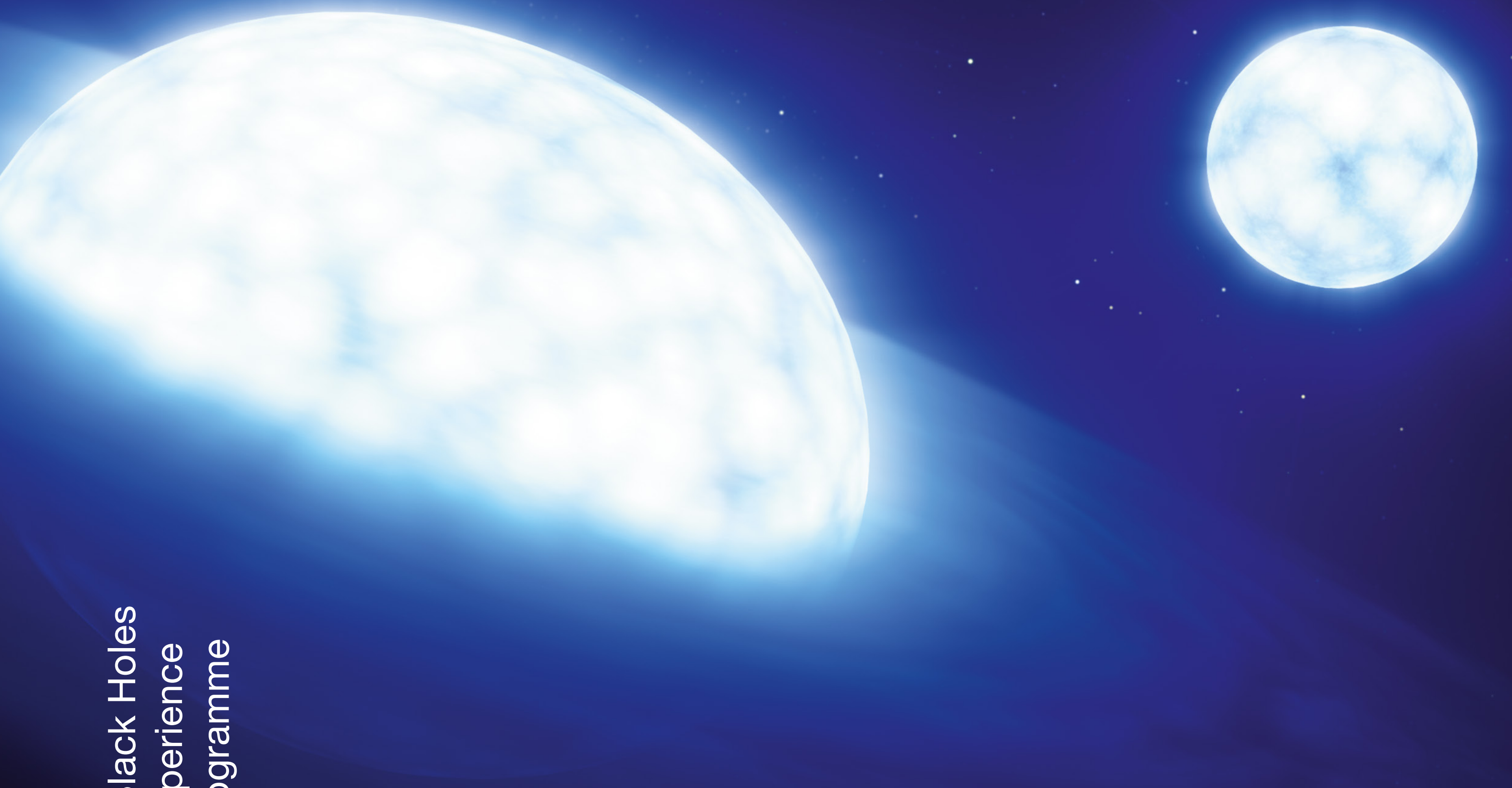
The Messenger

No. 186 | 2022



Stripped Stars and Quiescent Black Holes
Redesigning the ALMA User Experience
The ESO Summer Research Programme

ESO, the European Southern Observatory, is the foremost intergovernmental astronomy organisation in Europe. It is supported by 16 Member States: Austria, Belgium, the Czech Republic, Denmark, France, Finland, Germany, Ireland, Italy, the Netherlands, Poland, Portugal, Spain, Sweden, Switzerland and the United Kingdom, along with the host country of Chile and with Australia as a Strategic Partner. ESO's programme is focussed on the design, construction and operation of powerful ground-based observing facilities. ESO operates three observatories in Chile: at La Silla, at Paranal, site of the Very Large Telescope, and at Llano de Chajnantor. ESO is the European partner in the Atacama Large Millimeter/submillimeter Array (ALMA). Currently ESO is engaged in the construction of the Extremely Large Telescope.

The Messenger is published, in hardcopy and electronic form, four times a year. ESO produces and distributes a wide variety of media connected to its activities. For further information, including postal subscription to The Messenger, contact the ESO Department of Communication at:

ESO Headquarters
Karl-Schwarzschild-Straße 2
85748 Garching bei München, Germany
Phone +498932006-0
information@eso.org

The Messenger
Editor: Mariya Lyubenova
Editorial assistant: Isolde Kreutle
Copy-editing, Proofreading:
Peter Grimley
Layout, Typesetting, Graphics:
Lorenzo Benassi
Design, Production: Jutta Boxheimer
www.eso.org/messenger/

Printed by omb2 Print GmbH,
Lindberghstraße 17, 80939 Munich,
Germany

ISSN 0722-6691

Contents

Astronomical Science

Instrumentation

Astronomical News

Front cover: This artist's impression shows what the system HR 6819 might look like; it is composed of an oblate star with a disc around it (a Be "vampire" star; foreground) and B-type star that has been stripped of its atmosphere (background). New research using data from ESO's Very Large Telescope and Very Large Telescope Interferometer has revealed that HR 6819, previously believed to be a triple system with a black hole, is in fact a system of two stars with no black hole. The research team concludes that they have observed this binary system in a brief moment after one of the stars sucked the atmosphere off its companion, a phenomenon often referred to as "stellar vampirism". A review article on this (and a few other intriguing systems) is presented on pp. 3–9.
Credit: ESO/L. Calçada.

DOI: 10.18727/0722-6691/5255

Detecting Stripped Stars While Searching for Quiescent Black Holes

Julia Bodensteiner[1]
and Marianne Heida[1]
Michael Abdul-Masih[1]
Dietrich Baade[1]
Gareth Banyard[2]
Dominic M. Bowman[2]
Matthias Fabry[2]
Abigail Frost[2]
Laurent Mahy[3]
Pablo Marchant[2]
Antoine Mérand[1]
Maddalena Reggiani[2]
Thomas Rivinius[1]
Hugues Sana[2]
Fernando Selman[1]
Tomer Shenar[4]

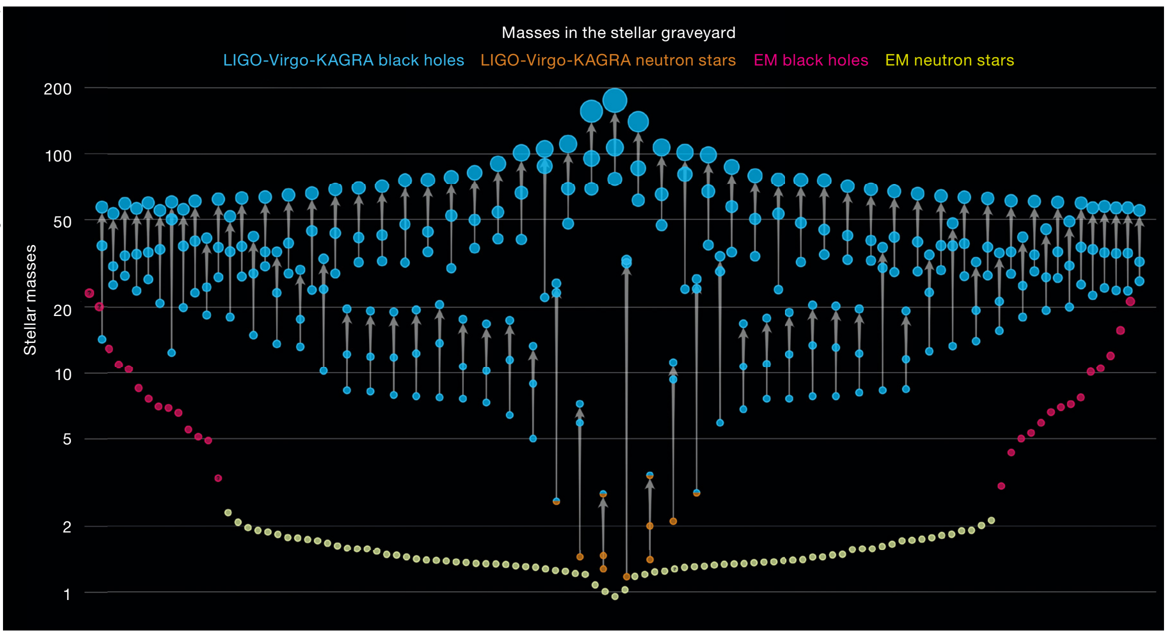
[1] ESO
[2] Institute of Astronomy, KU Leuven, Belgium
[3] Royal Observatory of Belgium, Brussels, Belgium
[4] Anton Pannekoek Institute for Astronomy, University of Amsterdam, the Netherlands

While the number of stellar-mass black holes detected in X-rays or as gravitational wave sources is steadily increasing, the known population remains orders of magnitude smaller than predicted by stellar evolution theory. A significant fraction of stellar-mass black holes is expected to hide in X-ray-quiet binaries where they are paired with a "normal" star. Although a handful of such quiescent black hole candidates have been proposed, the majority have been challenged by follow-up investigations. A confusion that emerged recently concerns binary systems that appear to contain a normal B-type star with an unseen companion, believed to be a black hole. On closer inspection, some of these seemingly normal B-type stars instead turn out to be stars stripped of most of their mass through an interaction with their binary companion, which in at least two cases is a rapidly rotating star rather than a compact object. These contaminants in the search for quiescent black holes are themselves extremely interesting objects as they represent a rare phase of binary evolution, and should be given special attention when searching for binaries hosting black holes in large spectroscopic studies.

Black holes as tracers of massive-star evolution

Massive stars play an important role in the Universe. They are sources of energetic radiation, forge heavy chemical elements from the nuclear reactions occurring in their cores, and provide dynamical and chemical feedback via their strong stellar winds. Stars massive enough to undergo core collapse may end their lives in a supernova explosion, releasing the freshly formed elements and possibly leaving behind a neutron star or a stellar-mass black hole. They can also collapse directly into a black hole, or explode in a pair-instability supernova without leaving a remnant behind (see, for example, Heger et al., 2003; Sukhbold et al., 2016). The specific factors that dictate which stars will reach a particular fate are not yet completely understood but they have implications for the type of supernova that will occur, the properties of the remnant they leave behind, and the enrichment of the interstellar medium (see, for example, Farmer et al., 2021; Laplace et al., 2021). Apart from the supernovae themselves, the distributions of black hole masses, spins and natal kicks provide important clues about the final stages of massive stars. Studying these ideally requires a large and unbiased sample of stellar-mass black holes, which is difficult to build up observationally.

Given that black holes are intrinsically dark objects, detecting them on their own is almost impossible. Currently, black holes are discovered mainly in two ways: as X-ray binaries, when they accrete material from a companion star, or as gravitational wave sources, when they merge with another black hole or neutron star. The black holes found in Galactic X-ray binaries tend to have lower masses



LIGO/Virgo/A. Geller/Northwestern University

Figure 1. Overview of black hole and neutron star masses detected using different techniques including gravitational wave detections by LIGO/Virgo/KAGRA (bright blue) and electromagnetic detections mainly in X-ray binaries (dark red). While the gravitational wave detections span the mass range ~ 3–100 $M_{\odot}$ for single black holes, those detected in X-ray binaries only go up to ~ 21 $M_{\odot}$.

(~ 5–20 $M_\odot$, Corral-Santana et al., 2016), while the black holes found by the Laser Interferometer Gravitational-Wave Observatory and its European counterpart (LIGO/Virgo) span a much larger mass range (3–100 $M_\odot$; see Figure 1 and, for example, Fishbach & Holz, 2017). The two populations are subject to different observational and evolutionary selection biases (for example, Tauris & van den Heuvel, 2006; Mandel & Farmer, 2018).

But these accreting and merging black holes are only the tip of the iceberg. Since most of the massive stars that have formed throughout the history of the Universe end their lives as black holes, and there is basically no mechanism to destroy them, many more of them should be out there. Population synthesis calculations predict a population of order 10^7 black holes in the Milky Way alone (van den Heuvel, 1992), of which only about 100 (confirmed and candidate) have been discovered in X-ray binaries. The vast majority of the remaining black holes are not accreting enough material to show up in X-ray observations and are therefore called quiescent black holes. There are several ways to potentially detect these: microlensing is a promising technique (Paczynski, 1986; Wyrzykowski & Mandel, 2020), as are astrometric detections using Gaia data (Breivik, Chatterjee & Larson, 2017; Janssens et al., 2021). In addition, it has been suggested that periodic variability of the orbital periods of several close binaries is due to a quiescent black hole as a tertiary component (Qian, Liao & Fernández Lajús, 2008; Liao & Qian, 2010; Er-Gang et al., 2019; Wang & Zhu, 2021). However, most of the candidates identified to date were found in spectroscopic studies by detecting the motion of a star orbiting a dark, unidentified object.

The spectroscopic search for quiescent black holes

Binary systems offer unique possibilities for determining the masses of stars and compact objects, for example using phase-resolved spectroscopic observations. If both components of a binary are visible in the spectra and their lines show radial velocity (RV) variations in antiphase with each other (also referred to as reflex motion), their mass ratio is simply the inverse of the ratio of their radial velocity semi-amplitudes. If, in addition to the mass ratio, the mass of one of the components of the binary is known, the mass of the second object automatically follows. A second way to obtain information on the masses of binary stars that is also useful for systems where only one object is visible in the spectra, is via the so-called binary mass function. This only requires knowledge of the orbital period and the radial velocity semi-amplitude of one of the binary components, and provides a strict lower limit on the mass of the other component (see, for example, Casares & Jonker, 2014). To obtain the actual mass of this second object, either the mass ratio of the binary or the mass of the first object has to be determined, as well as the orbital inclination.

When searching for X-ray-quiet stellar-mass black holes one should therefore look for stars with approximately sinusoidal radial velocity variations, indicating that they are part of a binary, but without a visible companion showing a reflex motion. The best candidates are early-type stars (which are generally more massive) with large radial velocity amplitudes and long orbital periods. These characteristics combined imply a high mass of the unseen companion. However, there are many possible reasons why this unseen companion cannot be discerned in the spectra other than its being a black hole. It could be a star that is not detected either because of low-quality data, or because it is faint compared to the initially discovered star. Another possibility is that the companion is rotating rapidly, causing its absorption lines to be broad and shallow.

Large surveys, both in train and planned, will provide extensive homogeneous spectroscopic datasets that enable scientists to mine for quiescent black holes (Gu et al., 2019; Yi, Sun & Gu, 2019). Surveys currently underway include those carried out with the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; Cui et al., 2012) and the Sloan Digital Sky Survey (SDSS; York et al., 2000). The near future will see surveys using the 4-metre Multi-Object Spectrograph Telescope (4MOST) which will enter operation in 2023 at the VISTA telescope in Paranal (de Jong et al., 2012) and the WHT Enhanced Area Velocity Explorer (WEAVE; Dalton et al., 2012) at the William Herschel Telescope. While the detection principle of quiescent black holes is simple, one should be aware of the contaminants mentioned above. Their diversity is illustrated by the competing explanations put forward for several of the candidate quiescent black holes discovered to date. Here we provide a short overview of the current sample of candidate quiescent black holes and their alternative interpretations, and then focus on one particular class of contaminants that is extremely interesting in its own right, namely stripped B-type stars with a rapidly rotating companion star.

Candidate quiescent black holes

Only a handful of candidate quiescent black holes have been reported to date. Three systems strongly suspected to contain a black hole with a relatively massive companion star are, MWC 656, a binary system of a black hole and a classical Be star (Casares et al., 2014); AS 386, a B[e] star with a ~ 7 $M_\odot$ dark companion (Khokhlov et al., 2018); and HD 96670, a ~ 22 $M_\odot$ O star in a close binary with a ~ 7 $M_\odot$ black hole and possibly a third component (Gomez & Grindlay, 2021). Both MWC 656 (Munar-Adrover et al., 2014) and HD 96670 (Grindlay et al., in preparation) were subsequently found to show faint X-ray emission with a hard power-law spectrum consistent with very low-level accretion onto a compact object; MWC 656 has also been detected in the radio, further strengthening its identification as a black hole accreting at a very low level (Dzib, Massi & Jaron, 2015). None of these three quiescent black holes has thus far been disputed. A recent addition to the list of black hole companions to massive stars is NGC 2004#115 (Lennon et al., 2021), a B-type star with a suggested 25 $M_\odot$ black hole companion. However, the presence of a massive compact object in this system hinges on the inferred orbital inclination of only 9 degrees, which has been challenged by El-Badry, Burdge & Mroz (2021).

There are six candidate quiescent black holes with low-mass stellar companions.

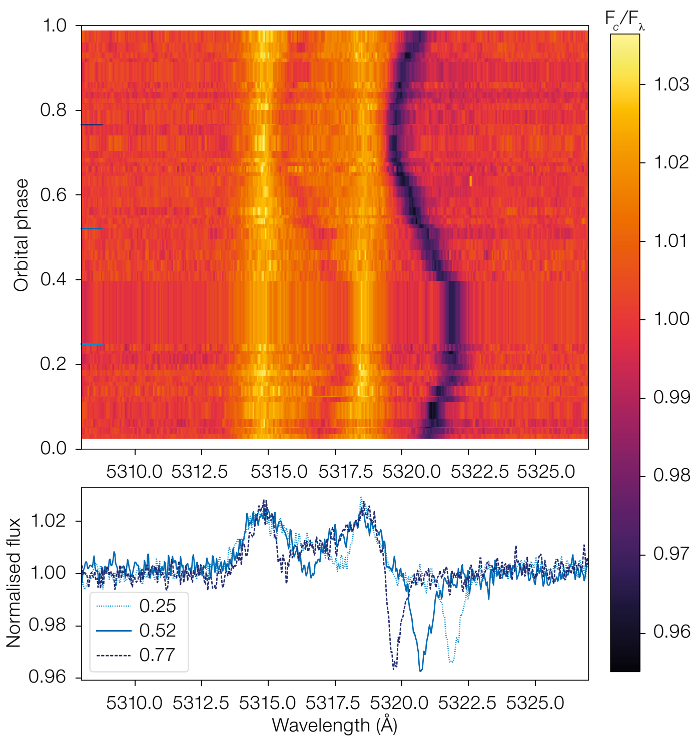


Figure 2. Phase-resolved spectra of HR 6819 showing the region around the Fe II line at 5316 Å, covering the orbital period of 40 days. The top panel shows the dynamical spectrum while the bottom panel shows three individual normalised spectra at phase 0.25, 0.52 and 0.77 as indicated in the legend. The double-peaked emission line (in bright), which seems to be stationary, is attributed to the Be star in the system, while the periodically shifting absorption lines (in dark) are attributed to the B-type star.

