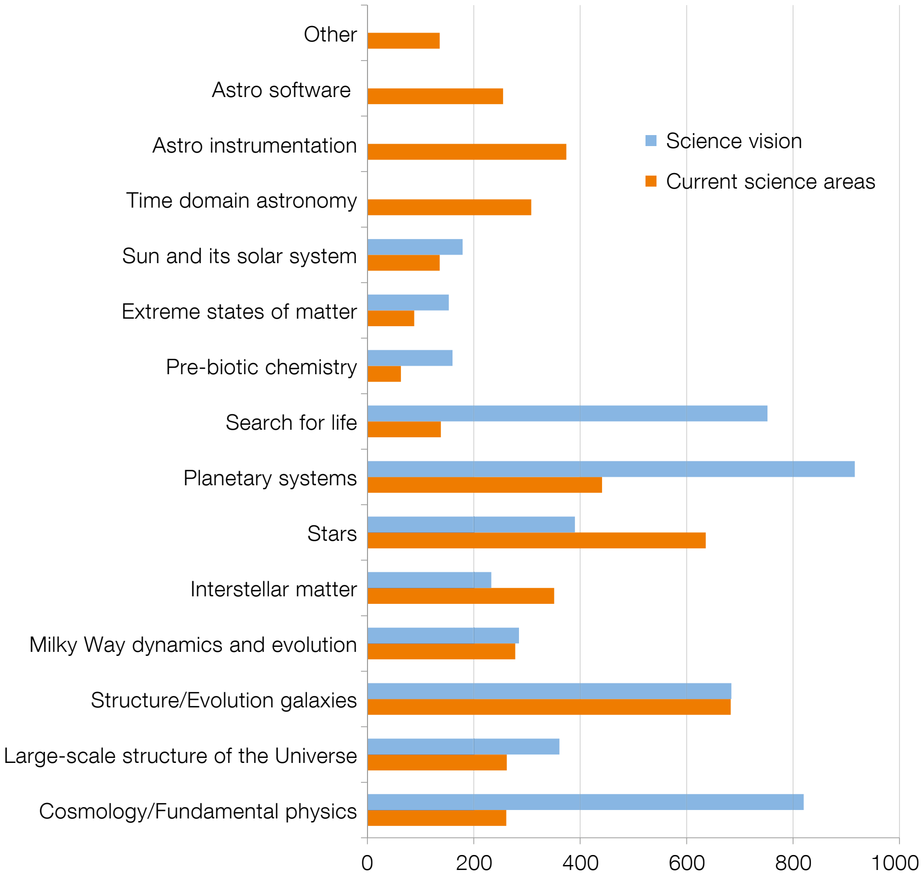


Figure 2. A direct comparison, in absolute numbers of preferences, between current individual research areas (light orange) and those identified by the respondents as dominating the astrophysical scene during the next decade (light blue). The four light orange bars at the top of the graph without a corresponding light blue bar correspond to the research areas that were omitted from the list of science vision topics.

The only research fields affected by a decrease in the number of preferences for the 2020–2030 decade are the more classical fields: stars and interstellar matter. If taken at face value, the outcome on the stellar field may be especially puzzling, considering that one of the main science cases for the E-ELT is concerned with resolving individual stars in external galaxies (for kinematic and chemical tagging purposes). Moreover, as will become apparent from the next section, this result is also at odds with the future capabilities and facilities identified by the community as most important. We note, however, that the two questions about current research interests and research areas dominating the future astrophysical scene were intentionally implemented with a slightly different logic. Question 1.6 (see Table 1), about current personal research interests, allowed the user to specify as many choices as necessary (in order to collect all their current research interests). Question 1.7, about the science vision, was instead restricted to a maximum of three choices (in order to collect only the most important areas, hopefully minimising the dispersion in the replies).

Section II — Present and future observing facilities

Section II followed up on the research interests emerging from Section I and paired them to the facilities that enable the users to achieve their science goals, inside and outside ESO's landscape.

Table 2. Questions from Section II of the ESO2020+ Users' Poll.

Section II – Present and future observing facilities		
2.1	Which capabilities will be most important for your research in the 2020+ timeframe?	See Figure 3
2.1.1	Please select the wavelength ranges and priorities for [your selection(s) of Q2.1]	See Figure 4
2.2	Are there observing capabilities missing at ESO for your research?	See text
2.3	Do you consider the support for visitor instruments an important capability for your research?	See text
2.4	Which facilities do your future research objectives require?	See Figure 5
2.5	Which other planned facilities are essential for your future research?	See Figure 6

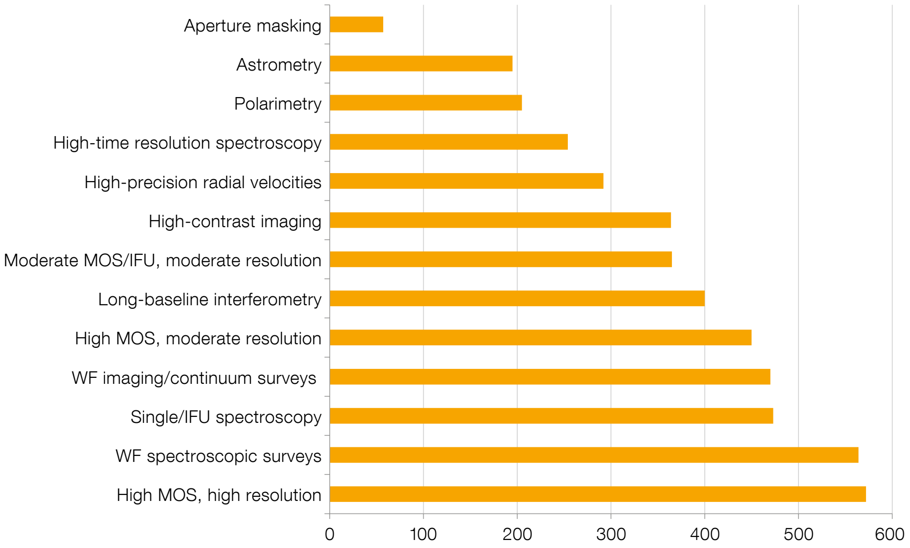


Figure 3. Users were asked to select the most important capabilities for their own research in the 2020–2030 timeframe. Responses are shown in absolute number of preferences, expressed for each option listed. A total of 4661 preferences were received.

The first question was about the most important capabilities for their research in the 2020+ timeframe. The respondents were allowed to make at most three choices and the distribution of all preferences is shown in Figure 3.

At face value, there seems to be a clear dominance of high-multiplex, high/moderate resolution spectroscopy, single/IFU (integral field unit) spectroscopy and wide-field (WF) imaging/continuum and spectroscopic surveys, which pairs well with the light orange bars displayed in Figure 2. However, interpreted carefully, Figure 3 is slightly more complex: first, by splitting the spectroscopic modes more finely than the other capabilities, we may be inadvertently boosting all spectroscopic entries; secondly, the analysis is based on a varying number of choices made by the different respondents (some may have chosen to specify all three choices they could make, others less); thirdly, the results may reflect the implicit bias in the targeted audience, because the number of users drawn from the ALMA Science Portal is at most one fifth of the total number of users who were invited to participate (depending whether one considers users with a unique account on the ALMA Science Portal — around 900 — and users who have an account on both portals — another 990). However, improving on the normalisation of the responses is not straightforward, because of the logic behind the questions. As noted earlier, this bias may reflect the distribution of wavelength domains among the respondents (see Figure 1), which in turn may be interwoven in the responses received in this section.

This first question was followed by a list of questions asking the user to specify, for each of the selected capabilities, the priority (Essential/Important/Somewhat Important) of different wavelength domains (0.3–0.4 μm, 0.4–1 μm, 1–2.4 μm, 2.4–20 μm, submillimetre [sub-mm], radio). We decided to combine all Essential/Important preferences given to each capability in the six wavelength domains (Figure 4) and normalise them to the total number of responses of the capability in the leading question. For example, the high multi-object (MOS), high-resolution capability received a total of 571 preferences (bottom bar in Figure 3); of those, 304 correspond to Essential/Important selections in the 0.3–0.4 μm interval, thus making up more than 50 % of the total.

With the exception of long-baseline interferometry, all the other observing capabilities received the largest number of preferences in the wavelength ranges 0.4–1 μm and 1–2.4 μm, followed by the 0.3–0.4 μm and the 2.4–20 μm intervals. The strong interest in the 0.3–0.4 μm region across all capabilities is noteworthy here, indicating a need for blue coverage that emerged also at the ESO2020+ conference.

For completeness, users were also prompted about the importance for their research that ESO continues to provide support for visitor instruments. The responses split almost equally between "Yes" and "No", with the latter leading just by a few percentage points (52 %).

After questions about capabilities, the users were asked about the facilities which were required by their scientific objectives. The net dominance of optical/infrared (IR) facilities (of any size, from 4 metre/8–10 metre, including a dedicated 10-metre spectroscopic telescope for the E-ELT) is notable. The detailed outcome is shown in Figure 5 and is based on a total number of 4575 choices (the answer was again limited to a maximum of three choices). As already commented for Figure 3, the replies may be affected by an implicit bias and reflect the wavelength range distribution of the user pool (see Figure 1).

Section II also touched upon the lack of specific facilities at ESO and the importance of other planned facilities (where users were asked to select all those that will be essential for their research

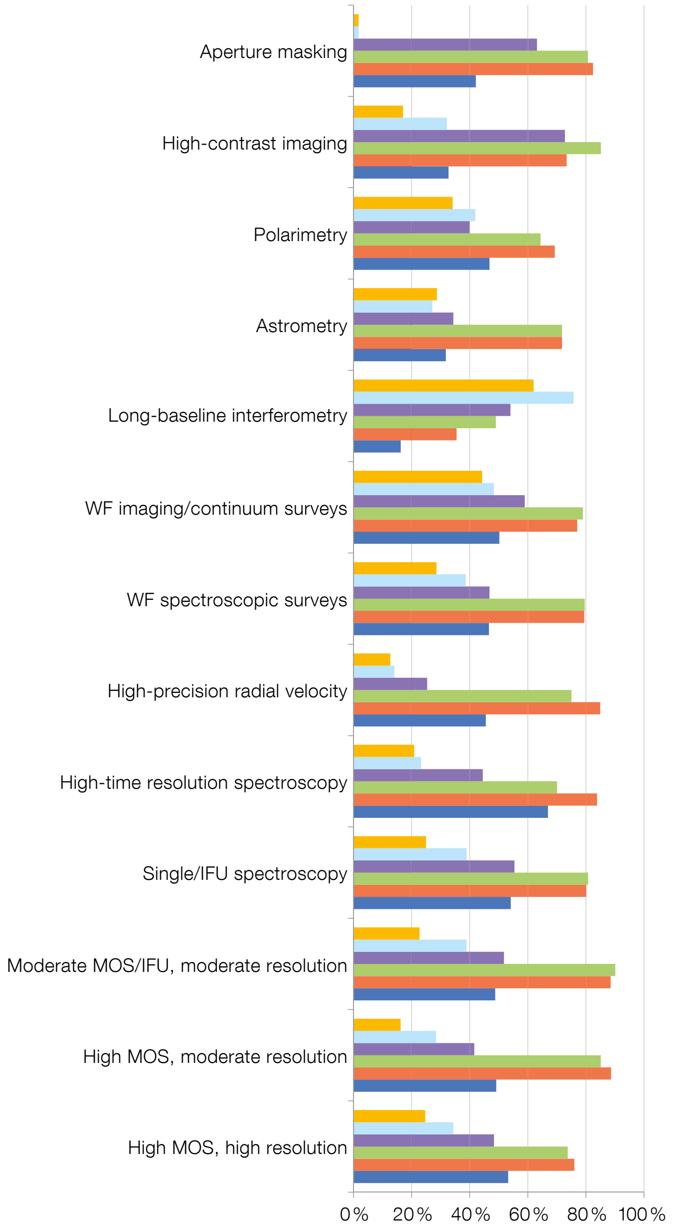


Figure 4. Similar to Figure 3 (in terms of y-axis), the bars now show the Essential/Important wavelength ranges per chosen instrumental capability.

objectives). The response to the question whether there were observing capabilities not available at ESO split almost equally (46% Yes, 54% No); those who answered "Yes" were asked to be more specific. There were nearly 800 individual comments spanning a wide range of options and mixing both capabilities (to the level of a specific instrument mode missing on an already operational VLT instrument) and facilities (e.g., X-ray and gamma ray).

Figure 6 displays which other facilities our pool of respondents deem to be essential for their future research objectives. A list of upcoming planned facilities was provided, but users were allowed to specify more and they are shown by the word cloud.

Section III — Time scheduling and observing modes

Sections III and IV covered ESO science policies and their implementation in terms of observing (this section) and data processing/archive capabilities (next section).

Almost twenty years ago, while preparing for the VLT, ESO captured its main policies and procedures on how to allocate telescope time at the VLT/VLTI in what then became the official ESO Science Policy document[2]. The arrival of VLT/I clearly marked a significant change for ESO and its community, moving from a classical type of observatory (how La Silla was run, back then) to a more challenging model that makes the best out of classical and queue observing (Visitor and Service Modes, VM and SM, respectively). Today, ESO's facility landscape has been further enriched and now includes Visible and Infrared Survey Telescope for Astronomy (VISTA) and the VLT Survey Telescope (VST) on Paranal, APEX and ALMA on Chajnantor. In the 2020+ timeframe, it will also include the E-ELT.

Despite several commonalities among its observatories, ESO operates its facilities in slightly different ways: only Visitor Mode observing on La Silla; only Service Mode observing on the two survey telescopes (VISTA and the VST), APEX and ALMA; both Service and Visitor Modes at the VLT/I. Section III touched on these aspects and probed the community's needs and ideas about types of observing programmes and observing modes (one question each, see Table 3). Neither question was mandatory. For the first question of Section III (Table 3), each programme type listed among the possible options scored the same number of responses (1775). This is because each entry had "No Answer" ticketed as the default value. Figure 7 thus shows the percentage of responses for the five types of programme, each of which sum to 100% of the responses.

The community expressed its strongest opinion about the necessity to have regular observing programmes, defined as an essential and/or very important channel to fulfil their research objectives, followed by Large Programmes and Public Surveys with a robust number of preferences (Essential, Very Important and Important). The overall opinion about Filler and Director's Discretionary Time Programmes is less clear: the responses are distributed more evenly among all priorities, though both have the largest percentage of "Not Important" responses (still relatively small,

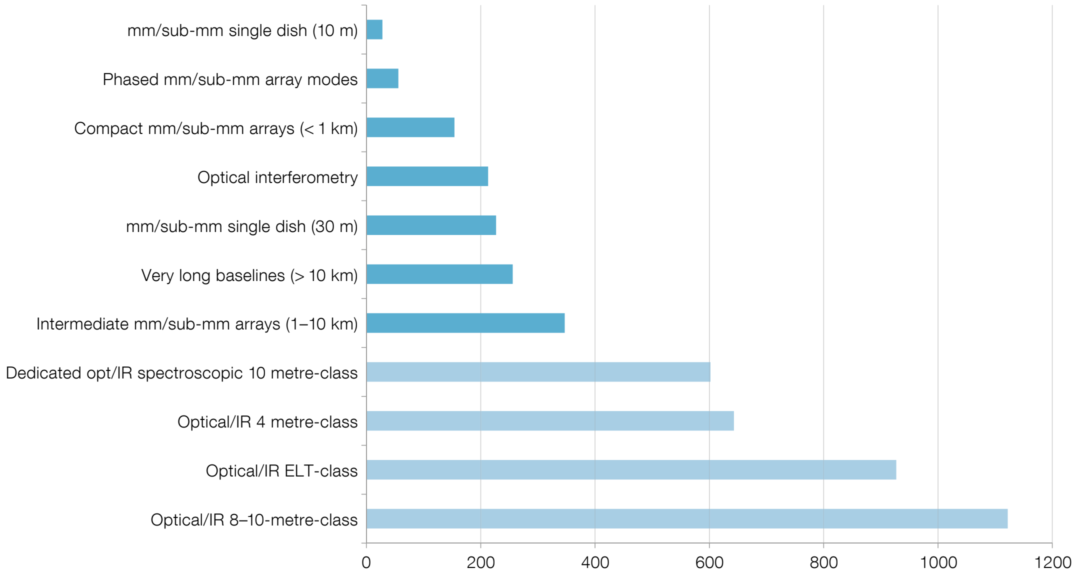


Figure 5. Users were asked to select which facilities will be required for their future research objectives. A total of 4575 responses were received. The bottom four bars (light blue) make up 72 % of all responses.

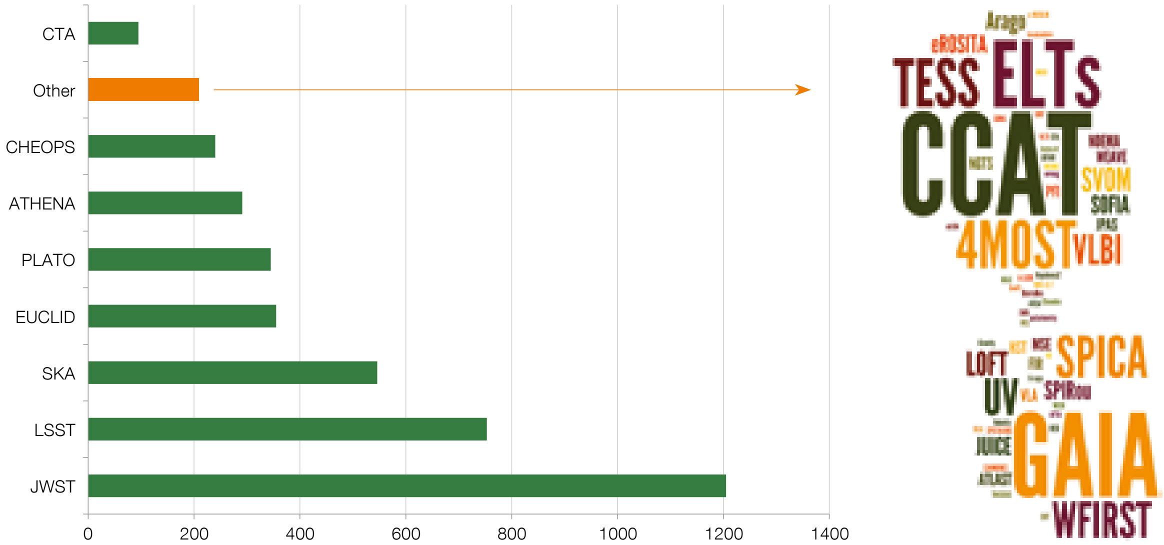


Figure 6. Bar chart and word cloud visualisation of the other facilities that users will likely use in the future. A total of 4039 responses were received.

Table 3. Questions from Section III of the ESO2020+ Users' Poll.

Section III – Time scheduling and observing modes

3.1	How important do you consider the following types of programme for your research objectives?	See Figure 7
3.2	Which of the following observing and scheduling capabilities are important for your research objectives?	See Figure 8

8 % and 12 % respectively). The majority of the respondents seem to have no specific opinion about these programme categories, which could also imply that their science programmes cannot be carried out as Filler Programmes, for example. For Filler Programmes in particular, this result will need to be reconciled with the ~ 40 % preference scored for the use of filler queues to exploit poor weather at La Silla Paranal (see Figure 8).

Next the users were faced with the question on the importance of the most common observing and scheduling capabilities for their own research objectives. The question was not mandatory and asked the users to specify their priorities for each of the three major ESO facilities, La Silla Paranal Observatory, ALMA and the E-ELT. Figure 8 summarises the results in terms of percentages corresponding to the number of preferences received and normalised to the total number of respondents (1775). Each facility should be looked at as an independent entry, since users were allowed to select any given option for all three facilities. In other words, if we take the Visitor Mode option at the bottom of the plot,

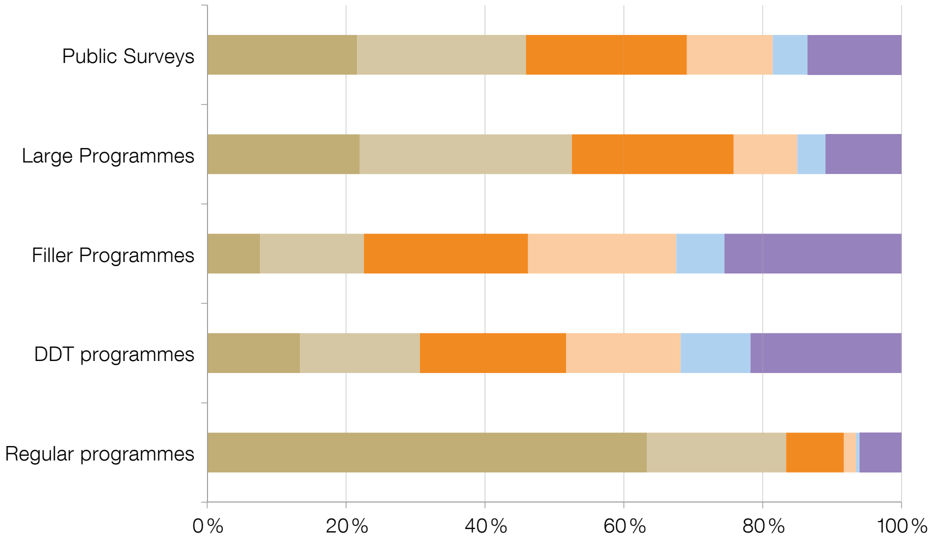


Figure 7. How respondents prioritised the importance of the different types of observing programmes that ESO currently offers to the community. (Calibration and Monitoring Programmes were excluded from the list of choices owing to the very low numbers received per semester.)

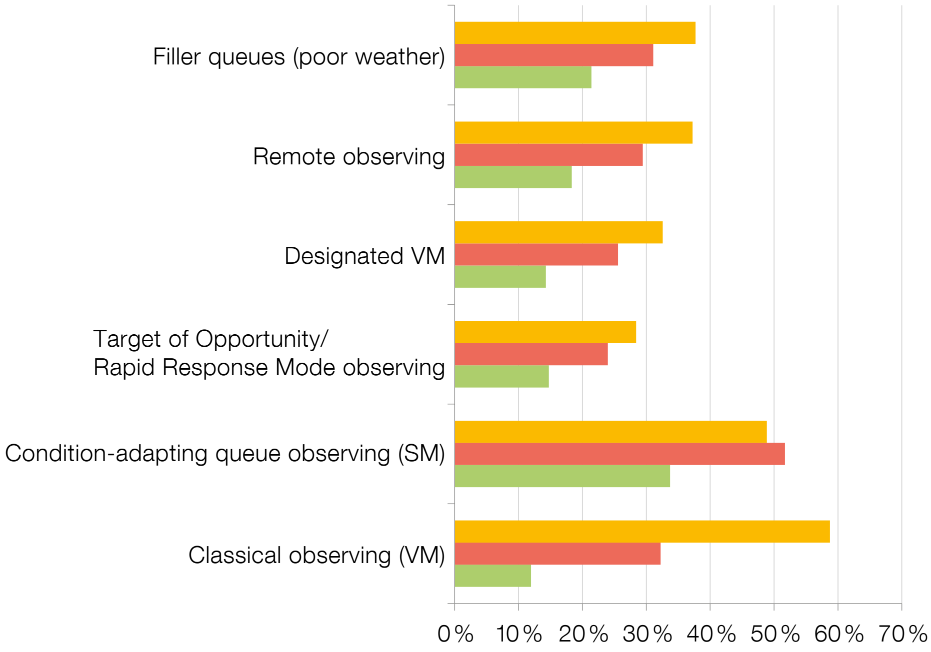


Figure 8. The observing and/or scheduling capabilities that the users deem important for their own research at the three main ESO facilities.

it means that 60% of respondents selected this option as important for their own research plans at La Silla Paranal. Nothing can be said about the remaining 40%: based on how the question was posed one could assume that 40% find Visitor Mode not important/relevant. However, we cannot exclude *a priori* that this 40% includes also those who would define themselves as "neutral", without a strong opinion about this specific mode.

A few remarks are in order. Condition-adapting queue observing is the mode that received the largest (absolute) number of preferences for both ALMA and the E-ELT and is one of the two preferred modes for La Silla Paranal. This is a clear recognition of the importance of what we call Service Mode for an optimised exploitation of ESO facilities. Noteworthy are the large number of preferences received by the option for classical observing (Visitor Mode) for La Silla Paranal, significantly larger than what could be considered alternative options, like Designated Visitor Mode or Remote Observing.

Section III offered users the opportunity to leave comments on missing capabilities and/or issues related to observing modes and scheduling. The variety of comments (approximately 150 in number) makes it impossible to render them in any graphical way. Among the responses were: Remote Observing as an important development for the future (independently of the facility); Service Mode observing on La Silla to better cope with monitoring programmes; more interactions with ALMA observing (also in terms of dedicated schools on ALMA hardware); more synergies with space missions (ESO involved as partner from the beginning, especially for those missions that will require ground-based support as part of their goals).

Section IV — Data management and services

Data management is part of both ESO's and ALMA's operational infrastructures: entailing the archiving of all raw science and calibration data; checking the performance of the instruments so that corrective measures can be applied in a timely manner; and making data available to the Principal Investigators (PIs) in real time and to the wider community later on.

Section IV aimed to collect feedback on aspects related to the exploitation of individuals' science data. This section comprised four main questions (see Table 4)

Table 4. Questions from Section IV of the ESO2020+ Users' Poll.

Section IV – Data management and services		
4.1	How important are the following data reduction software capabilities for your research objectives?	See Figure 9
4.2	How important is access to the following sorts of archived data products in order to maximise your scientific productivity?	See Figure 10
4.3	To maximise the scientific impact of data from ESO facilities, bearing in mind that ESO has finite resources, what level of support should be provided for ESO data? Currently all raw (science and calibration) data and data products are archived.	See Figure 12
4.4	For your research, how critical are the following functions/capabilities?	See Figure 11

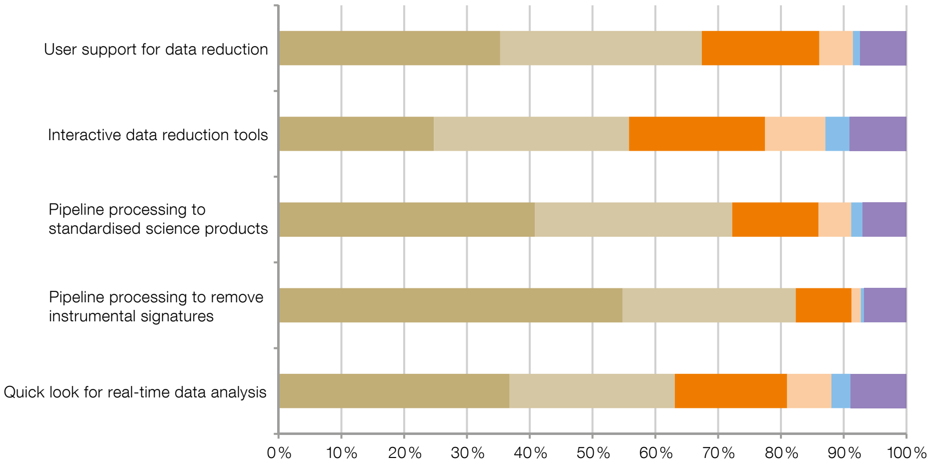
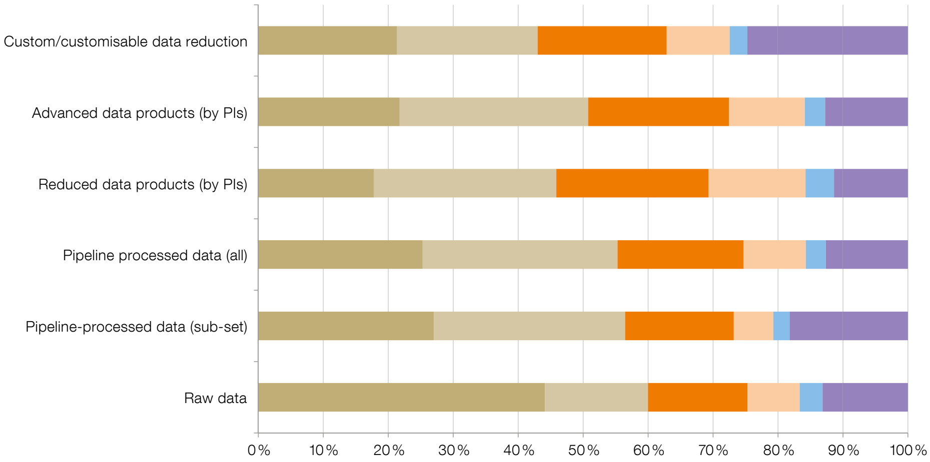


Figure 9 (above). Distribution of users' opinions and priorities on the availability of specific data reduction capabilities.