Three are located in the Galactic globular cluster NGC 3201, with minimum masses of ~ 4, ~ 4 and ~ 8 $M_\odot$, respectively (Giesers et al., 2018, 2019. Two systems, and V723 Mon and 2MASS J05215658+4359220, are red giants with a ~ 3 $M_\odot$ dark companion (Thompson et al., 2019; Jayasinghe et al., 2021; Masuda & Hirano, 2021). However, it has been pointed out that at least the latter system could also be a triple system with a giant tertiary star and an inner binary consisting of two main-sequence stars (van den Heuvel & Tauris, 2020; and see Thompson et al., 2020 for a response). The existence of a third, very similar system consisting of an evolved red giant with a 2–3 $M_\odot$ dark companion was proposed recently (Jayasinghe et al., 2022).

Finally, there are three systems, LB-1 (Liu et al., 2019), HR 6819 (Rivinius et al., 2020) and NGC 1850 BH1 (Saracino et al., 2021) that were recently reported as quiescent black holes accompanied by a B-type star. However, it was subsequently proposed that they are instead binary systems consisting of a stripped B-type star and another luminous star (Shenar et al., 2020b; Bodensteiner, et al., 2020; El-Badry & Quataert, 2021; El-Badry & Burdge, 2021; Frost et al., 2022). The nature of NGC 1850 BH1 is still highly debated: El-Badry & Burdge (2021) point out that, given the orbital parameters, the mass of the radial-velocity variable star must be much lower than that assumed by Saracino et al. 2021. This implies a lower mass for the unseen companion that moves it out of the black hole mass range. Stevance, Parsons & Eldridge (2021) add that theoretically the black hole scenario is very unlikely. We therefore focus on HR 6819 and LB-1 in the following.

The spectroscopic signature of LB-1 and HR 6819

LB-1 and HR 6819 share a specific spectroscopic signature. They both show narrow absorption lines indicative of a B-type star moving on a period of tens of days (that we will refer to as the RV variable star), as well as broad emission lines that appear stationary (see Figure 2). The interpretation of these systems hinges on 1) the source of the emission features, which could originate in an accretion disc, a circumbinary disc, or a decretion disc around a rapidly rotating star — a so-called classical Be star (Rivinius, Carciofi & Martayan, 2013) — and 2) whether the emission features are indeed stationary or instead show a small reflex motion with respect to the B-type star. If they are moving in anti-phase, then the B-type star and the source of the emission features form a binary system. If the emission lines are truly stationary, the B-type star orbits an unseen object and the source of the emission lines is either an unrelated star associated only by chance superposition, or it is a third, outer component, making the system a triple system.

The detection of rotationally broadened photospheric absorption lines in the spectrum in combination with the emission lines is evidence for the presence of a classical Be star, and thus settles 1) above. However, these absorption lines are difficult to detect as they are very shallow. Settling 2) above is also challenging as the emission features are broad and affected by superimposed, moving absorption lines from the B-type star, making a small radial velocity amplitude hard to detect. This is additionally complicated by the fact that the two stars have similar temperatures and therefore the same set of spectral lines.

Black holes or stripped stars in LB-1 and HR 6819?

In 2019 LB-1 made headlines as a binary system of a B-type star and a 70 $M_\odot$ black hole (Liu et al., 2019). They reported a small reflex motion of the H-alpha emission line but did not detect broad absorption lines. Interpreting the emission features as evidence for an accretion disc around a black hole and assuming a typical mass of ~ 5 $M_\odot$ for the B-type star then led to the large inferred black hole mass. As this exceeded predictions from stellar evolution theory, the finding triggered an intense debate. While theorists tried to reconcile theory and observations by adapting their black hole mass predictions (Groh et al., 2020; Eldridge et al., 2020; Safarzadeh, Ramirez-Ruiz & Kilpatrick, 2020; Belczynski et al., 2020), observers pointed out issues with the initial data analysis, in particular with the claim of reflex motion of the H-alpha line (Abdul-Masih et al., 2020; El-Badry & Quataert, 2020; Simón-Díaz et al., 2020; Irrgang et al., 2020). Based on new

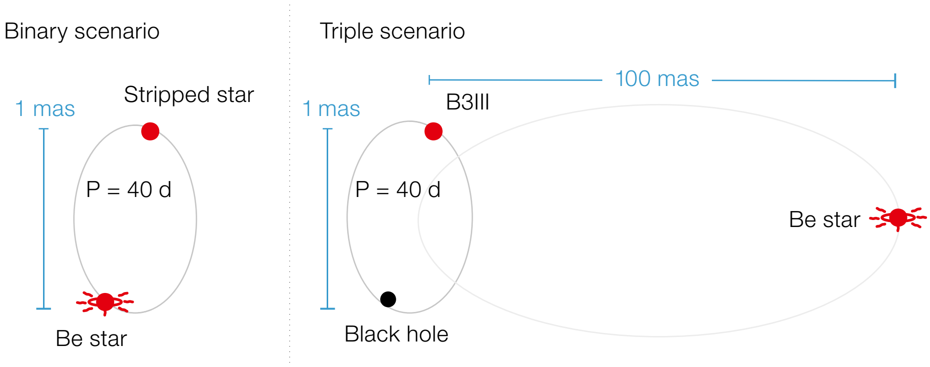


Figure 3. Schematic comparison between the binary and the triple scenario proposed for HR 6819. The projected distances on the sky between the two visible stars, the stripped star and the Be star in the binary scenario, and the B-type giant and the Be star in the triple scenario, are indicated in blue (Figures and symbols are not to scale).

near-infrared data, Liu et al. (2020) refined their analysis and reduced the claimed mass of the unseen companion. Using additional optical spectra, Shenar et al. (2020b) eventually detected broadened absorption lines, showing that instead of a black hole, the second object in the system is a Be star, although Lennon et al. (2021) have challenged this interpretation based on Hubble Space Telescope spectroscopy.

The broad absorption lines typical of a rapidly rotating star are more obvious in the high-quality spectra of HR 6819. In the 1980s, Dachs et al. (1981) and Slettebak (1982) had already noted the presence of both double-peaked emission lines due to a classical Be star, and narrow absorption features typical of a normal B-type giant in its spectrum. Maintz (2003) discovered that the narrow-lined star is on an orbit with a period of tens of days. With additional observations, Rivinius et al. (2020) showed that the star is moving on a 40-day period and reported that the absorption features of the Be star are consistent with its being stationary over a period of five years. Assuming a typical mass for the B-type star of ~ 5 $M_{\odot}$ and using the mass ratio obtained from the ratio of the RV semi-amplitudes would lead to an unphysical mass for the Be star if the two stars formed a binary. The Be star was thus interpreted as a third, outer component in a triple system, with the inner binary consisting of the B-type star and an unseen object of at least 4 $M_{\odot}$. As a normal star with this mass would have been visible in the spectra, this implied the presence of a stellar-mass black hole in the inner binary.

It was subsequently suggested that such a triple system would be unstable (Safarzadeh, Toonen & Loeb, 2020), and that the system could in fact be a quadruple (Mazeh & Faigler, 2020). However, the most robust challenge to the triple scenario came from three independent teams who re-analysed the optical spectra and found that the emission lines of the Be star do in fact show a subtle reflex motion with respect to the B-type star, as was found in LB-1 (Bodensteiner et al., 2020; El-Badry & Quataert, 2021; Gies & Wang, 2020). In this scenario, the B-type star and the Be star orbit around each other, removing the need for a third star or a black hole in the system. Figure 3 illustrates the different configurations of the binary and triple scenarios for HR 6819.

Stripped stars in disguise

Both LB-1 and HR 6819 can be explained as binary systems of a B-type star and a classical Be star, rather than involving a stellar-mass black hole or a triple configuration. However, the main reason that the black hole scenarios were invoked in the first place is that the projected orbital velocities determined for the narrow absorption lines of the B-type stars are much larger than the ones estimated from the emission lines tracing the Be stars. These large velocity ratios indicate a large mass ratio, implying that the mass of the B-type star is not in the typical range of 5–6 $M_{\odot}$ but is instead a much lower ~ 0.5 $M_{\odot}$, which is unusually low for B-type stars. In this interpretation, HR 6819 and LB-1 are thus post-mass-transfer binary systems. The mass donor, the present B-type star, has become a low-mass stripped star caught in a puffed-up stage (see also Irrgang et al., 2020), while the mass gainer, the present Be star, accreted matter and angular momentum and was spun up to rapid rotation, but has a normal mass for its spectral type.

Stripped stars are the cores of stars that have lost part or most of their H-rich envelope either by strong stellar winds (only feasible for stars with masses ≳ 20 $M_{\odot}$; for example, Puls, Vink & Najarro, 2008) or, as is the case here, by mass transfer in interacting binary systems (for example, Podsiadlowski, Joss & Hsu, 1992). Once the mass transfer is complete, the now-exposed helium core has to adjust to the lack of a stellar envelope and is thus puffed-up. After a subsequent contraction phase lasting around a million years, a new equilibrium is attained. Figure 4 shows a possible evolutionary path of such a stripped star in comparison to a single star. The overlap of the two tracks, in particular in luminosity, with the observed parameters of HR 6819 shows why such stars could be mistaken for a normal main-sequence star.

In the new equilibrium phase, the stars are compact and hot (with surface temperatures between 50 000 and 100 000 K) and emit primarily in the far UV (Götberg, de Mink & Groh, 2017; Götberg et al., 2018). At the upper end of the mass regime, stripped stars can launch powerful winds that result in strong emission lines (Wolf-Rayet stars), making them easier to detect (Breysacher, Azzopardi & Testor, 1999; Crowther, 2007; Shenar et al., 2020a). At lower masses, these so-called subdwarf OB stars (Heber, 2009) are not expected to exhibit emission lines in the optical, making their detection difficult (Wellstein, Langer & Braun, 2001; Wang et al., 2021). The properties of stripped stars in an intermediate mass range between Wolf-Rayet and subdwarf OB stars are still debated as they have so far eluded detection.

Given the relatively short lifetime of the contraction phase — it amounts to around 1% of the main-sequence lifetime of the Be star — we expect to find stripped stars primarily in the subsequent evolutionary phase, which lasts about 10 times longer and during which the stars are hot and compact. The properties of the stars reported as stripped stars in HR 6819 and LB-1, however, match those of stars at the beginning of the contraction phase shortly after the mass transfer stopped (Shenar et al., 2020b; Irrgang et al., 2020; Bodensteiner et al., 2020, El-Badry & Quataert, 2021). In fact, the larger radius (and hence higher luminosity) and the lower temperature (shifting the peak of the emission into the optical wavelength range) of the puffed-up stripped star make it easier to detect systems spectroscopically in this phase, despite its shorter duration and the fact that the stripped stars only resemble B-type main-sequence stars at the beginning of the contraction phase. These stars have temperatures and luminosities similar to those of a main-sequence B-type star, but the envelope stripping has reduced their mass to around 0.5 $M_{\odot}$. An additional observational characteristic that helps to spot them is that stripped stars are expected to be slow rotators, manifesting as narrow and deep absorption lines, as observed in LB-1 and HR 6819.

GRAVITY observations constraining the nature of HR 6819

Given the difficulties in measuring the orbital motion of the Be stars in LB-1 and HR 6819, both of the spectroscopic analyses presented above give plausible interpretations of the same observational dataset. Interferometric observations are the best way to obtain the definitive answer. The nearby (d ~ 300 pc) and bright (V = 5.4) HR 6819 system in particular is an ideal target for high-angular-resolution follow-up. The two proposed scenarios can be unambiguously distinguished by the spatial separation and motion of the two luminous sources: while they should only be 1–2 milliarcseconds apart and following a 40-day orbit according to the binary scenario, they should be significantly further apart and the Be star should be stationary on the month-long timescales of the observations according to the triple scenario with a black hole (see Figure 3).

Initially, speckle interferometry observations suggested the possible presence of a visible companion at around 120 milliarcseconds from the central source, favouring the triple scenario (Klement et al., 2021). Subsequently, higher-quality observations were executed using the Multi Unit Spectroscopic Explorer (MUSE) integral-field spectrograph at the Very Large Telescope (VLT) and the interferometric instrument GRAVITY at the VLT Interferometer (program ID 107.22R6, PI: Rivinius). While MUSE in its narrow-field mode covers the larger scales up to a few arcseconds, GRAVITY can resolve scales down to milliarcseconds.

As presented by Frost et al. (2022), the MUSE observations exclude the presence of a similarly bright source at around 120 milliarcseconds from the central source. The two GRAVITY epochs obtained approximately two weeks apart show two sources at a separation of ~ 1 milliarcsecond that switch position on the sky, as expected for a binary system on a 40-day orbit (see Figure 5). The two epochs thus unambiguously show that there are two luminous stars in a short-period binary, demonstrating that there is no black hole in the system.

Additional GRAVITY observations of HR 6819 (scheduled for April–September 2022, PI: Rivinius) will further allow the derivation of stellar parameters such as an accurate mass of the stripped star, which will be invaluable input for binary interaction models. Similarly, GRAVITY observations of LB-1 are scheduled before April 2022 (PI: Rivinius) and will hopefully pin down the nature of this

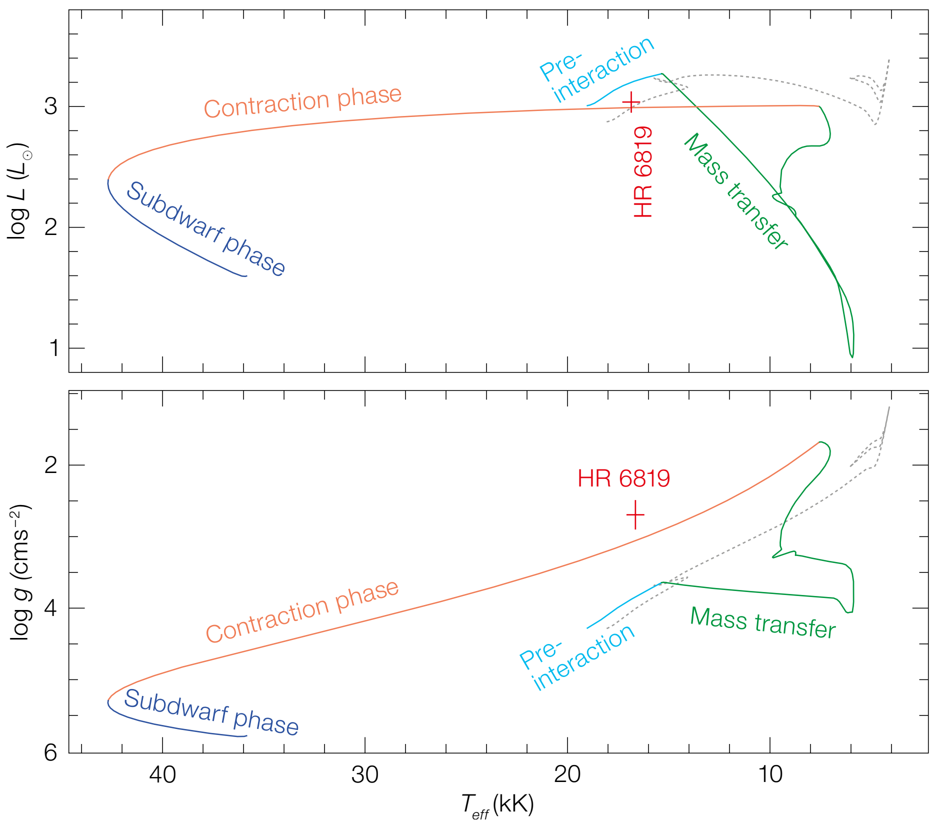


Figure 4. Possible evolutionary path of the stripped star in the HR 6819 system in a Hertzsprung-Russell (top panel) and a Kiel diagram (bottom panel), adapted from Bodensteiner et al. (2020). The different colours indicate different evolutionary phases and the red cross shows the observed properties of the stripped star in HR 6819. Note that the subdwarf phase lasts ~ 10 times longer than the contraction phase. Overplotted (in dotted grey) is the evolutionary track of a single star with an initial mass of 5.5 $M_{\odot}$. The Figure clearly shows that especially in temperature-luminosity space a contracting stripped star can be confused with a single main-sequence star, while the tracks are more separated in temperature–surface gravity space. A complete set of input files to reproduce the simulations underlying this figure can be found on Zenodo[2].

system as well, although its larger distance makes it a more difficult target (if the binary scenario proves correct, the two luminous stars will most likely not be resolved).

The way forward for large surveys

The quest for the missing black holes continues. The LAMOST, SDSS, 4MOST and WEAVE large-scale surveys will undoubtedly detect many binaries with only one visible component and a high mass function, implying the presence of a massive unseen companion that could be a black hole.

The detection of stripped stars in HR 6819, LB-1 and possibly also NGC 1850 BH1 teaches us two important lessons. First, the mass of the initially discovered RV variable star is very important. Such masses are often estimated from a rough translation of spectral type into mass, but we now know that seemingly normal B-type stars can also be recently stripped stars with a much lower mass. We expect many more binaries that are actually post-interaction systems containing a stripped star in disguise, as well as their direct progenitors and successors, to be detected in large-scale surveys. Examples of the latter two categories are systems found during the interaction phase (such as recently proposed by El-Badry et al., 2022), and rapidly rotating stars with hot, compact companions that have already returned to equilibrium (for example, pre-white dwarfs or subdwarfs; Gies et al., 2020; Wang et al., 2021). Second, when searching for quiescent black holes via the movement of their stellar companions, one needs to look extremely carefully for signals of a rapidly rotating star in the spectra. The detection of broad emission lines can be a strong observational signature of a Be star, but can in some cases also be attributed to the presence of an accretion disc around a compact object. Broad absorption lines are unequivocal evidence for a rapidly rotating star (with or without a decretion disc) but are much more difficult to detect.

The way forward will have to be through an interdisciplinary approach, taking advantage of the wealth of available observational information. High-spectral-resolution, high-signal-to-noise observations, for example with the Ultraviolet and Visual Echelle Spectrograph (UVES; Dekker et al., 2000) and the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO; Pepe et al., 2020) at the VLT, can help to identify the signatures of rapidly rotating companions as well as to obtain accurate parameters for the initially discovered RV variable stars. High-spatial-resolution spectroscopic follow-up, such as in the future with GRAVITY+ on the VLTI and the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph (HARMONI; Thatte et al., 2010) on ESO's Extremely Large Telescope (ELT), will be invaluable for distinguishing between scenarios with and without a black hole. Including multiwavelength data such as X-rays and radio may help to confirm the presence of a black hole accreting at very low rate. Long-term optical or near-infrared light curves can reveal low-amplitude orbital modulations that enable constraints on the orbital inclination to be set and may reveal a second luminous star even if it is not detected spectroscopically (Clavel et al., 2021; El-Badry, Rix & Heintz, 2021). Information from large-scale surveys, such as Gaia astrometry (and binary solutions in the future; Gaia Collaboration et al., 2016) or TESS photometry (Ricker et al., 2015) can also yield important pieces of the puzzle of understanding these newly detected systems. By employing these methods, we can not only better understand rare, post-interaction sources and thus binary evolution but also hone the search for black holes. After all, the presence of an intrinsically dark and quiet object can be only indirectly proven by rejecting all other possibilities.

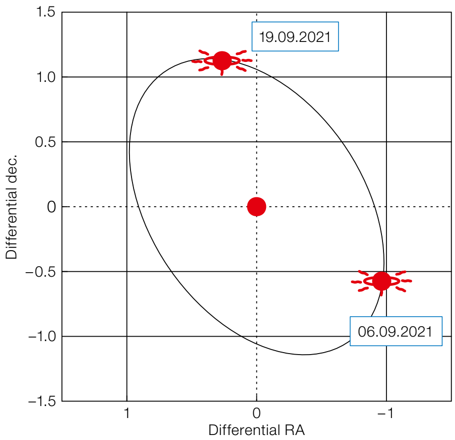


Figure 5. Relative astrometric orbit (black) of HR 6819 presented in Frost et al. (2022). The B-type star is fixed at coordinate (0,0) and the position of the Be star measured at two different epochs is indicated. It is obtained by simultaneously fitting the measured RVs of the B-type star and the astrometry obtained from interferometric observations with GRAVITY.

Acknowledgements

The authors would like to thank everyone involved in the HR 6819 project for their input and fruitful discussions. JB, MH and MAM are supported by an ESO Fellowship. DMB acknowledges a senior postdoctoral fellowship from the Research Foundation Flanders (FWO) with grant agreement no. 1286521N. PM acknowledges support from the FWO junior postdoctoral fellowship no. 12ZY520N. LM thanks the European Space Agency and the Belgian Federal Science Policy Office for their support in the framework of the PRODEX Programme. TS acknowledges support from the European Union's Horizon 2020 under the Marie Skłodowska-Curie grant agreement no. 101024605.

References

Abdul-Masih, M. et al. 2020, Nature, 580, E11
Belczynski, K. et al. 2020, ApJ, 890, 113
Bodensteiner, J. et al. 2020, A&A, 641, A43
Breivik, K., Chatterjee, S. & Larson, S. L. 2017, ApJL, 850, L13
Breysacher, J., Azzopardi, M. & Testor, G. 1999, A&AS, 137, 117
Casares, J. & Jonker, P. G. 2014, SSRev, 183, 223
Casares, J. et al. 2014, Nature, 505, 378
Clavel, M. et al. 2021, A&A, 645, A72
Corral-Santana, J. M. et al. 2016, A&A, 587, A61
Crowther, P. A. 2007, ARA&A, 45, 177
Cui, X.-Q. et al. 2012, RAA, 12, 1197
Dachs, J. et al. 1981, A&ASupp, 43, 427
Dalton, G. et al. 2012, Proc. SPIE, 8446, 84460P
Dekker, H. et al. 2000, Proc. SPIE, 4008, 534
Dzib, S. A., Massi, M. & Jaron, F. 2015, A&A, 580, L6
El-Badry, K. & Quataert, E. 2020, MNRAS, 493, L22
El-Badry, K. & Quataert, E. 2021, MNRAS, 502, 3436
El-Badry, K. & Burdge, K. B. 2021, submitted to MNRAS, arXiv:2111.07925
El-Badry, K., Burdge, K. B. & Mróz, P. 2021, MNRAS, in press, arXiv:2112.05030
El-Badry, K., Rix, H.-W. & Heintz, T. M. 2021, MNRAS, 506, 2269
El-Badry, K. et al. 2022, submitted to MNRAS, arXiv:2201.05614
Eldridge, J. J. et al. 2020, MNRAS, 495, 2786

Er-Gang, Z. et al. 2019, ApJ, 871, 10
Farmer, R. et al. 2021, ApJ, 923, 214
Frost, A. J. et al. 2022, submitted to A&A
Fishbach, M. & Holz, D. E. 2017, ApJL, 851, L25
Gaia Collaboration et al. 2016, A&A, 595, A1
Gu, W.-M. et al. 2019, ApJL, 872, L20
Gies, D. R. & Wang, L. 2020, ApJL, 898, L44
Gies, D. R. et al. 2020, ApJ, 902, 25
Giesers, B. et al. 2018, MNRAS, 475, L15
Giesers, B. et al. 2019, A&A, 632, A3
Gomez, S. & Grindlay, J. E. 2021, ApJ, 913, 48
Götberg, Y., de Mink, S. E. & Groh, J. H. 2017, A&A, 608, A11
Götberg, Y. et al. 2018, A&A, 615, A78
Groh, J. H. et al. 2020, ApJ, 900, 98
Heber, U. 2009, ARAA, 47, 211
Heger, A. et al. 2003, ApJ, 591, 288
Irrgang, A. et al. 2020, A&A, 633, L5
Janssens, S. et al. 2021, A&A, in press, arXiv:2111.06427
Jayasinghe, T. et al. 2021, MNRAS, 504, 2577
Jayasinghe, T. et al. 2022, submitted to MNRAS, arXiv:2201.11131
de Jong, R. S. et al. 2012, Proc. SPIE, 8446, 84460T
Khokhlov, S. A. et al. 2018, ApJ, 856, 158
Klement, R. et al. 2021, ATel, 14340
Laplace, E. et al. 2021, A&A, 656, A58
Lennon, D. J. et al. 2021, A&A, in press, arXiv:2111.12173
Liao, W.-P. & Qian, S.-B. 2010, PASJ, 62, 1109
Liu, J. et al. 2019, Nature, 575, 618
Liu, J. et al. 2020, ApJ, 900, 42
Maintz, M. 2003, PhD Thesis, University of Heidelberg, Germany
Mandel, I. & Farmer, A. 2018, arXiv:1806.05820
Masuda, K. & Hirano, T. 2021, ApJL, 910, L17
Mazeh, T. & Faigler, S. 2020, MNRAS, 498, L58
Munar-Adrover, P. et al. 2014, ApJL, 786, L11
Paczynski, B. 1986, ApJ, 304, 1
Pepe, F. et al. 2020, A&A, 645, A96
Podsiadlowski, P., Joss, P. C. & Hsu, J. J. L. 1992, ApJ, 391, 246
Puls, J., Vink, J. S. & Najarro, F. 2008, A&A Rev., 16, 209
Qian, S.-B., Liao, W.-P. & Fernández Lajús, E. 2008, ApJ, 687, 466
Ricker, G. R. et al. 2015, JATIS, 1, 014003
Rivinius, T., Carciofi, A. C. & Martayan, C. 2013, A&AR, 21, 69
Rivinius, T. et al. 2020, A&A, 637, L3
Safarzadeh, M., Ramirez-Ruiz, E. & Kilpatrick, C. 2020, ApJ, 901, 116
Safarzadeh, M., Toonen, S. & Loeb, A. 2020, ApJL, 897, L29
Saracino, S. et al. 2021, MNRAS, in press, arXiv:2111.06506
Shenar, T. et al. 2020a, A&A, 634, A79
Shenar, T. et al. 2020b, A&A, 639, L6
Simón-Díaz, S. et al. 2020, A&A, 634, L7
Slettebak, A. 1982, ApJS, 50, 55
Stevance, H. F., Parsons, S. G. & Eldridge, J. J. 2022, MNRAS, in press, arXiv:2112.00015
Sukhbold, T. et al. 2016, ApJ, 821, 38
Tauris, T. M. & van den Heuvel, E. P. J. 2006, in *Compact stellar X-ray sources*, ed. Lewin, W. & van der Klis, M., Cambridge Astrophysics Series, No. 39, (Cambridge, UK: Cambridge University Press), 623
Thatte, N. et al. 2010, Proc. SPIE, 7735, 77357Y
Thompson, T. A. et al. 2019, Science, 366, 637
Thompson, T. A. et al. 2020, Science, 386, 4356
van den Heuvel, E. P. J. 1992, in *Environment Observation and Climate Modelling Through International Space Projects. Space Sciences with Particular Emphasis on High-Energy Astrophysics*, ed. Hunt, J. J. & Guyenne, T. D., (European Space Agency), 29
van den Heuvel, E. P. J. & Tauris, T. M. 2020, Science, 368, 3282
Wang, L. et al. 2021, AJ, 161, 248
Wang, Z.-H. & Zhu, L.-Y. 2021, MNRAS, 507, 2804
Wellstein, S., Langer, N. & Braun, H. 2001, A&A, 369, 939
Wyrzykowski, Ł. & Mandel, I. 2020, A&A, 636, A20
Yi, T., Sun, M. & Gu, W.-M. 2019, ApJ, 886, 97
York, D. G. et al. 2000, AJ, 120, 1579

Links

[1] GRAVITY+ White Paper: https://www.mpe.mpg.de/7480772/GRAVITYplus_WhitePaper.pdf
[2] Data products and input files necessary to reproduce the simulations shown in Figure 4: https://doi.org/10.5281/zenodo.5875376

Around 60 million light-years away, in the constellation Virgo, the two galaxies NGC4567 and NGC4568, nicknamed the Butterfly Galaxies owing to their wing-like structure, are beginning to collide and merge into each other. This is depicted in this picture captured by the FOcal Reducer and low dispersion Spectrograph 2 (FORS2) instrument, which is mounted on ESO's Very Large Telescope (VLT) at Paranal Observatory in the Chilean Andes.

DOI: 10.18727/0722-6691/5256

ALMACAL: Surveying the Universe with ALMA Calibrator Observations

Martin Zwaan[1]
Rob Ivison[1]
Céline Peroux[1,2]
Jianhang Chen[1]
Anne Klitsch[3]
Aleksandra Hamanowicz[4]
Roland Szakacs[1]
Simon Weng[1,5]
Andrew Biggs[6]
Ian Smail[7,8]

[1] ESO
[2] Aix Marseille Université, CNRS, Laboratoire d'Astrophysique de Marseille, France
[3] DARK, Niels Bohr Institute, University of Copenhagen, Denmark
[4] Space Telescope Science Institute, Baltimore, USA
[5] Australia Telescope National Facility, CSIRO Space and Astronomy, Australia
[6] UK Astronomy Technology Centre, Royal Observatory Edinburgh, UK
[7] Centre for Extragalactic Astronomy, Department of Physics, Durham University, UK
[8] Institute for Computational Cosmology, Department of Physics, Durham University, UK

The Atacama Large Millimeter/submillimeter Array (ALMA) has accumulated thousands of hours of observing time on calibrator sources, which are typically bright quasars. These calibration scans are usually observed with the same instrumental setup as the science targets and have enormous potential for conducting science. ALMACAL is a survey that is exploiting these data which are accumulating "for free" with every scheduled ALMA observing project. Here, we present a brief survey status update and summarise the science that can be achieved. For instance, if data acquired during multiple visits to many ALMA calibrators are combined, low continuum noise levels can be reached, allowing the detection of faint dusty star-forming galaxies in a number of bands. Also, redshifted CO and other emission and absorption lines are detected in the ALMACAL data. The total on-source integration time for all ALMACAL scans to date amounts to approximately 2500 hours, more than all ALMA Large Programmes to date combined.

The ALMACAL pipeline

Every ALMA dataset delivered to a principal investigator contains observations of several calibrator sources. These calibrator observations are used to set the flux density scale, correct for the bandpass response, and solve for the complex gains as a function of time, which are all standard operations executed by the ALMA quality assurance procedure. According to the ALMA operations plan, these calibrator data are not protected with proprietary time and are accessible to any user immediately after the parent science dataset has passed quality assurance. At ESO, an ALMACAL[1] pipeline was developed that runs automatically on all delivered datasets. This pipeline executes the so-called scripForPI.py script, which comes with each data delivery, and produces fully calibrated calibrator data. The pipeline then solves again for the complex amplitude and phase solutions, this time using the highest possible time resolution allowed by the data. After applying these solutions, a point source model is fitted to the data and subtracted in visibility space, which leaves us with optimally calibrated and continuum-free data. Finally, in order to reduce the total data volume, the individual measurement sets are averaged in time and rebinned spectrally to a common channel separation of 15.6 MHz.

ALMACAL in numbers

Since Cycle 1, the ALMACAL pipeline has been run on more than 11 000 delivered datasets. As every dataset contains several calibrator scans, this implies that the total ALMACAL dataset comprises over 33 000 individual observations of calibrators. The contribution of different frequency bands to this total number is distributed very unevenly, with some 39% of the scans taken in Band 6. This reflects the popularity of this frequency band which, as it lies roughly in the middle of the ALMA frequency range, gives a good trade-off between atmospheric absorption and the brightness of dusty continuum sources. Band 3 follows, with about 31% of the scans, then Band 7 with 19%. The other bands together make up the remaining 11%. Altogether, ALMACAL has collected data for over 1000 calibrator fields so far. Of these calibrators, which are usually quasars, roughly 70% have spectroscopic redshifts and more will be obtained in an upcoming X-shooter programme in P109. After eight observing cycles, the total on-source integration time for all ALMACAL scans amounts to approximately 2500 hours and continues to grow (see Figure 1 for the integration time per field). For comparison, ALMA Large Programmes are typically awarded 50 to 150 hours of telescope time.

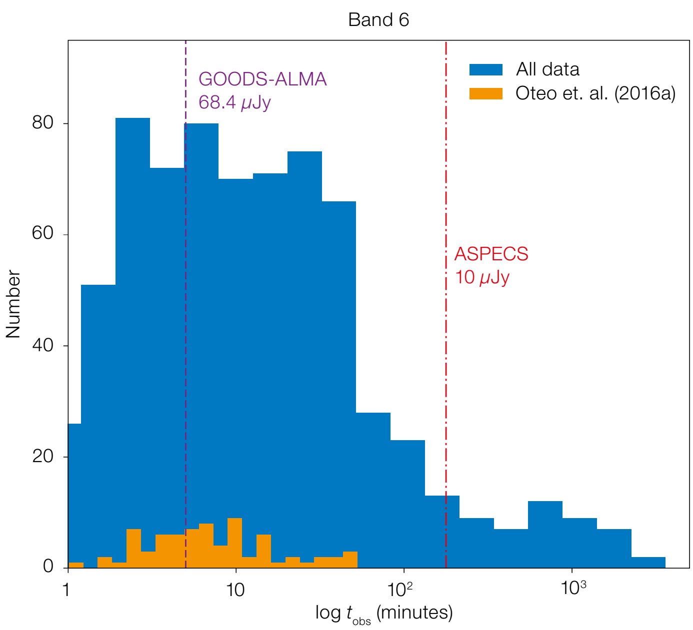


Figure 1. Number of ALMACAL fields as a function of accumulated integration time for data taken in Band 6. The blue histogram shows the current status, while the orange histogram represents the database in 2016. The two vertical lines show the rms noise level in the GOODS-ALMA and the ASPECS Band 6 continuum maps.

ALMA deliveries processed		11 138
Measurement sets (MOUSs) processed		33 038
Independent fields observed		1001
	Sky coverage	Number of observations
Band 3 (3 mm)	567 arcmin^2	~ 10 000
Band 4 (2 mm)	106 arcmin^2	~ 2000
Band 5 (1.6 mm)	28 arcmin^2	~ 500
Band 6 (1.2 mm)	93 arcmin^2	~ 13 000
Band 7 (870 μm)	32 arcmin	~ 6000
Band 8 (650 μm)	5 arcmin^2	~ 700
Band 9 (450 μm)	1 arcmin^2	~ 200
Band 10 (350 μm)	0.1 arcmin^2	~ 100
Imaging noise level		down to 10 μJy beam^{-1}
Total integration time		~ 2500 hours

Table 1. A summary of ALMACAL survey statistics. This is the status of the survey at the end of Cycle 7, i.e., 1 October 2021.

ALMACAL compared to targeted ALMA surveys

Clearly, the total amount of observing time accumulated in the ALMACAL database cannot be easily surpassed by PI programmes and the sheer volume of data offers a number of advantages. Firstly, the total sky coverage in Band 3 (~ 100 GHz) amounts to approximately 567 arcmin^2, where we count the area of the primary beams out to the half-power point. In Band 6, this drops to about 93 arcmin^2 and in Band 8 to 5 arcmin^2. For comparison, the ALMA Spectroscopic Survey in the Hubble Ultra Deep Field (ASPECS) is currently the deepest ALMA untargeted or "blind" survey, covering 2.9 arcmin^2 at a sensitivity of 9 μJy beam^{-1} in Band 6 (González-López et al., 2020). GOODS-ALMA[a] covers 72 arcmin^2, but with a significantly lower sensitivity of around 68 μJy beam^{-1} (Gomez-Guijarro et al., 2021).

Since ALMA calibrators lie quasi-randomly across the southern sky, ALMACAL's survey area is also very distributed. In essence, the survey areas listed in Table 1 are spread over ~ 30 000 degrees^2. For science based on serendipitous line and continuum detections and which aims to derive statistical properties of the Universe (for example, cosmic gas density or source counts), this distribution implies that the results are nearly immune to the effects of cosmic variance that hamper most deep-field surveys.

Along with these obvious strong points, there are a number of challenges associated with ALMACAL data, both in terms of data reduction and scientific interpretation. Of the latter, an obvious one is that because ALMACAL consists of pointed observations of bright calibrators, it is not a truly blind survey, in contrast to, for example, ASPECS. For science that requires a random sampling of the Universe, it must be assessed whether the bright calibrator source in the field implies that the field is tracing a cosmic over-density. Submillimetre galaxies, for example, are known to cluster around bright quasars and radio galaxies (see, for example, Stevens et al., 2003, 2004). However, there are two arguments in favour of the premise that ALMACAL is not biased in that sense. Firstly, the calibrators are predominantly blazars (97%; Bonato et al., 2018) and are thus bright submillimetre sources as a consequence of the fact that their jets point towards the observer (Urry & Padovani, 1995) rather than because they are particularly massive — clustering around most of these sources is therefore likely to be minimal, and their gravitational lensing potential is similarly reduced. Secondly, the redshifts over which continuum- or line-detected galaxies are found are typically unrelated to the redshifts of the calibrators themselves (see, for example, Hamanowicz et al., 2022, submitted to MNRAS).