Figure 10 (below). Distribution of users' opinions and priorities on accessing specific data products (as listed on the y-axis).

Key to Figures 9 and 10:

- Essential
- Very Important
- Important
- Somewhat Important
- Not Important
- No Answer



and further opportunities to provide individual feedback. None of the questions required a mandatory answer, with a default No Answer option (to be interpreted as having no specific opinion).

Three out of the four questions were formulated in view of the respondents' research objectives and scientific productivity. The users were asked to express their opinion on the importance of: 1) different data reduction software capabilities for their research activities; 2) access to a variety of data products in order to maximise scientific productivity; 3) specific functions/capabilities. The fourth question was formulated in more general terms and required the respondents to express their views on which level of data support (both in terms of data processing and data archiving) would be needed to maximise the scientific impact of data collected at ESO facilities. Figures 9–12 summarise the distribution of responses in terms of criticality.

There is a lot of information embedded in these figures, which clearly calls for a more in-depth analysis. The most obvious take-away message is that users consider support for data products (via tools to properly treat the data and/or via types of products made available to them through the ESO Science Archive) extremely important for their own research activities. In fact, approximately half of the respondents consider it critical to have advanced data reduction tools and pipelines for their research projects (55%, see Figure 11) and believe that ESO should routinely process and archive most or all science data in order to maximise the impact of ESO data (50%, see Figure 12).

Most questions of this section (4.1, 4.2 and 4.4, see Table 4) were formulated in order to collect the broadest overview on the different levels of importance of several aspects related to data management. The respondents were not asked to prioritise their preferences, therefore we are unable to go deeper in the interpretation of the distribution of responses. For example, we note that for question 4.2, i.e., how essential/very important is the access to different types of archived data products for one's individual research, all options (raw data, pipeline processed data (subset), pipeline processed data [all]) scored around 55–60%, despite the fact that the latter two options could have also been interpreted as mutually exclusive. Similarly, one may question how significant the differences are between the other options: advanced data products created by the PIs scored 51%, followed by reduced data products created by PIs (46%) and custom/customisable data reduction (43%).

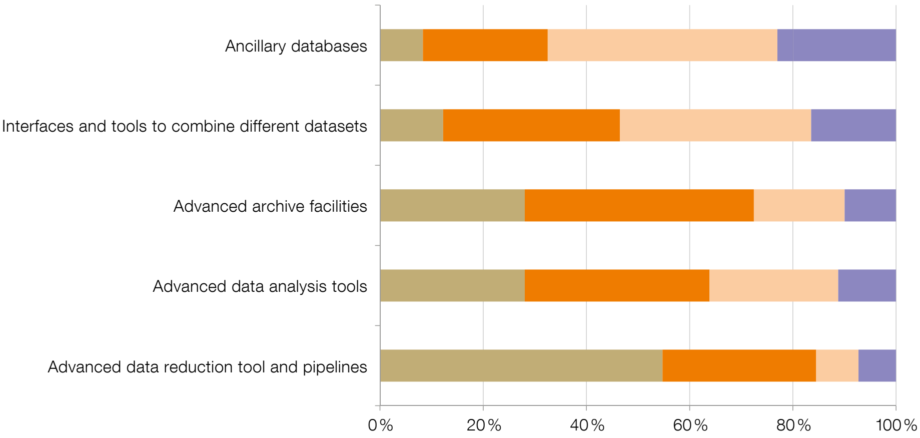
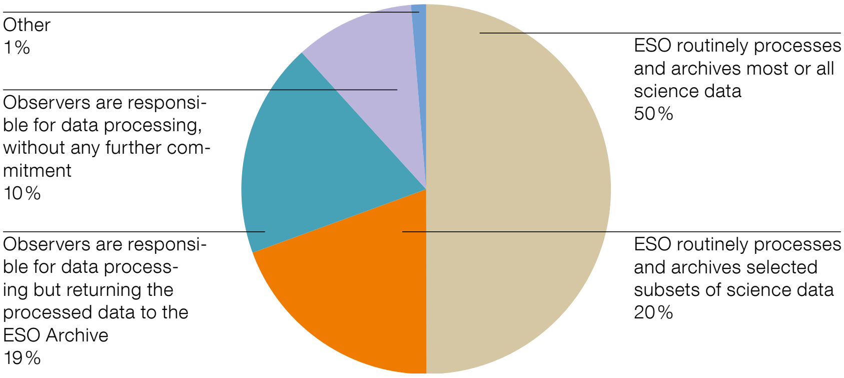


Figure 11 (above). Distribution of user answers on five different data-related functions/capabilities. The default choice was set to No Answer and users were warned that this would be interpreted as having no particular opinion on that specific item.

Figure 12 (below). Distribution of responses on the level of support that ESO should provide.



On the other hand, in question 4.4, about the criticality of different functions/capabilities for one's research, the differences among the proposed options are more significant (see Figure 11). Here, for instance, 55% of the respondents consider it critical to have advanced data reduction tools and pipelines available, but only 28% asked for advanced archive facilities.

With respect to the level of overall support that should be provided for ESO data, half of the community is of the opinion that most or all science data should be routinely processed and archived, whereas the other alternative options (selective processing of datasets by ESO and PI data processing with commitment to return the data products to ESO) scored only 20% each.

Concluding remarks

The poll was a successful exercise, both in terms of the number of responses and the quality and relevance of feedback received. As is always the case, our poll suffers from some intrinsic biases. The results are, however, sufficiently solid to guide and support future implementations. The community poll represents an important component of the ESO2020+ Science Prioritisation exercise and it was folded into the final recommendations prepared by the working group.

The ensemble of opinions represents the largest feedback ever collected by ESO from its users in a systematic manner. It provides important details about our astronomical community, in terms of its current scientific interests, future research goals and expectations.

We believe that this poll will serve ESO well in different respects: there is an enormous amount of information, not only for ESO2020+, but also for the more immediate future of ESO, on existing facilities and instrument capabilities already available to the community. Apart from the area of future facilities, for which many other considerations have to be considered, the areas pertinent to science policies and their implementation (operations) have provided a clear picture in terms of types of programmes, observing modes and data support. The poll has indicated how essential regular observing programmes are, on all facilities — the respondents acknowledge the importance of Large Programmes and the new trend of Public Surveys, but they have emphasised the need to keep regular observing programmes on all ESO facilities, i.e., there continues to be strong support for research projects led by individuals and small groups. Regarding data support, the poll results show that the community appreciates the end-to-end support provided by ESO (e.g., ESO should process and archive most of the science data).

We will continue to search for interesting correlations among the results. For instance, a test between the career stage of the respondent and the preferred level of support that ESO should provide, in terms of data processing and data archiving, showed that the younger generations may have different views from their senior colleagues. It is thus important to understand the invaluable feedback received from the ESO community via the poll in order to maintain ESO at the forefront of future astrophysical and technological developments.

Acknowledgements

Sangeeta Mysore, Stephane Marteau and Lowell Tacconi-Garman from the User Support Department are thanked for their support in the technical implementation and launch of the poll.

Links

[1] Science Priorities at ESO: http://www.eso.org/public/about-eso/committees/stc/stc-85th/public/STC-551_Science_Priorities_at_ESO_85th_STC_Mtg_Public.pdf

[2] ESO Science Policy document: http://www.eso.org/sci/observing/policies/cou996-rev.pdf

G.Hüdepohl (atacamaphoto.com)/ESO

Preparing for a night of observations at the Paranal Observatory. An aerial view of Paranal at sunset looking towards the Pacific coast. See Picture of the Week 31 August 2015.

Astronomical Science

FORS1 image (combination of *V*- and *I*-bands) of M95 (NGC 3351) in the nearby Leo I galaxy cluster at 10 Mpc distance. NGC 3351 is a barred spiral galaxy and many dust structures are seen in extinction, both in the spiral arms and along the bar. This galaxy also has a circum-nuclear star-forming region, but shows no sign of an active galactic nucleus. More details can be found under Picture of the Week for 19 March 2012.

HARPS Observes the Earth Transiting the Sun — A Method to Study Exoplanet Atmospheres Using Precision Spectroscopy on Large Ground-based Telescopes

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Exoplanetary transits offer the opportunity to measure the transmission of long, tangential pathlengths through their atmospheres. Since the fraction of the observed stellar light taking these paths is very small, transit photometric and spectrophotometric measurements of light curves require very high levels of measurement stability, favouring the use of intrinsically stable space telescopes. By studying the Rossiter–McLaughlin effect on the radial velocity of the transited star, pure, high-precision radial velocity measurements can be used to estimate the changes in planetary atmospheric transmission with wavelength: a promising method for future studies of small planets with very large ground-based telescopes since it removes the requirement for extreme photometric stability. This article describes a successful feasibility experiment using the HARPS instrument to measure reflected moonlight during the penumbral phases of a Lunar eclipse, effectively providing an observation of an Earth transit.

Introduction

Lunar eclipses provide an opportunity to study the atmospheric properties of the Earth in a geometry that is similar to that of an exoplanet transiting its parent star. During such a transit, the small fraction of the stellar light that grazes the exoplanet's atmosphere carries the imprint of the atmospheric composition and its distribution with altitude. This signature has been detected photometrically (often spectrophotometrically) and interpreted for a number of exoplanetary systems and has provided the first glimpses of planetary atmospheres beyond the Solar System. Analogous studies of Lunar eclipses over recent years (Pallé et al., 2009; Vidal-Madjar et al., 2010; Arnold et al., 2014; Yan et al., 2015a) have allowed us to construct a baseline to be used for future exoEarth atmospheric characterisation.

Since the atmospheric signature is encoded within a tiny fraction of the total stellar light, the photometric observations require the extreme precision and stability that can be achieved relatively easily in space. For ground-based observations however, continuous monitoring of standard stars falling within the field of view of the observing instrument is required. An alternative observational technique, based on the well-known Rossiter–McLaughlin (RM) effect, allows us to access the effective radius of the transiting planet and its variation with wavelength by making precision radial velocity measurements of the star outside of and within the transit. The classical Rossiter–McLaughlin effect was first used for the study of eclipsing binary stars (McLaughlin, 1924; Rossiter, 1924) and describes the radial velocity anomaly of a star when a body (star in the case of an eclipsing binary, or a planet) passes in front of a star, occulting a small area of the rotating stellar surface.

Our method, based on the RM effect, exploits the masking of different parts of the stellar disc as the transit proceeds, producing varying combinations of stellar rotational and surface motions that depend both on the position of the transiting planet within the stellar disc and on its effective radius. Since the effective radius is a proxy for the variation of the transmitted light as a function of wavelength, the radial velocity signal will carry information about the planet's atmospheric composition. This application of the RM effect, first suggested by Snellen (2004), has the important advantage of not requiring high photometric precision and so is very suitable for large ground-based telescope observations employing stable, high resolution spectrometers; a procedure that does not require the monitoring of reference stars.

In order to explore and test the feasibility of this RM-based technique, we have applied it to observations of a Lunar eclipse made with the High Accuracy Radial velocity Planetary Searcher (HARPS) spectrograph on the 3.6-metre telescope at La Silla. We show that such an observation enables us to retrieve the transmission spectrum of the Earth's atmosphere at a level that clearly shows the Rayleigh scattering and the ozone Chappuis band absorption (Yan et al., 2015a).

Lunar eclipses and exoplanet transits

A Lunar eclipse is a relatively frequent astronomical phenomenon that must have excited interest since early hominids gazed at the sky. The phenomenon occurs when the Moon traverses the shadow of the Earth. During an eclipse, the Moon first moves into the Earth's penumbra making the Lunar surface brightness drop dramatically. It will then, if the geometry is right for a total eclipse, pass into the umbra to produce the deep-red Copper Moon that is mostly, but not entirely, the result of Rayleigh scattering in the Earth's atmosphere.

If your point of view was on the Lunar surface itself, you would actually witness the Earth transiting the Sun. This is similar to an observation of an exoplanet transiting its star (visualised in Figure 1) with the obvious difference in the relative angular sizes of the star and the planet. Consequently, by employing the Moon as a mirror, we are able to regard the Earth as an exoplanet and to observe its transit. Such an observation gives us the chance to test and tune methods and strategies for studying, hopefully in the near future, the transits of Earth-like exoplanets.

The HARPS observation

The typical way of observing a transit signal employs photometry, i.e., observing the light curve. However, pure, precision spectroscopic observations can also be applied by utilising the RM effect. This method has now been applied to more than 80 exoplanet systems to give information about stellar rotations and planetary orbital geometries.

In order to obtain the RM effect of the Earth transiting the Sun, we have

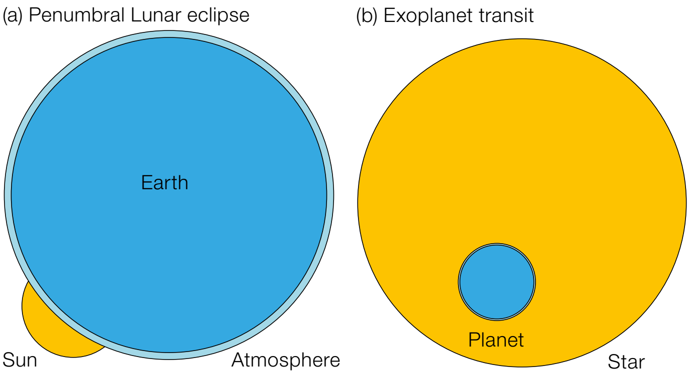

Figure 1. (a) Schematic of the Earth and the Sun viewed from the Moon during the penumbral Lunar eclipse. (b) Schematic of an exoplanet transit. The geometries of both are similar.

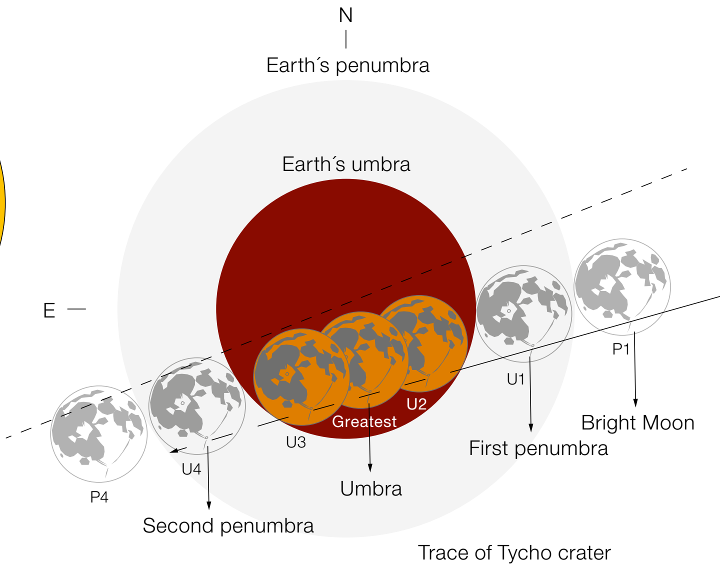

Figure 2. The trajectory of the Lunar crater Tycho during the HARPS observation. The observation covers all the stages of the eclipse. The figure is reproduced from the NASA Lunar eclipse page[1].

observed spectra of a fixed point on the eclipsed Lunar surface as the penumbral eclipse proceeded. Our observations were made throughout the Lunar eclipse of 15 April 2014, for which the entire eclipse was visible from the La Silla Observatory, using HARPS (Yan et al., 2015a). We chose to observe the Tycho crater for this observation because its albedo is high and a large part of its trajectory lies within the penumbral region (see Figure 2 for the trajectory of the crater Tycho).

In total, we obtained 382 Lunar spectra that cover all the eclipse stages, i.e., the penumbral eclipse, the umbral eclipse and out of eclipse (which we call here the bright Moon). The radial velocities (RVs) derived from these spectra are measured and are plotted in Figure 3. Here the RV caused by the orbital motions of the Sun–Earth–Moon system have been corrected using the Jet Propulsion Laboratory (JPL) Horizon Ephemeris[2].

The plot in Figure 3 shows the RV curve of the Rossiter–McLaughlin effect of the Earth transiting the Sun. When the Moon enters the first penumbra, the Earth begins to block the redshifted part of the Solar disc, thus the observed RV becomes negative (a negative value means the spectrum is blueshifted). At the umbral stage, the RV gradually changes from a blueshift to a redshift. The detailed umbral RV is relatively complicated because it is influenced by the actual properties (including cloud patterns) of the Earth's atmosphere as it refracts the sunlight. When the Moon enters the second penumbral stage, the RV is redshifted since the Earth obscures mainly the blueshifted rotating region of the Solar disc. The RV gradually decreases during this stage as the Moon moves out of the penumbral shadow.

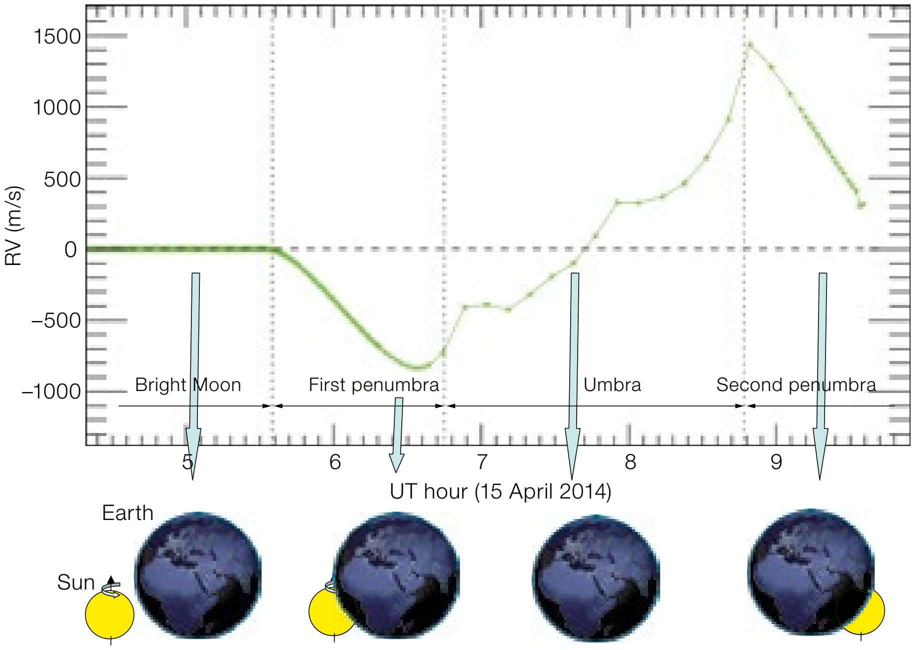

Figure 3. The observed RV during the Lunar eclipse. This is the Rossiter–Mclaughlin effect RV curve of the Earth transiting the Sun. The schematic of the Earth–Sun system as viewed from the Moon is indicated at the bottom.

The transmission spectrum of the Earth's atmosphere

Transmission spectroscopy is one of the main techniques employed to characterise exoplanet atmospheres. The traditional way is to observe the planetary absorption by comparing the stellar spectra in and out of transit. With transmission spectroscopy, various molecular and atomic species in exoplanet atmospheres, such as CH_4, H_2O, CO_2 and sodium have been discovered.

As was pointed out by Snellen (2004), the amplitude of the RM effect is wavelength-dependent because it is determined by the effective planetary radius, which is modulated by the wavelength-dependent differential atmospheric absorption. Thus the wavelength-dependent RM amplitude encodes the transmission spectrum of the planetary atmosphere.

We analysed the RM effect of the Earth transit at different wavelengths — in bands defined by the individual HARPS echelle orders — and Figure 4 shows the wavelength-dependent RM amplitudes. The Sun itself has wavelength-dependent parameters such as limb darkening and the spectral line blueshift caused by Solar convection. By utilising the fact that the stellar rotation is antisymmetric across the transit path while the surface motions are symmetric with respect to the Solar disc centre, we have removed the second of these effects and thus the structure of the RM amplitude RV curve is dominated by the Earth's atmospheric transmission.

The transmission spectrum of the Earth's atmosphere has been observed and modelled before (e.g., Yan et al., 2015b). It is known that atmospheric scattering and ozone absorption are the dominant features at optical wavelengths in the Earth's transmission spectrum. Ozone is particularly interesting because it originates from molecular oxygen and its presence is regarded as a bio-signature.

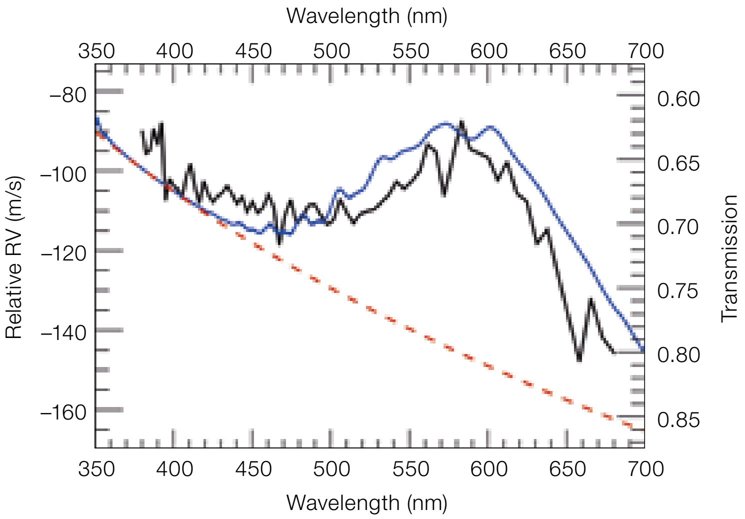

Figure 4. The RM amplitude at different wavelengths (black line). Here the RVs are relative values. The transmission spectral model of the Earth's atmosphere is also plotted (blue line) for comparison. The red dashed line indicates the Rayleigh scattering contribution in the spectral model.

In order to better understand the result in Figure 4, we built a transmission spectral model that contains the ozone absorption and the Rayleigh scattering of the Earth's atmosphere. The model is overlaid on the RM amplitude curve and their overall structures are seen to be very similar. In the blue part of the spectrum, the RM amplitude is large because the Rayleigh scattering is strong and thus the atmosphere appears thicker. The broad peak around 600 nm is due to ozone Chappuis band absorption. The RM amplitude towards the red becomes smaller because both the ozone absorption and the Rayleigh scattering get weaker, making the effective atmospheric thickness smaller.

Exoplanet atmosphere characterisation

Our Lunar eclipse observation with HARPS demonstrates the RM effect method to be an effective technique for atmosphere characterisation. A particular advantage of this method compared to the traditional spectrophotometric technique is that no photometric reference star is needed. Thus this method is a particularly promising technique for exoplanet atmosphere characterisation using very large ground-based telescopes, such as the European Extremely Large Telescope (E-ELT).

Observing the RM effect during a Lunar eclipse is relatively easy since the Moon is much closer to the Earth than to the Sun, amplifying the transit signal. For exoplanet transits, the radial velocity change caused by the planetary atmosphere is very much smaller and is consequently more difficult to measure. However, with the next generation very large telescopes and high precision, high stability instruments, such as the HIRES on the E-ELT and the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) on the Very Large Telescope, the RM method is ready to be applied to exoplanet atmospheric characterisation.

Acknowledgements

We would like to thank Valentin Ivanov and Lorenzo Monaco for their support of the observation, and also Gaspare Lo Curto and Andrea Chiavassa for helpful discussions.

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[1] The NASA Lunar eclipse page: http://eclipse.gsfc.nasa.gov/lunar.html
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Simultaneous HARPS and HARPS-N Observations of the Earth Transit of 2014 as Seen from Jupiter: Detection of an Inverse Rossiter–McLaughlin Effect

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Although there will not be another transit of Venus visible from the Earth until 2117, transits of other planets, including Earth, will be visible from other planets. We describe high resolution spectroscopic observations of the transit of Earth visible from Jupiter in January 2014 made with the HARPS North and South spectrographs. A Rossiter–McLaughlin effect was observed but with reverse sign and ~ 200 times larger. The result, presented in Molaro et al. (2015), was not at all what was expected and the explanation eventually led to the discovery of a new effect, a sort of inverse Rossiter–McLaughlin effect that has never been observed before.

Transits in the Solar System

Transits of Venus and Mercury in front of the Sun are major historical events. Johannes Kepler in 1627 predicted the transit of Venus of 1631, but died one year before the event, and Pierre Gassendi, who tried to observe the transit, missed it since it was not visible from Europe. Jeremiah Horrocks realised that transit of Venus occur in pairs separated by eight years and he successfully observed the transit in 1639. Since then only six other transits of Venus have taken place. In 1716 Sir Edmund Halley suggested the use of the transits of Venus to find a value for the distance of the Sun, the astronomical unit. Major expeditions to the most remote parts of the world were organised and a value for the astronomical unit was obtained with Halley's method.

On 6 June 2012 using the Moon as a mirror, we detected the Rossiter–McLaughlin (RM) effect due to the eclipse by Venus of the Solar disc with a precision of few cm s^{-1} (Molaro et al., 2013). When a body passes in front of a star the occultation of a small area of the rotating stellar surface produces a distortion of the stellar line profiles, which can be measured as a drift in the radial velocity. The phenomenon was first observed in eclipsing binaries by McLaughlin (1924) and Rossiter (1924). The RM effect has now been observed in almost one hundred exoplanets, providing important information on orbital geometry and showing that several exoplanets have very tilted orbits. The Venus observations demonstrated that the RM effect can be measured even for transits of exoplanets of Earth size or smaller, and that transits in the Solar System can be studied with reflected sunlight.

The observation of the transit of Venus via the Moon implies that other transits can also eventually be seen in the Solar System, since transits from other planets occur each time heliocentric conjunctions take place near one of the nodes of their orbits, with the obvious exception of the innermost planet, Mercury. These rare events have been studied in detail by Meeus (1989), who found that the Earth will be seen transiting the Sun from Mars in 2084 and from Jupiter on 5 January 2014, and again in 2026.

Observations of the 2014 Earth transit

During transits, the integrated Solar light can be recorded as it is reflected by the planet from which the Earth is seen to be transiting in front of the Sun, thus offering a surrogate for a direct view. Jupiter itself is not a good sunlight reflector due to its high rotational velocity and to the turbulent motions of its atmosphere, but its major rocky moons are better reflective mirrors. In Figure 1 the Earth and the Moon are shown as they would appear to an observer on Jupiter on 5 January 2014. Due to the small angular size of the Earth, the predicted RM effect is extremely small, only about ~ 20 cm s^{-1}. Interestingly, together with Earth, the Moon will also produce a transit on the Solar surface, but with an even smaller RM of ~ 2 cm s^{-1}.

The timing of the Earth transit differs slightly between the moons and Jupiter itself and varies from one moon to another: the moons arrive at the alignment slightly before the planet, about 30 minutes in the case of Europa and about one hour for Ganymede. The view of the Jovian system on 5 January 2104 from an observer on the Sun is illustrated in Figure 2. The moon Io was behind Jupiter during part of the event.

Unfortunately in January 2014 there was no suitable observing site on Earth where Jupiter could have been observed during the entire length of the transit. The transit could not be observed at all from Mauna Kea and the high spectral resolution facilities that could deliver very precise radial velocity measurements for the duration of the transit were not available at other suitable astronomical sites. La Palma and La Silla were the only observatories where a fraction of the phenomenon could be followed with high resolution spectrographs that are able to deliver the required radial velocity precision.