Blazar jets or dust emission

Further challenges emerge when we search for continuum emission from dusty galaxies in ALMACAL fields. Single-band detections of the dust continuum of background galaxies can in principle be easily confused by jet emission from the calibrator sources (see, for example, Klitsch et al., 2020). Radio maps that are often available from the literature can help identify jet emission, and in some cases symmetric continuum emission around the central source is indicative of jet emission. However, multiband ALMACAL observations are often available which help to establish with high certainty the origin of the emission. Jet emission should have a synchrotron spectrum which increases with decreasing wavelength, whereas dust emission is modified black-body radiation, the intensity of which increases in the opposite wavelength direction.

Central bright sources

Having bright sources at the centre of the field may raise questions about the dynamic range achievable in ALMACAL continuum imaging. We find that in general the central point source subtracts very well, leaving no significant artifacts in the image. Having a bright point source at the centre of the field means that atmospheric and electronic antenna-based temporal amplitude and phase variations can be solved with high accuracy and image dynamic ranges of up to 10^5 can be achieved in this way. However, in some cases residual structure is present after point source subtraction. This often manifests itself as prominent "ears" around the central source, symmetric patterns whose origin lies in small amplitude calibration errors that are not yet well understood. When combining many ALMACAL observations to produce deep images, we take care to omit these individually affected data sets by inspecting individual images.

Random frequency settings

The frequency settings of ALMACAL datasets are defined by the science goals of the observations from which the calibrator data are extracted and as a result each calibrator has a different frequency coverage. Some calibrators are covered by only a few GHz in a single band, while others are observed in all ALMA bands with full coverage in selected regions. For the purpose of conducting spectral surveys, the redshift coverage is therefore fairly random and inhomogeneous. For an individual calibrator, the achieved noise level in an ALMACAL image cube can vary by a factor of a few as a function of frequency.

Incomplete ancillary data

ALMA cosmological surveys target mostly well-studied fields for which a multitude of multi-wavelength ancillary data are available to help establish the redshifts of new detections and provide measurements of stellar mass, star formation rates, etc. Given the non-contiguous sky coverage of ALMACAL, similar data are rarely available and obtaining them is an unrealistic goal given the extensive number of follow-up observations that would be required. However, as the ALMA calibrators are also used by other interferometers operating over the full radio, millimetre and submillimetre spectrum, ancillary data are readily available in these regimes, and there is the promise that some of the quasars will be useful as beacons for adaptive optics at shorter wavelengths.

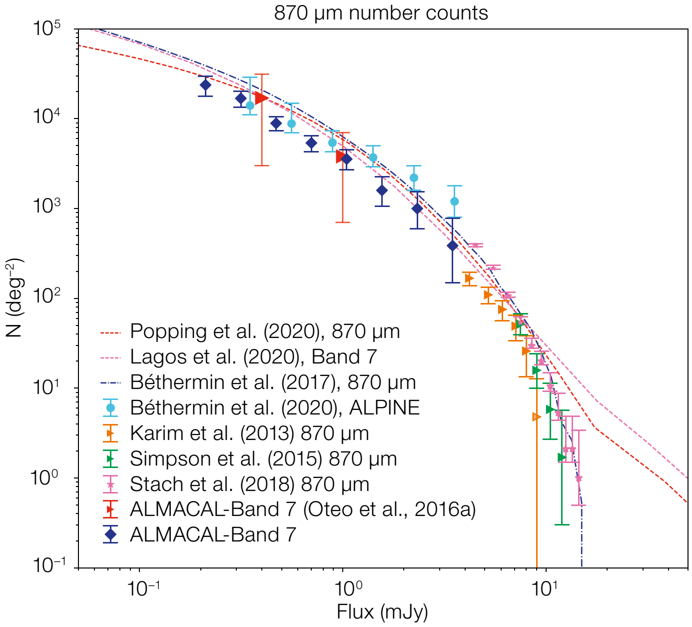


Figure 2. Cumulative Band 7 (870 μm) number counts of dusty star-forming galaxies derived from ALMACAL (Chen et al., in preparation), along with previous results and models from Popping et al. (2020) and Lagos et al. (2020). Previous ALMACAL results from Oteo et al. (2016a) are shown in red.

ALMACAL Science

Since the start of the project in 2016, ALMACAL has produced science results focusing primarily on four main areas: the properties of dusty star-forming galaxies, the evolution of molecular gas, extragalactic absorption lines, and active galactic nucleus (AGN) physics. Given the richness of the dataset, many other science questions can be addressed and we invite the community to get in touch for possible collaborations. Here we provide a brief overview of some of the ALMACAL science highlights so far.

Dusty star-forming galaxies

Embarking on this project, our original aim was to use the ALMA calibrator data to search for dusty star-forming galaxies, to establish their space density and their contribution to the cosmic far-infrared background. The first ALMACAL publication (Oteo et al., 2016a) addressed exactly this topic and presented number counts of 870-μm and 1.2-mm detections, demonstrating the feasibility of ALMACAL for this purpose. Klitsch et al. (2020) extended this technique to Band 8 (650 μm), using data from 81 ALMA calibrator fields, together covering a total area of 5.5 arcmin^2 and reaching noise levels as low as σ = 47 μJy beam^{-1}, such that the sky density of 650-μm sources was established. The full cosmic infrared background was recovered, which means that the contribution from objects below our detection limit of 0.7 mJy must be very small. Since these initial publications, the ALMACAL data volume has grown substantially and improved multi-band number counts are currently being evaluated. For example, Figure 2 presents the latest Band 7 (870 μm) ALMACAL number counts along with previous results and models that will be presented soon (Chen et al., in preparation).

A striking example of a high-resolution case study is provided by the ALMACAL

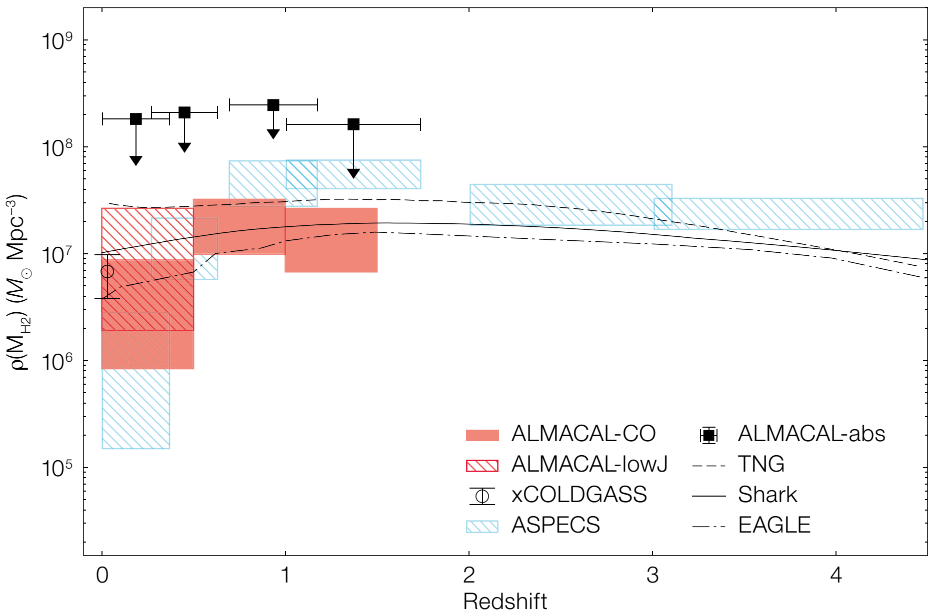


Figure 3. The evolution of molecular gas mass density with redshift as measured from an ALMACAL pilot survey (Hamanowicz et al., 2022, submitted to MNRAS; red boxes). The filled boxes represent the results of a simulation-based source classification, while the red dashed box corresponds to assuming all CO detections are the lowest-J transitions. The black points show the ALMACAL absorption-line constraints (Klitsch et al., 2019b). The results of ASPECS (Decarli et al., 2020, in blue) are also shown, along with the z = 0 reference from xCOLD GASS (Fletcher et al., 2021), and the TNG, Shark and EAGLE simulation results.

analysis of the J1058+0133 field, which is one of the brightest blazars close to a Cosmic Evolution Survey (COSMOS) field. Oteo et al. (2017) found two bright submillimetre galaxies, achieved 20-milliarcsecond spatial resolution for these two galaxies, and identified nearly 20 emission lines.

The evolution of the cosmic molecular gas mass density

The random sampling of the Universe in frequency and sky position makes ALMACAL ideally suited for an untargeted survey for CO emission lines, enabling a measurement of the cosmic molecular mass density as a function of redshift. Molecular gas provides the fuel for the formation of stars and many of the properties of galaxies are determined by the amount of gas they contain, more specifically how efficient they are at converting their innate gas into stars. It is therefore essential to probe the evolution of cold gas over cosmic time. The first steps towards using ALMACAL for this purpose were made by Hamanowicz et al. (2022, submitted to MNRAS), who restricted the search to a small subsample of deep observations (see Figure 3). Based on this analysis it was possible to set limits on the molecular mass density. The ALMACAL team is now embarking on a new analysis using the full dataset and thus increasing the probed volume by a factor of 50.

Absorption lines.

Another way of studying the evolution of the gas mass density of the Universe is to use intervening absorption lines seen in the spectra of background quasars. For neutral hydrogen, this method has been shown to be very productive and surveys for damped Lyman-alpha systems have provided accurate measurements of Omega(HI). Radio surveys for intervening 21-cm absorption are now becoming productive (ASKAP-FLASH, etc.) and it therefore seems logical to use ALMA observations of calibrators to search for the absorption signal of CO caused by galaxies along the line of sight to the calibrator. An initial study has been carried out by Klitsch et al. (2019b) who, despite a cumulative redshift pathlength (summed over all calibrators) of approximately Δz = 180, found no new extragalactic absorbers. This demonstrates the extremely small cross-section of high-density molecular gas. However, the study did put new constraints on the evolution of Omega(H_2) and many Galactic absorption lines were identified.

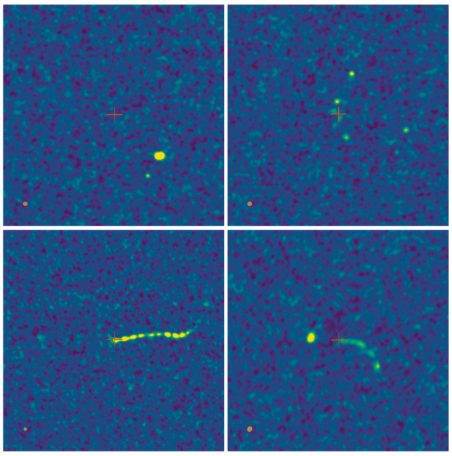


Figure 4. Examples of ALMACAL continuum fields. Each of the fields is centred on a bright (~ 1 Jy) continuum source, which has been subtracted in uv-space. The top two fields show examples of multiple detections of dusty star-forming galaxies. Detection of the same sources in other ALMA bands allows the confirmation of their being dust SEDs. In contrast, the bottom two examples show jet emission, emanating from the central quasar. The bottom-right panel is based on Band 3, the others on Band 7.

In addition, ALMACAL has been used to identify CO emission lines from galaxies associated with strong Lyman-alpha absorption systems, occasionally identifying multiple CO transitions and indicating a more excited interstellar medium in these types of galaxies (Klitsch et al., 2019a).

AGN physics

As stated above, some images of ALMA calibrator sources show powerful jets emanating from the central AGN. The standard ALMA calibration procedure, which assumes the calibrator to be a point source, is usually not affected by these jets as their flux is negligible (<< 1%) compared to that of the point source. Figure 4 shows two examples of jets seen in ALMACAL data.

On the topic of AGN, ALMACAL data offer many other avenues for research, including long-term multi-band flux monitoring and line absorption and emission from the AGN host galaxies. A beautiful example of a study of the morphology and kinematics of the gas surrounding 3C273 based on calibrator data was presented by Husemann et al. (2019). The CO (1-0) emission shows an arc-like structure around the AGN, which is a 12.9-Jy continuum source in ALMA Band 3.

Concluding remarks

We first presented the ALMACAL survey in the Messenger in 2016 (Oteo et al., 2016b). At that time, we showed our first 1.2-mm continuum number counts, based on observations of 240 individual calibrators. Since then, the number of observed calibrators and their individual on-source integration times have grown by an order of magnitude, and new data are still coming in almost every day. In this short article, we have provided some examples of the science that ALMACAL has produced and which is currently being worked on. There are undoubtedly other applications of these data and we welcome collaborations with the community to enable this science.

References

Béthermin, M. et al. 2020, A&A, 643, A2
Béthermin, M. et al. 2017, A&A, 607, A89
Bonato, M. et al. 2018, MNRAS, 478, 1512
Decarli, R. et al. 2020, ApJ, 902, 110
Fletcher, T. J. et al. 2021, MNRAS, 501, 411
Gomez-Guijarro, C. et al. 2022, A&A, 658, A43
González-López, J. 2020, ApJ, 897, 91
Husemann, B. et al. 2019, ApJ, 879, 75
Klitsch, A. et al. 2019a, MNRAS Lett., 482, L65
Klitsch, A. et al. 2019b, MNRAS, 490, 1220
Klitsch, A. et al. 2020, MNRAS, 495, 2332
Karim, A. et al. 2013, MNRAS, 432, 2
Lagos, C. et al. 2020, MNRAS, 499, 1948
Oteo, I. et al. 2016a, ApJ, 822, 36
Oteo, I. et al. 2016b, The Messenger, 164, 41
Oteo, I. et al. 2017, ApJ, 837, 182
Popping, G. et al. 2020, ApJ, 891, 135
Riechers, D. et al. 2019, ApJ, 872, 7
Simpson, J. M. et al. 2015, ApJ, 799, 81
Stach, S. M. et al. 2018, ApJ, 860, 161
Stevens, J. A. et al. 2003, Nature, 425, 264
Stevens, J. A. et al. 2004, ApJ, 604, L17
Urry, C. & Padovani, P. 1995, PASP, 107, 803

Links

[1] ALMACAL website: https://almacal.wordpress.com

Notes

[a] GOODS-ALMA is an ALMA survey at 1.1 mm of the southern field of the Great Observatories Origins Deep Survey (GOODS), itself centred on the Chandra Deep Field South.

DOI: 10.18727/0722-6691/5257

The Isolated Magnetic White Dwarfs

Stefano Bagnulo[1]
John D. Landstreet[1,2]

[1] Armagh Observatory and Planetarium, UK
[2] University of Western Ontario, Canada

About one star in four will end its life as a magnetic white dwarf. Although magnetism is a very common feature in degenerate stars, we still do not know much about its origin and evolution. Our volume-limited spectropolarimetric survey of white dwarfs reveals statistical characteristics that may help to understand it.

Introduction

White dwarfs (WDs) are the last stage of more than 90% of stars, and more than 20% of those stars possess strong magnetic fields. The field strengths encountered range over four dex, from tens of kG up to about 1000 MG, and are roughly dipolar. On the timescale of a few decades of observations, they show no evidence of secular changes. The origin of these fields is a subject of active debate. The old fossil-field theory of retention and compression amplification of main sequence star fields was rejected by Kawka & Vennes (2004) because this process cannot produce nearly enough magnetic WDs (MWDs). Among the more recent proposals the most plausible seem to be dynamo models, such as a dynamo operating in a convective main sequence stellar core with the flux retained until final collapse (for example, Stello et al., 2016), or a dynamo created during the common-envelope phase leading to the merger of a close binary into a single WD (for example, Tout et al., 2008). A contemporary dynamo acting in the degenerate stellar core after its crystallisation has started has recently been proposed to explain at least the weakest fields of MWDs (Isern et al., 2017).

Observations may help to discriminate amongst different scenarios but may also lead to conflicting conclusions. As with many physical phenomena, our understanding of stellar magnetism depends on the constraints that we are able to obtain from observations. We have just finished carrying out a nearly complete volume-limited survey of magnetic fields in nearby WDs, providing the first data set from which a clear overview of the occurrence and evolution of the fields in MWDs can be obtained. In this article we describe the new data and discuss some of the ways in which they may be used.

Detection techniques for magnetic fields in white dwarfs

It is helpful to start by discussing the ways in which the field of a WD may be detected and measured, and several situations are illustrated in Figure 1.

The spectral types of WDs are designated by two or more letters, starting with the letter D, which means "degenerate", followed by a capital letter, A, B, C, Q or Z, that reflects the presence of specific spectral features. "A" means that hydrogen lines are present, and "B" that only helium lines are visible in the spectrum. A DC star exhibits a featureless spectrum, while DQ stars have spectra dominated by atomic and/or molecular carbon lines. The letter Z means that the spectrum of the star shows metal lines.

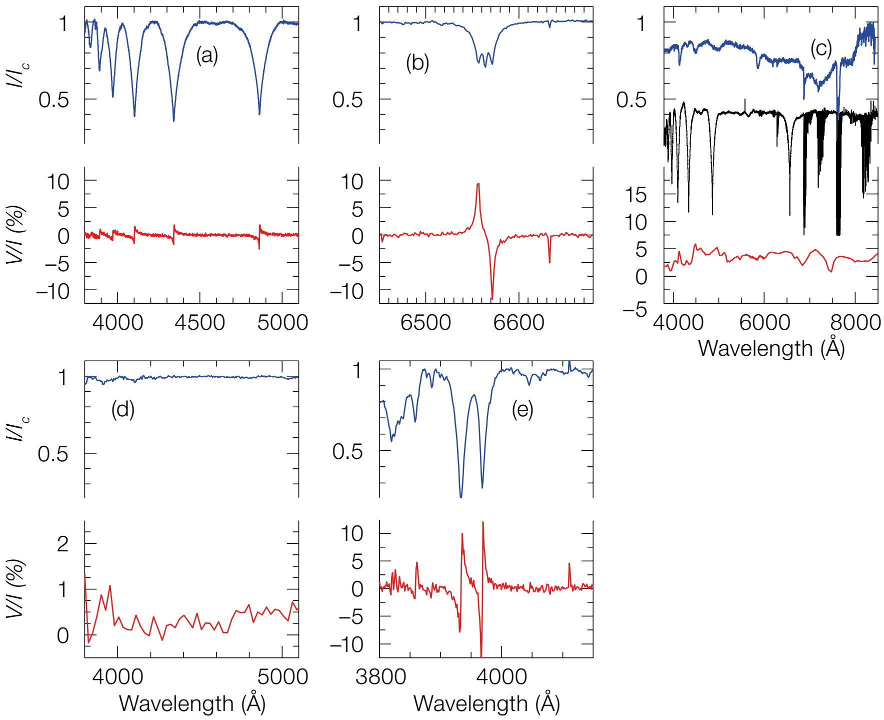


Figure 1. Panel (a) shows the intensity and the circular polarisation spectrum of the weakly magnetic star WD 1105-340 (which has an estimated field modulus of about 150 kG). The H lines do not split when observed with a normal spectrograph, but they may be broadened and polarised, and fields can be easily detected via spectropolarimetric techniques. For fields stronger than a few hundred kG, H Balmer lines split in intensity, as shown in panel (b) for the case of star WD 0011-721 (which exhibits a ~ 350 kG field modulus). The lines are both split and circularly polarised, so the magnetic field may be detected both via normal spectroscopy and via spectropolarimetry. The blue solid line of panel (c) shows the intensity spectrum of the H-rich white dwarf Grw+70°8247, with a field that has a strength of several hundred MG. At that field strength, the components of the spectral lines wander in the spectrum. A blue component of H-α appears at 5900 Å and a red component of H-β at 4200 Å. Without a magnetic field, the spectrum of this star would appear like the spectrum of 40 Eri B, shown with black solid lines. The red solid line is the spectrum of circular polarisation. In the case of featureless white dwarfs, such as WD 0708-670 of panel (d), a star that is so cool that no lines are formed, the magnetic field may be detected only in polarimetric mode, if the field is strong enough to polarise the continuum (we are talking about fields strength > 1MG). However, if the otherwise featureless spectrum has metal lines (DZ stars), the presence of a weak magnetic field may be revealed by their polarisation, as in the case of WD 1009-184 shown in panel (e), where deep Ca lines appear strongly polarised. All data in the Figure were obtained with FORS2, except for those of Grw+70°8247, obtained with ISIS, and of 40 Eri B, obtained with ESPaDOnS.