The two High Accuracy Radial velocity Planetary Spectrographs (HARPS) at La Silla and La Palma are twins. They are both housed in a vacuum, are thermally isolated, stable and equipped with an image scrambler that provides the uniform spectrograph–pupil illumination that is essential for high precision radial velocity observations. The HARPS-N (La Palma) and HARPS (La Silla) observations that we made comprise a series of hundreds of spectra of Europa and Ganymede covering the range from 380 to 690 nm. At the epoch of the observations, Europa and Ganymede had visual magnitudes of 5.35 and 4.63 mag and apparent diameters of 1.02 and 1.72 arcseconds, respectively. The integration times of the observations were 60 or 120 s and delivered a signal-to-noise ratio of ~ 200 each at 550 nm with a resolving power of *R* ~ 115 000. The observations are described in Molaro et al. (2015).

We started observing Ganymede on the night preceding the transit in order to determine the pre-transit characteristic

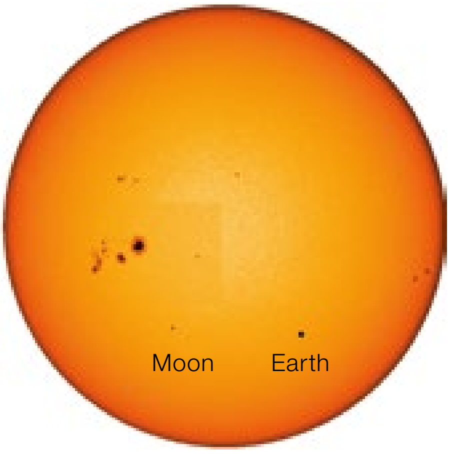

Figure 1. Composite image of the Sun with the Earth and Moon as seen from Europa at 19:00 UT on 5 January 2014. The sizes are to scale with the Earth's size of 4.2 arcseconds and the diameter of the Solar disc of 369 arcseconds. The Solar image is from a Solar Dynamics Observatory (SDO)/NASA Helioseismic and Magnetic Imager (HMI) Intensitygram at 617.3 nm on 5 January 2014 and shows prominent sunspots in the approaching Solar hemisphere. The total duration of the passage was 9 h 40 m.

Solar radial velocity. The following night we selected Europa to cover the second fraction of the transit as much as possible. In the night following the transit, we made observations of both Europa and Ganymede to determine the post-transit characteristic Solar radial velocity.

The radial velocities were obtained with the HARPS and HARPS-N pipelines, but we computed the proper kinematical corrections. These included not only the motions of the observer relative to Jupiter's moons at the instant when the light received by the observer was reflected by the moons, but also the radial velocity components of the motion of the moons relative to the Sun at the instant the light was emitted by the Sun. All these quantities have been computed using Jet Propulsion Laboratory (JPL) Horizon Ephemerides[1] following the recipies of Molaro and Monai (2012).

Figure 2. View of the Jovian system on 5 January 2014 from an observer on the Sun or on the Earth. From Jupiter the Earth transit started at MJD (Modified Julian Date) 56662.70, while its moons arrived somewhat in advance of the alignment with Jupiter.

A radial velocity anomaly

The whole set of corrected Solar radial velocities obtained from the spectra of Jupiter moons taken over the course of the three nights from both sites, after subtraction of the radial velocity baseline of 107.5 m s^{-1}, is shown in Figure 3.

The La Palma observations show a sudden drop of ~ 7 m s^{-1} after about one hour. Moreover, at the start there is a difference of about 4 m s^{-1} between the two spectrographs, with the La Silla sequence slightly lower. In the following night at about mid-transit the radial velocity rose very quickly until it reached a peak of 37 m s^{-1} and then declined almost monotonically, with a persistent small difference between the two spectrographs. In the night after the transit, the radial velocities are back to the values preceding the transit.

The observed pattern was completely at odds with our expectations: when observed, the Earth was eclipsing the receding Solar hemisphere and the RM effect should have produced a small blue shift of the lines. On the contrary, we observed a redshift change of 37 m s^{-1}, i.e. ~ 400 times greater than expected. Also the radial velocity drift lasted well beyond the end of the transit. The anomaly in radial velocity cannot have an instrumental origin. This is demonstrated by the fact that the two observatories give consistent results and such large RV anomalies have never been observed with these spectrographs. Thus the anomaly must have a physical origin.

It is known that Solar activity could affect the radial velocity of the Solar lines and indeed in Figure 1, the Solar image of 5 January 2014, does show the presence of several sunspots. However, the characteristic change in radial velocities is on a timescale of the Solar rotation and therefore no effect is expected during a relatively short period of ~ 10 hours. We inspected the Birmingham Solar Oscilla-

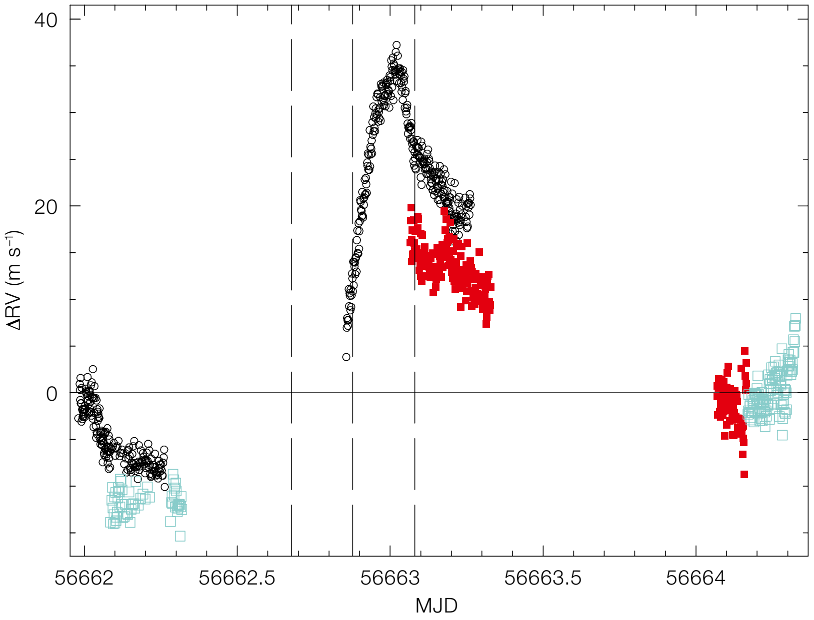

Figure 3. Radial velocities measured with HARPS on 4–6 January 2014. Open black circles are observations of Europa from La Palma while colour squares are the observations of Ganymede (cyan) and Europa (red) from La Silla. A constant offset of 107.5 m s^{-1}, as measured far from the transit, is taken as the instrumental baseline and was subtracted from the data. The vertical dashed lines mark the expected ingress and egress of the Earth's transit as seen from Europa.

tions Network (BiSON) archives containing Solar radial velocities for January 2014 to check whether short-term strong Solar activity coincided with the transit. The BiSON data were captured from several sites and provided continuous monitoring of the Solar activity proximate to the transit. The BiSON velocity residuals are shown in Figure 4 and do not show any peculiarity, thus ruling out definitively the possibility that the anomalous radial velocities depend on a peak of activity of the Sun.

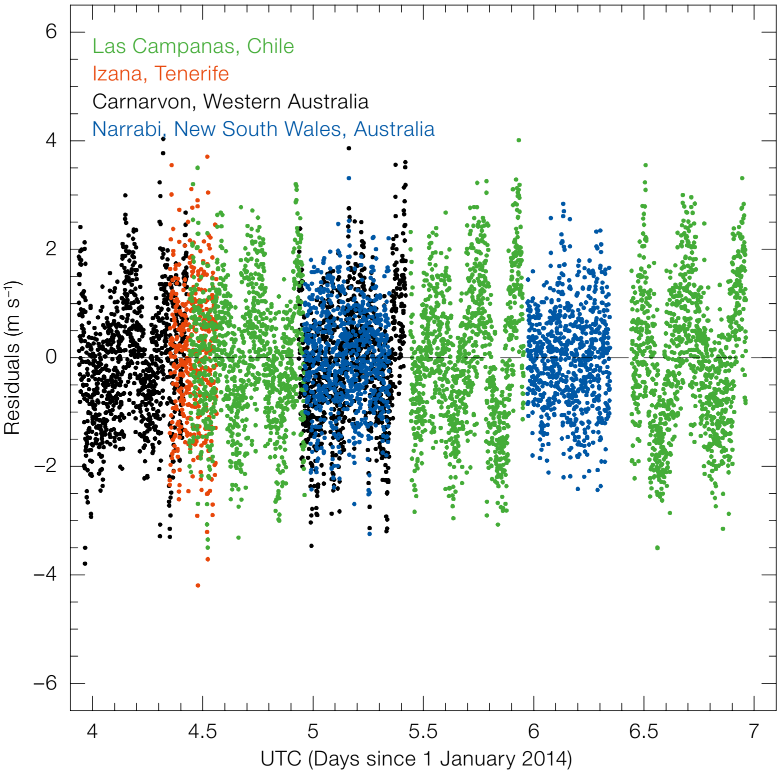

Figure 4. Archival BiSON Solar observations containing velocity residuals on the same days as our transit observations. The data are from: Narrabri, New South Wales, Australia (red points); Carnarvon, Western Australia (black); Izana, Tenerife (red); and Las Campanas, Chile (green). Courtesy of Steven Hale.

An inverse RM effect induced by the opposition surge

Thus the effect is real, and it took us a whole year to understand that what is observed was due to an entirely new phenomenon produced by the opposition surge on the icy moon Europa (Molaro et al., 2015).

The opposition surge is the brightening of a rocky celestial surface when it is observed at opposition. The precise physical origin is not yet completely understood and "shadow hiding" or coherent backscatter have been proposed. The former stems from the fact that when light hits a rough surface at a small phase angle, all the shadows decrease and the object is illuminated to its largest extent. In the coherent backscatter theory, the increase in brightness is due to a constructive combination of the light reflected from the surface and by dust particles. The constructive combination is achieved when the size of the scatterers in the surface of the body is comparable to the wavelength of light. At zero phase, the light paths will constructively interfere, resulting in an increase in the intensity, while as the phase angle increases constructive interference decreases.

A characteristic feature of the opposition surge is the brightening of the planet as the phase angle decreases. During the transit, Solar photons which graze the Earth have smaller angles than photons coming from regions of the Solar disc far away from the Earth's edge. Thus they produce an effective increase in the radiation coming from the region of the Sun just behind the Earth as it moves across the face of the Sun. During its passage across the Sun, the Earth acts as an effective lens and the light magnification produces a radial velocity drift which is opposite in sign to that expected from a Rossiter–McLaughlin effect, but of identical physical origin.

Thus, instead of receiving less radiation from the Solar hemisphere that the Earth is crossing, we are receiving more radiation because of the enhancement produced by the effect of the opposition surge of the reflecting body. This effect not only compensates for the partial Solar eclipse by the Earth, but is able to produce an opposite and much stronger radial velocity drift.

A toy model

The opposition surge is not fully understood and we cannot make a quantitative prediction of the distribution of the light enhancement as a function of the angular distance from the position of the transiting Earth. However, a simplified model, which accounts for the asymmetric emission from the two rotating Solar hemispheres, can explain most of the features of the RV curve that we observed.

In a simplified model we considered a circular region centred on the Earth of radius 6 arcminutes and with uniformly enhanced emission, and computed the effect in RV as if it were due to the RM effect, but reversing the sign to simulate the emission rather than the eclipse. The theoretical RM during the transit is computed using the formalism of Gimenez (2006). Since there is a degeneracy between the area and the intensity of emission, we simply scaled the radial velocity to the observed one, but preserved the shape.

The result is plotted in Figure 5. The predicted radial velocity rise follows the observations quite well. The peak is reached when the transiting Earth is at about three quarters of the Solar receding hemisphere. This is the position where we expect the strongest effect on the radial velocity due to the combined

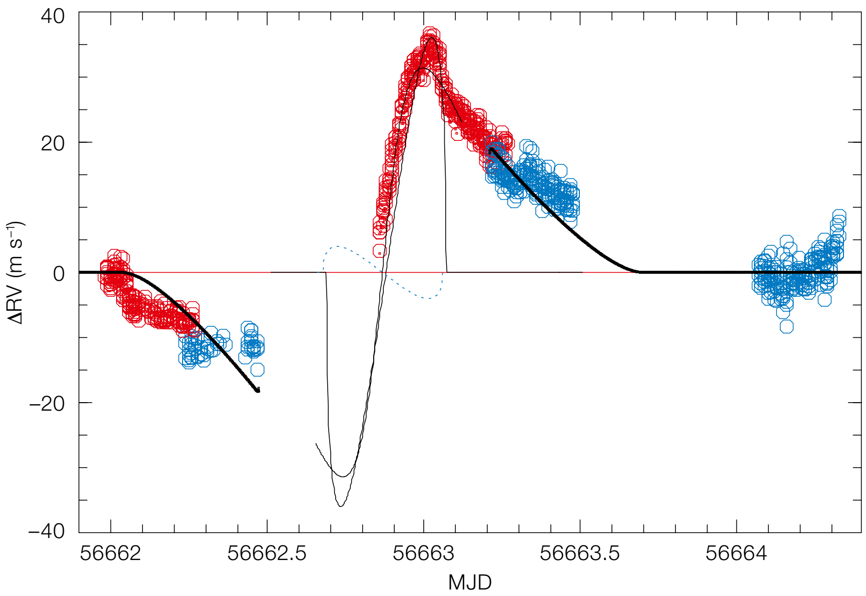

Figure 5. Model of the inverse Rossiter–McLaughlin RV drift induced by an increase in the Solar emissivity in the region behind the Earth's transit trajectory due to the opposition surge. The thin black line shows the drift expected from a small area moving with the Earth, while the thick line shows a drift coming from a larger area with a radius of ~ 10 arcminutes required to match the start of the radial velocity drift. The gap between the two models is due to the numerical impossibility of computing an RM effect for the total eclipse. The data points from La Silla (blue) are delayed by 0.1468 MJD to compensate for the longitude difference between the observatories of La Palma and La Silla. The blue dotted line shows the expected Rossiter–McLaughlin effect amplified by a factor of 50. The inverse RM effect detected is about 400 times larger than the expected RM due to the Earth's transit.

effect of the almost tangential rotational velocity and of the limb darkening of the Sun. During the decline, a break in the slope with a more gentle decrease is observed in proximity to the Earth's egress. The region with enhanced emission has been enlarged to 10 arcminutes to allow the RV anomaly to extend well outside the transit.

It should be noted that the model simulation does not end abruptly with the end of the Earth transit. This is because the opposition surge is also present when the Earth has just left the face of the Sun. For many hours after the end of the transit, the opposition surge makes the Solar hemisphere that has just been left by the transiting Earth brighter than the more distant one and the radial velocity decreases smoothly while the Earth is moving away.

The RVs are still high many hours after the end of the transit and it is only during the following night that we again measured a constant normal radial velocity. Assuming the opposition surge is quite symmetric, it probably started and ended ~ 15 hours before and after the transit, when the Earth was at a projected distance of about 10 arcminutes from the Solar limbs.

As we have already noted, the almost simultaneous observations from the two observatories give slightly different radial velocities. The RV values from La Silla are always lower by 4 to 10 m s^{-1} than those from La Palma, and in particular during the transit event. This difference is too large to be explained only by systematics and it is quite probable that the different locations on Earth of the two observatories experience a slightly different opposition surge. In other words, the distance from the Earth's edge could have been relevant in determining the intensity of the opposition surge and therefore the radial velocity value. The time difference between the longitudes of La Palma and La Silla is 0.1468 MJD (modified Julian date), while they have similar distances from the equator. This implies that, after this time interval, La Silla will be at approximately the same distance from the Earth's edge as La Palma. In Figure 5 we have shifted the data points from La Silla by this time difference and it is possible to see that they provide a much better continuity and overlap with the values measured at La Palma, regardless of the fact that the alignment has slightly changed in the meantime. This finding indeed suggests that the intensity of the opposition surge is very sensitive to the location of the observer on Earth, and in particular to the distance to the Earth's projected edges.

There is also the possible presence of a double peak around the position of the maximum of the radial velocity, which is suggestive of the presence of two components. While the broad component could be associated with a diffuse area of enhanced emission, the narrower component could be due to a peak of emission localised in proximity to the Earth. The result of simulated emission originating in a relatively small area around the Earth is plotted as a thin line in Figure 5 and it reproduces the peak quite well.

Prospects for another transit

The next Earth transit from Jupiter will occur in 2026, but it will be a grazing transit. However, since we have observed the effect of the opposition surge when the Earth was at an angle as high as ~ 10 arcminutes, we can predict that this unique phenomenon can be observed again, although with a lower amplitude in radial velocity. We really hope to have a very high resolution spectrograph (e.g., HIRES) at the European Extremely Large Telescope (E-ELT) to follow this new Earth transit.

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RAFT I: Discovery of New Planetary Candidates and Updated Orbits from Archival FEROS Spectra

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The first results of the Reanalysis of Archival FEROS specTra (RAFT) project are presented. We have analysed FEROS data for five stars with proposed planetary companions in order to test the reliability of the solutions with our new methodology. For HD 11977, HD 47536 and HD 110014 we confirm the presence of one orbiting companion. We reject the presence of a second companion around HD 47536, as well as the planets detected around HD 70573 and HD 122430. Finally, we propose the existence of a new second planetary companion around the giant star HD 110014.

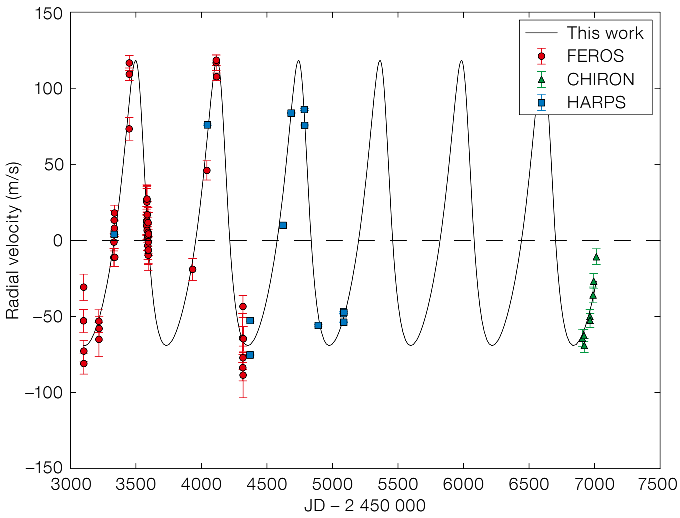

Figure 1. RV measurements for HD 11977.

Exoplanetary science is a burgeoning field in astronomy, focusing on the detection and study of planets outside the Solar System. Indirect techniques are mostly used to study exoplanets, one of them being the radial velocity (RV) method, which can be described as follows: when a star has an orbiting companion, it will move in a small orbit due to the gravitational pull produced by the companion. It is possible to measure the radial velocity of the star at different epochs through the Doppler effect and that way derive characteristics of the companion, such as its minimum mass and orbital period, through the application of simple Keplerian models.

The RV method uses spectrographs to measure the spectrum of a star and retrieve the flux from the source as a function of wavelength. After identifying the spectral lines, we measure the velocity of the star as a function of the time of observation. For this study, we used archival spectra from the Fibre-fed Extended Range Optical Spectrograph (FEROS; Kaufer et al., 1999), which has an operating spectral resolution of *R* = 48 000 and a large wavelength range (~ 350–920 nm). Several exoplanet systems have been detected with FEROS, but some of these have been thrown into doubt after reanalysis of the spectra. These differing results were obtained because of improvements in the calibration technique, and by the discovery that the FEROS pipeline barycentre correction did not include a correction for the precession of the coordinates (Müller et al., 2013). In this work the reanalysis of five stars using FEROS is presented: HD 11977, HD 47536, HD 70573, HD 110014 and HD 122430, all of which have a reported planet orbiting them. A more detailed version of this work can be found in Soto et al. (2015).

All the data we analysed were obtained from the ESO archive[1]. We reduced and calibrated the spectra using the FEROS pipeline, but disabled the barycentric correction. To obtain the shift of the spectral lines, we cross-correlated the spectra with a template (spectrum for the star with a high signal-to-noise). We then computed our own barycentric correction and applied it to the velocities. Finally, we measured the internal drift, which can be due to changes in pressure and temperature within the instrument enclosure, by measuring the velocity shift of the thorium–argon lines that are observed simultaneously with the stellar spectra, and we then removed this velocity from the radial velocity measured for each epoch.

For this work, we have also used data from three other instruments: HARPS (High Accuracy Radial velocity Planet Searcher; Mayor et al., 2003), a spectrograph with which it is possible to reach an accuracy on the order of 1 m s^{-1}; CORALIE (Queloz et al., 2000), for which it is possible to obtain an accuracy of ~ 6 m s^{-1}, or better, for most of the observations; and CHIRON (Tokovinin et al., 2013), with which it is possible to reach a precision in velocity of ~ 6 m s^{-1} (Jones et al., 2014).

In the following sections, the RAFT I results for the five stars are presented and discussed.

HD 11977

This is a giant star, with a mass of 2.31 $M_{\odot}$), and a metallicity of −0.16 dex, with respect to Solar. A planet was discovered by Setiawan et al. (2005), with a minimum mass of 6.5 Jupiter masses (M_{Jup}) and an orbital period of 711 days. We reanalysed 48 spectra for this star from FEROS, and also included 13 spectra from HARPS and eight spectra taken with CHIRON. We were able to detect a period of 625 days in the data. Starting from that period, we minimised the orbital parameters of the system and found a signal produced by a planet orbiting this star with a period of 621 days, a minimum mass of 6.5 M_{Jup} and eccentricity of 0.3. The data, along with the fit, are shown in Figure 1. The precision of this

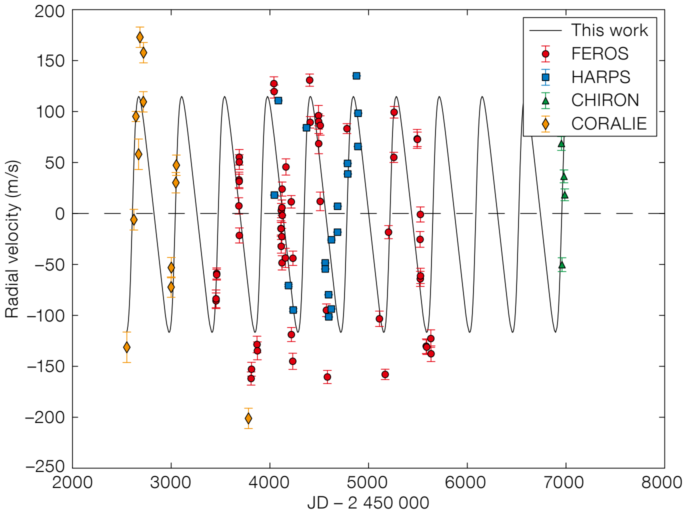

Figure 2. RV measurements for HD 47536.

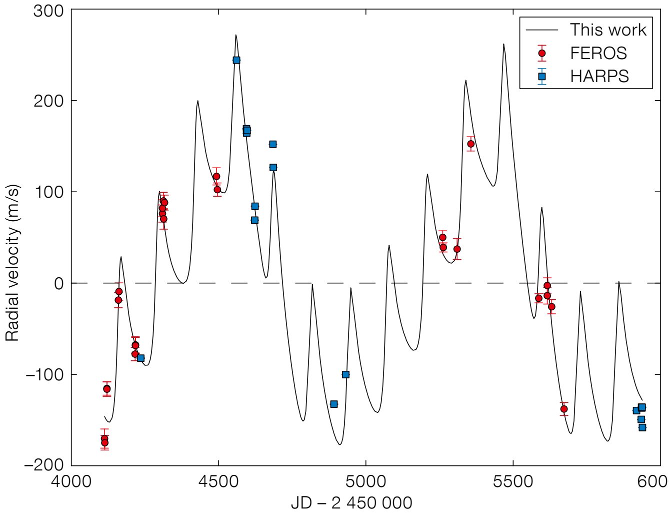

Figure 3. RV measurements for HD 110014.

solution is 11.2 m s^{-1}, significantly better than the one found previously, leading us to believe these parameters for the system are more accurate.

HD 47536

This giant star has a mass of 0.98 $M_{\odot}$ and a metallicity of −0.65 dex, making it the most metal-poor star in our sample. It was studied in two different publications. In the first (Setiawan et al., 2003), a planet with a period of 619 days was found, and later (Setiawan et al., 2008), after adding more radial velocities, a two-planet solution was reported: one signal with a period of 430 days, and the other with a period of 2500 days.

We reanalysed 56 spectra from FEROS, 18 from HARPS, 12 from CORALIE, and six from CHIRON. We found a period of 434 days in the data, and starting from that we found a solution for a planet with a period of 434 days, a minimum mass of 4 M_{Jup} and an eccentricity of 0.3. The precision of this solution is 51.7 m s^{-1} and is shown in Figure 2. We tried to find another planet in this system, but were not able to find any period that could provide a first solution. We did fit a planet with a period of 2500 days, obtaining a solution with two planets and a precision of 48.9 m s^{-1}. Although the two-planet solution has a better precision than the one-planet solution, it is not a great improvement. We found that the probability that the two-planet configuration is similar to the one-planet one is ~ 70 %. This shows that the two-planet solution is not a genuine configuration for the system given the current data, (the data is being overfitted), and therefore it only supports the existence of one planetary companion.

HD 110014

This giant star has a mass of 2.09 $M_{\odot}$ and a metallicity of 0.14 dex, making it the star with the highest metallicity in our sample. In de Medeiros et al. (2009) it was claimed that there is a planet orbiting the star with a mass of 9.5–11.1 M_{Jup} and a period of 835 days. We reanalysed 25 FEROS spectra for this target, and also included 17 data points from HARPS. Our periodogram search located a period of 833 days, and starting from this period we obtained a solution agreeing with a planet of minimum mass 13.7 M_{Jup} and period of 936 days. This solution has a scatter of 44.6 m s^{-1}.

The residuals from this fit hinted at the presence of a second signal with a period of 133 days. When we tried to add a new planet to the system with this starting period, we obtained a new configuration, consisting of two planets orbiting the star: one with a period of 882 days and a minimum mass of 10.7 M_{Jup}, and the second with a period of 130 days and a minimum mass of 3.1 M_{Jup}. This fit is plotted in Figure 3. The scatter around this solution is 19.4 m s^{-1}, significantly better than the one-planet solution. We also found that the probability that the two solutions are similar is essentially 0 %, meaning that this is the statistically preferred configuration.

HD 122430

This is a giant star with a mass of 1.68 $M_{\odot}$ and metallicity of −0.09 dex, making it another metal-poor star. Setiawan (2003) reported the discovery of a planet with a period of 344 days and minimum mass of 3.71–6.04 M_{Jup}. We reanalysed the FEROS data for this star, consisting of 42 radial velocities and also included six observations taken with HARPS. We were not able to find any significant period in the data, so we tried to fit a solution for a planet with a starting period equal to the one published before, and then minimised the orbital parameters. We finally obtained a solution for the orbit of a planet with a period of 455 days, minimum mass of 2.1 M_{Jup}, and eccentricity of 0.6. The root mean square (RMS) scatter on the solution was 29.3 m s^{-1} and the fit is shown in Figure 4. Even though the scatter is smaller than we obtained for other fits, we are still not certain about the existence of this companion because of the lack of a significant period in the data. We conclude that there is not enough data to confirm the presence of a companion around this star.

HD 70573

This is a very young star, with an estimated age of 78–125 Myrs, about 5 % of the Solar age, and a mass of 1.0 $M_{\odot}$. Its rotational period was found to be 3.296 days from photometry. A planet was announced in Setiawan et al. (2007), with a mass of 6.1 M_{Jup} and an orbital period of 852 days. We reanalysed 55 spectra taken with FEROS for this star and could find only one significant period in the data. That period was 3.296 days, remarkably similar to the star's rotational period. We fit a curve with this period and obtained a scatter of 36.4 m s^{-1}. The curve is shown in Figure 5. When we tried to fit the solution published before, we obtained a scatter of 78.78 m s^{-1}, much worse than our previous fit. We also found a period of 833 days, close to the orbital period of the planet candidate, produced by the window function of the data. This means that the planet found before could correspond to a signal produced by the sampling of the data, and therefore would not be a signal produced by the presence of a planet orbiting this star.