A spectral line formed in a stellar atmosphere in the presence of a magnetic field may be broadened or split into various components, and is polarised. For fields of less than about 1 MG (1 MG = 100 Tesla), Zeeman splitting of a spectral line observed in intensity is linearly proportional to the field modulus, and circular polarisation of line components is sensitive to the longitudinal component of the magnetic field averaged over the stellar disc. Broadening effects, such as pressure broadening and the low resolving power commonly used for WD spectroscopy, can wash out the Zeeman effect in intensity. In circular polarisation, the Zeeman polarisation signature is more easily detectable than Zeeman splitting, especially for fields weaker than a few hundred kG. The signal of linear polarisation is smaller than that of circular polarisation and is not often used for WD field detection.

The interpretation of the spectra of magnetic degenerate stars is more complicated than for most of other kinds of stars, because the field may be so strong that it departs from the linear Zeeman regime. We need to consider situations in which the fields are so strong (around 10^9 G) that the magnetic and Coulomb forces are of comparable strength, and both spectral and polarisation structure may be totally different from the familiar Zeeman effect.

The take-away message is that spectroscopy of WDs with strong lines is sensitive to fields with a strength between roughly several hundred kG and perhaps 100 MG, while spectropolarimetry makes possible detection limits of order 1 kG. In addition, some WDs are cool enough to have no spectral lines at all. Magnetic fields in these featureless DC WDs cannot be detected with spectroscopy, but may still be revealed by polarimetry if they are strong enough to polarise the continuum (at least of order 1 MG).

Earliest studies of stellar magnetic fields

The most natural reason that comes to mind to explain the occurrence of a magnetic field in a stellar atmosphere is the presence of a dynamo acting at the time of the observations, as in the Sun. Dynamo action is a very complex phenomenon, but the essential idea is that shear in a very good conductor (a stellar interior, for example) can amplify a tiny seed field to an easily detectable strength. One might suspect that shear, and thus field strength, is also related to the stellar rotation velocity, and may be higher in more rapidly rotating stars than in more slowly rotating stars. We now understand that this link between stellar rotation and dynamo action is actually not so direct, but at the time of the earliest observational efforts a driving idea was that magnetic fields may be closely connected with stellar rotation. A connection between stellar rotation and dynamo action was the idea that Babcock wanted to test when he started his spectropolarimetric observations just after WWII (Babcock, 1947). At the same time, Blackett (1947) predicted that WDs would spin rapidly because of the conservation of angular momentum as they collapse, and that consequently they should host extremely strong fields.

WDs were too faint for Babcock's instruments, but various kinds of main sequence stars were systematically investigated, and it soon became clear that, contrary to earlier expectations, magnetic fields were present mainly in the slowly rotating, chemically peculiar stars of the upper main sequence, the so-called Ap and Bp stars (Babcock, 1958). The presence of a magnetic field could not be ascribed to an active dynamo, not only because these stars rotate particularly slowly, but also because they lack a convective envelope, which is the typical environment in which a dynamo could act. The proposed explanation was that the magnetic field of an Ap or Bp star could be the fossil remnant of a magnetic field that was present in a previous stage of the star's life, maybe even the interstellar field frozen into the matter during star formation.

The motivation for the search for magnetic fields in WDs in the late 1960s was the idea (originally proposed by former ESO Director General Lodewijck Woltjer to one of us more than 50 years ago) that, because of flux conservation, WDs that were descendants of Ap and Bp stars could host fields as strong as 100 MG. These attempts led eventually to the discovery of the first MWD (Kemp et al., 1970). But the fact that MWDs were discovered by searching for the descendants of Ap/Bp stars does not mean that MWDs are in fact the descendants of Ap/Bp stars, and indeed this explanation has been called into question now that it is clear that MWDs are much more common in stellar samples than magnetic Ap/Bp stars are.

Motivation of a spectropolarimetric volume-limited survey

A key strategy for understanding the magnetic fields that were gradually discovered, over 50 years, in a small fraction of WDs has been to search for statistical characteristics of the observed magnetic fields, and correlations with other stellar parameters. These correlations may help us to find an explanation for the origin of the magnetic fields.

It has been suspected for decades that magnetic fields are found more frequently in cooler than in hotter WDs (remember that WDs simply cool down with time, so that usually cooler means older and hotter means younger). However, it has been proposed that this result could be an artefact due to an observational bias. Liebert (1988) noted that magnetic field are more frequent in more massive than in less massive WDs. Because of the nature of degenerate matter, higher-mass WDs are smaller, hence fainter than lower mass stars, therefore a magnitude-limited survey would tend to focus on low-mass WDs (the unconscious bias of most surveys). Liebert, Bergeron & Holberg (2003) suggested that this bias is more effective in hotter massive stars than in cooler massive stars, creating thereby the false impression that magnetic fields are more common in cooler than in hotter stars. Another important finding, again by Liebert et al. (2005), was that when we observe a system composed of a WD and a main sequence star in a non-interacting but very close binary system, we never detect a MWD.

These two findings led to the hypothesis that a magnetic field could be the byproduct of the merging of two stars in a close binary system, creating a single

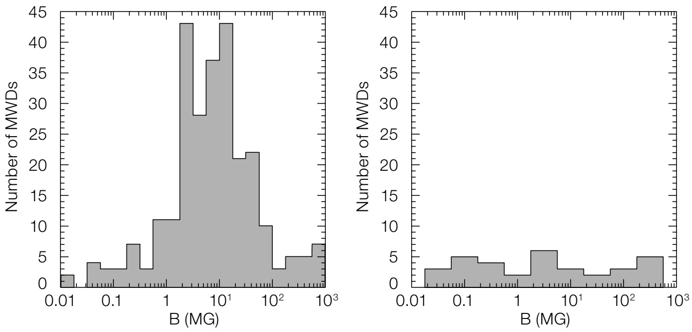


Figure 2. Left panel: the distribution of the field strength for the MWDs obtained using literature data, mainly low-resolution intensity spectra (from Ferrario, Wickramasinghe & Kawka, 2020). Right panel: the distribution of field strength in MWDs obtained from our volume-limited spectropolarimetric survey.

isolated MWD (Tout et al., 2008). Numerical simulations by Briggs et al. (2015) predicted that the distribution of the field strength produced by merging is very similar to the distribution observed among all known MWDs. A variation of this mechanism was proposed to explain another observed characteristic, that WDs which exhibit metal lines in their atmospheres are more frequently magnetic than normal WDs. The presence of metal lines in the atmospheres of some WDs is due to the accretion of a debris disc around the star, probably the remnant of a planetary system. It has been proposed that, similarly to what happens in the merging scenario, the angular momentum lost by the material accreting onto the WD is transformed into shear and then into magnetic energy (Schreiber et al., 2021).

The reality is that some of the observational statistics presented in recent years can easily be called into question. Firstly, it can be reasonably argued that the fact that the observed field strength distribution peaks around 1 to 100 MG is actually the result of an observational bias. Most of the discoveries of MWDs come from the observations of Zeeman-split lines observed in low-resolution spectroscopy by the Sloan Digital Sky Survey, which is effectively sensitive to the range 1 to 100 MG. In contrast, it has been suggested that there may exist a population of WDs with field strengths as weak as a few kG, and that this population could actually be quite large (Aznar Cuadrado et al., 2004). It is also suspected that the spectra of WDs with fields of more than 100 MG may frequently appear in the SDSS spectra as simply noisy, and the fields may be missed. Secondly, the evidence is that DZ stars appear more frequently magnetic than non-DZ stars.

However, we cannot really say whether WDs with metal lines are more frequently magnetic than WDs without metal lines, or whether metal lines allow the observer to detect weak magnetic fields that would be undetected if metal lines were not present in the stellar atmosphere (we recall that only very strong magnetic fields may be detected in featureless stars, or in stars with very weak H lines).

New insights from a volume-limited spectropolarimetric survey of isolated white dwarfs

To obtain the clearest possible view of the occurrence of detectable magnetic fields in WDs, we decided to look at the sample of all WDs within 20 pc of the Sun (about 150 WDs) using spectropolarimetric techniques. These targets represent a fairly unbiased sample of the end points of more than 90% of completed stellar evolution in our part of the Milky Way, and thus provide evidence about the production rate and evolution of both WDs and of their magnetic fields as a function of time over the past 10 Gyr. This sample is small enough to enable us to carry out a careful analysis of each individual member, but large enough to provide some meaningful statistical results. Target selection was possible thanks to Gaia Data Release 2 data (Hollands et al., 2018). The use of spectropolarimetry allowed us to greatly expand the range of strengths within which fields could be detected.

Our survey was carried out with the FOcal Reducer and low dispersion Spectrograph 2 (FORS2) at ESO's Very Large Telescope, the Echelle SpectroPolarimetric Device for the Observation of Stars (ESPaDOnS) at the Canada-France-Hawai'i Telescope, and the Intermediate-dispersion Spectrograph and Imaging System (ISIS) at the William Herschel Telescope. In the course of our survey we observed about 100 WDs, typically at least a couple of times each (Bagnulo & Landstreet, 2021). Most of our targets had been previously observed only in low-dispersion spectroscopic classification surveys. Our new

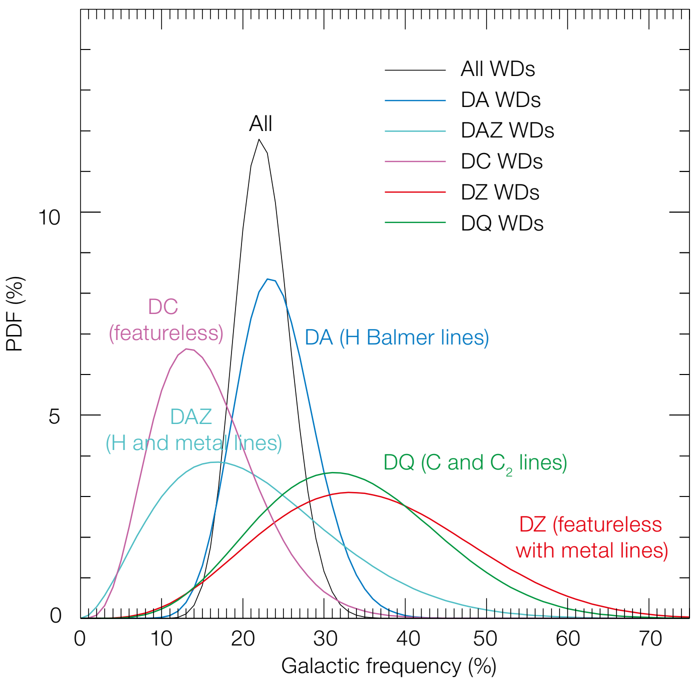


Figure 3. The probability density functions (PDFs) of the Galactic frequency of MWDs of various spectral classes.

observations are characterised by a magnetic field detection precision typically 1 dex better than previous spectropolarimetric surveys, and two dex better than what is obtainable with spectroscopy. We discovered 13 new MWDs, which is about 40% of all MWDs now known in the local 20-parsec volume. In addition to the observational effort, we also had to associate to each star its own stellar parameters, which was possible thanks to a rich literature.

Results

Figure 2 shows the histogram of the distribution of the magnetic field strength of all known WDs before our survey, compared with what we have found in the local 20-parsec volume. Our results suggest a picture quite different from that proposed in the recent literature, with a field strength distribution that is almost constant per decade of field strength from about 40 kG to 1000 MG.

We have correlated the frequency of occurrence of magnetic fields by stellar type, as a function of age, and as a function of mass. Having found that 33 out of 152 WDs are magnetic, Bayesian statistics enables us to calculate the probability density function for the Galactic WDs, as shown in Figure 3. We infer that the frequency of magnetism in all WDs has a peak around 22% and likely ranges between 20% and 25%. This is such a large number that we must now regard magnetism not as a fringe interest, but as an important contributor to WD physics.

The sample of WDs in the local 20-parsec volume is dominated by DA WDs, which represent more than 50% of the total (see blue solid line in Figure 3). The frequency of magnetic fields in DZ stars indeed seems higher than that in normal DA WDs (brown solid line), while featureless DC stars seem to be outliers, in that the field frequency peaks around only 13%. But in DC stars we cannot detect fields weaker than a few MG; therefore, if the field strength distribution is flat, the percentage of magnetic DC stars is probably at least twice as high as measured, and comparable with that of DA WDs. The real outliers of this plot are the DQ stars, because in this kind of star, as for DC

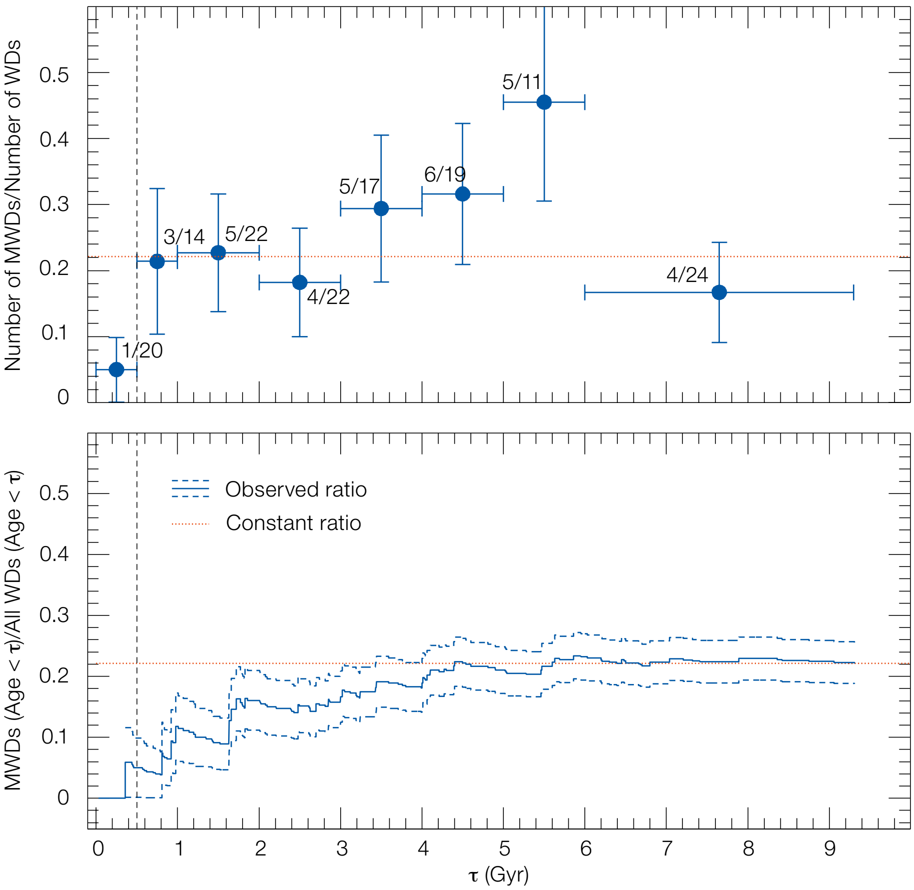


Figure 4. The top panel shows the ratio between the number of MWDs and the number of all WDs that are produced during the interval of time represented by the horizontal error bars, as a function of cooling age τ. The fraction *M/N* printed close to the symbols represents the number of MWDs (*M*) and all WDs (*N*) in the interval of time. The vertical error bars represent the uncertainties associated with the frequency of the occurrence of MWDs extrapolated to the Galactic WD population. In the bottom panel, the blue solid line represents the ratio between the observed MWDs younger than the abscissa value τ and all WDs younger than τ; the blue dashed lines show the ± 1-σ uncertainties of that frequency. The red dotted line refers to a constant ratio between MWDs and all WDs. The region shaded in red highlights the interval of time with a marked deficiency of MWDs.

stars, only fields stronger than a few MG can be detected. However, the magnetic frequency in the local DQ WDs is already higher than in DA WDs. This means that either DQs have a magnetic field much stronger than average, or that a magnetic field is more frequent in DQs than in any other kind of WD.

Perhaps the most interesting result of our survey is the fact that while MWDs are quite common, our data show that there is a marked deficiency of young MWDs: only one out of 20 stars younger than 500 million years is magnetic (see Figure 4). This result confirms what has long been suspected, that magnetic fields are more common in older than in younger WDs. We fully confirm the well-known result that the average mass of MWDs is higher than the average mass of the non-MWDs, but there is also some marginal evidence that higher mass is a feature primarily of the youngest MWDs. This result seems to be supported by data outside the local 20-parsec volume, and this is the object of an ongoing survey.

Finally, Figure 5 shows an age-mass diagram, where the solid lines show the age at which a WD of a certain mass starts the process of core crystallisation (blue lines refer to H-rich atmospheres, and red lines refer to He-rich atmospheres). The empty symbols show the non magnetic WDs, and the solid symbols show the magnetic white dwarfs in the 20-parsec volume. This plot suggests that magnetic fields occur about twice as frequently after the core crystallisation phase starts than before.

Interpretation

Let's see now how the mechanisms proposed to explain the magnetic field stand up against the observational constraints.

The original idea that MWDs are the descendants of the magnetic chemically peculiar stars of the upper main sequence may be still correct, but it is certainly not the entire story, since Ap/Bp stars account for less than 10% of all A and B type stars, and we know that at least 20% of WDs are magnetic. Of course the magnetic field could be still the remnant of a field that originated inside any star at any previous evolutionary stage, for example in the asymptotic giant branch phase. We do not see evidence of ohmic decay, and we may need to hypothesise that the fossil field is emerging from the interior of the star with time.