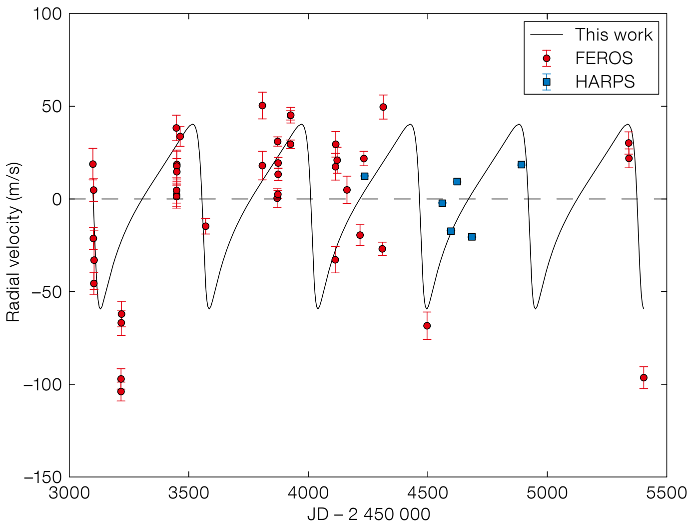

Figure 4. RV measurements for HD 122430.

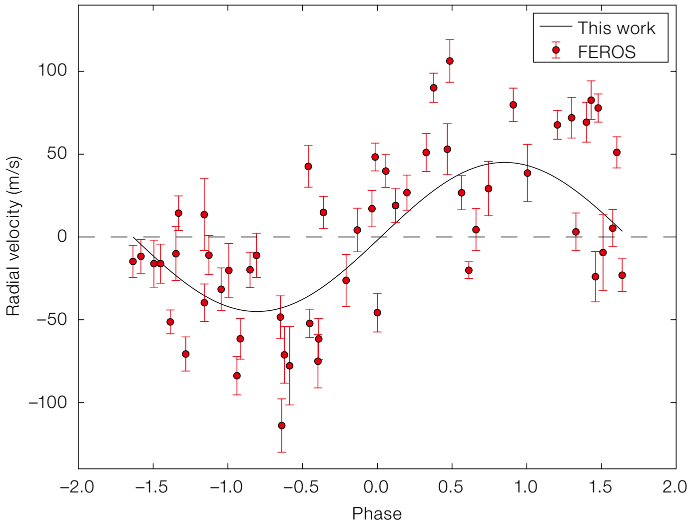

Figure 5. Phased RV measurements for HD 70573.

Activity indices and photometric analysis

The shift produced by the spectral lines in a star can be produced not only by the movement of said star, but also by phenomena in its photosphere, like dark spots on the stellar surface, or velocity fields produced by stellar convection zones. We computed three tests to verify if our velocities were a product of these phenomena. First, we calculated the S-index, which measures the change in the flux from the Calcium II HK lines. These are chromospheric lines that are affected by the magnetic activity within the star. Then we performed a bisector analysis, which detects asymmetries in the line profiles caused by intrinsic phenomena, by computing the bisector velocity span (BVS). This measures the velocity difference between the bottom and top parts of the cross-correlation function (CCF) used to measure the radial velocities. Finally, we analysed the CCF full width at half maximum. More details about the use of these indices can be found in numerous works, e.g., Dumusque et al. (2014), Jenkins et al. (2014), etc. For all the stars we found no significant correlation between the radial velocities and the activity indices for each epoch, which led us to conclude that activity within the stars is not the cause of the claimed Doppler signals.

We also studied the photometry of the stars for which we confirm a companion, *viz*. HD 11977, HD 47536, and HD 110014. We obtained the photometric data from the All Sky Automated Survey (Pojmanski, 1997). We found no periods in the data that could match the period of any detected companions. For example, if the signal from the proposed second companion orbiting HD 110014 was produced by a dark spot on the surface of the star, then it should cover 13.8 % of the surface. If that was the case, then a period of 130 days should be seen in the photometry of HD 110014, but we do not find any. That led us to discard the possibility that the 130-day signal is produced by a rotating spot group on the stellar surface.

The planets found in this work follow the trend that the higher the metallicity of a star, the higher the probability of detecting an orbiting planet. This trend can be seen in the case of HD 110014, which was the star with the highest metallicity in our sample and is the one with the highest number of planets. One special case however is HD 47536. According to Reffert et al. (2015), there is almost 0 % probability of finding a planet orbiting a giant star with metallicity of –0.65 dex. The existence of a planet around HD 47536 shows that it is possible to form planets with masses on the order of the mass of Jupiter around even very metal-poor stars.

We plan to continue with the RAFT project by reanalysing FEROS data for other giant stars. Most of these stars belong to programmes aimed at detecting giant planets in this poorly studied parameter space, leaving us with a sample of around 80 stars that we plan to study in the future.

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[1] ESO Archive: http://archive.eso.org


ESO/Y. Beletsky

Night view over the La Silla Observatory from the north featuring the Galactic Plane. In the foreground is the Swedish ESO Submillimetre Telescope (SEST), which was decommissioned in 2003. The experience gained on the SEST paved the way towards the Atacama Pathfinder Explorer (APEX) and the Atacama Large Millimeter/submillimeter Array (ALMA). In the background is the dome of the-3.6-metre telescope.

Using Solar Twins to Explore the Planet–Star Connection with Unparallelled Precision

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This year marks the 20th anniversary of the first definitive detection of an exoplanet orbiting a Sun-like star by Mayor and Queloz (1995). Almost 2000 exoplanets have been discovered since this breakthrough, but many fundamental questions remain open despite the enormous progress: How common are analogues of the Solar System? How do planets form and evolve? What is the relationship between stars and planets? We are observing stars that are near-perfect matches to the Sun to provide new insights into the above questions, thus exploring the planet–star connection with unprecedented precision.

The relationship between stars and planets

Stars and planets are formed from the same natal cloud and the two processes occur on similar timescales, and thus a natural connection between stars and planets is expected to arise at these early stages. The formation of rocky planets requires refractory elements, i.e., those that condense at high temperatures (about 1500 K), which are found in the inner protoplanetary disc. In contrast, giant planets are rich in volatile elements that can condense only at low temperatures (< 200 K) and are found in the outer region of the proto-Solar nebula. As the process of planet formation and the last stages of star formation are coeval, chemical signatures of planet formation can be imprinted on the outer zones of stars, because the late-accreted gas could be depleted in some chemical elements by the sequestration of the different chemical elements needed to form planets.

The most-studied signature of a relation between stars and planets is the higher frequency of close-in giant planets around metal-rich stars (Gonzalez, 1997). Stars with metallicities higher than the Sun are observed to have a higher chance of hosting a close-in giant planet, reflecting the trend that giant planet formation is enhanced in discs of higher metallicity. Planet engulfment events can also enhance the stellar metallicity, as predicted, for example, by Laughlin & Adams (1997) and probably observed in one star of the γ Velorum cluster by Spina et al. (2014). Iron is used as a proxy for stellar metallicity because it has many lines in the spectra of Solar-type stars, and it is thus easier to estimate its content. About a decade after the discovery of the correlation between giant-planet frequency and iron abundance, it was suggested from observational studies that there is no significant correlation between Neptune-mass planets and the iron abundance of the host star (e.g., Sousa et al., 2008; Ghezzi et al., 2010).

For more than a decade after the landmark discovery by Gonzalez (1997), no other firm relations are known for elements other than iron. This is because the most optimistic minimum uncertainties in chemical abundance analyses are 0.05 dex (Asplund, 2005), which are too high to convincingly detect the effect of rocky planets such as the Earth (predicted to be only a few times 0.01 dex). Our group was the first to achieve the requisite milestone 0.01 dex precision (Melendez et al., 2009), by performing a strictly differential analysis between Solar twins and the Sun, opening new windows on the study of the planet–star connection.

Solar twins and planet signatures

Solar twins are stars with physical characteristics (effective temperature, surface gravity and chemical composition) similar to the Sun. With stellar atmospheres so similar to the Sun, many systematic effects that plague chemical abundance analyses are removed when each spectral line is analysed differentially between the Solar twin and the Sun, allowing a precision of 0.01 dex to be achieved. Our precision has been tested by performing differential abundances in the Sun using two different asteroids (Bedell et al., 2014), achieving an element-to-element scatter of only 0.006 dex (Figure 1). We have also studied Solar abundances at different Solar latitudes, achieving an agreement of 0.005 dex for all elements, and 0.002 dex for the refractory elements (Kiselman et al., 2011).

Our improved 0.01 dex precision led to a breakthrough in 2009, when we showed that the chemical composition of the Sun is anomalous when compared to the average composition of Solar twins. The Sun appears to be deficient in elements that are abundant in the Earth and other rocky material in the Solar System (Meléndez et al., 2009; Ramírez et al., 2009). Importantly, there is a robust correlation between the abundance anomalies and the dust condensation temperature in the proto-Solar nebula (see Figure 2). This strongly suggests a relationship with the formation of terrestrial planets in the Solar System, as verified quantitatively by Chambers (2010), who showed that the deficiency of refractory elements in the Sun could be eradicated by adding back a few Earth masses of rocky material with the abundance pattern of the Earth and meteorites.

Other recent work by our group used the binary pair of Solar twins 16 Cyg to search for signatures left over from giant planet formation (Ramírez et al., 2011; Tucci Maia et al., 2014). The secondary

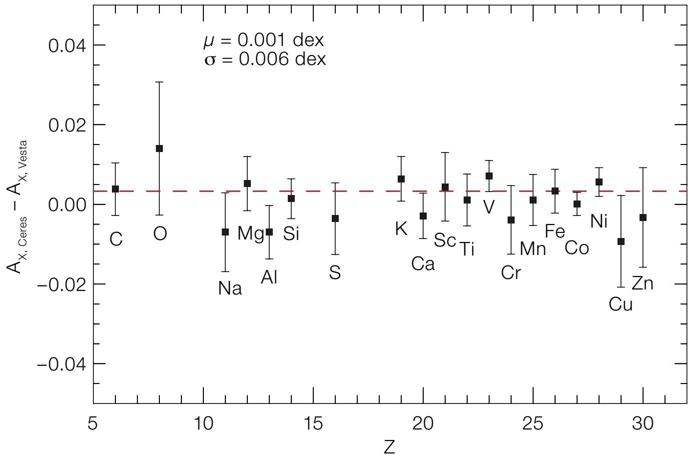

Figure 1. Chemical abundance differences between the Solar abundances obtained through reflected light off the asteroids Ceres and Vesta (Bedell et al., 2014), show an element-to-element scatter of only 0.006 dex.

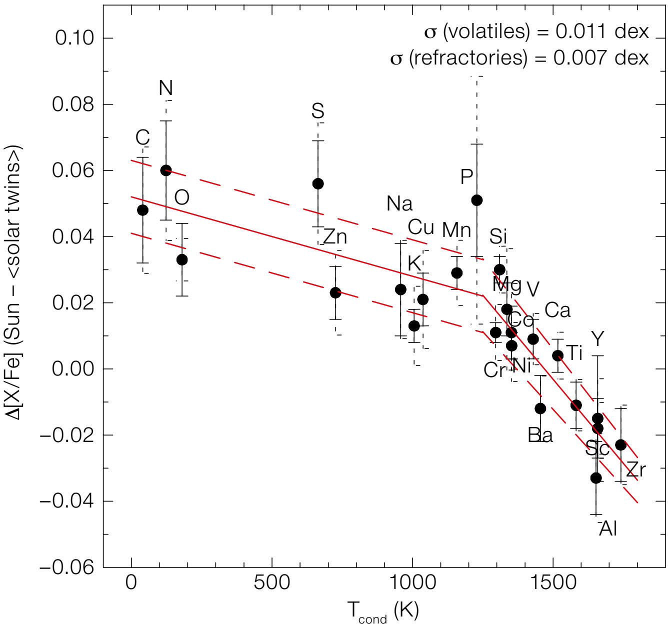

Figure 2. Chemical abundance differences between the Sun and the average of 11 Solar twins (Meléndez et al., 2009). The refractory elements in the Sun are deficient compared to the volatile elements, perhaps due to the formation of the rocky planets in the Solar System.

star (16 Cyg B) has a giant planet, while no planet has been found around the primary star (16 Cyg A). Naïvely both stars should have the same chemical composition, as they were born from the same natal cloud; however, the stars have a distinct chemical composition, with the star hosting the giant planet being more deficient in both volatile and refractory elements, perhaps because they were used to form the giant planet. A trend with condensation temperature has been suggested (Tucci Maia et al., 2014), and it could be the signature of a rocky core in the giant planet (see Figure 3). Abundance differences have been also found in the binary pair of stellar twins XO-2, where both stars in the pair host planets, providing important clues about planet formation (Ramírez et al., 2015; Teske et al., 2015; Biazzo et al., 2015).

Searching for planets around Solar twins

The synergy between accurate (0.01 dex) chemical composition determination that can be achieved in Solar twins and precise (1 m s^{-1}) radial velocities to characterise planets around these stars, allows us to study the planet–star connection at an unprecedented level of detail. Furthermore, the use of the Sun as a standard is a key part of our project, as the Sun is the only known star that hosts a planet where life thrives. In order to exploit these advantages, in 2011, we started a four-year Large Programme (188.C-0265) to use the High Accuracy Radial velocity Planetary Searcher (HARPS) to search for planets around Solar twins. We also acquired high-resolution, high signal-to-noise (S/N) spectra at the 6.5-metre Magellan Telescope to determine the stellar parameters and precise chemical composition of our sample Solar twins.

The HARPS observations are taken with a total integration time of about 15 minutes, so that oscillations from the stars are averaged to below 1 m s^{-1}. Detailed

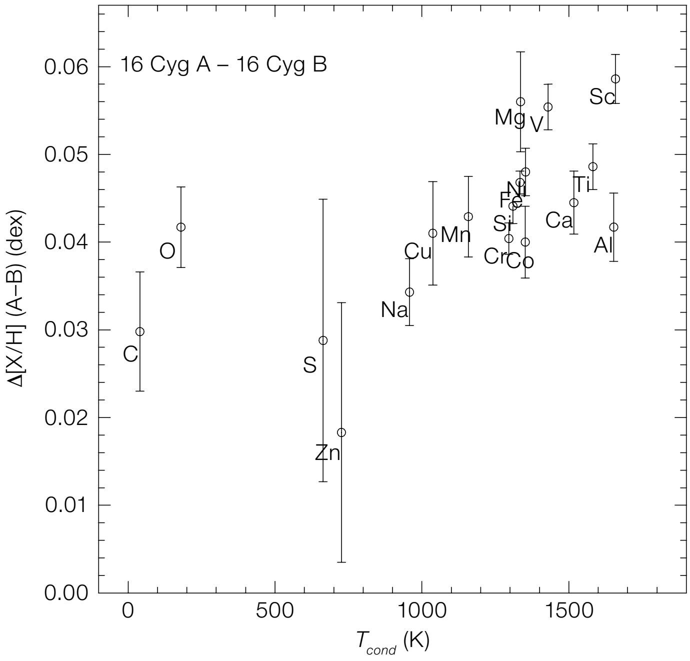

Figure 3. Abundance differences between the binary Solar twins 16 Cyg A and 16 Cyg B. The star without planets is enhanced in both volatiles and refractories, i.e., the star with a detected giant planet (16 Cyg B) is deficient in those elements, probably because they were used to form the giant planet 16 Cyg Bb. The trend with condensation temperature (T_{cond}) could be a signature of the rocky core of the giant planet.

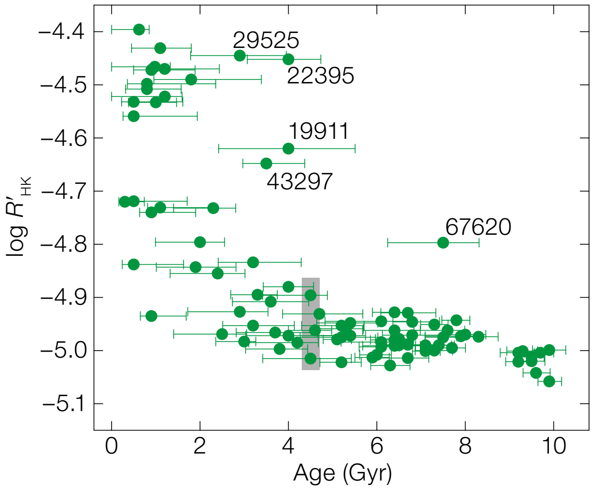

Figure 4. Evolution of stellar activity (as characterised by the R'_{HK} index, measured from the ionised calcium H and K lines) as a function of stellar age in our sample of Solar twins (Ramírez et al., 2014), showing a clear decline of stellar activity (R'_{HK}) with increasing ages. The grey bar represents the variation of the Sun's activity during its 11-year cycle; outlier stars are labelled by HIP (Hipparcos catalogue) number.

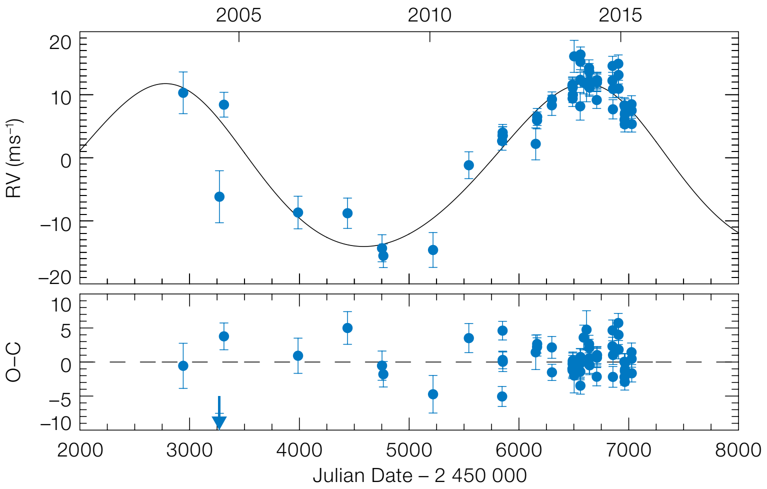

Figure 5. Radial velocity curve after subtracting the effects of stellar activity for the Solar twin HIP 11915 (Bedell et al., 2015). The data indicates a Jupiter twin, meaning a Jupiter-mass planet at about the same star–planet distance that Jupiter is from the Sun, i.e., about five times the Earth–Sun distance.

modelling of stellar activity is carried out on our HARPS dataset, because activity can induce radial velocity variations that could mimic the effect of planets. Different tests are performed to verify whether the signatures are due to planets or to other effects.

First scientific results

We have already characterised the stellar parameters and stellar activity of our sample of Solar twins (Ramírez et al., 2014), showing that they encompass ages covering the whole main sequence of a star like the Sun (a one-Solar-mass Solar-metallicity star). The sample of Solar twins can be used to study age effects on planets, stellar activity (see Figure 4), stellar rotation, stellar nucleosynthesis and the influence on galactic chemical evolution (e.g., Meléndez et al., 2014; Nissen, 2015).

Our HARPS observations have imposed stringent upper limits on the presence of planets in some Solar twins (Monroe et al., 2013; Meléndez et al., 2014), and revealed several planet candidates. Our first published planet (Bedell et al., 2015) is a Jupiter twin around the Solar twin HIP 11915 (see Figures 5 and 6). The planet has the same mass as Jupiter (within the errors) and it is located at 4.8 astronomical units (au) from its host star, quite similar to the Sun–Jupiter distance (5.2 au). According to current theories (e.g., Walsh et al., 2011; Batygin & Laughlin, 2015, Izidoro et al., 2015), Jupiter may have played a key role in the configuration of the Solar System, with stable small rocky planets in the inner region and stable giant planets in the outer region. The existence of a Jupiter twin around the Solar twin HIP 11915 opens up the possibility of a similarly stable planetary system occurring around HIP 11915. Furthermore, the abundance pattern of this Solar twin is similar to the Sun, as it is also deficient in refractory elements, and therefore enhances the chances of rocky planets being present in that system (Melendez et al., in prep.).

We are currently working on the characterisation of new planets from our sample of Solar twins. Some of the radial velocity curves for the planet candidates from our programme are shown in Figure 7. We are also working on the chemical composition of the sample of stars, to study the refractory and volatile elements (Bedell et al., in prep), and other elements, like lithium (e.g., Monroe et al., 2013; Carlos et al., in prep) and beryllium (e.g., Tucci Maia et al., 2015), that are important probes of stellar evolution.

Outreach impact

Communicating astronomy to the public is an important aspect of our programme. The far-reaching results of our project have appeared in many different countries, including different media targeting the general public (newspapers, radio, TV, internet), and also magazines specialising in science such as *Sky & Telescope, Astronomy*, and others. Our most recent discovery of a Jupiter twin around a Solar twin even had a live appearance on the most-watched TV station in Brazil (Globo), and many interviews in the national and international media were given relating to this discovery.

We have also had two ESO press releases related to our programme[1,2], and both have received wide national and international coverage, being among the most successful releases issued by ESO. One of the releases included a press conference at the Universidade de São Paulo, with live transmission.

Future prospects

Although our programme has been affected by bad weather (about one third of the time was lost), clear signatures of planets have been revealed in several of our Solar twin stars. As we approach the end of our programme, we are finalising our list of planet discoveries. The planets we find with HARPS, together with the precise abundances for our sample stars, will shed new light on the connection between stars and planets, and on how unique the Solar System is.

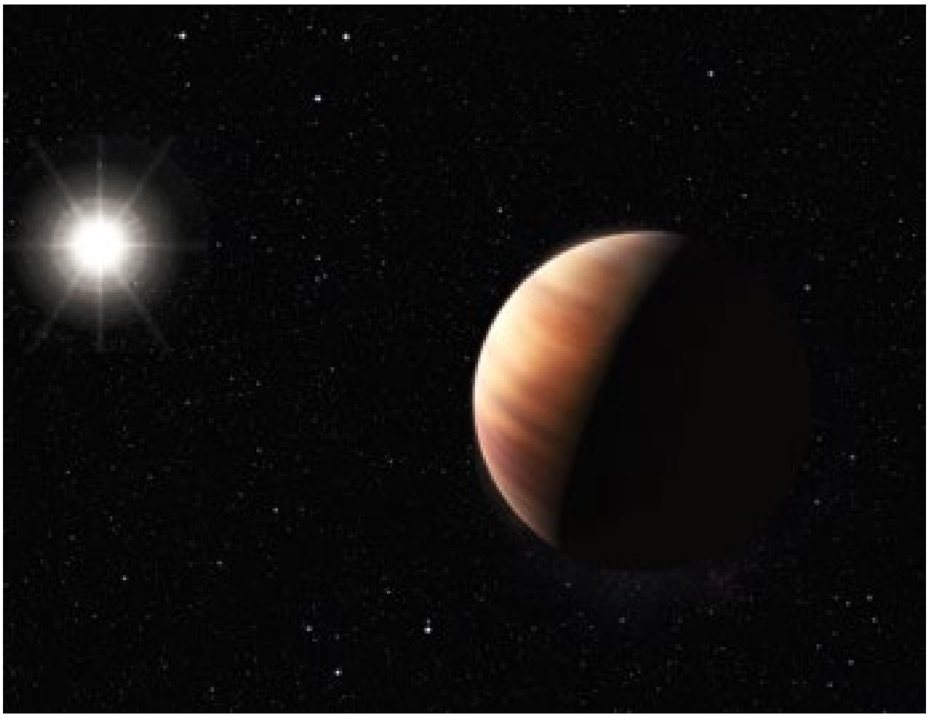

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Figure 6. Artist's impression of the Jupiter twin around the Solar twin HIP 11915 from the press release.

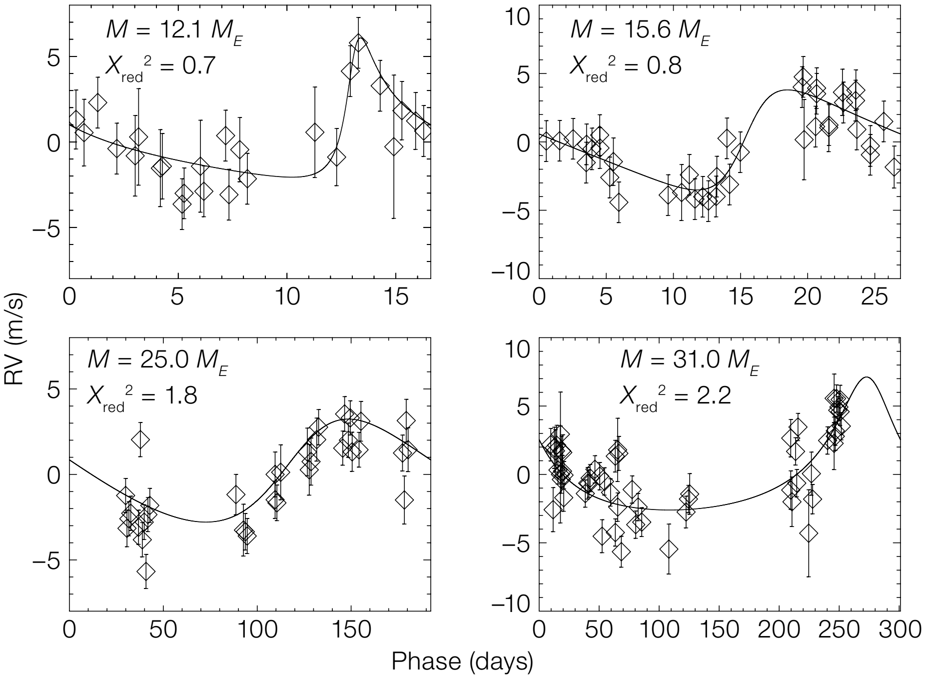

Figure 7. Radial velocity curves of planet candidates to be published from our HARPS programme. The derived mass (in Earth masses, M_E) and the reduced X^2 is shown on each plot.

Acknowledgements

Our Brazilian-led planet search programme is made possible thanks to the agreement signed between ESO and Brazil in December 2010, aiming to make Brazil a Member State of ESO (as recently ratified by the Brazilian Congress). After the agreement was signed in late 2010, Brazilian astronomers were allowed to apply for observing time at all ESO facilities, and in 2011, our project was approved as the first Brazilian-led ESO Large Programme. We are grateful to all the people involved in making Brazil an ESO Member State. We are also grateful to all scientists and engineers who made HARPS possible. We acknowledge funding by FAPESP and the National Science Foundation.

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Links

[1] Jupiter twin discovered around Solar twin: http://www.eso.org/public/news/eso1529/

[2] Oldest Solar twin identified: http://www.eso.org/public/news/eso1337/

Red Supergiants as Cosmic Abundance Probes

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By studying a galaxy's present-day chemical abundances, we are effectively looking at its star-forming history. Cosmological simulations of galaxy evolution make predictions about the relative metal contents of galaxies as a function of their stellar mass, a trend known as the mass–metallicity relation. These predictions can be tested with observations of nearby galaxies. However, providing reliable, accurate abundance measurements at extragalactic distances is extremely challenging. In this project, we have developed a technique to extract abundance information from individual red supergiant stars at megaparsec distances. We are currently exploiting this technique using the unique capabilities of KMOS on the VLT.

A well-known correlation exists between the mass of a galaxy and its metal content, whereby more massive galaxies tend to be more metal-rich (Lequeux et al., 1979). This is understood qualitatively as being due to progressive enrichment by stellar and supernova nucleosynthesis, moderated by the infall of pristine gas and outflow of enriched material via winds. This enriched gas escapes more easily from lower-mass galaxies due to the shallower potential well, preventing them from reaching high metallicities, and gives rise to the functional form of the mass–metallicity [*Z*] relation we see today. State-of-the-art cosmological simulations (e.g., Shaye et al., 2015) make specific predictions about the quantitative nature of the mass–metallicity relation, which makes it possible to test the current theories of galaxy evolution under the dark energy, cold dark matter framework.

Such tests, however, require reliable and robust measurements of a galaxy's chemical abundances. Historically this has been done using emission lines from extragalactic H II regions. The "direct" method requires measurements of auroral lines, such as [O III] 436.3 nm, which allows the observer to uniquely determine the gas temperature and, crucially, the abundance of the element. Unfortunately, these auroral lines are often very weak, especially at high metallicity. This means that one must attempt to derive abundances based on only the strong emission lines (e.g., [O III] 500.7 nm), which contain no temperature information on their own, by calibrating against either results from the direct method or from photoionisation models. The limitation of these strong-line methods is that they have well-known systematic offsets from one another, particularly at high metallicity, where two different calibrations may give results ~ 0.8 dex apart (Kewley & Ellison, 2008).

In order to solve this problem, our team has been pioneering new ways to obtain the metallicities of external galaxies by studying their constituent stars individually. The stars chosen as targets must be: (a) young, so that their abundances reflect those of H II regions; and (b) luminous, so that they can be observed at megaparsec distances. This means that the obvious targets of choice are supergiants — massive, post main-sequence stars, which can outshine entire globular clusters and dwarf galaxies. Substantial recent progress has been made using optical spectroscopy of blue supergiants (BSGs; see Kudritzki et al. [2014] and references therein). However, to really take advantage of the next generation of telescopes such as the European Extremely Large Telescope (E-ELT), it is crucial to reduce our dependence on optical techniques and move to the near-infrared (NIR). At these wavelengths, the gain from adaptive optics will be the most profound, as the increase in sensitivity scales with the fourth power of the mirror diameter.

Red supergiants: A novel, NIR-based technique for extragalactic metallicity studies

To this end, in recent years we have been developing a technique to obtain extragalactic abundances using NIR spectroscopy of red supergiants (RSGs). These stars are extremely bright ($> 10^5 L_\odot$), young (< 30 Myr), and have the advantage that their fluxes peak at NIR wavelengths. A challenge for abundance work using these stars is that they are cool, with effective temperatures around 4000 K, and so their spectra are dominated by absorption from thousands of molecular lines. Historically this has meant that high spectral resolving powers were needed to study individual lines, making these stars unsuitable for extragalactic work due to the large integration times required.

In order to adapt these techniques to be useful at extragalactic distances, in Davies, Kudritzki & Figer (2010) we identified a spectral region around 1.2 μm that is relatively free of molecular lines, the dominant features being those of neutral metallic atoms. We then demonstrated that metallicities relative to Solar (defined as [*Z*]) may be determined from moderate spectral resolutions of only R ~ 3000, making this technique viable at large distances, and well-suited to the latest multi-object spectrographs (MOSs), such as the *K*-band Multi-Object Spectrograph (KMOS) on the Very Large Telescope (VLT). Using instrument simulators, we then demonstrated the potential with the E-ELT, showing that we could measure [*Z*] at distances of 75 Mpc (Evans et al., 2011).

Building the tools for the job

Spurred on by the potential of this technique, we set about developing the necessary analysis tools. The initial task in this project was to build a suite of model spectra from which we can derive high-precision abundances. We generated a grid of MARCS (Model Atmospheres in Radiative and Convective Scheme) model atmospheres (Gustafsson et al., 2008), computed under the assumptions of spherical symmetry and local thermodynamic equilibrium (LTE), which span the parameter ranges in effective temperature, surface gravity, microturbulence and metal abundances appropriate for RSGs. We use these models to compute synthetic spectra with full non-LTE radiation transport for the diagnostic chemical elements Fe, Si, Mg and Ti (Bergemann et al., 2012; 2013; 2015). Fitting the models to the data is done by a χ^2-minimisation process of matching the observed strengths of the diagnostic metal lines, described in detail in Davies et al. (2015).

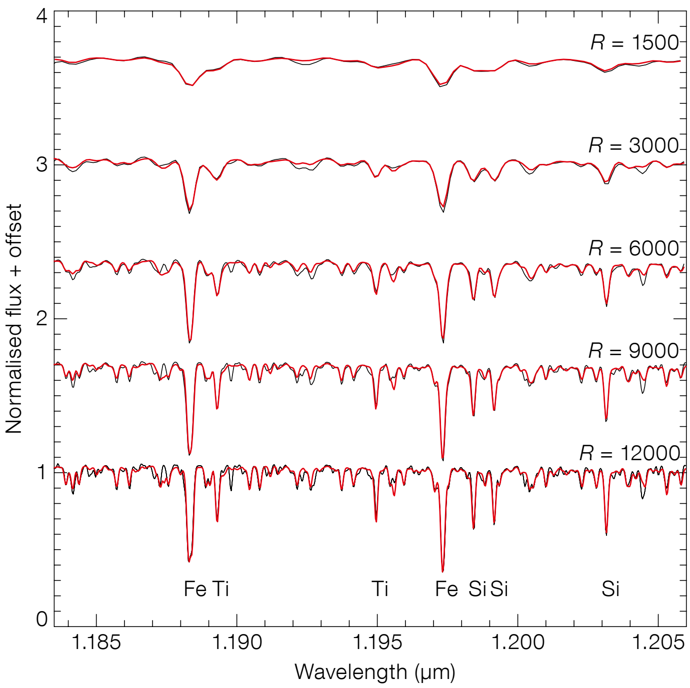


Figure 1. A spectrum of an RSG in Per OB1 observed with Subaru and IRCS in black, and the best-fitting model (red), at bottom. The other spectra are the same data but degraded to lower resolution and re-fit, showing that the diagnostic lines are still identifiable down to resolutions of $R = 3000$. Taken from Gazak et al. (2014a).

Road-testing in the Milky Way

The next phase of our project was to demonstrate that our technique works at high precision in the Solar Neighbourhood. For our target we chose the nearby Perseus OB1 association, which contains several RSGs, and which we can safely assume all have the same metallicity. Using high-resolution spectroscopy from the Infrared Camera and Spectrograph (IRCS) on the Subaru Telescope, we obtained a metallicity averaged over all RSGs in the region consistent with Solar, $[Z] = -0.02 \pm 0.08$, as would be expected (Gazak et al., 2014a). Further, by degrading the spectral resolution of the data and repeating the analysis, we showed conclusively that this technique is stable down to resolutions of $R < 3000$, typical of MOS instruments (see Figure 1).

Extragalactic baby steps: The Magellanic Clouds

With the technique now proven at Solar metallicities, the first sub-Solar metallicity systems to be studied were the Large and Small Magellanic Clouds (LMC and SMC). The data here were provided by X-shooter on the VLT (Davies et al., 2015). From analysis of ten and nine stars in the LMC and SMC respectively, we measured average metallicities of $[Z]_{\mathrm{LMC}} = -0.37 \pm 0.14$ and $[Z]_{\mathrm{SMC}} = -0.53 \pm 0.16$, consistent with contemporary results from observations of hot supergiants (see Davies et al. [2015] and references therein).

The added value of the X-shooter data was that, in addition to the coverage of our spectral window at 1.2 μm, we obtained spectra covering the whole of the optical and near-infrared, from 0.3–2.5 μm. This allowed us to verify that the temperatures we obtain from our narrow window in the *J*-band were consistent with those from fits to the spectral energy distributions. The agreement for the SMC stars was excellent, while the LMC stars were also similar to within the errors, aside from the two stars in our sample with the highest temperatures.

Beyond the Local Group with KMOS: A study of NGC 300

Our first target beyond the Local Group was chosen to be the Sculptor Group member NGC 300. This galaxy is a relatively nearby (2 Mpc) face-on spiral with a strong abundance gradient, as measured from H II regions with the direct method, and with BSGs (Bresolin et al., 2009; Kudritzki et al., 2008). It is therefore an excellent testbed to provide one more validation of our technique.

For these observations, we employed the new VLT NIR multi-object spectrograph KMOS. Since our project requires high-precision absorption-line spectroscopy of the highest possible quality, it is therefore essential that we take the greatest care in removing sky emission and telluric features from our data. After extracting the calibrated datacubes using the KMOS data reduction pipeline, we found that variations in spectral resolution and wavelength calibration were introducing noise into the final spectra. In Figure 2, we demonstrate these variations across the field of view of one integral field unit (IFU), as measured from the sky emission lines. We corrected for this effect in a process we call KMOGENIZATION, whereby we smooth the spectra at each spaxel down to a level which is common to all spaxels to be extracted. This is usually defined to be $R = 3000$–3200. The spatially varying wavelength calibration effects are minimised by only extracting spectra within a 1 spaxel radius of the flux peak. Although this discards a small amount of flux, this is more than compensated for by the reduction in artefacts that can be introduced when removing sky and telluric features. Repeated observations of the same target, for which the wavelength calibration may vary throughout the night, were co-added onto a master wavelength scale without resampling, so as to minimise systematic noise.

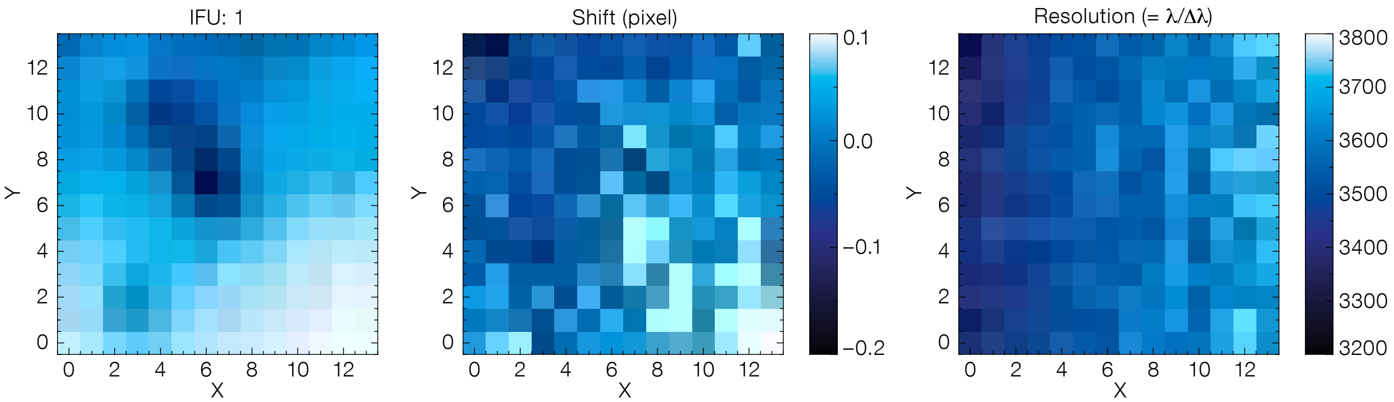


Figure 2. Output from our KMOGENIZATION software. The left panel shows the wavelength-collapsed image of one KMOS IFU, in this case IFU#1, which has been positioned on a star cluster in NGC 4038. The centre and right panels show the spatial variations in wavelength calibration and spectral resolution respectively. We correct for these variations to minimise systematic noise in our extracted spectra.

After the spectra were extracted and analysed, the RSG-based metallicity gradient was constructed (Gazak et al., 2015), and is shown in Figure 3. The agreement between the RSG gradient and that from observations of BSGs is remarkable — the gradients are identical to within the errors, and with a systematic offset of only 0.05 dex. The agreement between the RSG/BSG gradients and that of the direct H II region measurements is equally striking, see Bresolin et al. (2009).

A survey of the mass–metallicity relation in the local Universe with KMOS

With all the validation and road-testing phases complete, we are now beginning to construct a mass–metallicity relation for galaxies in the nearby Universe based only on observations of RSGs. The weapon of choice for this project is KMOS, with its multiplexing, spectral range and resolving power being ideally suited to our technique.

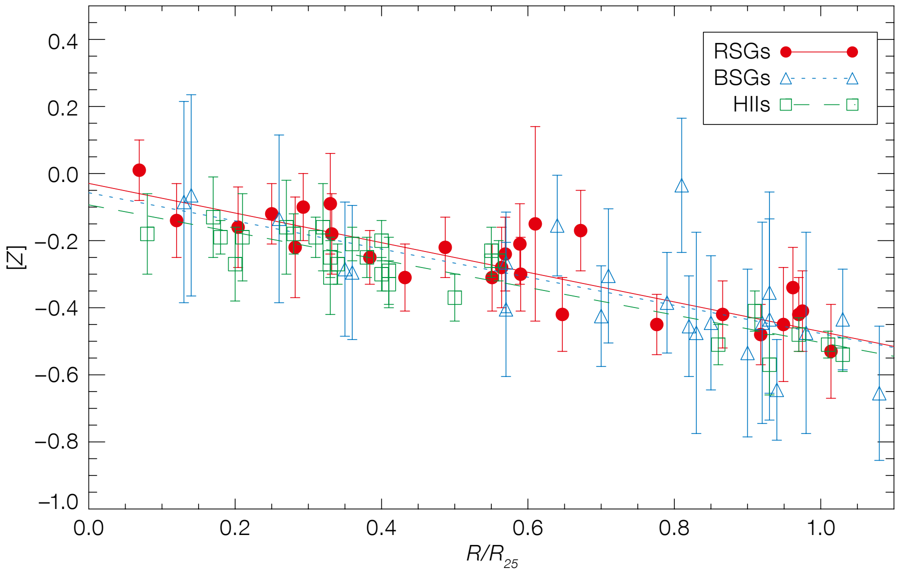
We began with a recently published study of NGC 6822, which found a mean abundance of [*Z*] = −0.52 ± 0.21 (Patrick et al., 2015). This will continue with a study of Sextans A (data taken April 2015), and a recently approved KMOS programme to observe NGC 55, WLM and IC1613 in Period 96.

One step beyond: RSG-dominated star clusters

When observing stars at very large distances, the issues of crowding and source blending must always be considered. For this project, RSGs are so much brighter than any other class of star in the near-infrared that the only blending sources to worry about are other RSGs. It is well known that massive star clusters with ages between 7–50 Myr may contain dozens of RSGs. If such a cluster was at a distance so great that it was totally unresolved and appeared as a point source, and we mistook it for a single abnormally bright RSG, what would we see?

Our hunch was that an unresolved star cluster dominated by RSGs would have the spectral appearance in the *J*-band of a single RSG. Firstly, since the RSGs in the cluster are effectively coeval, and the RSG lifetime (< 1 Myr) is short compared to the age of the cluster, all the RSGs should have roughly the same mass and hence gravity. Secondly, since the stars formed from the same molecular cloud, they should have the same metallicity. Finally, we know from our previous studies that RSGs span only a narrow range in temperature and microturbulence. Our prediction was therefore that the spectrum of an unresolved cluster of 100 RSGs would be indistinguishable from that of one of its constituent stars, but be 100 times brighter. This then means we could use our technique on massive star clusters at distances ten times further than for individual stars.

Figure 3. Radial metallicity gradient in NGC 300, as measured from RSGs (red points), BSGs (blue points), and direct method (auroral line) H II region observations, illustrating the stunning agreement between the different methods.



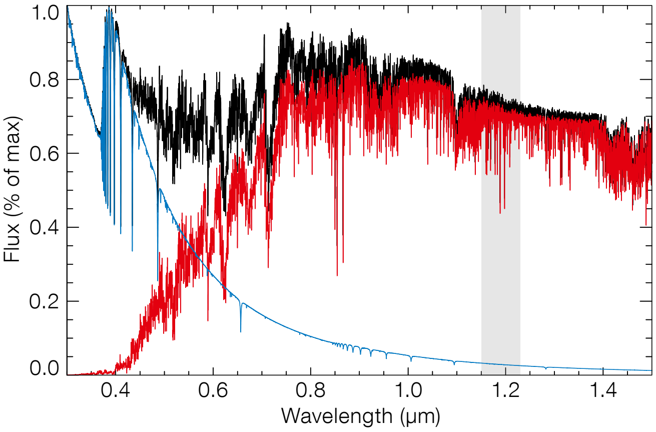


Figure 4. The relative contributions to the overall flux of a 15 Myr old star cluster by the RSGs (red) and the rest of the stars (blue). Our *J*-band spectral window for deriving metallicities is shown in grey. The figure shows that 95 % of the flux at *J* comes from the RSGs, which are only 0.1 % of the stars. From Gazak et al. (2014b).

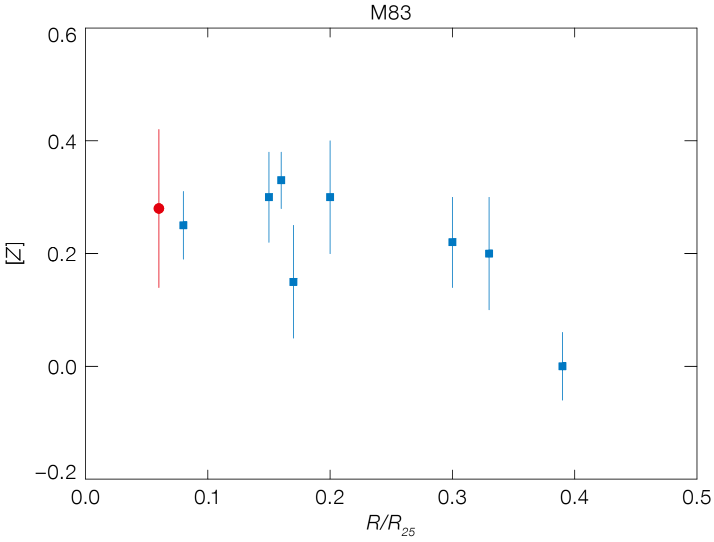
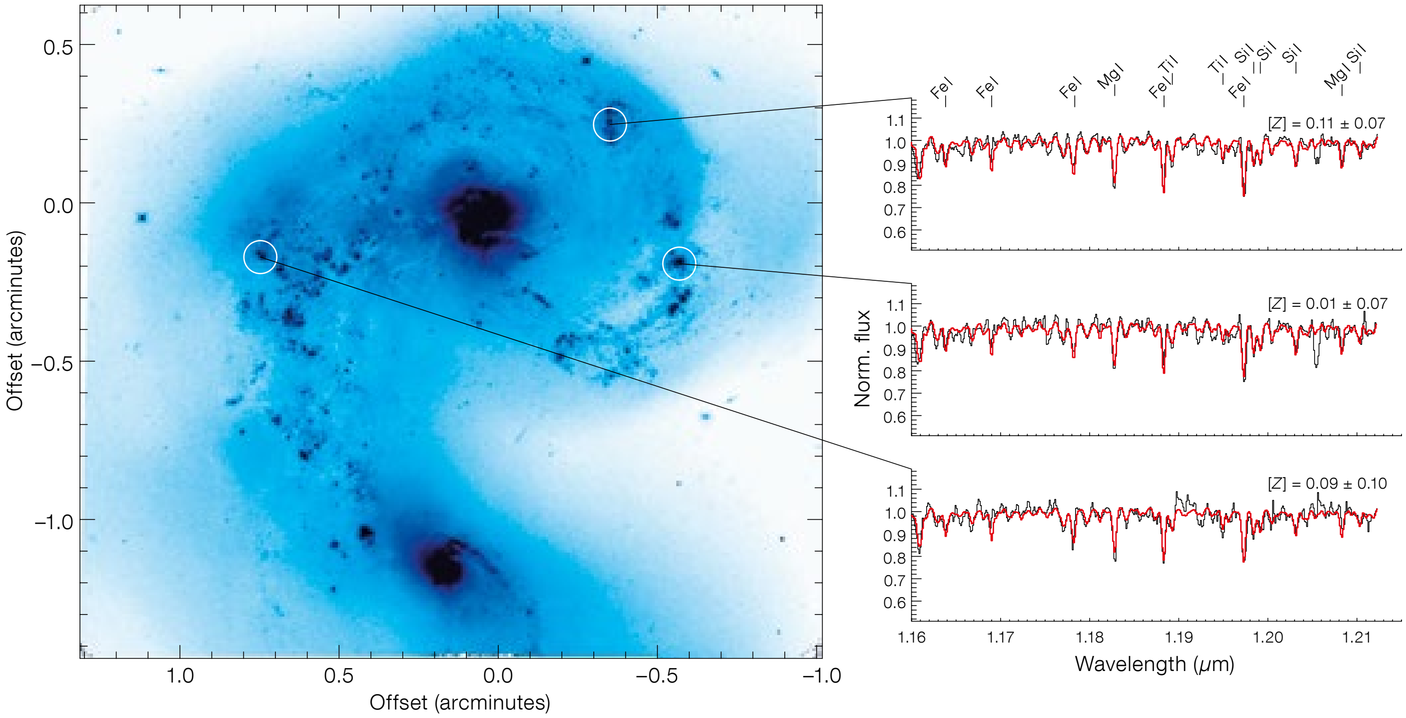


Figure 5. The metallicity of an RSG-dominated star cluster close to the centre of M83 (red), as measured in Gazak et al. (2014b), plotted against galactic radius. The blue points show a recent study of the same galaxy using BSGs (Bresolin, Kudritzki & Gieren, in prep). The agreement between the two methods is excellent, providing further evidence that the RSG-cluster method can determine accurate metallicities.

This is a prediction that was confirmed in Gazak et al. (2014a; 2014b), where the spectra of the individual RSGs in Per OB1 were combined to make a mock star cluster spectrum. This spectrum was then analysed in the same way as that of a single star, with an almost identical metallicity retrieved. We also performed population synthesis experiments to show that the RSGs account for > 95 % of the flux in the *J*-band (Figure 4), and that neither the age of the cluster nor the contribution to the *J*-band flux by the other stars has a significant effect on the inferred metallicity.

This RSG cluster based technique was first utilised on bright objects in M83 and

Figure 6. Hubble Space Telescope Wide Field Camera 3 *J*-band image of the Antennae Galaxies, illustrating the locations of the observed star clusters that contain dozens of RSGs. Their KMOS spectra are shown on the right (black), along with their best-fitting models (red) and abundances.



NGC 6946 in Gazak et al. (2014b), using the Infrared Spectrometer And Array Camera (ISAAC) on the VLT and the SpeX medium resolution spectrograph on the NASA Infra-Red Telescope Facility (IRTF) respectively. Our result of a super-Solar metallicity in the centre of M83 is in excellent agreement with recent observations of BSGs in the same galaxy (Bresolin, Kudritzki & Gieren, in prep.; see Figure 5).

Our first study of a sample of massive young clusters across a galaxy is to be submitted shortly. We obtained KMOS observations of three clusters in the interacting galaxy NGC 4038 (one half of the Antennae system), showing that the galaxy has a flat abundance gradient — consistent with theoretical predictions for merging galaxies (Lardo et al., in prep; see Figure 6).

Prospects

We have shown in this article that RSGs are extremely powerful cosmic abundance probes, and in combination with instruments like KMOS can provide high-precision metallicities at distances of several megaparsecs. The next stage of our project is to provide an RSG-based mass–metallicity relation that will have the power to directly test cosmological simulations of galaxy formation. The first set of KMOS observations required to complete this are scheduled for the coming semester.

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The nearby dwarf irregular galaxy NGC 6822 (Barnard's Galaxy) is shown in an MPG/ESO 2.2-metre telescope image taken with the Wide Field Imager (WFI) with *B*, *V* and *R* broad band filters and a narrow Hα filter. Young shell H II regions with prominent Hα emission are visible in the outer regions of the galaxy. See Release eso0938 for more details.

Directors General, of ESA, Johann-Dietrich Wörner (left), and ESO, Tim de Zeeuw, after the signing of a cooperation agreement at the ESO offices in Santiago, Chile. See Announcement 15064 for details.

J. Velasquez/ESO

A view towards the ALMA Operations Support Facility (OSF) from Cerro de Macón. See Picture of the Week for 13 April 2015.

Report on the ESO Workshop

Satellites and Streams in Santiago

held at ESO Vitacura, Santiago, Chile, 13–17 April 2015

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Galactic satellites and tidal streams are arguably the two most direct imprints of hierarchical structure formation in the haloes of galaxies. At this ESO workshop we sought to create the big picture of the galactic accretion process, and shed light on the interplay between satellites and streams in the Milky Way, Andromeda and beyond. The Scientific Organising Committee prepared a well-balanced programme with 60 talks and 30 poster contributions, resulting in a meeting which was greatly enjoyed by the more than 110 participants at the venue, and worldwide via Twitter (#SSS15).

Introduction

Near-field cosmology has become increasingly important over the past few decades. While the current concordance cosmological model (Lambda Cold Dark Matter [ΛCDM]) has been very successful in reproducing and predicting the properties of the Universe on large scales, several possible tensions have been identified on small scales ($\lesssim$ 1 Mpc). Issues like the "missing satellite problem", the "core/cusp problem", "too big to fail", and detections of satellite discs around the Milky Way (MW) and M31 pose challenges to our understanding of structure and star formation in the early Universe, and the feedback between baryons and dark matter.

But how well do we understand what it means to be a satellite of the MW or M31? Even in the era of high-precision cosmology, we are still uncertain about the total masses of the two dominant galaxies in the Local Group, their assembly histories and the shape and extent of their dark matter haloes — key aspects for gaining a consistent picture of these galaxies and their satellite systems in a ΛCDM context. On the contrary, the discovery of transition objects at the star cluster–dwarf galaxy interface has made things more complicated. It has blurred the historical distinction between satellite classes, putting in question our understanding of tidal transformation and the census of small stellar systems.

Although these aspects of near-field cosmology have become more and more prominent in the age of surveys, there has not been a conference on both satellites and streams in over a decade. This five-day ESO workshop (see the workshop poster, Figure 1) therefore met with a great demand for presentation slots, and the registration had to close early due to the overwhelming interest.

Figure 1. Conference poster showing the Milky Way with its most prominent satellite, the Large Magellanic Cloud, over Santiago. The upper part of the poster shows a collection of tidal streams from the *Via Lactea Cauda* simulation.

Based on the scope of the meeting, the week was divided into three parts. First, satellites and the satellite systems of the Milky Way, M31 and other nearby galaxies were discussed. This was followed by presentations on observations and modelling of tidal streams, and the final part of the workshop was dedicated to the star cluster–dwarf galaxy divide. The grouping into these sessions was of course not strict, and, as intended, many presenters pointed out important connections between satellites and streams. The workshop programme, with links to many of the presentations, can

Figure 2. Conference photo taken in the garden of the ESO Vitacura premises.

Stephane Courteau

be accessed online[1]. The participants are shown in the gardens of ESO Vitacura in Figure 2.

The meeting was opened by the ESO Director General Tim de Zeeuw, giving an overview of the ESO facilities and an exciting outlook for the field into the European Extremely Large Telescope era, when it will be possible to resolve stellar populations out to the Virgo Cluster.

Satellite systems

Galactic satellites give us an account of low-mass substructures at the present day. However, in order to put these satellites into the context of structure formation within the ΛCDM framework, their masses, and especially their dark matter content, have to be understood. In the first talk of the satellite session, Jorge Peñarrubia discussed the advances, problems and challenges of mass modelling of dwarf galaxies. Although modelling might help to put constraints on the nature of dark matter (density cores/cusps), he clearly called for more (kinematic) data to inform the models. In the spirit of the meeting's title, and like many other speakers, he also presented an interesting new idea, using the streams of satellites to break the core/cusp degeneracy. Calling it a "diversity problem" rather than a cusp/core problem, Chervin Laporte demonstrated the large phenomenology of dark matter in galactic satellites due to a possible re-growth of cusps in cored galaxies via accretion of dark matter subhaloes or other dwarf galaxies — further complicated by baryonic effects on the central density profiles of satellites.

Michelle Collins then gave a recount of the dozens of newly discovered satellites in the Milky Way and M31 haloes from surveys like the Pan-Andromeda Archaeological Survey (PAndAS; see Figure 3). In her presentation, a mass–size diagram (Figure 4) made its first appearance and ended up being the plot shown most often during the meeting. In particular the divide between dwarf galaxies and globular clusters in this diagram is currently being populated with newly discovered objects, most of which cannot be classified by their photometry alone — which is why we had an entire session on this topic at the end of the meeting. Collins furthermore pointed out that kinematic data may often be ambiguous as some of the satellites seem to have had recent gravitational interactions and encounters, while others like Hercules and Willman 1 appear to be entirely out of equilibrium, making mass determinations hard, if not impossible.

Finding new satellites and following up the discoveries with deeper photometry and/or spectroscopy has become a sport. Yet only through this important exercise will we eventually get a complete census of substructure in the local Universe. After seeing the great successes of PAndAS, we heard further results and outlooks from ongoing and upcoming surveys with the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST) by Jeff Carlin, on the Large Binocular Telescope (by Giacomo Beccari) and the Magellan Telescope (Denija Crnojevic), all looking for more substructure in the local Universe.