Another idea that we have mentioned above is that the available orbital energy and angular momentum of a close binary system could lead to the creation of a strong magnetic field via dynamo action during the common-envelope phase. If merging occurs, the result would be a single, high-mass, high-field MWD. The calculations by Briggs et al. (2015) predict a distribution of magnetic field strength between 1 and 100 MG, which is not what we observe. Therefore the merging scenario is a candidate explanation for a fraction of the observed magnetic fields (maybe the rare young, high-mass MWDs?), but not for all, and there is no evidence of close binary systems' being frequent enough to explain the observed high frequency of MWDs.

The high frequency of magnetic fields observed in stars with metal lines suggests that such WDs are unusually likely to host fields. However we have found that once we remove from the statistics all DAs younger than 500 million years, DZs are not more frequently magnetic than normal DAs.

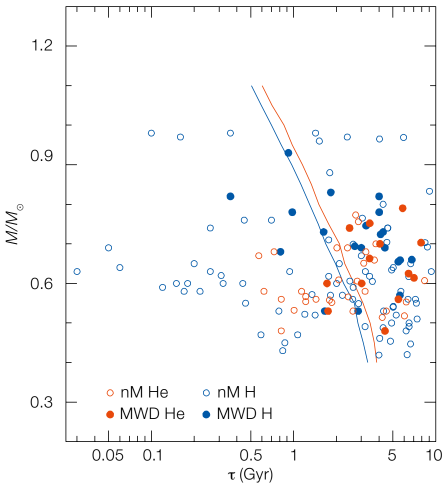


Figure 5. Cooling-age – mass diagram for magnetic (solid symbols) and non-magnetic (empty symbols) WDs, showing the boundary at which crystallisation convection begins as a WD cools with age, for stars with "thick" (blue solid lines) and "thin" (red solid lines) hydrogen layers.

It has been suggested that during crystallisation in the C-O core of a typical WD, separation and sinking of the solidifying O component lead to strong convection in the core. Provided that the WD is rotating rapidly, a dynamo of the same type that produces the magnetic fields of Earth, Jupiter, and M dwarfs can operate (Isern et al., 2017). This theory may well be consistent with the evidence that fields are more frequent after the crystallisation phase. However, this dynamo requires rapid rotation to function in a saturated state and thus produce detectable fields. This is not generally observed in WDs. Also, even in rapidly rotating stars, it remains to be demonstrated how this mechanism may produce fields stronger than 1 MG.

In conclusion, there is no single mechanism amongst those that have been proposed that is capable of explaining all the observations, so perhaps several of those discussed are acting.

To continue to provide constraints it will be necessary not only to expand the survey but also to model the magnetic fields, and try to understand whether different classes of morphologies exist.

Acknowledgements

The new observations used for our survey were made with the FORS2 instrument at the ESO Telescopes at the La Silla Paranal Observatory under programmes ID 0101.D-0103, 0103.D-0029 and 0104.D-0298; with ESPaDOnS on the Canada-France-Hawai'i Telescope (CFHT) (operated by the National Research Council of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique of France, and the University of Hawai'i), under programmes 15BC05, 16AC05, 16BC01, 17AC01, and 18AC06; and with the ISIS instrument at the William Herschel Telescope (operated on the island of La Palma by the Isaac Newton Group), under programmes P15 in 18B, P10 in 19A and P8 in 19B. This research as made use also of additional FORS2, Ultraviolet and Visual Echelle Spectrograph (UVES) and X-shooter data obtained from the ESO Science Archive Facility.

JDL acknowledges the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC), funding reference number 6377-2016.

The authors would like to acknowledge the great help consistently offered by the support astronomers and instrument and telescope operators at the three observatories during the entire observing campaign.

This work has made use of data from the European Space Agency (ESA) Gaia mission (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC; https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

References

Aznar Cuadrado, R. et al. 2004, A&A, 423, 1081
Babcock, H. W. 1947, ApJ, 105, 105
Babcock, H. W. 1958, ApJS, 3, 141
Bagnulo, S. & Landstreet, J. D. 2021, MNRAS, 507, 5902
Blackett, P. M. S. 1947, Nature, 159, 658
Briggs, G. P. et al. 2015, MNRAS, 447, 1713
Ferrario, L., Wickramasinghe, D. & Kawka, A. 2020, AdSpR, 66, 1025
Isern, J. et al. 2017, ApJL, 836, L28
Kawka, A. & Vennes, S. 2004, IAU Symposium No. 224, ed. Zverko, J., Ziznovsky, J., Adelman, S. J. & Weiss, W. W., (Cambridge, UK: Cambridge University Press), 879
Kemp, J. C. et al. 1970, ApJ, 161, L77
Hollands, M. A. et al. 2018, MNRAS, 480, 3942
Liebert, J. 1988, PASP, 100, 1302
Liebert, J., Bergeron, P. & Holberg, J. B. 2003, AJ, 125, 348
Liebert, J. et al. 2005, AJ, 129, 2376
Tout, C. A. et al. 2008, MNRAS, 387, 897
Schreiber, M. R. et al. 2021, MNRAS Lett., 506, L29
Stello, D. et al. 2016, Nature, 529, 364

A photograph of an Atacama Large Millimeter/submillimeter Array (ALMA) antenna at the ALMA Operations Support Facility (OSF). Part of the Milky Way can be seen in the night sky above the antenna.

S. Otarola/ESO

DOI: 10.18727/0722-6691/5258

Redesigning the ALMA User Experience from End to End

Evanthia Hatziminaoglou[1]
George Privon[2]
Yoshito Shimajiri[3]
Carmen Toribio[4]
Gergö Popping[1]
Liz Guzman-Ramirez[5]
Sabine König[4]
Adele Plunkett[2]
Kazi Rygl[6]
Adam Avison[7]
Andy Biggs[1]
María Díaz Trigo[1]
Fabrizia Guglielmetti[1]
Enrique Macias Quevedo[1]
Luke Maud[1]
Anna Miotello[1]
Dirk Petry[1]
Suzanna Randall[1]
Felix Stoehr[1]
Eelco van Kampen[1]
Martin Zwaan[1]

[1] ESO
[2] National Radio Astronomy Observatory, Charlottesville, USA
[3] National Astronomical Observatory of Japan, Tokyo, Japan
[4] Onsala Space Observatory, Chalmers University of Technology, Sweden
[5] University of Leiden, the Netherlands
[6] INAF – Institute of Radioastronomy, Bologna, Italy
[7] Jodrell Bank Centre for Astrophysics, University of Manchester, UK

In the middle of the COVID-19 pandemic and while the ALMA antennas were still powered down, ALMA launched a global initiative to Redesign the User eXperience (RedUX). The RedUX Working Group (WG) interviewed ALMA users worldwide, equally spread amongst the three regions (North America, East Asia and Europe) between November 2020 and May 2021. The discussions that took place at the RedUX interviews were distilled and concrete suggestions for improvements were passed by the RedUX WG to individual teams responsible for ALMA software components, WGs or regions, as well as to the ALMA Integrated Science Operations Team.

Redesigning the User eXperience (RedUX)

Based on insights gained by previous interactions with the global Atacama Large Millimeter/submillimeter Array (ALMA) user community, such as the ALMA end-to-end user experience survey conducted in late 2019 and early 2020, ALMA launched RedUX to further improve the ALMA user experience. RedUX adopted a wide, holistic approach by conducting a series of individual interviews, the goals being to make the use of ALMA an exciting, educational and productive experience for all users and to help increase the scientific output of the facility. The RedUX Working Group (WG) issued a call for volunteers willing to be interviewed on their past, present and prospective experience with ALMA, published in the ALMA newsletters of the three regions between 15 September and 1 October 2020. Although the total number of interviews carried out (69 in total) is very small compared to the total number of ALMA users worldwide (more than 10 000 registered ALMA users at the time of writing), they spanned all levels of career stage and interferometry expertise as well as scientific profile and interests. The users were spread geographically amongst the three regions and were interviewed by the respective WG representative. The ALMA user journey was split into phases and steps (see Figure 1) and every individual touchpoint was addressed. The individual interviews approached the ALMA user experience from various angles simultaneously collecting feedback on all touchpoints of the user experience.

This feedback was translated into concrete suggestions, passed by the RedUX WG for implementation to the teams responsible for ALMA software components and WGs and to the ALMA Integrated Science Operations Team (Zwaan et al., 2021). Some of these suggestions, accompanied by actions under consideration globally within ALMA or locally in Europe, are presented below.

Example advances in selected ALMA subsystems

The ALMA Science Portal has undergone a major change of its look and feel, in light of many of the recommendations made by the RedUX WG following the users' feedback. Figure 2 shows the new main page, with a modern layout. The content of the Science Portal has also been reorganised; information has been regrouped and it is now easier to find and access.

The ALMA Science Archive interface is another user-facing subsystem that is implementing changes in line with the feedback received from ALMA users. Small requests, such as additional metadata on the interface, have already been scheduled for implementation. As several of the items on the feedback list were already in planning, the RedUX feedback was also taken into account in prioritising future implementations.

The Snooping Project Interface (SnooPI[1]), the ALMA Observing Tool, and the Helpdesk also attracted feedback from RedUX, some of which has already been

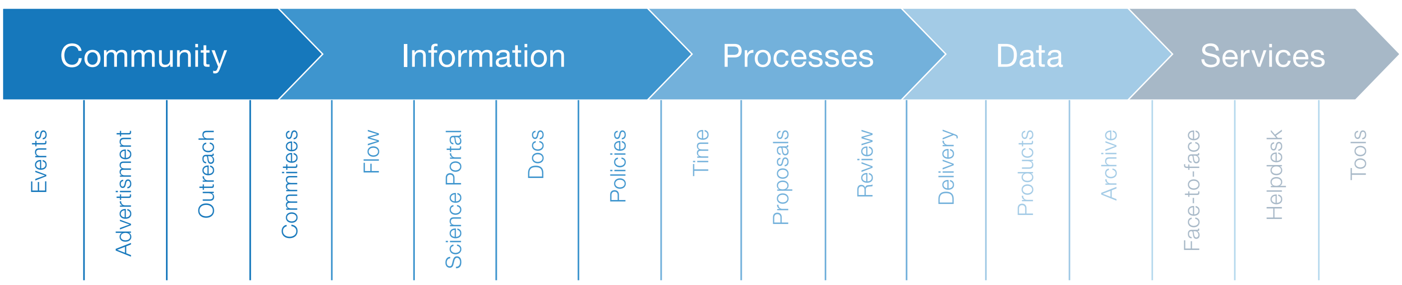


Figure 1. The ALMA user journey map.

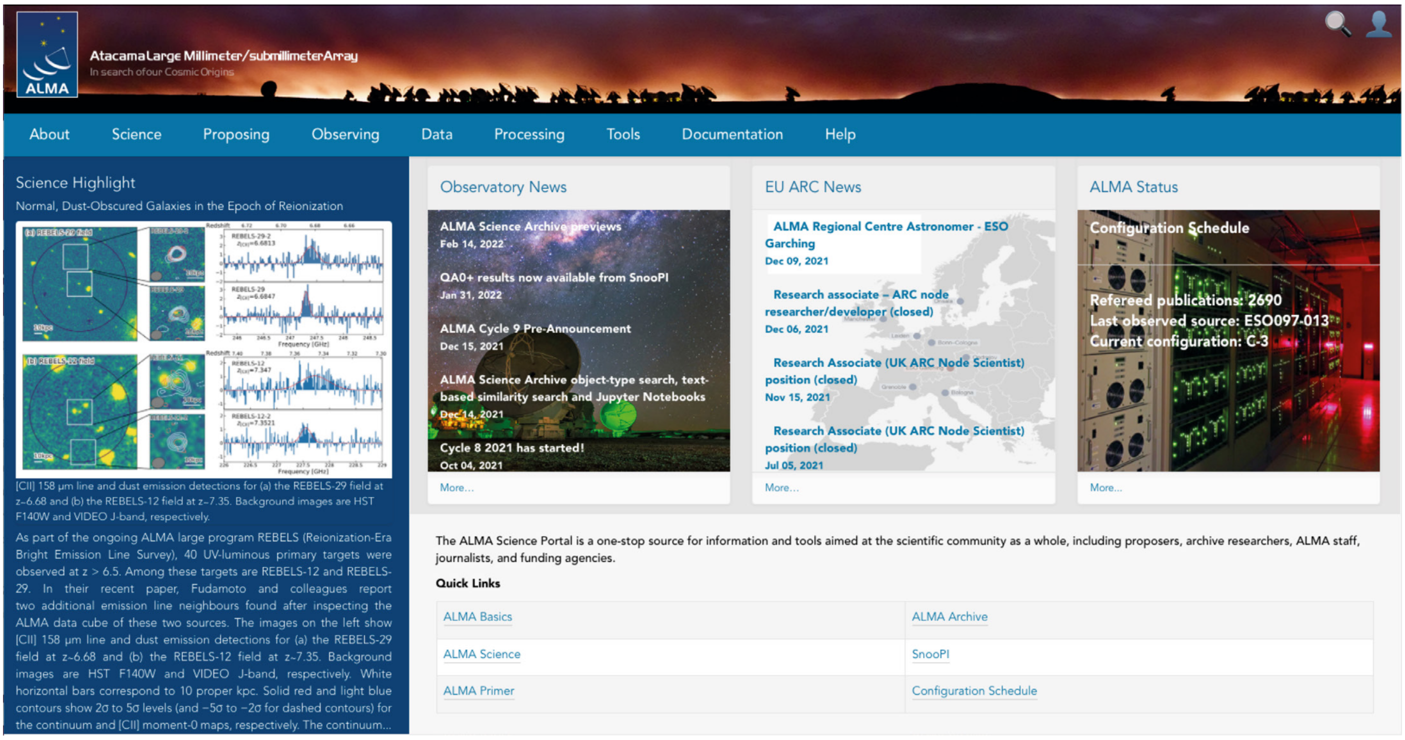


Figure 2. The revamped ALMA Science Portal, with a modern look and feel and a reorganised content.

implemented. Examples of implementations within SnooPI include the possibility to export the calibrator data for each Scheduling Block (SB) in a table format and the sorting of SBs based on properties such as band, array, execution etc.

Improving the ALMA user experience

Thanks to the discussions with the users, many good ideas for improvements in the end-to-end ALMA user experience emerged that were brought forward to the Integrated Science Operations Team. They range from improvements in communication between the project and the community to ways of maximising the use of the ALMA deliverables to user support services and everything in between. Below we summarise some of these ideas, which will be leading future ALMA developments in user support matters.

Communication

As RedUX took place in the middle of the COVID-19 pandemic, the way ALMA responded to the pandemic and the resulting working conditions were major topics of discussion at the interviews. Most users felt that the cancellation of the ALMA Cycle 8 Call for Proposals was the right decision, made in a timely manner and communicated promptly and clearly to the community. Nevertheless, more timely and centralised information dissemination would be appreciated, accompanied by the reasoning behind every decision — in particular, but not solely, in times of crisis. Furthermore, it was felt that more real-time information would be helpful to keep the community up to date and to allow for better planning on the part of the users. Regular and frequent news on upcoming and future capabilities as well as development activities is something the community is eagerly waiting for and the prompt communication of newly found problems that directly affect the users, such as issues with the data or the reduction software, would be much appreciated. As a response to these concerns, ALMA is now looking into ways of improving the information flow towards the community.

One way to engage the ALMA community is through surveys like the ones that were performed from the start of ALMA operations up to and including Cycle 6. These surveys aimed to learn from the users about the quality of the services provided to the community but evolved over time from general queries about all the services to more targeted queries on specific services and tools, following significant developments in those services or tools. The possibility of running focused surveys and regularly publicising the results and follow-up actions is being evaluated. That would allow users to be aware of where the pressure for future developments lies and of the actions taken by the project to accommodate users' needs. For clarity, the provenance and purpose of all ALMA-related surveys will have to be unequivocally identifiable, whether they originate from within the project or from, for example, external committees.

ALMA deliverables

Most of the interviewees re-image the products that are delivered to them. The reasons for doing so include (but are not limited to) the need for parameter optimisation to match their scientific needs or more advanced reduction such as self-calibration or data combination. Many users are worried that less seasoned colleagues are perhaps not aware of the fact that ALMA products can often be improved beyond what the quality assurance process is delivering. This is the case, for instance, for dynamic-range-limited images. Archival researchers in particular, who are used to science-ready data from facilities operating at other wavelengths, may not be fully aware of this aspect of ALMA deliverables. To better guide users, the option of additional training and documentation is being explored, to ensure that they understand the potential need for reprocessing.

The Common Astronomy Software Application (CASA) is the package used by the majority of ALMA users for data reduction and analysis and, inevitably, it was discussed in depth in the interviews. Users reported difficulties following the development of the various CASA versions, updates and bug fixes, and also difficulties with maintaining various CASA versions on their computers. Multiple versioning was also reported to potentially result in poor referee reports, as referees are not always aware of the CASA and pipeline version a data set should be using. Remote, centralised, user-initiated data processing would circumvent the need for users to keep up with CASA versioning. It would also be useful to users who do not have direct access to powerful computers, as was the case for many scientists working under non-optimal conditions during the pandemic. As a result, such a service would further promote archival science. As ALMA and CASA mature, issues affecting proprietary and archival data are being identified. An automatic and regular reprocessing of the contents of the ALMA archive, as done by other large facilities, would ensure that the contents of the ALMA archive were always up to the most up-to-date standards. Reprocessing could be implemented as an alternative to, or in parallel with, user-initiated processing.

User-support services

Face-to-face support is the most valued user-support service offered by the ALMA Regional Centres (ARCs) and it is the one that ensures that the array can be accessible to all users, even those with no expertise in interferometry. Nevertheless, many users still report not being fully aware of the suite of support services offered by the ARCs. Furthermore, some users, and in particular the less experienced ones, may not recognise the need for face-to-face support or may not know how to phrase their needs, both things that prevent them from requesting support. The ARCs are exploring avenues to improve the advertising of the available support services. Furthermore, as expertise spreads in the ALMA user community the need for basic face-to-face support is shifting towards supporting less experienced users. At the same time, there is an increasing need for more specialised support such as working with visibilities, imaging of mosaic data, self-calibration and data combination. The ARCs quickly reacted to the pandemic and adapted their services by offering virtual support, thereby opening new possibilities for interactions with the community. And while it is universally accepted that nothing can replace the value of in-person interactions, virtual support facilitates the logistics and adds flexibility in the user support practices.