Eduardo Balbinot then presented the rich harvest from the Dark Energy Survey (DES) data release 1, giving us a detailed look at the structure and formation history of the Large Magellanic Cloud (LMC), as well as of the nine newly discovered satellites around the Magellanic Clouds. Later in the meeting, Vasily Belokurov talked more about the independent discovery of these satellites in the DES data. Both groups have follow-ups on one satellite, Reticulum II, confirming that it is in fact a dwarf galaxy. Similarly, Erik Tollerud presented his newest findings in the Galactic Arecibo *L*-band Feed Array (GALFA) survey. The two newly discovered, gas-rich, low-mass galaxies represent the progenitors of the dwarf galaxies that we find around larger host galaxies. Understanding this transformation from gas-rich to quenched galaxy is not straightforward, as Thorsten Lisker explained and Rachael Beaton later on confirmed.

Numerical simulations are getting up to speed with the flood of observational data. Coral Wheeler presented high-resolution hydrodynamical simulations of isolated dwarf galaxies to understand their satellites, finding a few ultra-faint satellites around each of these low-mass hosts and making them interesting testbeds for ΛCDM. Else Starkenburg showed results from her semi-analytical models of dwarf galaxies, which are particularly useful to test the physics inside the satellites and gain intuition about their evolution.

Accretion of satellites

Accretion and disruption of satellites can give us important insights into the build-up of bulges and haloes of galaxies. Benjamin Hendricks demonstrated this approach for globular clusters (GCs) in Fornax, and Ryan Leaman shed light on the accretion history of the Milky Way using its GCs as tracers of dwarf galaxy infalls. Similarly, tidal streams provide insights on the star formation histories of individual dwarf galaxies, as Thomas de Boer demonstrated in the example of Sagittarius.

But larger infalling galaxies, or major mergers, could also trigger the formation of new satellites — known as tidal dwarf galaxies. Pavel Kroupa argued that these satellites could be long-lived, and pollute (or entirely make up) the satellite populations of host galaxies. Kinematically correlated satellite populations in the Milky Way and M31 halo could point towards such a formation scenario. However, Pierre-Alain Duc argued that the formation of tidal dwarf galaxies through mergers is less likely than expected, and that the objects thus formed do not resemble the satellites found in the local Universe. From the numerical side, Sylvia Ploeckinger is developing the tools to perform full hydrodynamical simulations of tidal dwarf galaxies to study their long-term survivability.

Marcel Pawlowski, Rodrigo Ibata and Noam Libeskind then gave detailed descriptions of the co-rotating structures around the Milky Way, Andromeda and Centaurus A. The speakers pointed out that the chances of finding such planes in ΛCDM appears to be rather low, but may have to do with either larger mergers bringing in lots of satellites or infall of satellites along the cosmic web. Gurtina Besla added the Large and Small Magellanic Clouds to this picture, discussing different infall scenarios for the two satellite galaxies. She argued that if the LMC originally had a mass of > 10^{11} $M_{\odot}$, it should have brought in at least seven massive satellites. Moreover, she pointed out that a massive LMC may have shifted the barycentre of the Milky Way, which could potentially affect all stream modelling. The satellite session thus concluded with lots of intriguing problems and open questions. In many cases, satellite orbits appear to be the missing ingredients to answer these questions, which is where tidal streams may come in handy.

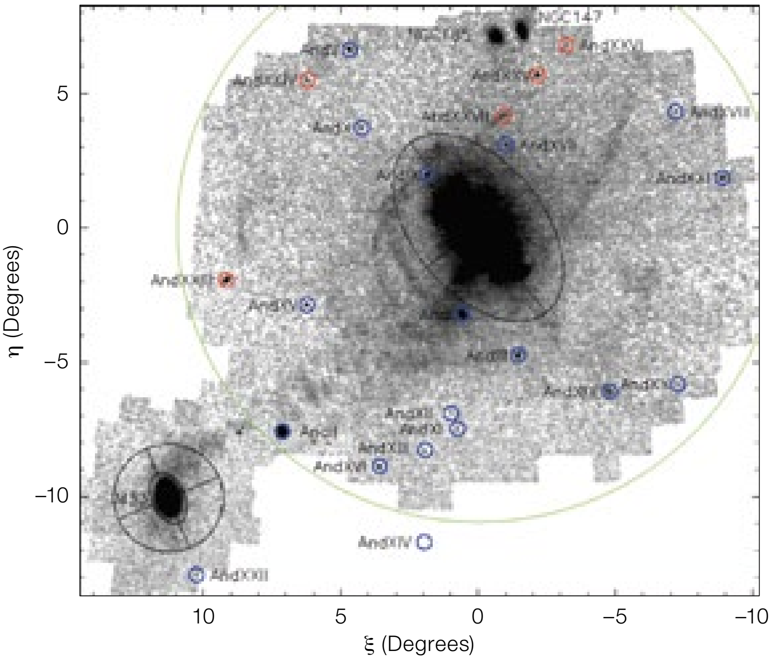

Figure 3. The surface density of colour-selected stars in the PAndAS footprint is shown. Andromeda and M33 are clearly visible, as well as lots of smaller satellites and a complex network of streams. From Richardson et al. (2011).

Tidal streams

Tidal streams are tracers of how satellites get accreted and disrupted. They make up an as-yet unknown percentage of halo stars, complicating the modelling and interpretation of the stellar halo. But, due to their coherence in phase space, they also enable us to measure the shape of the gravitational potentials of their host galaxies, constrain the orbits of their progenitors, and provide insights into the chemo-dynamical evolution of satellites. As a first speaker of the session, Rodrigo Ibata presented modelling approaches and promising streams that need to be modelled, such as the Giant Southern Stream (GSS) in M31 (Figure 3). Karrie Gilbert then showed results from the Spectroscopic and Photometric Landscape of Andromeda's Stellar Halo (SPLASH), shedding light on the merger event that created the GSS and related shells in the M31 halo. She pointed out that the halo of Andromeda shows clear signatures of further mergers with smaller galaxies. Edouard Bernard added insights on the GSS's star formation history from Hubble Space Telescope (HST) data, and possible links to a star formation event in M31.

Essential for our understanding of satellites, streams and their host galaxies are proper motion measurements. Tony Sohn presented HST observations, giving valuable insights on the internal kinematics, the gravitational potential of the Milky Way, and even the kinematics of streams. Iskren Georgiev presented first-epoch data from a Palomar 5 proper motion measurement with the HST. The data provide tight constraints on the distances to the cluster and its stream and their stellar mass functions, which significantly help to inform models of this system. Yet, most insights on streams have come, and are still coming, from wide-field imaging surveys. In this context, Blair Conn presented results from the PanSTARRS1 survey, concluding that the Monoceros overdensity could be either a stream, a flare or a ripple in the Galactic Disc. Heidi Newberg argued for the latter, backing up her arguments with signatures of such a density wave in Sloan Digital Sky Survey (SDSS) data. A different approach of finding and characterising halo substructure was presented by Kathy Vivas, who showed the extent of the Virgo overdensity as seen by RR Lyrae stars.

Putting all this into context, the “old cow” of the stream business (his words), Steven Majewski, gave an excellent historical overview of how tidal streams were discovered and modelled in the past twenty (forty?) years, and on how the discovery of the Sagittarius stream led to a paradigm shift in the astronomical community, since it was a striking confirmation of hierarchical structure formation. Carl Grillmair followed up with a complete census of the 21 currently known streams in the Halo of the Milky Way (most of which he discovered himself). Based on the present-day globular cluster population, Mark Gieles estimated that this number should be a factor of four times higher, whereas Grillmair estimates it to be a factor of ten higher. Grillmair pointed out that, although the northern sky looks like a “weaved carpet”, there is a significant lack of stream detections on the southern hemisphere.

Aaron Romanowsky extended this census to M31 and beyond, emphasising that streams are found in basically any galaxy with deep enough photometry. He pointed out that for distant galaxies, since stars are too faint for spectra, globular clusters or planetary nebulae have to be used to get kinematic data for investigating stream-like substructures. With the example of M87, he then demonstrated that these tracers can in fact be used to detect accretion events. Michael West followed up on that with the investigation of halo substructure using computer-vision techniques, that is, by applying the versatile Hough transformation to globular cluster maps.

Modelling tidal streams

Fast and efficient ways of modelling tidal streams have become available in recent

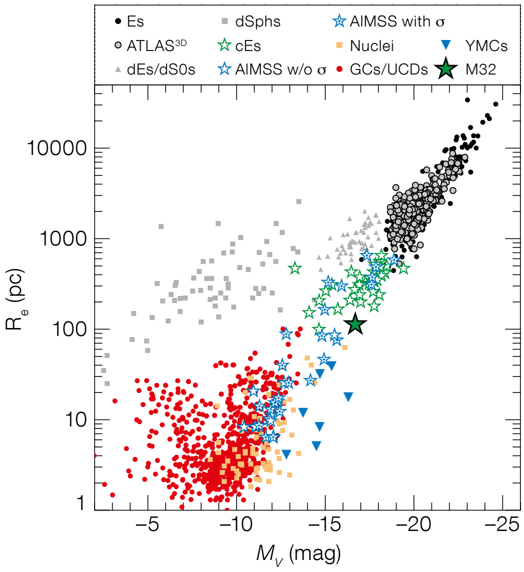

Figure 4. This mass–size plot from Norris et al. (2014) depicts absolute magnitude, as a tracer of stellar mass, versus effective radius, as a proxy for size. It contains nearly all known satellites in the local Universe. Globular clusters (red) and dwarf galaxies (grey squares) form two distinct sequences, which merge onto a common mass–size sequence defined by elliptical galaxies. Newly found objects close this gap between the two satellite populations.

years. Yet, applications to real data are still the exception. With the flood of kinematic data in mind, which will soon come from the Gaia satellite (mid 2016/early 2017), Amina Helmi gave an excellent overview of action-angle modelling of streams and phase-space substructure. She emphasised that streams are significantly simpler structures in action-angle space than in phase space, which makes this formalism a promising technique to model large numbers of streams. Based on the Aquarius simulations, she estimated that Gaia should be able to detect about 400 streams in the Solar Neighbourhood. Building on Helmi's talk, Jo Bovy introduced his Python galpy software, which can be used to efficiently generate stream models, and which is entirely based on the simple nature of streams in action-angle space. Then Robyn Sanderson demonstrated how this framework can be used to disentangle stream memberships of stars in the (messy) Galactic Halo, and in this way constrain the potential of the Milky Way.

The kinematically cold streams detected in the Milky Way Halo, such as GD-1 and Palomar 5, are very thin — surprisingly thin. In this context, Raymond Carlberg demonstrated the effects of a realistic, i.e., triaxial and substructured, dark matter halo on the width of tidal streams. He concluded that the potential of the Milky Way should rather be filled with streams looking like "overcooked spaghetti". In this context, Sarah Pearson presented her modelling results, showing that the only triaxial halo model currently known for the Milky Way dark matter profile that can successfully reproduce the Sagittarius stream, fails in reproducing the thin and curved morphology of the Palomar 5 stream. She explained that the triaxiality of the gravitational potential leads to significant stream fanning, resulting in puffy streams that do not resemble the SDSS observations of Palomar 5. Andreas Küpper followed up on Pearson's talk, by identifying (probable epicyclic) substructures within the stream of Palomar 5. He demonstrated how these, when modelled correctly, turn globular cluster streams into high precision scales, constraining models of Palomar 5, the Milky Way and the Solar position and motion within the Galaxy.

But substructure in tidal streams may also arise from dynamical encounters with dark matter subhaloes. Denis Erkal explained within a mathematical framework how these dark satellites affect stellar streams and what we can learn about dark matter from a single gap in a stream. This will certainly be an important use for tidal streams in the future, since ΛCDM predicts thousands of satellites around Milky-Way-size galaxies, whereas our current number count of luminous satellites lingers around 40–50. Why some satellites contain luminous matter and why most others are probably devoid of baryons has to be understood, if the ΛCDM model of cosmology is to prevail.

With this outlook we ended the streams session and moved on to satellite properties and tidal transformation. From the variety of tidal features around satellites seen in the stream session it became clear that we have to expect many satellites to be tidally affected, altering properties like mass, size and velocity dispersion.

The star cluster–dwarf galaxy interface

Properties of satellites differ substantially, from compact, relatively low-mass globular clusters to extended, high-mass dwarf galaxies with complex chemical compositions. The discovery of transition objects at the star cluster–dwarf galaxy interface has blurred the historical distinction between these satellite classes. Exploring this interesting region in the mass–size plane was therefore an integral part of this workshop.

One of the main questions was the nature of ultra-compact dwarf galaxies (UCDs). Are they massive globular clusters, compact dwarf galaxies or disrupting satellites? In an attempt to answer this question, Carolin Wittman presented imaging data to search for tidal features around low-mass galaxies in galaxy clusters. She found signs of tidal disruption around one UCD. Similarly, Michael West presented data on the M31 satellite G1, which shows clear signs of tidal disruption, and G1 may therefore be a nucleated dwarf galaxy rather than a globular cluster.

Oleg Gnedin showed that globular clusters are fundamentally different from dwarf galaxies. These dense systems formed during galaxy mergers — from the early gas-rich Universe to the present day — following a universal log-normal mass function. Dissolving GCs in the inner regions of galaxies may spiral into the centres and form nuclear star clusters; dissolving GCs in the outer regions of galaxies, such as the Milky Way satellite Crater (the true nature of which is actually still under debate), may appear like ultra-faint dwarf galaxies. Relying on results from numerical simulations, Mike Fellhauer then added that GCs, when brought completely out of virial equilibrium through tidal shocks, can mimic ultra-faint dwarf galaxies (UFDs) like Hercules and Segue 1. In a similar fashion, but with opposite sign, Filippo Contenta presented results from N-body simulations showing that dissolving GCs are unlikely to contribute to the UFD population. But not all star clusters that fall into in the gap between the bulk of GCs and dwarf galaxies within the mass–size plane (Figure 4) are necessarily ultra-faint. Extended outer-halo clusters like Palomar 14 or Crater have half-light radii that are a factor of ten times higher than usual for GCs. Paolo Bianchini weighed the hypothesis that these extended clusters could have been formed as compact within the weaker tidal fields of dwarf galaxies, and then fallen into the Milky Way Halo. He found that such clusters do indeed expand, but not enough to resemble the extended GCs in the Milky Way, leaving their origin as an open question.

What exactly is a galaxy? Several speakers tried to answer this controversial question. Jay Strader defined it as a bound collection of stars whose properties cannot be explained by a combination of baryons and Newton’s law of gravity. Referring to previous speakers, he pointed out that a mass-to-light ratio is not a well-defined quantity for systems that are not in virial equilibrium, and, hence, should not be used for this distinction. Instead, he proposed to use metallicity spread as a diagnostic to distinguish a star cluster from a galaxy. It was noted, however, that the existence of a mass–metallicity relation detected in extragalactic GC systems (the blue tilt) suggests metallicity spreads to be a natural feature of massive GCs. Thus, not even a metallicity spread may be a sufficient criterion to define a galaxy. Strader suggested that, until enough data exists, newly found objects should not be named, since otherwise star clusters like Crater end up having names following the Local Group dwarf galaxy naming convention.

In a series of excellent presentations, Dougal Mackey, Duncan Forbes, Jean Brodie and Mark Norris reviewed how the mass–size diagram has filled up over the last few decades (or rather centuries since the first discovery of a GC in 1665). Many of these new objects have been found in M31, and most of those through the PAndAS survey. These data also show that the GCs in the outer halo of M31 are highly correlated with streams, strengthening the accretion scenario. It was also shown that, even though new discoveries of extended clusters have slowly filled up the mass–size plane, the two dominant populations of satellites are still “regular” GCs and dwarf galaxies. Many more of these exotic, extended systems have been found outside the Local Group by the SAGES Legacy Unifying Globulars and GalaxieS (SLUGGS) survey.

Ultra-compact dwarf galaxies

UCDs were, again, the topic of the final day of the meeting. Even after the previous sessions, their origin was still unclear: are they the massive end of the globular cluster mass function, or are they stripped nuclei of dwarf galaxies? The session was a back-and-forth of good arguments for each hypothesis. Michael Hilker pointed out that nuclear star clusters and UCDs fall into the same region of the mass–size plane. He also showed observations of UCDs with clear signs of tidal disruption. Yet he concluded that the number and properties of UCDs seem to be incompatible with them being entirely made up of stripped nuclei. In an attempt to resolve the cluster/galaxy question, Matthias Frank put forward the provocative definition that “a globular cluster is something that is made up of globular cluster stars”. With this definition in mind, he found that X-shooter spectra of UCDs put them on the same sequence with GCs, when looking at them in the CN–MgFe plane. With even more ESO data, Karina Voggel found, from a large sample of > 100 Fornax UCDs imaged with the FOcal Reducer and low dispersion Spectrograph (FORS), that their distribution around Fornax follows the distribution of the GCs. She finds an overabundance of GCs in the vicinity of UCDs, which she interprets as support for the stripping scenario — even though less than 20 % show signs of tidal disruption in the form of an extended stellar halo. Mark Norris, furthermore, reasoned that UCDs with an absolute magnitude $M_V < 13$ have to be stripped nuclei, since they lie 5σ away from the cluster luminosity function.

No matter what they are, UCDs are among the most extreme stellar systems. Jean Brodie presented observations of the densest stellar systems in the local Universe. M60-UCD1 and M59-UCD3, being typical examples of these hypercompact clusters, even showing signs of central supermassive black holes. Anil Seth presented integral field unit observations of M60-UCD1, showing that this massive UCD indeed hosts a supermassive black hole that makes up about 15 % of the galaxy’s mass. Such overly massive black holes could be explained through tidal stripping of larger dwarf galaxies in a host galaxy potential.

In further presentations on the kinematics of GCs, UCDs, and compact ellipticals (cEs), Mark Norris and Adrien Gouérou demonstrated how important integral field units have become for the investigation of extragalactic compact stellar systems, as they should all be called. In the final presentation of the meeting, Florent Renaud gave a fascinating outlook on how the formation of UCDs and GCs can be traced in high-resolution numerical simulations. He demonstrated how compact stellar systems can expand during galaxy mergers, and form UCD-like objects. The meeting was concluded by the honorary conference photographer Stephane Courteau, who gave an entertaining summary in pictures (and kindly made his conference photos available to the public[2]).

Based on the success of this workshop, the organisers hope that there will be many more Satellites and Streams meetings in the future.

Acknowledgements

The organisers would like to thank Maria Eugenia Gómez, Paulina Jirón, the team of ESO IT and General Services, and the entire Local Organising Committee. Heartfelt thanks go also to ESO’s Directorate for Science for supporting this workshop.

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Links

[1] Workshop programme with access to presentations: http://www.eso.org/sci/meetings/2015/Satellites2015/program.html

[2] Gallery of conference photos: http://www.astro.queensu.ca/people/Stephane_Courteau/gallery.php

Report on the ESO Workshop

Stellar End Products: The Low-mass – High-mass Connection

held at ESO Headquarters, Garching, Germany, 6–10 July 2015

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There are many similarities in the mass-loss processes between evolved low-mass and high-mass stars and the workshop brought together observers and theoreticians to compare and contrast the asymptotic giant branch and red supergiant evolutionary phases. Asymmetric and collimated mass loss, bipolarity, binarity, stellar rotation and magnetic fields were among the key topics explored. Many results were displayed from state-of-the-art high spatial resolution facilities, such as ALMA and the VLTI. A summary of the workshop topics is presented.

Figure 1. The STEPS attendees photographed in front of the entrance to the Headquarters extension.

The mass loss from cool asymptotic giant branch (AGB) and red supergiant (RSG) stars leads to the formation of planetary nebulae and supernovae, respectively, and puts a large amount of material into the interstellar medium (ISM). Collectively it is therefore an important process for understanding the ecology of a galaxy and the lifecycles of stars of both low and high mass. There have been significant recent advances in both the observations and theory of the late stages of stellar evolution, motivating a workshop to consider the synergies of AGB and RSG evolution. High-resolution facilities, such as the Very Large Telescope Interferometer (VLTI) in the near infrared and the Atacama Large Millimeter/submillimeter Array (ALMA) in submillimetre and millimetre wavebands, and other telescopes such as Hubble Space Telescope, start to resolve scales down to the size of the stars themselves. These new data provide an opportunity to revisit the outstanding questions of late stellar evolution, which formed the core topics of the workshop.

The workshop extended from Monday afternoon to Friday, providing an intense 24 invited review talks, 24 contributed talks and five lively discussion sessions. There were 46 posters, and a special session with on Wednesday afternoon was provided so that the posters could be appreciated and discussed with *Bier und Bretzen*. The 113 participants (see Figure 1) enjoyed extensive snacks and a conference dinner in Garching. We provide a summary of the sessions in chronological order of the meeting. Many of the talks are provided on the workshop web page[1] and copies of many of the posters are also available[2].

Opening reviews

The first afternoon was devoted to overviews of the exploration of AGB and RSG stellar products from the observational side. The workshop was opened by the ESO Director General, Tim de Zeeuw, who emphasised that one of ESO's core missions is to provide scientific coordination and dissemination of scientific results though meetings just like the present workshop. Of course its other mission is to provide observing facilities, and he described the current and future state of the Observatory, with emphasis on the European Extremely Large Telescope, which has now entered the construction phase. The first scientific talk was a grand overview by Albert Zijlstra, in which the important role of mass loss in evolved stars of all masses for the enrichment of the ISM was laid out. The topic of asymmetry of the mass loss at all stages was introduced and was a recurrent theme throughout the meeting. The roles of stellar binarity and rotation in driving the asymmetries of mass-loss nebulae were also introduced and the striking similarity of the spiral CO outflow from the AGB star R Scl mapped by ALMA (Maercker et al., 2012) and the spiralling dust nebula around the Wolf–Rayet (WR) star colliding wind binary WR 140 (Williams et al., 2009) was duly remarked.

Eric Lagadec presented a summary of the closely related meeting to commemorate Oliver Chesneau, entitled "The Physics of Evolved Stars"[3], which was held in Nice in June. The topics of the meeting had many similarities with the workshop, covering Chesneau's work on low- and high-mass stars with particular emphasis on the use of high resolution and interferometry for studying the shapes and surfaces of stars and their immediate environments. One highlight selected by Lagadec was the VLTI PIONIER (Precision Integrated-Optics Near-infrared Imaging ExpeRiment) observations of Antares (α Sco), revealing 16 lobes of the visibility function. The Chesneau Prize Lecture was presented by Julian Milli as part of that meeting.

Hans Olofsson described millimetre/submillimetre and radio observations of the envelopes and photospheres of AGB and RSG stars and the large number of different molecular species (~ 80 in AGB, and

~ 25 in RSG) detected, but with many lines left unidentified (called *U*-lines). Currently the determination of the mass-loss rates is still only good to ~ 50 % despite sophisticated modelling. ALMA will be the key to advances in this field and is already showing interesting results, such as the resolution of the stellar surface of Mira (Vlemmings et al., 2015). Roberta Humphreys then reviewed the evidence for mass loss in RSGs from optical and near-infrared (NIR) observations. Near- and mid-infrared imaging and spectroscopy are now providing increasing detail on the mass loss, revealing it to be episodic and driven by pulsation and convection. The presence of bow shocks and dust concentrations remote from the stellar surface, together with measurements of their radial velocities and proper motions, diagnoses the effects of continuous and episodic mass loss on the nearby environment. The archetype of this category is of course η Car, which has shown several individual many-$M_{\odot}$ ejections over the last 170 years.

The introductory sessions closed with presentations on the capabilities of ALMA and optical–NIR interferometry. These facilities are particularly well-matched to study the details of the circumstellar, and stellar, regions of AGB and RSG stars. Leonardo Testi described the current state of ALMA and plans for Cycle 4 (including linear polarisation) and Cycle 5 (Band 5 for 163–211 GHz). Only three optical–NIR interferometric instruments now survive from the developments of the 1990s — the Navy Precision Optical Interferometer (NPOI), the Center for High Angular Resolution Astronomy (CHARA) and the VLTI — as reviewed by Jean-Philippe Berger. On the VLTI, the two second-generation instruments, GRAVITY for NIR spectro-imaging and microarcsecond astrometry, and MATISSE (Multi-AperTure mid-Infrared SpectroScopic Experiment) for mid-infrared spectro-imaging, will be commissioned in the next few years. Berger emphasised how, increasingly, image reconstruction will lead to more realistic imaging capabilities, such as with the VLTI’s four-telescope beam combiner PIONIER. With its increased efficiency, PIONIER facilitates interferometric surveys. Berger closed by seeking input from the evolved star community for plans for the VLTI in the next decade.

Stellar evolution and atmospheres

The session was opened by Georges Meynet on the physics of massive stars. The challenges are to explain how the observed properties of rotation, magnetic fields and binarity are affected by environment and evolution, and what their influence on the structure of the stellar interiors is. Rotation is an active topic in the research on massive stars and causes mixing, driven by shear or meridional currents; however an efficient transport mechanism for angular momentum still seems to be lacking. Meynet introduced the flux-weighted gravity–luminosity relationship, which is very tight and showed how it demonstrates that the mass-loss rate in RSGs cannot be very high, except at the end of evolution, prior to a supernova explosion. Paola Marigo described modelling of the molecular chemistry of AGB star atmospheres in terms of pulsations, which provide shocks leading to non-equilibrium chemistry. The AGB atmosphere is very dynamic and HCN abundances, for example, can vary through the pulse cycle. Alain Jorisson described a technique for exploring the velocity field within the stellar atmosphere based on a method by Schwarzschild using the cross correction of spectra with masks sampling different line formation depths. Using this method, a full spectrum can be synthesised as a function of T_{eff}, g, M, Z, etc. Applications to the AGB star Mira (o Ceti) and the RSG star μ Cep based on long-term spectral modelling were described.

Pierre Kervella presented an invited talk on high-resolution observations of RSG atmospheres, concentrating on Betelgeuse and Antares. The VLTI and ALMA have resolved the surface of Betelgeuse (diameter ~ 40 milliarcseconds [mas]) and the few convective cells resolved appear to be nearly as large as the star itself (see Figure 2). SPHERE ZIMPOL (Spectro-Polarimetric High Contrast Exoplanet Research – Zurich Imaging Polarimeter) observations of Betelgeuse in the *V*-band show that it is not round and, in the NIR, an incomplete dust shell with dust plumes is visible. From time-lapse imaging, these dust features show plane-of-sky velocities in the range 10–40 km s^{-1}. Michael Gordon discussed yellow supergiants (YSGs), caught between excursions between the red and blue at the high luminosity end of the Hertzsprung–Russell (HR) diagram. By searching for such stars in M31 and M33, a sample of 30 YSGs has been found from photometry. Based on extensive and high time resolution observations with CoRoT and Kepler satellite data, Benoit Mosser described the modelling of stellar oscillations. While, in the Sun, pressure (p) waves can account for the asteroseismological data, in RSGs mixed gravity (g) and p waves dominate. Mosser described the seismically enriched HR diagram for subgiants and red giants, where mass as well as *L* and T_{eff} allows the stellar evolution to be mapped and the late evolutionary stages to be distinguished (Mosser et al., 2014).

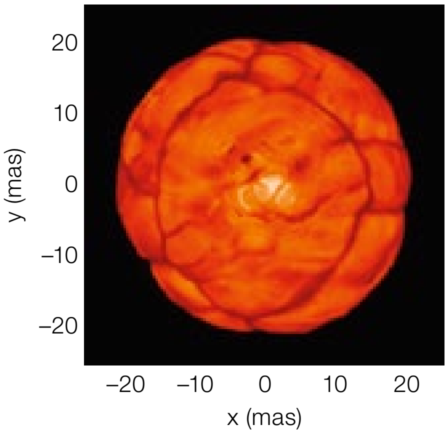

Figure 2. Intensity map of the best-matching snapshot of a radiative hydrodynamics simulation of Betelgeuse at 2.2 μm based on AMBER observations. From Montarges et al. (2014).

In the discussion session, the view was expressed that the in-depth study of individual (quite probably peculiar) stars should be conducted in conjunction with a transition to surveys. On the question of when a supernova (SN) occurred — in the blue or red supergiant phase — it was suggested that the frequency of SN types which will emerge from the many SN surveys underway could be a useful diagnostic.