Perhaps one of the most striking outcomes of RedUX is the degree to which the user community relies on the project to increase expertise in the community. ALMA's goal from the start was to be a telescope for all astronomers and, thanks to the success of the user support structure that has been put in place in the ARCs, this goal has become a reality. Nevertheless, users would like to get more out of the support services, especially in terms of training and scientific

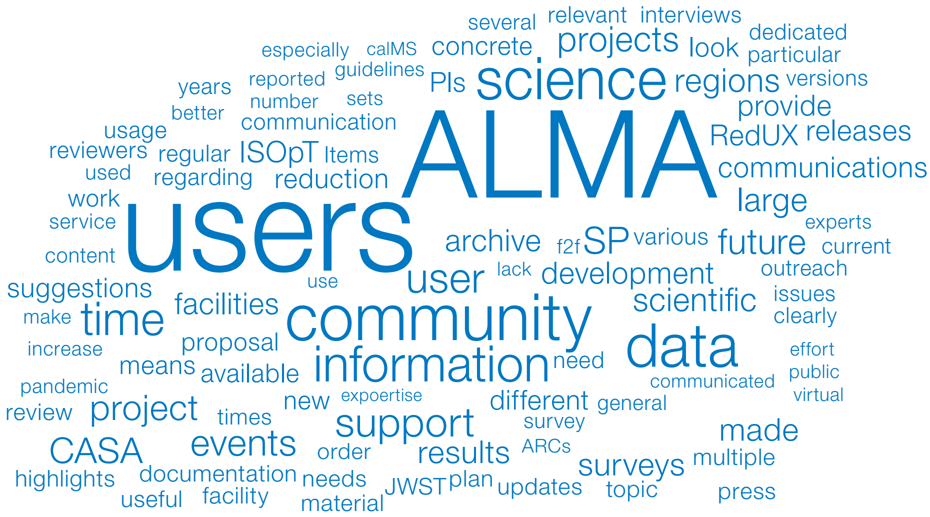


Figure 3. Word cloud summarising the recommendations brought by the RedUX WG to the ALMA Integrated Science Operations Team.

community build-up. To this end, events targeting specific audiences, events covering a wider range of topics, and cross-regional events are all being looked at. The demand for ALMA-specific interferometry schools was clearly articulated in all three regions. There is also a huge demand for tutorials and educational material at all levels and, in addition to new material that will be produced as a response to this demand, an effort will be made to better organise and centralise the scattered material already available. Finally, ALMA users would like to see the project facilitate connections amongst the members of the community, especially in times of crisis. This can be achieved via dedicated communication channels, virtual get-togethers, short topical talks with time for discussion, online forums and suchlike.

To address all the above, a comprehensive list of recommendations was brought to the ALMA Integrated Science Operations Team. While providing the full list is outside the scope of this article, a word cloud summarising the recommendations is presented in Figure 3, with science, data, communications, development and support being concepts featuring prominently there.

Follow-up of RedUX recommendations in Europe

The ARCs are the interfaces between the ALMA project and their respective user communities. The user-support services provided to these communities are adjusted to the circumstances and needs of each of the regions and, although similar in essence, may differ in implementation. As a result, much of the feedback received from the users and, subsequently, many of the recommendations presented by the RedUX WG, in particular on topics related to the growth of the user base and the strengthening of the expertise in submillimetre interferometry in the community, were region-specific and may be handled by each of the ARCs individually. These efforts will be coordinated amongst the regions, to ensure a uniform implementation of new and improved user support practices across the project.

The European ARC is heavily involved in observatory support processes like Quality Assurance (Petry et al., 2021) and Extension and Optimisation of Capabilities (Maud et al., 2021). Nevertheless, user support remains one of its major roles. All users with the European ARC as their "preferred ARC" in their ALMA user profile are provided with support by the European ARC network. The user-support tasks are shared amongst the ESO ARC in Garching and the seven ARC nodes located in Bologna (Italy), Bonn/Cologne (Germany), Grenoble (France), Leiden (the Netherlands), Manchester (UK), Ondrejov/Prague (Czech Republic) and Onsala (Sweden). For a description of the European ARC network see Hatziminaoglou et al. (2015).

A number of actions are already taking place in Europe as an immediate response to the feedback received via RedUX, some of which are presented below.

- The network put together a WG composed of staff from the European ARC network, dedicated to raising awareness amongst European ALMA users about the support and services offered by the network to the ALMA community. The WG meets regularly and discusses strategies to increase the visibility of the nodes in their communities, to improve the transfer of ALMA expertise knowledge from the nodes to the European community, to strengthen the role of the network in building and maintaining the European ALMA community and to continuously engage this community to use ALMA and its new observing modes for their science.
- In the interviews with European users it became obvious that the structure of ALMA and also the role and composition of the oversight committees were unclear, as was the way to provide feedback to the project. To address these uncertainties, an article was published in the ESO Messenger to clarify ALMA's organisational structure, to advertise the European Science Advisory Committee and to indicate the various ways in which users can provide feedback to the project (Zwaan et al., 2021).
- A new series of monthly talks, named ALMA recounts of Cosmic Conundrums[2], was established in December 2021. Each talk focuses on a major question in modern astrophysics. Each invited speaker — one per talk and an expert in the field — describes the context of the question they were asked to address and then focuses on the ALMA contribution to the field, past and future. In addition to illustrating the major scientific advances made thanks to the power of ALMA, the talks are also intended for astronomers who have not yet used ALMA for their science.
- ALMA and interferometry are often perceived, especially by non-experts, as mysterious or complicated. ALMA experts from the European ARC network prepared a series of three-minute videos[3], under the title "ALMA explained", to present basic ALMA and interferometry principles in a simple but scientifically robust manner. The videos target astronomy students and early-career scientists not acquainted with ALMA or the principles of interferometry and were released via the network's webpages[4] and YouTube channel[5]. The collection is being continuously updated with new additions.
- The European ARC Newsletter[6] has been restructured following user feedback and is now published on a monthly basis. Other than announcements of general interest, it features short polls that aim to solicit immediate feedback from the community and highlights of ALMA results led by astronomers with European affiliations.
- Following requests from almost all the European users who were interviewed, the first ALMA school is now being prepared by the European ARC network, with the support of the OPTICON-RadioNet Pilot[7] and with a target date sometime in autumn 2023.
- New European ARC network webpages are in the making. The pages will be repurposed and converted into a useful inventory for all European user support matters.

Conclusions

RedUX user feedback included issues that were already known to the project but also some that had either gone unnoticed so far or whose importance may have been underestimated. Overall users agreed that there is a general ALMA community feeling; there are, however, large fluctuations within this general statement. Depending on their geographic location, the relation of their institute or group to ALMA and the level of expertise and involvement of their immediate surroundings in ALMA, users may feel varying degrees of connection to the project. The ARCs will intensify their efforts to engage with their communities and to further advertise their services to accommodate the changing needs of the ALMA user base. At the same time, ALMA is looking into ways of improving information flow and of opening more communication channels with the community.

RedUX showcased how users see ALMA not just as a facility but as a project leading the users through their science. The requests for more training and training material, for topical workshops and for coordination to establish links amongst members of the community clearly demonstrate that the community relies heavily on the ALMA project to increase user expertise, to expand the user base and to even establish new collaborations that will allow for an even better use of the facility. The ARCs are ceaselessly adapting their services to accommodate these needs, to expand the user base, to continuously train new generations of interferometrists and to strengthen expertise in the community, keeping ALMA at the forefront of astronomical research.

The facility will remain the primary instrument for an important fraction of current ALMA users worldwide for the foreseeable future, with the potential to produce ground-breaking science. By ensuring a continuous collaboration between the project and the user community, ALMA's scientific output can be enhanced and will remain prominent in the astronomical landscape even in the era of upcoming facilities like the James Webb Space Telescope and ESO's Extremely Large Telescope.

Acknowledgements

We would like to thank all the ALMA users and prospective users who participated in RedUX and for the enjoyable and insightful interviews we had with them.

References

Hatziminaoglou, E. et al. 2015, The Messenger, 162, 24
Maud, L. et al. 2021, The Messenger, 183, 13
Petry, D. et al. 2021, The Messenger, 181, 16
Zwaan, M. A. et al. 2021, The Messenger, 184, 16

Links

[1] SnooPI: https://almascience.eso.org/observing/snoopi
[2] ALMA recounts of Cosmic Conundrums: https://www.eso.org/sci/facilities/alma/arc/alma_recounts.html
[3] European ARC videos: https://www.eso.org/sci/facilities/alma/arc/ALMA_explained_videos.html
[4] European ARC webpages: https://www.eso.org/sci/facilities/alma/arc.html
[5] European ARC YouTube channel: https://www.youtube.com/channel/UCXsYQxxTSF-o23UP7HU_jYQ
[6] European ARC Newsletter: https://www.eso.org/sci/facilities/alma/news/arc-newsletter.html
[7] OPTICON-RadioNet Pilot: http://www.orp-h2020.eu

A very bright and large point dominates the top half of this picture of the sky above ESO's Very Large Telescope (VLT) on Cerro Paranal in Chile's Atacama Desert. But if you take a closer look, you will notice it is not just one point but two, very close to each other. What you see is in fact a conjunction of Jupiter and Saturn.

F. Char/ESO

A person's welcoming silhouette is outlined against one of the Auxiliary Telescopes (ATs) at ESO's Paranal Observatory in the Chile's Atacama Desert, as the coalsack nebula waves its majestic hello — a dark smudge in the middle of the night sky.

Gideon Yoffe/ESO

DOI: 10.18727/0722-6691/5259

The ESO Summer Research Programme 2020 and 2021

Nicola Pietro Gentile Fusillo [1]
Michele Ginolfi [1]

[1] ESO

The ESO summer research programme, a great success when it was first held in 2019, is now a regular event in the ESO calendar. Because of the restrictions resulting from the global pandemic, the second and third programmes were held in a virtual format without hosting the participating students in Garching. Nonetheless, both programmes attracted over 400 applicants from over 50 countries. In 2020 and 2021, 11 successful students (at BSc and MSc level) were invited to carry out scientific projects under the supervision of ESO Fellows and staff members for six weeks between July and August. The students carried out research in different fields of astronomy, from galactic structures to stellar evolution and planetary formation.

Motivation and organisation

Many top-class international universities and research institutes offer summer programmes to give undergraduate students their first taste of a research environment and an opportunity to enrich their CVs. The ESO summer research programme was born out of the ESO Fellows' desire to host a similar initiative in Garching, establishing a new way for ESO to interact with the community and allowing the Fellows to gain some experience of supervising students. The first programme, in 2019, proved to be a hit, with highly positive feedback from the students and the ESO Fellows and staff involved. In the wake of this success, the Director for Science made available funding to make the ESO summer research programme a yearly event, triggering the organisation of the second and third programmes. This involved booking ESO apartments and office space, setting up the website, organising the application process and selecting students, planning lecture series and, most importantly, designing and leading the research projects.

The response from the community was incredible. More than 400 valid applications were received in 2020 and 2021 from university students from 54 countries (Figure 1). Participants were selected by first distributing the applications amongst all potential supervisors for an initial ranking, followed by a final selection by an internal committee of Fellows. The final lists of six students (for each programme) were agreed upon to achieve the best possible gender balance and to prioritise applicants from ESO member states, our host country Chile, and ESO's strategic partner, Australia. Each selected student was then interviewed before a formal offer of a place on the programme was made. However, the chaotic events which affected the world over the past two years significantly impacted the plans for the summer research programme. The second programme in 2020 was initially advertised as being held in person at Garching, but with the sudden evolution of the global pandemic, it became necessary to move the programme entirely online. As a result, one of the selected students unfortunately had to decline the offer to attend because of incompatible timezones. The 2020 programme went forward with five projects and five students attending remotely.

The third programme, in 2021, was launched from the start as an online event, and all applicants were made aware that all activities would take place during core work hours in central European time. For both of the virtual programmes, the successful applicants were offered the opportunity to make a two-week visit to ESO in the following year if the global situation allowed it. Unfortunately, the restrictions have not yet allowed the students to travel to Garching safely.

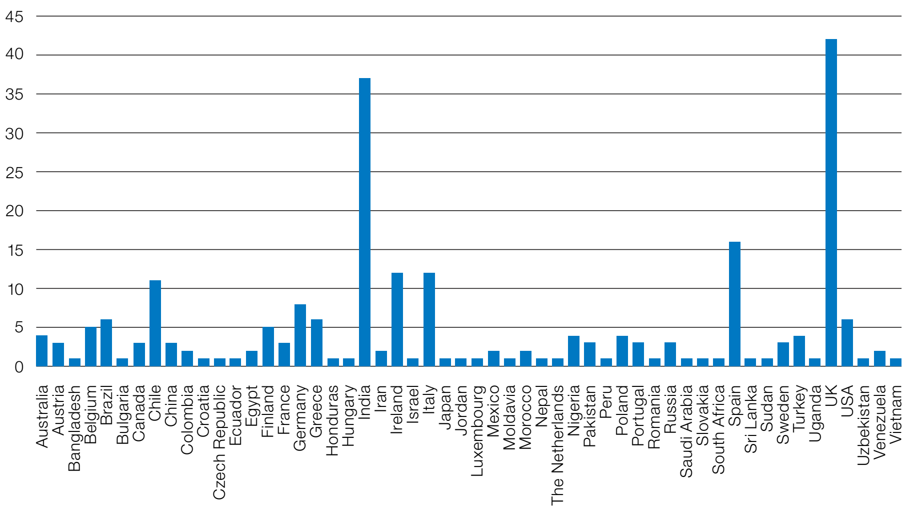


Figure 1. Number of applications per country received for the third ESRP in 2021.

Programme overview

Despite the apparent limitations of a virtual format, the second and third programmes each still had a vibrant and varied schedule. Events began with an introduction workshop, open to all ESO staff, in which the Director General welcomed the students and introduced ESO as an organisation (Figure 2). The project advisors then presented their projects, and the students were given a chance to introduce themselves. During the six weeks of the programme, most of the activities were carried out on the Microsoft Teams platform, with specific channels for each project and for specific events. While working on their research projects, under the supervision of one or more ESO Fellows, the students also attended a series of lectures spanning various astronomical topics, from instrumentation to black holes and exoplanets, given by ESO Fellows and staff members.

All students were also invited to attend the regular scientific activities of ESO (all happening online), including talks, science coffees, and informal meetings. The final event of each programme was a concluding workshop where each student gave a 15-minute presentation of their work in front of all ESO staff in attendance. The events in 2020 and 2021 were very well attended by ESO personnel and showcased the incredible science that the students achieved during this relatively short programme (Figure 3).

Students and their research projects

Second programme: July–August 2020

Probing the atmospheres of outer worlds: transmission spectroscopy of exoplanets

Advisors: Paulo Miles-Páez & Henri Boffin
Student: Yared Reinarz (Universidad Católica del Norte, Chile)
In this project, the student embarked on the analysis of time-resolved spectroscopic data of hot Jupiters while transiting their host star. The spectra were obtained with one of the best instruments on ESO's Very Large Telescope (VLT), the FOcal Reducer and low-dispersion Spectrograph 2 (FORS2). This project looked at how the transit depth of the planet changes as a function of wavelength and thereby probes the presence of atoms and molecules, or even clouds, in the planet's atmosphere. By comparing the results obtained for several hot Jupiters, it is possible to look for correlations and to put constraints on the place where a planet formed and how it moved.

Searching for intermediate-mass black holes

Advisors: Marianne Heida & George Lansbury
Student: Zofia Kaczmarek (University of Warsaw, Poland)
This student analysed broadband optical spectra of a large sample of candidate hyperluminous X-ray sources (HLX) obtained with the Double Spectrograph on the 200-inch Hale Telescope at Palomar Observatory. Identifying the visible emission lines in the spectra allowed the determination of the redshifts of the HLX candidates. By comparing these with the redshifts of nearby galaxies the student was able to classify each source as either a bona fide HLX — possibly hosting an intermediate-mass black hole — or a foreground or background source.

Not going out quietly: variability in dying stars

Advisors: Nicola Gentile Fusillo, Anna Pala & Tommaso Marchetti
Student: Alina Vorontseva (University of Tartu, Estonia)
This project focused on large-scale data mining and combining different datasets to discover variable white dwarfs amongst the objects identified by the Gaia spacecraft. The student explored in detail the most promising candidates and attempted to uncover the origin of the observed variability though simple modelling and comparison with known objects. The student learned how to handle large datasets and utilise photometric observations from a vast array of surveys. They developed novel numerical methods to assess stellar variability and familiarised themselves with the principle of time-resolved observations as well as the basic physics of white dwarfs, both isolated and in binaries.

Comparing ground- and satellite-based climate data for atmospheric studies of astronomical relevance

Advisors: Tony Mroczkowski & Carlos de Breuck
Student: Pablo Gómez Toribio (Universitat Politècnica de Catalunya, Spain)
Atmospheric transmission is one of the most important factors in characterising a site for millimetre and submillimetre astronomy. This project focused on the study of recent, high-resolution satellite data on the climate and compared the data to those from weather stations at the Atacama Pathfinder EXperiment (APEX) and Atacama Large Millimeter/submillimeter Array (ALMA) sites. The student analysed new data from satellites monitoring the Earth to characterise

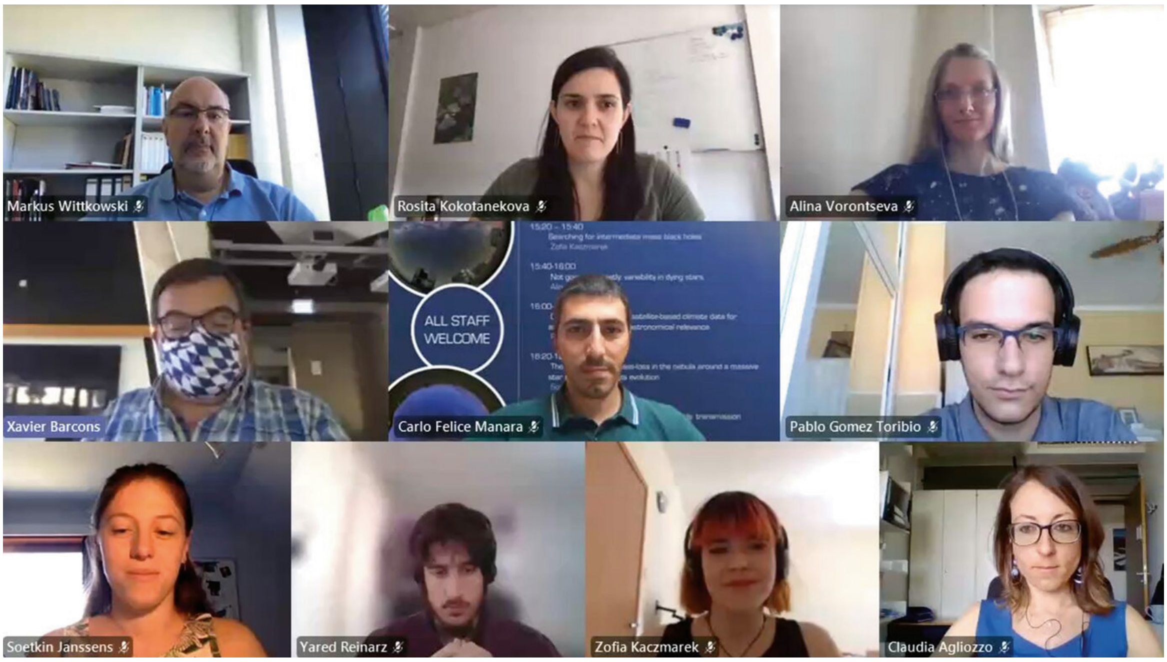


Figure 2. Screenshot taken during the welcome workshop of the second ESRP in 2020.