Mass-loss mechanisms and dust

Susanne Hoefner opened with a theoretical view of the dynamical atmospheres of AGB stars. Stellar pulsations

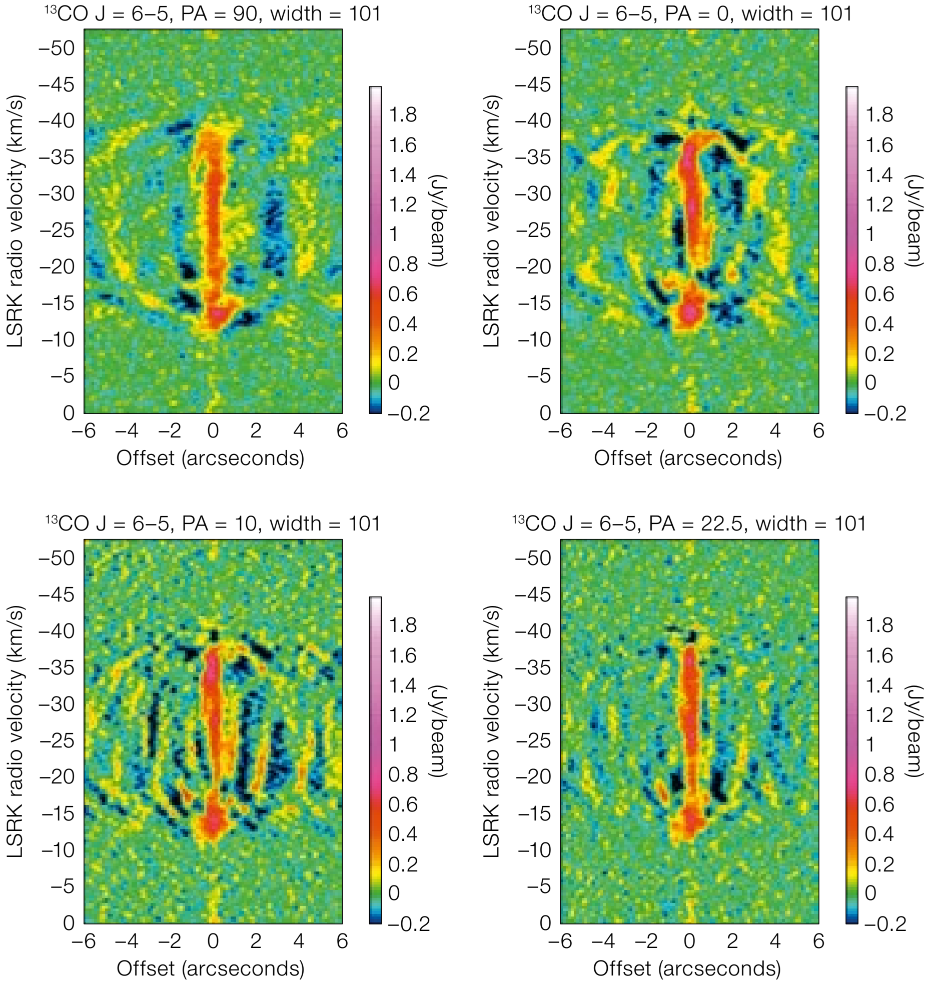

Figure 3. Position–velocity diagrams for CW Leo from ALMA ^{13}CO J = 6–5 emission at 661.067 GHz shown at four position angles of 90, 0, 10 and 25 degrees (indicated). From Decin et al. (2015).

and convection drive shock waves; dust can form in the atmosphere in the wake of these shocks. Radiation pressure on the condensed dust then drives mass loss. The type of the AGB star, M- or C-type, then sets the dust formation as either O or C for that fraction of the matter not locked in CO. The infrared opacity of C grains is featureless, but silicate grains have many features; in O-rich stars the candidate species for driving the mass loss is Mg_2SiO_4. Magnesium silicate grains with sizes in the range 0.1 to 1 μm appear to drive realistic winds in the models. More dust species are being investigated for their role in wind driving, especially for C/O < 1. Sara Bladh showed some of these time-dependent wind models for M-type stars, and how the photometric variations though the pulsation cycle are well matched.

The wind of the O-rich AGB star R Dor was studied by Theo Khouri, who presented impressive SPHERE VISPOL narrow- and broadband images. The wind is modelled by silicates and Al_2O_3. Then ALMA data on the C-rich AGB star CW Leo, a bipolar source, were presented by Ward Homan; this source shows a binary-star-induced spiral, similar to R Scl but with a different viewing angle; see the position–velocity diagrams in Figure 3.

Graham Harper gave a remote presentation from Colorado, which worked faultlessly. He described modelling of the extended atmospheres of RSGs. The primary aim is to measure flows (outflow and turbulence) in the wind acceleration zone of supergiants, such as VV Cep and Betelgeuse. Alfvén-wave-driven outflows are still considered as viable, and observations to detect the 26 μm [Fe II] line in emission to study the circumstellar emission of Betelgeuse and test the magnetohydrodynamic (MHD) models were described. Claudia Paladini presented VLTI observations of AGB stars with a range of instruments, including AMBER and PIONIER, to map the surface features. It appears that AGB stars are not necessarily round, and the circumstellar shell changes shape though the pulsation period, as observed for Mira. Polarimetric imaging of Betelgeuse was presented by Xavier Haubois. The NIR polarimetric observations (Norris et al., 2012) of the thin inner dust shell are complemented by SPHERE ZIMPOL polarimetry. Peter Scicluna showed high-contrast polarimetry observations with SPHERE of the RSG VY CMa with evidence for large (~ 1 μm) grains.

Anita Richards explored the properties of the clumps and asymmetries in the circumstellar environments of mostly O-rich stars. The material is driven, before it condenses to dust, either by shocks in sub-photospheric layers or perhaps by the hottest dust condensing. The dense regions are probed by H_2O 22 GHz maser spots, and, from the number of maser spots, it is suggested that between two and five clouds are produced per stellar period, perhaps originating in spots on the stellar surface. These clumps, but not the masers themselves, probably survive ejection to contribute to the outer shells: in AGB stars the masers only survive a few months, but persist for years in RSGs. Radio continuum studies of extended thermal atmospheres of RSGs were considered by Eamon O'Gorman for Betelgeuse and VY CMa. A typical F_ν slope of $\alpha = 1.3$ is measured, steepening to $\alpha = 2.5$ at longer frequencies, and the temperature, mass and density of the dusty envelope can be determined. Dinesh Shinoy described NIR adaptive optics polarimetry of IRC+10 420 and VY CMa observed with the Large Binocular Telescope (LBT) mid-infrared camera (LMIRCAM) and the polarimeter on the Multi-Mirror Telescope (MMT-Pol). In VY CMa linear polarisation up to 60 % was detected, suggesting optically thick dust scattering.

Lyn Matthews described Jansky Very Large Array (JVLA) observations of some Galactic Cepheid stars to search for evidence of mass loss that could help to explain why the observed and model masses are not in good agreement. The discussion formed a comparison of the mass loss in high- and low-mass stars: it appears that AGB stars are more efficient at producing dust than the higher mass RSGs.

Binaries, shells and shaping

Since it is considered theoretically challenging to understand how single stars can develop strong asymmetries in their mass loss, and especially produce the elaborate morphologies of some planetary nebulae (PNe), such as bipolar, multipolar, jets, etc., formation through binary interactions is a very attractive alternative. Orsola de Marco presented theoretical progress towards explaining the frequency of asymmetrical PNe through binary interactions, and in particular close binary interactions. Roche lobe overflow (RLOF) is considered a promising mechanism and the number of known observed short-period binaries is increasing as long-term monitoring projects probe this domain. Wind RLOF can lead to larger accretion rates than wind accretion and may be able to power the jets observed in some PNe. Three-dimensional hydrodynamical modelling of common envelope binary evolution is underway. The binary star theme was continued by Shazrene Mohamed, but for higher-mass stars, such as Betelgeuse. The results of simulations show that the formation of bow shocks and Rayleigh–Taylor instabilities in the circumstellar media, and the role of binary stars, are central for the creation of tails (such as for Mira), pinwheel nebulae (such as for WR 140) and, of course, for novae.

Michael Hillen showed the first milliarcsecond image of the post-AGB binary star IRAS 08544-4431 taken with PIONIER. ALMA observations of binary AGB stars were presented by Sofia Ramstedt using CO as the main tracer of circumstellar gas and concentrating on sources with well-known binary separations. One of these is Mira, where the combination of ALMA and Atacama Pathfinder Experiment (APEX) covers the compact and extended circumstellar structures: the fast wind from the evolved secondary has blown a hole in the slower primary star wind. A spiral structure, but viewed more end on than for R Scl (or IRC+10 216, Cernicharo et al., 2015), was found for W Aql (also featured in the prize poster by Magdalena Brunner). SPHERE ZIMPOL *V*- and *R*-band polarisation images at a resolution of ~ 17 mas of the low-mass 141-day period binary system L2 Pup were shown by Migeul Montarges (Figure 4). The structure was modelled by a dust disc using the RADMC-3D radiative transfer code; the binary with a separation of 3 au was resolved. L2 Pup is suggested to be the progenitor of a bipolar PN. Another instrumental approach to resolving structures at high resolution, described by Foteini Lykou, is aperture masking using a single telescope, but multiple apertures. Using NACO (Nasmyth Adaptive Optics System and Coude Near Infrared Camera) the central star of R Scl was marginally resolved into a binary. In V Hya, NACO aperture masking shows the structure changing with time.

Henri Boffin showed the observational progress towards resolving discs or binary stars, using a range of facilities from VLT direct images (resolution ~ 0.5 arcseconds), to Hubble Space Telescope or ground-based adaptive optics imaging (to 0.02 arcseconds) to VLTI PIONIER closure phase imaging at 1 mas. A mini survey with PIONIER of symbiotic stars was outlined: for HD 352, a semi-detached binary, a tidally distorted elliptical image of major axis diameter 1.6 mas was modelled. A series of PIONIER observations of the high-mass binary, HR Car, shows the orbital motion over a period of less than one year to a fraction of a mas. Sebastian Ohlmann described modelling of the common envelope phase of binary evolution using the AREPO 3D hydrodynamics code (from W. Springel) for the evolution of the circumstellar structures.

Magnetic fields

Agnes Lebre introduced the field of stellar magnetism from a ten-year harvest of spectropolarimetry. A recent Zeeman survey of single G–K giants by Aurière et al. (2015) shows the most magnetically active stars are concentrated in a strip on the HR diagram associated with the first dredge up and core He-burning phases. Another magnetic strip occurs at the tip of the RGB/AGB, with observed fields at the 1 Gauss level (also covered in the prize poster by Benjamin Tessore); a several Gauss magnetic field has been detected in the Mira star, χ Cyg (Lebre et al., 2014), which also displays a linear polarisation signature, indicating a departure from spherical symmetry at the photosphere. The detection of magnetic fields in AGB stars and PNe was considered by Wouter Vlemmings and whether the focusing of material into jets, as is common in young stellar objects, could occur in these late evolutionary phases. Magnetic fields are detected in masering spots and there is an inverse correlation between spot size and magnetic field, with SiO masers being the most compact and with the highest fields. Extrapolating these fields back to the stellar surface suggests a field ~ 3 Gauss in the case of the Rotten Egg Nebula (OH 231.8+4.2).

Submillimetre polarimetry to determine the alignment of paramagnetic grains in circumstellar envelopes was described by Laurence Sabin, using the Sub-Millimeter Array (SMA) and Combined Array for Research in Millimeter-wave Astronomy (CARMA, now being decommissioned). Linear polarisation of 3–4 % is detected in OH 231.8+4.2, but in the C-rich nebula CRL 618 the peak polarisation was 0.7 %, attributed to the smaller C grains. Alizee Duthu continued the same theme and showed a detection of the magnetic field in the AGB star IRC+10 216 from hyperfine lines of CN, but no detection in the mature C-rich PN NGC 7027. In the discussion on magnetic fields, it was stressed that the MHD models should be linked to radiative models for a consistent treatment. The possibility of bias in selecting binary sources and peculiar/spectacular objects to win telescope time was again raised.

Evolved stars and the cycle of matter

This shorter session, during which the products of late evolution were placed into a galactic perspective, began with Iain McDonald, who considered the amount of matter returned to the ISM

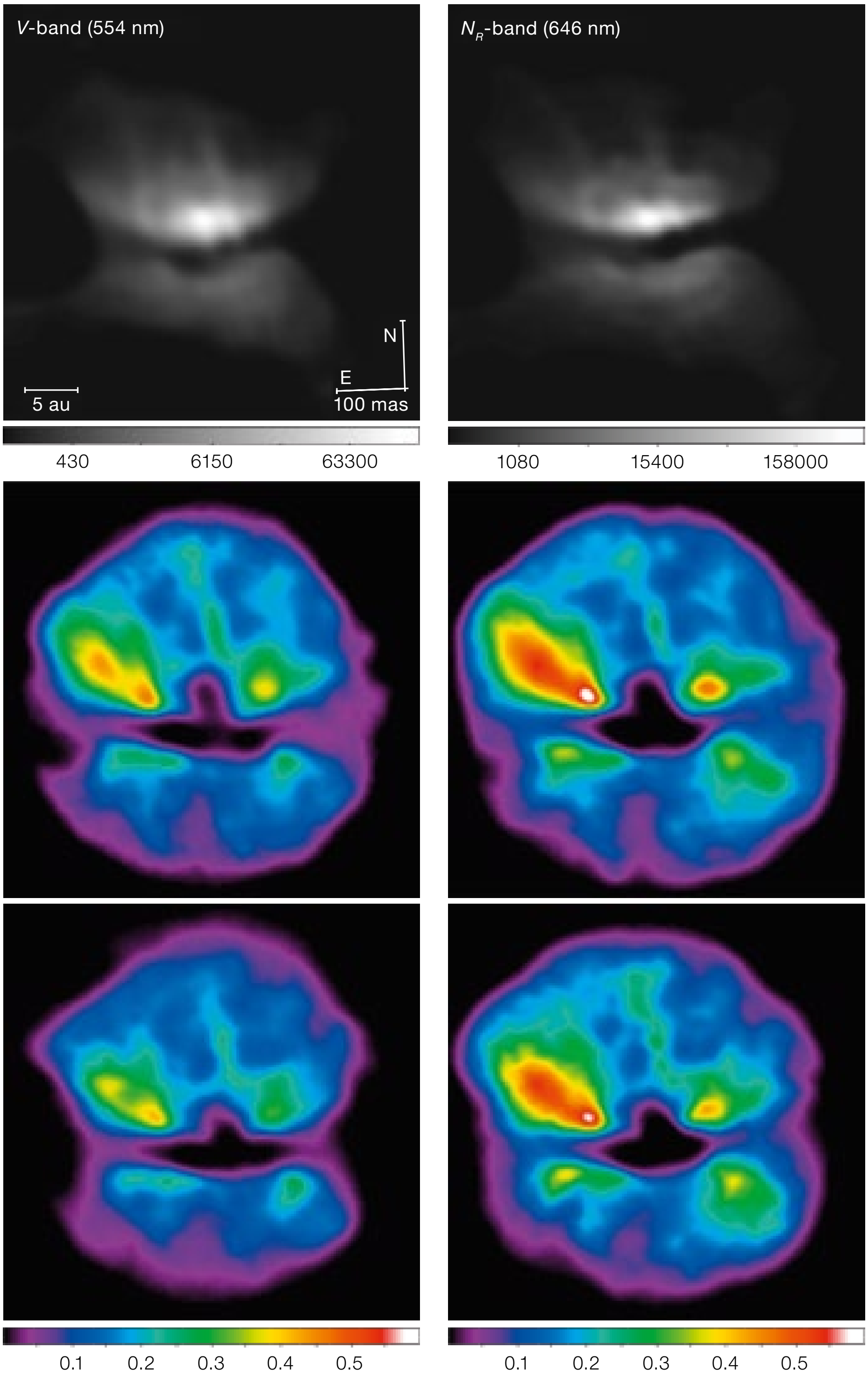

Figure 4. SPHERE ZIMPOL images of L2 Pup in *V*-band (left) and *R*-band (right). Upper: The deconvolved intensity image (log scale); Middle: The linear polarisation from the non-coronagraphic frames; Lower: Linear polarisation from the coronagraphic frames. The field of view is 0.60 by 0.60 arcseconds. From Kervella et al. (2015).

(dust and gas) from the stellar late stages. Mass loss before the onset of dust-driven winds must occur, and even low-metallicity [*Z*] AGB stars need to undergo substantial mass loss (and make dust). Large amplitude pulsations may be an effective source of mass loss before the dust is produced and radiation pressure drives mass expulsion. However the mass-loss rates, velocities and gas-to-dust ratios of AGB stars are still not well known, especially as a function of metallicity and environment, and improved values are required to parameterise the mass return to the ISM, especially pertinent to low-*Z* environments. For the case of RSGs, Jonathan Mackey looked at the effect of surrounding ionising conditions on mass-loss products. In the harsh ionised environment of a young massive cluster, even a neutral wind from a cool supergiant will be ionised, such as for W26 in Westerlund 1. The neutral shell of an AGB star could also be ionised in specific environments, such as a globular cluster.

Evolutionary end products: Planetary nebulae

Moving to the end products of evolution, planetary nebulae, from M < ~ 8 $M_\odot$ stars, were the following topic. Joel Kastner gave a contemporary perspective on how wind shaping depends on successive episodes of asymmetry. The fast wind and partially ionised zone is a source of extended X-ray emission and the outer regions of partially ionised, neutral gas, dust and molecules are a rich source for infrared emission. The ChanPlans survey of point and extended X-ray emission in nearby (< 1.5 kpc) PNe was described (Kastner et al., 2012). The X-ray spectra from Chandra can provide the temperature of the hot shocked wind bubble (median ~ 0.7 keV) and its chemistry from the high ionisation emission, e.g., from C and O lines. Some PN exhibit a compact high temperature core (too hot for thermal emission of the PN central star), pointing to the presence of close binaries.

Another aspect of post-AGB evolution was revealed by molecular line mapping, showing the presence of Keplerian discs around the stars, in the presentation by Valentin Bujarrabal. Although the dynamics of AGB and PN expansion seems to be primarily a Hubble law (*viz.* expansion proportional to the distance from the star), some young sources (such as the Red Rectangle and 89 Her) show a compact rotating disc around the star, which may be responsible for launching a jet and decisive to the morphology of the PN. An APEX survey of H_2O maser emission (321 GHz) from water fountain sources was shown by Daniel Tafoya: from multiple epochs, the proper motions of the outflowing maser spots can be traced.

The subsequent evolutionary phase of the central star after the PN, as a white dwarf (WD), was considered by Mark Hollands, who described the detection of metal lines in the atmospheres of cool WDs. In around 15 % of a sample of cool WDs, the lines of Na and Mg are split by the Zeeman effect by fields in the 2–10 MGauss range. The fields may be attributed to a spun-up fossil field or binary merger.

Evolutionary end products: Supernovae

A review of the last steps in the evolution of high-mass stars — as progenitors of supernovae (SNe) — was given by Rubina Kotak. On account of the difficulty of detection and the sparsity of cases, detection of SN progenitors and postgenitors makes confirmation of the progenitor star(s) contentious in the majority of cases. The route to SNIa (Chandrasekhar mass explosion) is generally considered to be either via a WD and a main sequence star (single degenerate route) or two evolved stars such as WDs (double degenerate route), but a variety of other routes is also postulated. The huge increase in monitoring campaigns of SNe and possible SN progenitor sites has led to one system being confirmed as a single degenerate (SN2011fe), but only one possible double degenerate candidate (He2-48, to explode in ~ 700 Myr; Santander-Garcia et al., 2015), has been identified. As sample sizes increase, sub-Chandrasekhar mass SNe are identified, suggesting even that the 1.4 $M_\odot$ explosion may not be the norm. Carolyn Doherty, who received the first prize in the poster competition, showed that super-AGB stars, with masses 6.5–10 $M_\odot$ could be a route for electron capture SNe, leaving behind a neutron star. In the field of core collapse SNe, Kotak showed that there are now some good pre- and post-explosion images showing that high-mass stars can “disappear” after explosion (black hole formation), but the occurrence of core collapse SNe in crowded star-forming regions affects the identification of progenitors and remnants. Imposter SN explosions, perhaps more like the great explosion of η Car, appear to be quite common.

Recent findings on SN 1987A (a core collapse SN of an 18–20 $M_\odot$ RSG) were highlighted by Mikako Matsuura, including the large mass of cold (~ 20 K) dust discovered by ALMA at 450 µm (Matsuura et al., 2014), the detection of emission from cold (~ < 100 K) molecules and the time evolution of the ring and ejecta. The cold dust is possibly amorphous carbon, or carbonaceous, but it is not clear how much of this apparently large amount of dust will survive the reverse shock and be released into the ISM. The cold molecular emission includes some silicate, probably formed deep within the SN explosion. The ring of emission lit up by the shock is now starting to fade and is expected to disappear by ~ 2025. The rise time of type II SNe was treated by Santiago Gonzalez using higher-redshift SNe collected in the Carnegie SN Project to explore the very early times. RSGs with circumstellar material may produce a steeper rise, or a plateau after the peak luminosity.

Noam Soker presented a lively talk on nebulae powered by central explosions emphasising MIJets (Must Include Jets), which are also needed to produce single-star core-collapse SNe. Jets must also be important in forming the circumstellar structures of low-mass stars and the results of hydrodynamic models were presented. Many examples of nebulae were shown with evidence for jets, such as MyCn18, which has similarities to the rings of SN 1987A, and even bipolar nebulae in radio galaxies driven by jets.

Workshop summary

Franz Kerschbaum took up the challenge laid down by Tim de Zeeuw of synthesising the seemingly diverse topics of the workshop. Indeed there were many times during the workshop when it seemed irrelevant whether the observed and modelled structures arose from low- or high-mass stars. Kerschbaum used stills from the Hitchcock film, *The 39 Steps*, as his linking images. Among the topics he noted were, that optical–NIR interferometry is now a mainstream technique, worries that the photocentres of objects, such as Betelgeuse, will change depending on the stellar surface structure (relevant for Gaia), new thoughts about connecting properties and classes and putting objects into new boxes, the role of the larger-scale environment on mass lost by stars and better characterisation of mass loss generally (particularly velocity).

Acknowledgements

The other members of the SOC — Leen Decin, Susanne Hoefner, Roberta Humphreys, Eric Lagadec, Paola Marigo, John Monnier, Anita Richards (with particular appreciation for organisng the poster competition) and Wouter Vlemmings — are warmly thanked for their continuous support. Jason Grunhut and Kate McGuire very efficiently ensured the flow of presentations and speakers. The ESO IT helpdesk provided invaluable support and Sarolta Zahorecz contributed to the local organisation and staffing of the reception desk. Special thanks go to Hildegarde Haems who was responsible for ensuring that so many details of the workshop ran without a glitch, and for whom this was her baptismal workshop at ESO. Stella Chasiotis-Klingner is also gratefully acknowledged for contributing to the logistics and organisation before Hildegarde took over.

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Links

[1] STEPS Workshop programme: http://www.eso.org/sci/meetings/2015/STEPS2015/program.html
[2] Access to poster papers: http://www.eso.org/sci/meetings/2015/STEPS2015/posters.html
[3] Programme of the meeting “The Physics of Evolved Stars”: http://poe2015.sciencesconf.org/

Report on the
Chilean Exoplanet Meeting

held at ESO, Vitacura, Santiago, Chile, 4 June 2015

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Henri Boffin[1]

[1] ESO

The contribution of the Chilean scientific community to the field of exoplanetary research has been crucial in advancing our understanding of this relatively new discipline of astronomy. In order to highlight these achievements, present current areas of research and instrumentation development, and foster further collaborations, a one-day exoplanet focus meeting was organised at ESO Vitacura. A summary of the meeting is presented.

The meeting comprised talks spanning most fields of exoplanetary research, such as radial velocity and transit surveys, atmospheric studies, direct imaging and free-floating planets, as well as an historical overview of exoplanet research in Chile. Presentations of all the talks can be viewed online[1]. Furthermore, presentations on new instrumentation, such as the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) and the upgraded Very Large Telescope (VLT) spectrometer and imager for the mid-infrared (VISIR), or the Fibre Dual Echelle Optical Spectrograph (FIDEOS) destined for La Silla, could provide ideas for new channels of investigation. As an additional bonus, the contribution of the Atacama Large Millimeter/submillimeter Array (ALMA) to exoplanet studies was presented; in particular the role of debris discs in planetary formation and evolution was discussed. The meeting also benefited from an invited talk by Pedro Figueira from the University of Porto who presented a thorough history of exoplanet detection and characterisation.

A bit of history

The meeting began with an historical overview of exoplanet research, presented by Dante Minniti from Universidad Andrés Bello in Santiago. As he reminded the audience, exoplanet science in the Chilean community started as a concerted effort in 2003, with a summer school. This quickly brought fruits, with the first Chilean exoplanet discovered in 2004, the hot Jupiter around OGLE-TR-133. Many others followed, such as those made by the N2K consortium, the Magellan planet search and the ESO Large Programme 666. Following on, the efforts and contributions of the second generation of exoplanet scientists in Chile were highlighted, which included a variety of radial velocity search programmes and surveys, as well as transit searches, such as HAT-PI, spearheaded by Andrés Jordán at Universidad Católica. Finally, the outlook for the future of this science in Chile was highlighted, which was the perfect way to lead into presentations from the participants.

Radial velocity searches

James Jenkins highlighted three radial velocity (RV) search programmes currently ongoing at the Universidad de Chile. Firstly, the Calan–Hertfordshire Extrasolar Planet Search (CHEPS), which is a collaboration with the University of Hertfordshire (UK), aims to better characterise the Doppler signals of metal-rich stars. This search effort is intimately linked to ESO facilities, by following up the interesting targets with SPHERE. The other two searches, RAFT (Re-analysis of Archival FEROS Spectra) and CHIRON, headed by Maritza Soto and Matías Díaz respectively, were also highlighted, and then later developed by the corresponding principal investigators. The RAFT survey (see the article by Soto et al., p. 24) is a reanalysis of archival Fibre-fed Extended Range Echelle Spectrograph (FEROS) data, whereby an improvement to the barycentric velocity correction of the pipeline has yielded the detection of new planetary candidates, as well as the rejection of other previously confirmed planets (Soto et al., 2015). CHIRON is a high-resolution spectrograph on the 1.5-metre Small & Moderate Aperture Research Telescope System (SMARTS) at the Cerro Tololo InterAmerican Observatory (CTIO) and has been in use since 2014 in a campaign to find rocky exoplanets. A first discovery from this search effort was shown.

Two spectrographs

Besides the astrophysical contribution from the community, there is now a concerted effort from Chilean institutions, in particular the Centre of Astro-Engineering of Universidad Católica, in developing new instrumentation. Two of such projects were presented by Matías Jones.

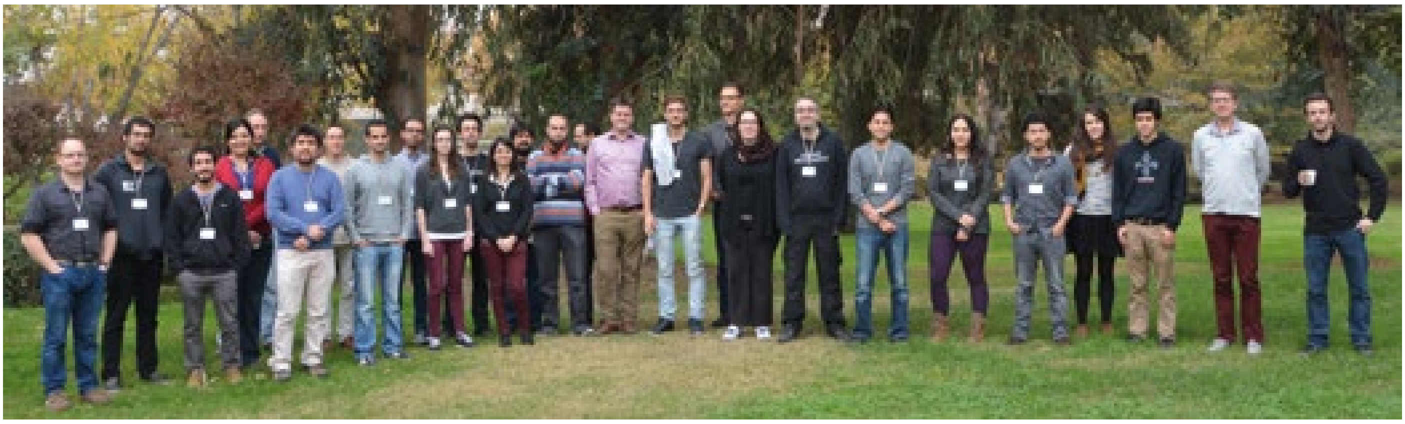

Figure 1. Participants at the Chile Exoplanet Meeting in the gardens at ESO Vitacura.

The almost completed FIDEOS is a stable, high-resolution spectrograph aimed at detecting exoplanets and brown dwarfs with high precision radial velocity measurements, as well as following up transiting planetary candidates. The secondary goals of the project include age determination of field stars in the Galaxy, RV of eclipsing binaries, studying circumstellar environments, monitoring massive star eruption phenomena, chemical abundances and stellar parameters, amongst others. FIDEOS has a resolution of 45 000, covering the spectral range of ~ 420–860 nm. It is a dual fibre-fed spectrograph for simultaneous observation of an astronomical object and the calibration lamp. An iodine cell mounted at the telescope–spectrograph interface provides a secondary alternative spectral calibration source. Additionally, the instrument is mounted on a fixed optical bench without any moving parts, whereby the CCD shutter and the enclosure are thermally controlled, ensuring opto-mechanical stability. The spectrograph is mounted on the Universidad Católica del Norte (UCN) 1-metre telescope at La Silla (Tala et al., 2014).

Details of a further spectrograph, TARdYS (TAO Aiuc high Resolution (d) *Y*-band Spectrograph), were also presented. This fully Chilean funded and designed project is planned for installation at the foreseen 6.5-metre optical–infrared telescope of the University of Tokyo Atacama Observatory (TAO) at an altitude of 5640 metres above sea level. This is an $R \sim 60\,000$ echelle spectrograph with the aim of achieving high precision RV measurements, covering the spectral range of roughly 900–1100 nm.

Reflected light from 51 Peg b

ESO student Jorge Martins presented a technique that obtained a direct detection of reflected stellar light from the planet surrounding 51 Peg, using the High Accuracy Radial velocity Planet Searcher (HARPS) spectrograph (Martins et al., 2015). Utilising the cross correlation function method with a binary mask with 3600 lines, Martins and his collaborators were able to obtain the direct signal from the planet after the stellar signature had been removed. From the analysis of this reflected signal, the team was able to determine an inclination of ~ 80° for the orbit of this planet, which puts it agonisingly close to it being a transiting planet. Subsequently, this inclination yielded a value for the true mass of the planet of 0.46 M_J, making it an inflated hot Jupiter with a large albedo. These results were obtained from the fitted signal shown in Figure 2, which has a normalised amplitude of 6.0×10^{-5}, at a detection significance of 3.7σ.

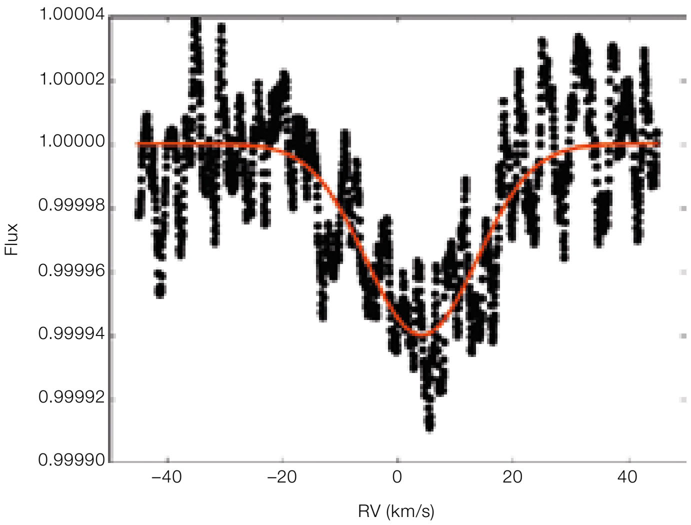

Figure 2. The reflected light signal from 51 Peg b is shown as a function of the radial velocity, including the Gaussian fit (red line). From Martins et al. (2015).

High-contrast imaging with SPHERE

High-contrast imaging represents the most direct method of detection and characterisation of extrasolar planets. With the advent of extreme adaptive optics systems implemented on a variety of large-class telescopes, astronomers have been able to directly detect and image a handful of exoplanets, such as those around HR8799 or β Pictoris. This technique requires extremely high angular resolution, as well as high contrast. Julien Milli, the instrument fellow for SPHERE recently commissioned on the VLT, presented some preliminary results from the commissioning data taken by the consortium. Benefiting from an extreme adaptive optics system and unique post-processing techniques, this instrument produces extremely stable, high Strehl ratio and diffraction-limited images.

One of the most recent results with SPHERE is the observation of the G9V star GJ758, located 16 parsecs away (Vigan et al., 2015). SPHERE confirms the presence of a sub-stellar companion, with an additional possible planetary candidate. Further campaigns will be required to confirm the nature of this new candidate and to determine whether it is bound to the system or not. As well as its high-contrast imaging capabilities, SPHERE will provide a wide range of spectroscopic and polarimetric modes of observation.

The new VISIR and exoplanets

As the only mid-infrared instrument mounted at a telescope in the southern hemisphere, VISIR has recently gone through an upgrade and is now fully operational at Unit Telescope 3 of the VLT (Käufl et al., 2015). Daniel Asmus, the instrument fellow for VISIR, highlighted the new possibilities for exoplanetary research using this newly upgraded instrument. Operating in the *N*- and *Q*-bands, it is able to take diffraction-limited images with resolution of 0.25–0.4 arcseconds. One of the new modes introduced in this instrument is the coronagraph with an annular groove phase mask, optimised at 12 μm and planned for full commissioning in July 2015. Medium resolution spectroscopy, burst mode imaging and sparse aperture masking are also soon to be commissioned/offered.

VISIR has already been used to study protoplanetary and debris discs. Future studies of transiting exoplanets in the mid-infrared with VISIR will be especially interesting when observing occultations, as exoplanets are relatively bright in the mid-infrared compared to their host stars. However, some challenges still remain in the form of high background noise in this wavelength domain, as well as VISIR's relatively small field of view. There are currently some ongoing ESO programmes to investigate the feasibility of such observations with VISIR. The relative brightness of planets in this regime also opens up the possibility of directly imaging exoplanets with this excellent angular resolution instrument.

Besides the talks mentioned above, Elyar Sedaghati from ESO Santiago presented results on transmission spectroscopy of the exoplanet WASP-19b, performed with the VLT's FOcal Reducer/low dispersion Spectrograph 2 (FORS2) instrument, for the purpose of characterising its atmospheric properties (Sedaghati et al., 2015). This observation was made possible through the exchange of the previously damaged longitudinal atmospheric dispersion corrector (LADC) prisms (Boffin et al., 2015). Bill Dent from ALMA gave an introduction to some of the capabilities of the now fully functional submillimetre interferometer; possible applications to study exoplanets, young exoplanetary systems and protoplanetary discs were highlighted. Mark Booth, from the Universidad Católica discussed the place of debris discs in planetary systems, as well as the consequences of interactions between young planets and their neighbouring environments. Finally, Holger Drass, from the same institute, presented some preliminary results from deep HAWK-I and KMOS observations of the Orion Nebula Cluster, where a second peak in the sub-stellar initial mass function points to the possible presence of free-floating planetary mass objects.

Acknowledgements

This one-day meeting was made possible through the support of the ESO Office for Science in Vitacura. Special thanks go to Claudio Melo, Paulina Jíron and María Eugenia Gomez for helping with organising various aspects of the meeting.

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Links

[1] Introduction, programme, list of participants and the presentations can be found at: http://www.eso.org/sci/meetings/2015/Exoplanets2015.html

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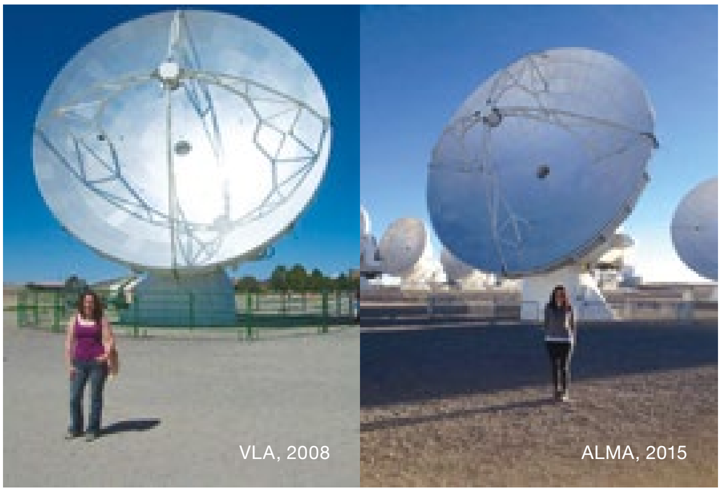
Fellows at ESO

Lizette Guzman-Ramirez

Ever since I can remember I have always been fascinated by the Moon, so I guess that was how my interest in astronomy started. I'm originally from a small town in the north of Mexico, called Saltillo. I lived there with my parents and sister until I was seventeen, when I moved to the centre of Mexico to do my undergraduate degree in physics. By the time I decided to do physics, I was already planning to be an astronomer, although I didn't know what being an astronomer really meant. During my study of physics I learnt many things, but almost nothing related to astronomy. Luckily I managed to get a grant for an astronomy summer school organised by the Centre for Radio Astronomy and Astrophysics (CRyA) of the Universidad National Autonoma de Mexico (UNAM). Those two weeks in the summer of 2004 were a turning point in my life as an astronomer — they convinced me that I wanted to be an astronomer and learn about the Universe.



Lizette Guzman-Ramirez

To receive a physics degree in Mexico you have to do a thesis on a research topic related to physics. To do this, I moved to the south of Mexico, to the CRyA, to work on an astronomy project, and this was to become the start of my career as an astronomer.

I had the pleasure and honour to work with Yolanda Gomez on my project. She taught me everything about planetary nebulae, and, most importantly, how to analyse interferometric data using the Astronomical Image Processing System (AIPS). My thesis project was on measuring the distances to planetary nebulae using a technique called expansion parallax, where you observe the same planetary nebula at two different epochs. Then, because of the high resolution of radio interferometry from the Very Large Array (VLA), you can measure the expansion of the nebula. Having the expansion in the plane of the sky and the velocity corresponding to this expansion, gives the distance straightaway, so it is a simple and neat way to get the distance to a stellar object. I realised back then that knowing the distance to an astronomical object is one of the most important parameters an astronomer needs so that they can start to understand its luminosity, mass, temperature, and to be able to make an accurate model of the object.

After this short project, I was more convinced than ever that astronomy was my ideal job. Therefore I applied for a grant to do a Masters degree at the same institute, to keep working with Yolanda Gomez and measuring the distances to more planetary nebulae. In Mexico the Masters programme lasts two years, or four semesters; for the first three semesters you have to take courses, covering anything from star formation to cosmology. In the last semester you prepare for an exam, called the general exam and anything from the last year and a half will be covered in this exam. In the third semester I went to the VLA summer school to learn more about interferometry and data reduction. During this summer school we visited the site where the antennas are based; that was an amazing experience and I also saw the first prototype of what was going to be an ALMA antenna (see Figure). I remember thinking back then that my next dream would be to work for ALMA.

During the last semester when I was preparing my exam, my Masters supervisor, Yolanda, told me about a conference that she thought it would be good for me to go to: the Asymmetric Planetary Nebulae IV conference, held in La Palma, in 2007. This was my first international conference, and the one at which I could meet all the authors of the “famous” papers I was reading. I think this conference also marked a milestone in my life in astronomy; I met a lot of people with whom I am now working, and, more specifically, the conference summary was given by Albert Zijlstra, who became my PhD supervisor a few months later.

After passing my exam and getting the Masters degree, I applied for a grant to do my PhD in England and by the beginning of 2009 I was living in sunny Manchester, ready for four years of full-on research towards a PhD in astrophysics at the Jodrell Bank Centre for Astrophysics of the University of Manchester.

I moved to Manchester with the idea that, because it was going to be so different from Mexico, I was not going to like it, and that the weather was going to be my worst enemy. It turned out that those four years in Manchester were probably some of the best years of my life. I met amazing people and I ended up loving the city and its rain. After a year of living in Manchester I really learnt to appreciate the Sun and warm days. From 2009 to 2013 I specialised in infrared and optical astronomy and performed a lot of spectroscopic observations in order to find new planetary nebulae in the Galaxy. I had to do the observations with small-ish telescopes in the US, South Africa and Australia. During my travels I met a few people from each institute, and I ended up spending three months in Sydney, Australia, working at Macquarie University with Quentin Parker, and two months in ESO Garching, working with Eric Lagadec on some infrared data taken with the VISIR instrument on the VLT. This was my first encounter with data from an 8-metre telescope and with ESO specifically. These infrared data made me focus more on observations of polycyclic aromatic hydrocarbons (PAHs) in planetary nebulae, and more specifically, trying to understand their formation and evolution in different environments.

During my PhD I worked as a teaching assistant in the physics department of the University of Manchester and I taught Spanish to English students who had received an Erasmus grant to go to Spain for a year, in order to help them in their preparations. I really enjoyed teaching, but I always loved going observing a lot more, so I decided that I wanted to work at an observatory. This decision led me to the next step on my career, applying for an ESO Fellowship to work for ALMA. In the last months of my PhD my supervisor gave me some data that was abandoned in his hard drive; this was radio interferometry data from the VLA, and I analysed them with CASA (Common Astronomy Software Applications). I had to get all my rusty knowledge on AIPS back and used the AIPS-to-CASA guides. This gave me a huge advantage when I applied for the ESO Fellowship, because I already knew how to use CASA, the software used to analyse ALMA data.

Luckily I was awarded the ESO Fellowship, so in April 2013 I moved to Chile to start a new chapter of my life. I was happy to be back in a country where I could speak Spanish again, where it turns out that in Chile people speak Chilean (not exactly Spanish), but I think I manage to understand them and make myself understood “most” of the time. I’m on the third year of my Fellowship now, and I have to start thinking about the next step already. But the last three years have been nothing but amazing. I really enjoy going up to the ALMA Observatory; for me the ESO Fellowship is a great compromise between your science and being able to learn all about the instrument you are using, from planning the observations to delivering the data. During the Fellowship, I have done observing shifts, collecting as much data as possible, and have also done commissioning shifts, where we test new software, try different modes, and test the telescope to its limits, like the Long Baseline Campaign in 2014, or the high frequency campaign.

On one of my recent trips to the ALMA Observatory I went to visit the antennas (at 5000 metres above sea level) and I remembered my photo from the summer school back in 2008. So I took a similar photo to remind myself that whatever dream you have, with enough effort and dedication, you can reach it. Now I just need to keep dreaming!

Rebeca Aladro

I had the luck to grow up in a house full of books. My mum always liked to read science fiction and outreach. I fondly remember a couple of books, written by Carl Sagan and Isaac Asimov, which I read when I was in school. I was fascinated by the explanations about physics and the Universe. I exerted myself to understand all these strange theories about quarks, the Big Bang and the first seconds of the Universe, black holes, and many others. Of course, I just grasped half of the things (if that), but the curiosity was already there.

Time passed, and for many years I basically continued to read outreach and science fiction. Questions accumulated in my mind: what was there before the Big Bang? How does a black hole form and die, and what happens inside? Some questions that, years after, when motivated by curiosity, I began to study astrophysics, I discovered do have not answers so far. It's so funny that you decide to embark on a career to understand those rare things, only to find out that we do not have answers for many of them. Plop!

I studied astrophysics in Tenerife, where I met my husband. As a student at La Laguna University and Instituto de Astrofísica de Canarias (IAC), my little bit of experience was centred on optical telescopes. But when the moment to look for a PhD place came, I chose to do my thesis in radio astronomy, at the Institut de radioastronomie millimétrique (IRAM). I admit that I had no idea of what radio astronomy was. But the prospect of working at a telescope and living in Granada (in the south of Spain) was very tempting. During the interview for my PhD, my supervisor explained to me how cool the 30-metre telescope was (is). And I was completely surprised to hear that the pixel size changed with the observed frequency, and that they were very proud of a new instrument of 3 × 3 pixels (only!). Oh yes, radio astronomy is a different world!

Rebeca Aladro

My PhD thesis was about the study of the physical and chemical properties of the molecular clouds in the central parts of active galaxies, where starburst events and supermassive black holes are typically found. In particular, the study centred on how the cold gas is influenced by the heating processes taking place in such regions (mainly ultraviolet [UV] fields, shocks, X-rays, cosmic rays, or a combination of them). During those years, I carried out duties at the 30-metre telescope during 25 % of my time, learning the basics related to observation at millimetre and submillimetre wavelengths, instrumentation, and single-dish data reduction.

I also learned other important things. Probably one of the most important was how the life of an astronomer really is. I still wonder why they don't talk about that during career sessions. The pros and the cons. When you finish university you have your head full of numbers and theories, but know nothing about real life. Again, when I started a PhD, I had no idea that giving talks at international conferences is a big part of the deal. I remember the two months prior to my first talk with terror and anxiety. The idea of quitting even crossed my mind. But I survived, as we all do. I learned to confront and overcome my concerns, and that made me stronger and more independent.

After completing my PhD I moved to University College London as a postdoc. There I worked with time and optical depth dependent chemical models, which I applied to NGC 1068, one of the most famous Seyfert 2 galaxies. Simultaneous modelling of the abundances of 25 molecular species had never been performed before, and allowed me to constrain the physical characteristics of the circum-nuclear molecular gas, strongly influenced by cosmic rays and UV fields. On the personal side, although there for only one year and a half, my husband and I really enjoyed London. Yes, living in a place that you like is for me as important as working. We are not only astronomers. Before that, we are people and we have to enjoy life.

My second and current postdoc is at ESO Chile, with duties at ALMA and APEX. I had the luck to arrive at a very exciting moment, when ALMA started the first Early Science observations. Being part of the operations of such a big interferometer, whose potential we are just starting to realise, is really exciting and motivating. Just few days ago we were celebrating a new milestone, reaching 1770 baselines with 60 antennas.

However, my time in Chile is now coming to an end. In September we are moving to Sweden for my fourth ESO Fellowship year, plus another postdoc. I will continue doing ALMA duties from the Nordic Arc Node while, on the research side, I will be studying the molecular outflows of active galaxies, a quite new topic in radio astronomy. Many questions are just starting to be addressed — such as the quenching effects of the outflows in the star formation and activity of a galaxy.

Personnel Movements

Arrivals (1 July–30 September 2015)

Europe	
Cikota, Aleksandar (HR)	Student
Cirasuolo, Michele (IT)	E-ELT Programme Scientist
De Cia, Annalisa (IT)	Fellow
Ellis, Richard (UK)	Visiting Senior Scientist
Faran, Tamar (IL)	Student
Hallakoun, Naama (IL)	Student
Hartke, Johanna (DE)	Student
Lavail, Alexis (FR)	Student
Nicholson, Belinda Annette (AU)	Student
Surot Madrid, Francisco (CL)	Student
Tuti, Mauro (IT)	E-ELT Programme Controller

Chile	
Badinez, Rodrigo (CL)	Instrumentation Engineer
Dias, Bruno (BR)	Fellow
Espinoza, Marcela Estefanía (CL)	Telescope Instruments Operator
Martin, Sergio (ES)	Operations. Staff Astronomer
Perez-Beaupuits, Juan-Pablo (CL)	User Support Astronomer
Velásquez, José (CL)	Telescope Instruments Operator

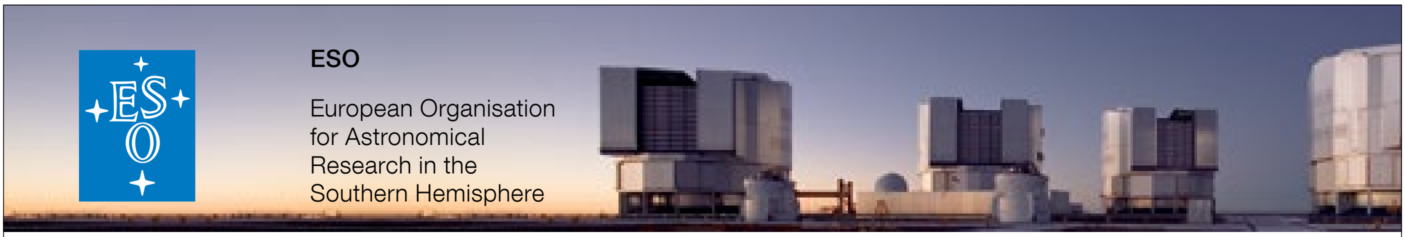
Departures (1 July–30 September 2015)

Europe	
Bode, Anita (DE)	Secretary/Administrative Assistant
Buzzoni, Bernard (FR)	Optical Technical Engineer
Gibson, Neale (UK)	Fellow
Gullberg, Bitten (DK)	Student
Murray, John (UK)	Senior Mechanical Engineer
Noirot, Gaël (FR)	Student
Pitchford, Lura Katherine (US)	Student
Wang, Ke (CN)	Fellow

Chile	
Beamin, Juan Carlos (CL)	Student
Dumas, Christophe (FR)	Head of Science Operations Paranal
Kruehler, Thomas (DE)	Fellow
Kublik, Basilio (CL)	IT Infrastructure Specialist
Matrà, Luca (IT)	Student
O'Neal, Jared (US)	System Engineer
Pérez, Manuel Angel (ES)	Operations Staff Astronomer
Sababa, Nadja (CL)	Administrative Assistant
Vlahakis, Catherine (UK)	Deputy Programme Scientist
Wesson, Roger (UK)	Fellow

ESO/A. Santerne

Star trails towards the south celestial pole photographed over the La Silla Observatory. See Picture of the Week for 24 August 2015.



ESO

European Organisation
for Astronomical
Research in the
Southern Hemisphere

ESO Studentship Programme 2015/2016 — Second Call

The research studentship programme of the European Southern Observatory provides an outstanding opportunity for PhD students to experience the exciting scientific environment at one of the world's leading observatories for a period of up to two years.

ESO is the foremost intergovernmental astronomy organisation in Europe. Its approximately 110 staff astronomers, 40 Fellows and 50 PhD students conduct front-line research in fields ranging from exoplanets to cosmology, offering one of the most vibrant and stimulating scientific settings anywhere in the world.

ESO's studentship positions are open to students enrolled in a PhD programme in astronomy or related fields. Students accepted into the programme work on their doctoral project under the formal supervision of their home university, but they come to ESO to work and study under the co-supervision of an ESO staff astronomer, normally for a period of between one and two years. Studentships may be hosted either at ESO's Headquarters in Garching (Germany) or at ESO's offices in Santiago (Chile), where up to two positions per year are provided for students enrolled in South American universities.

Applicants and their home institute supervisors should agree upon and coordinate their research project jointly with their prospective ESO supervisor. For this purpose the ESO supervisor should be contacted well in advance of the application deadline (15 November 2015). A list of potential ESO supervisors and their research interests can be found at http://www.eso.org/sci/activities/personnel.html. A list of PhD projects currently being offered by ESO staff is available at http://www.eso.org/sci/activities/thesis-topics.html.

ESO Chile students have the opportunity to visit the observatories and to get involved in small technical projects aimed at giving insights into the observatory operations and instrumentation. Such involvement is also strongly encouraged for Garching students. In addition, students in Garching may attend and benefit from the series of lectures delivered in the framework of the International Max-Planck Research School on Astrophysics. ESO students are expected to contribute to the science life at ESO, participating in the activities promoted by the Offices for Science, including organising seminars and workshops, science gatherings, training sessions, outreach initiatives, etc.

Students who are already enrolled in a PhD programme in the Munich area (e.g., at the International Max-Planck Research School on Astrophysics or a Munich University) and who wish to apply for an ESO studentship in Garching, should provide a compelling justification for their application.

If you are interested in enhancing your PhD experience through an extended stay at ESO, then please apply by completing the web application form available at http://jobs.eso.org/.

Please include the following documents in your application:
- a cover letter;
- a Curriculum Vitae, including a list of publications, if any;
- copies of your university transcript and certificate(s) or diploma(s);
- a summary of your master's thesis project (if applicable) and ongoing projects, indicating the title and the supervisor (maximum half a page);
- an outline of the proposed PhD project highlighting the advantages of coming to ESO (recommended one page, maximum two);
- the names and contact details of your home institute supervisor and the ESO local supervisor. They will be automatically invited to submit a recommendation letter, however, applicants are strongly advised to trigger these invitations (using the web application form) well in advance of the application deadline;
- a letter from the home institute that: i) guarantees financial support for the remaining PhD period after the termination of the ESO Studentship; ii) indicates whether the prerequisites to obtain the PhD degree at the home institute have already been met.

All documents should be typed in English (but no translation is required for the certificates and diplomas).

Previously the ESO Studentship application deadline was only in May of each year, but a second application round has now also been opened. The closing date for applications is 15 November 2015. Review of the application documents, including the recommendation letters, will begin immediately. Incomplete or late applications will not be considered.

Candidates will be notified of the results of the selection process during December 2015. Studentships will normally begin between January and June 2016.

Further information

For more information about the studentship programme please see: http://www.eso.org/studentship.

For a list of current ESO staff and fellows, and their research interests, please see: http://www.eso.org/sci/activities/personnel.html.

A list of PhD projects currently being offered by ESO staff can be found at: http://www.eso.org/sci/activities/thesis-topics.html.

Details on the employment conditions and benefits are available at: http://www.eso.org/public/employment/student.html.

For any additional questions, please contact:

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For Chile: Claudio De Figueiredo Melo, Tel. +56 2 4633032,
email: cmelo@eso.org.

Although recruitment preference will be given to nationals of ESO Member States (Austria, Belgium, Brazil, the Czech Republic, Denmark, Finland, France, Germany, Italy, the Netherlands, Poland, Portugal, Spain, Sweden, Switzerland and United Kingdom), and, for Chile, to students enrolled in a South American university, no nationality is in principle excluded.

The post is equally open to suitably qualified female and male applicants.

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Contents

The Organisation

Sarna M. & Stępień K. – Astronomy in Poland 2
Primas F. et al. – Shaping ESO2020+ Together: Feedback from the Community Poll 6

Astronomical Science

Yan F. et al. – HARPS Observes the Earth Transiting the Sun — A Method to Study Exoplanet Atmospheres Using Precision Spectroscopy on Large Ground-based Telescopes 17
Molaro P. et al. – Simultaneous HARPS and HARPS-N Observations of the Earth Transit of 2014 as Seen from Jupiter: Detection of an Inverse Rossiter–McLaughlin Effect 20
Soto M. et al. – RAFT I: Discovery of New Planetary Candidates and Updated Orbits from Archival FEROS Spectra 24
Meléndez J. et al. – Using Solar Twins to Explore the Planet–Star Connection with Unparallelled Precision 28
Davies B. et al. – Red Supergiants as Cosmic Abundance Probes 32

Astronomical News

Küpper A. & Mieske S. – Report on the ESO Workshop "Satellites and Streams in Santiago" 38
Walsh J. et al. – Report on the ESO Workshop "Stellar End Products: The Low-mass – High-mass Connection" 43
Sedaghati E. & Boffin H. – Report on the "Chilean Exoplanet Meeting" 49
Fellows at ESO – L. Guzman-Ramirez, R. Aladro 51
Personnel Movements 54
ESO Studentship Programme 2015/2016 — Second Call 55

Front cover: Colour image of the Galactic star-forming region IC 4628, (also know as Gum 56) taken with the MPG/ESO.2.2-metre telescope and the Wide Field Imager (WFI). Images in three broadband filters (*B*, *V*, *R*) and two narrowband filters, featuring the emission lines of Hα and [O III]500.7 nm, were combined. The broadband filters emphasise the stellar and extinction features and the narrow filters the emission produced by photoionisation from several O stars in this H II region. IC 4628 is part of the Sco OB I association at a distance of about 2 kpc. See Release eso1535 for more information.