Figure 3. Screenshot taken during the closing workshop of the third ESRP in 2021.

the Total Precipitable Water (TPW) at 1–2 kilometres resolution and compared their measurements to weather station data from APEX and ALMA.

The fingerprints of mass-loss in the nebula around a massive star near the end of its evolution
Advisors: Claudia Agliozzo & Neil Phillips
Student: Soetkin Janssens (Katholieke Universiteit Leuven, Belgium)
This project aimed to estimate the nebular mass around a massive star near the end of its life, by evaluating different emitting components using ALMA submillimetre continuum and spectroscopic data. The student analysed integral-field-unit spectroscopic data to infer the geometry of the nebula, and thus the mass-loss mechanism, from the radial velocities of the brightest optical emission lines. These results were compared with the large mass-loss estimated from modelling of the star, and thus allowed the evolutionary state of this star to be determined. The student analysed and modelled different astrophysical emission mechanisms observed in gaseous nebulae, and learned how to derive meaningful astrophysical quantities from these. They gained familiarity with multiwavelength data from different telescopes and instruments, and learned to adopt a multiwavelength approach.

Third programme: July–August 2021

Spiral arms as drivers of chemical enrichment in galaxies
Advisors: Laura Sánchez-Menguiano & Dimitri Gadotti
Student: Anna Lena Schaible (University of Stuttgart, Germany)
In this project, the student performed a thorough analysis of the gas metallicity distribution in the galaxy NGC 4981 searching for enrichment patterns linked to its spiral structure. The student worked with high-resolution observations (part of the Time Inference with MUSE in Extragalactic Rings [TIMER] project) collected with the powerful Multi Unit Spectroscopic Explorer (MUSE) instrument mounted on the VLT. The student gained valuable experience of analysing optical spectroscopic data, performing tasks such as fitting spectra to derive the gas emission and chemical abundances, and tracing spiral arms, all aiming to answer the question of whether spiral arms are more metal-rich than the underlying galaxy disc.

Go with the flow: probing the flows and fate of gas in barred spiral galaxies
Advisors: Francesca Fragkoudi, Eric Emsellem & Adrian Bittner
Student: Rodrigo Ferrer Chávez (Autonomous University of Yucatán, Mexico)
In this project the student explored state-of-the-art numerical simulations of gas flow in barred spiral galaxies, to map a multi-dimensional view of these processes. Some of the questions the student tackled with these simulations were: i) how gas flowing into the central regions of barred galaxies builds up nuclear discs and rings; ii) what the properties of these structures are; and iii) how much of the gas is able to reach deep into the centre of the galaxy to where the supermassive black hole resides. The student also had a chance to compare these simulations with observational data of spiral galaxies taken with MUSE on the VLT.

From birth to death: the multiple faces of accretion
Advisors: Anna Pala, Carlo Manara & Nicola Gentile Fusillo
Student: Anirudh Ravishankar (Indian Institute of Science Education and Research, India)
In this project, the student investigated different accreting systems, particularly young stellar objects and accreting white dwarfs. By combining the exquisite spectroscopy obtained with the VLT and accurate photometry from the ESA Gaia space mission, the student learned to identify these two classes of objects from their fundamental observational properties. Furthermore, they used the data provided to unveil the detailed structure of the flowing material, seeing almost in real time how matter is accreted onto two different types of system, one at the start and one at end of stellar evolution. With this work the student gained insight into the physics of the accretion process and a broad understanding of the ongoing quest for a unified accretion theory.

The mysterious [CII] emission in the interstellar medium of galaxies
Advisors: Michele Ginolfi, Gergö Popping & Paola Andreani
Student: Louise Kluge (Heidelberg University, Germany)
This project aimed to compile the largest dataset of [CII] observations, at any cosmic time and for any type of galaxy, by combining existing samples with new/archival ALMA data. The student explored the redshift evolution of the [CII]-based empirical relations and used statistical methods to study their dependencies on other properties and physical quantities, such as galaxy class, stellar mass and, when possible, metallicity, dust mass and molecular gas fraction. The results obtained represent valuable information on the origin of [CII] and its link to galaxy properties, and can serve as a benchmark for modelling the physics of the interstellar medium. The student also gained valuable experience of mining the ALMA archive, handling ALMA data, and using statistical tools, as well as learning about interstellar medium physics and galaxy evolution.

Probing the building blocks of planets with ALMA
Advisors: Łukasz Tychoniec, Maria Koutoulaki & Leonardo Testi
Student: Paulina Palma (University of Chile, Chile)
This project aimed to shed light on how, when and where interstellar dust starts to stick together to form the seeds of planets. The student tackled the project by analysing ALMA data, both archival and from new observations. The student acquired valuable skills associated with the calibration, imaging, and modelling of the ALMA data and learned to extract key astrophysical results from them. The student gained a deeper understanding of interferometric techniques, which are key to the study of stars and planets in the making. In addition to acquiring these critical practical skills and valuable experience with state-of-the-art data, the student also had the opportunity to broaden their knowledge on a variety of topics covering astrophysics and astrochemistry.

Measuring IMF in high density stellar systems, i.e. relic galaxies and globular clusters
Advisors: Magda Arnaboldi, Lodo Coccato, Chiara Spiniello (Oxford) & Carlos Barbosa (University of San Paulo)
Student: Natalie Grasser (University of Vienna, Austria)
This project focused on determining the stellar initial mass function (IMF) in relic galaxies and in globular clusters (GC). The student carried out full spectral fitting of optical and near-infrared high-signal-to-noise spectra to determine the IMF slope and other stellar population parameters (age, total metallicity, [alpha/Fe]) for GCs and relics, using state-of-the-art single stellar population models. They then compared the IMF slope to the other stellar parameters, with the aim of assessing any relations or dependencies. With the inclusion of GCs the student was able to probe these relations to much lower masses, lower velocity dispersions and lower metallicity values than had been done before. This work provided a valuable contribution towards establishing whether there is a mass (or better a luminosity) threshold at which the IMF change to bottom-heavy sets in.

Feedback and future programmes

An online form was set up to allow the participating students to provide feedback on the programme. Despite the difficulties and limitations of the virtual format (particularly in 2020), the student response was overwhelmingly positive. The students were also interviewed to capture their opinions more directly, and their responses were presented in the ESOblog in 2020[1] and 2021[2]. Their words highlight how much they enjoyed their research experience and valued their time with ESO.

The repeated success of the programme has not been overlooked by ESO's management. Funding for the fourth programme has already been secured, and its organisation is well under way. We hope this time to welcome our successful applicants in person.

Acknowledgements

The ESO Fellows and postdocs in Garching acknowledge the active support and encouragement of the Director for Science, Rob Ivison, the ESO Faculty, and several ESO students, staff and administrative assistants. In particular, we thank Nelma Silva for her excellent support with all aspects of the organisation. We acknowledge funding from the Directorate for Science to cover the costs associated with the programme and the stipends for the students.

Links

[1] ESO blog "A summer of astronomy" 2020: https://www.eso.org/public/unitedkingdom/blog/summer-of-astronomy/
[2] ESO blog "A summer of astronomy" 2021: https://www.eso.org/public/blog/2021-summer-research-students/

DOI: 10.18727/0722-6691/5260

ESO Fellow Days 2021 in Cyberspace

Edmund Christian Herenz[1]
Tommaso Marchetti[1]
Michele Ginolfi[1]
Pei-Ying Hsieh[2]

[1] ESO
[2] Joint ALMA Observatory, Santiago, Chile

We used the unique circumstances of the global pandemic to reboot the ESO Fellow Days as a virtual online meeting. More than twenty Fellows connected to a two-day meeting on 20 and 21 October 2021 via the collaboration platform Microsoft Teams and the virtual reality space Gather. The activities of the event were chosen in advance by public vote. Feedback from the participants testified to their overall satisfaction and exposed the need to have meetings between Chilean and Garching Fellows on a regular basis.

The ESO Fellow Days were originally envisioned as internal ESO symposia held in turn in Santiago and in Garching. They were seen as a means to advertise the high-level science done by the Fellows within the organisation (Emsellem, Klaassen & West, 2011). These meetings also allowed fellows to interact with each other and provided career-building activities aimed at them. However, the last ESO Fellow Days were in 2012 (West & Emsellem, 2012) and the current generation of Fellows were missing out on the exchange with their peers on the other side of the globe. As new forms of remote collaborative opportunities gained traction during the pandemic, the idea of having a virtual meeting, organised by Fellows, was born. The duration and activities of this event were decided by public vote from an initial list of ideas that were brainstormed by the organisers.

Guided by the vote, we organised two half-day (mornings in Chile, afternoons in Germany) programmes that consisted of career-building activities and free-form discussion. After the meeting we gathered feedback from the participants in the form of a survey in which participants could score their satisfaction with the agenda items on a scale from 1 (very dissatisfied) to 5 (very satisfied), with free-text fields that allowed them to submit more detailed comments. Overall the meeting was a success, the general satisfaction level being 4.3, and the meeting duration was seen optimal.

Our meeting kicked off with a welcome address by ESO Director General Xavier Barcons. In his speech he emphasised how Fellowship holders establish an important link between the astronomical community and ESO. This is exemplified by the fact that numerous former Fellows now hold leading positions at world-class astronomical research institutions where they are actively involved in the development of new instrumentation for ESO facilities.

The public vote regarding possible career-building activities at the Fellow Days revealed a strong interest in guidance on European Research Council grant applications. With financial support from the Santiago Office for Science we hired a professional research consultant offering grant-writing services for research and innovation projects. The 90-minute seminar — Touching the Stars with ERC —provided an introduction to the ERC application and evaluation process. Many questions during the session reflected interest in the topic, although the post-meeting survey showed that not all participants were equally satisfied with the seminar (score: 3.2). Some survey respondents approved of the introductory nature, but others would have preferred a deeper exposition tailored more specifically to astronomers.

Current Fellows also wanted to connect with former Fellows. This was achieved by organising a 90-minute panel discussion with ESO Fellowship alumni. The panel consisted of five alumni at three different career tracks[a]: corporate, academic, and staff at ESO. Getting first-hand accounts of post-fellowship CVs offered a glimpse of the existing opportunities. The lively discussion with the panellists provided encouragement to the current Fellows in respect of their future careers. This get-together with alumni was regarded by many participants as the highlight of the Fellow Days (satisfaction score: 4.8) and should therefore be repeated in future.

We also wanted to provide space for informal interactions, as this was an important component of the real-world Fellow Days. However, classical video conferencing software does not allow for the desired spontaneity and hence we used Gather[1], a video chat platform that incorporates spatial dynamics. We set up dedicated meeting spaces in Gather for different areas of scientific interest (stars, galaxies, and planets) and a general hangout space (Figure 1). The latter was the platform for lively exchanges on the differences in the duties of Chilean and Garching Fellows. The opportunity to connect via Gather was generally well received (satisfaction score: 3.8), but some participants would have preferred a more structured approach. However, it was our intention to emulate the “chaotic” social component of a meeting, where serendipitous exchange may lead to new creative insights and future collaborations. Maybe this important component of real-world meetings cannot be translated adequately into the virtual realm.

Still, while we could not meet in person, the expansion of online meetings and remote working during the pandemic enabled the Fellows of the organisation to come closer together. We hope that the tradition of having ESO Fellow Days will be continued by the coming generations of ESO Fellows. Networking is necessary for sharing perspectives and gaining new

Figure 1. ESO Fellows discussing science and duties using the Gather platform at the Fellow Days 2021. Top: General hangout space. Bottom: Topical meeting rooms.

ideas. The ESO Fellow Days could be seen as a cornerstone of the ESO Fellowship in the future, to the benefit of Fellows' careers and ESO in the long term.

Acknowledgements

The organisers wish to thank the Heads of the Offices for Science in Vitacura (Itziar De Gregorio Monsalvo, Linda Schmidtobreick) and Garching (Paola Andreani, Giacomo Beccari) for encouraging us to organise this meeting and Nelma Silva (Garching) for practical help with the organisation.

References

Emsellem, E., Klaassen, P. & West, M. 2011, The Messenger, 144, 53

West, M. & Emsellem, E. 2012, The Messenger, 147, 44

Links

[1] Gather: https://www.gather.town/

Notes

[a] The non-academic corporate track was represented by Jason Grunhut, a 2012 Garching Fellow who now leads a Data Science Team at TELUS Digital in Canada, and Carla Gil, a 2006 Chile Fellow, who now is an Associate Director at Genmab in Denmark (see "Fellows at ESO" in The Messenger No. 157, p.54 and No. 136, p.78, respectively). The academic track was represented by Kate Maguire, a 2013 Marie Curie Fellow hosted in Garching (The Messenger No. 158, p.61) who now is an Assistant Professor at Trinity College Dublin in Ireland, and Andra Stroe, a 2015 Garching Fellow (The Messenger No. 166, p.69), who now holds the Clay Fellowship at the Center for Astrophysics | Harvard & Smithsonian in the US. The route towards becoming staff at ESO was represented by Andrea Mehner, a 2011 Chile Fellow (The Messenger No. 153, p.43), who is now an ESO Astronomer with duties at Paranal Observatory.

Aerial view of La Silla Observatory, ESO's original observing site. It is located on the outskirts of the Chilean Atacama Desert, 600 km north of Santiago de Chile and at an altitude of 2400 metres.

DOI: 10.18727/0722-6691/5261

Report on the ESO Workshop

Atmospheres, Atmospheres! Do I look like I care about atmospheres?

held online, 23–27 August 2021

Henri M. J. Boffin[1]
Eleonora Alei[2]
Núria Casasayas Barris[3]
Stella-Maria Chasiotis-Klingner[1]
Camilla Danielski[4]
Chloe Fisher[5]
Siddharth Gandhi[6]
Ryan MacDonald[7]
Emily Rickman[8]
Elyar Sedaghati[1,4]
Jiri Zak[1]

[1] ESO
[2] ETH Zurich, Switzerland
[3] Leiden Observatory, the Netherlands
[4] Instituto de Astrofísica de Andalucía, Granada, Spain
[5] University of Bern, Switzerland
[6] Warwick University, UK
[7] Cornell University, Ithaca, New York, USA
[8] ESA, Space Telescope Science Institute, Baltimore, Maryland, USA

The discovery rate of exoplanets has been such that we have now moved from a simple detection regime to one in which planets can be characterised. Alongside precise determinations of planetary radii and bulk compositions, the properties of their atmospheres are now being revealed. This provides a powerful window onto the formation history of planetary systems, the composition of the initial protoplanetary disc in which planets form, and the locations of planet formation. Moreover, this allows us to study various chemical and thermodynamical processes in the upper atmosphere, as well as to probe planetary interiors. ESO recently organised an online workshop on these topics, with some quite unique aspects: it addressed results from transmission and emission spectroscopy from the ground in the study of exo-atmospheres; it looked at synergies with studies of giant planets in the Solar System; it provided two days of hands-on activities to prepare the future generation; and it included invited talks by the most promising young scientists working in this field.

Transiting exoplanets, that is, those passing across the disc of their host stars, present an unrivalled opportunity to study and characterise the physical properties of exoplanets and in particular of their atmospheres. The atmospheric metallicity, temperature structure, cloud properties, and dynamics can be revealed by studying either spectroscopic imprints in starlight traversing an exoplanet's upper atmosphere — a technique known as transmission spectroscopy — or the light emitted from the planet's dayside — emission spectroscopy. A whole host of ions, atoms and molecules have been detected through a variety of, often complementary, techniques, such as differential spectrophotometry using low- to mid-resolution spectroscopy, and high-resolution spectroscopic techniques, including the use of cross correlation. These detections serve as unique and strong diagnostics of chemical and dynamical processes in the exo-atmospheres.

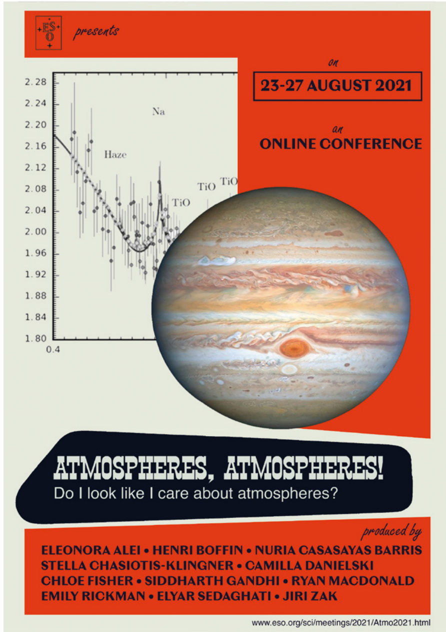


Figure 1. Conference poster. Jupiter image credit: NASA, ESA, A. Simon (Goddard Space Flight Center) and M. H. Wong (University of California, Berkeley) and the OPAL-Team.

A unique conference

Even if the pioneering work on exoplanet atmospheres was done with the Hubble Space Telescope, and much hope is now placed on the James Webb Space Telescope (JWST), most results have come from ground-based facilities, with ESO instruments — mostly the FOcal Reducer and low-dispersion Spectrograph 2 (FORS2), the Ultraviolet and Visual Echelle Spectrograph (UVES), the CRyogenic high resolution InfraRed Echelle Spectrograph (CRIRES), the High Accuracy Radial velocity Planet Searcher (HARPS), and the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) — playing a central role. Soon the upgraded CRIRES (CRIRES+) and the Near InfraRed Planet Searcher (NIRPS) will also be major tools for such studies. Elsewhere, instruments such as the Inamori-Magellan Areal Camera and Spectrograph (IMACS), the Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Echelle Spectrographs (CARMENES) instrument, and the OSIRIS integral field spectrograph, to name but a few, have also contributed to the field. Additionally, ground-based observations of exoplanetary atmospheres, especially those at visible and near-infrared wavelengths, will be essential in anchoring retrieval models by lifting degeneracies for JWST spectra, since the latter will not have coverage in those bands. Furthermore, ground-based, high-resolution observations will provide atmospheric details inaccessible to the spectral resolution of JWST.

This ESO conference accordingly brought together the communities working theoretically and observationally on understanding exoplanet atmospheres, with an emphasis on using ground-based facilities. It also tried to include those working on the atmospheres of close-in exoplanets and those studying the atmospheres of giant planets in our Solar System, to compare methodologies and see where synergies exist or could be made. The workshop had the further goal of preparing the next generation of astronomers to embark on this exciting and essential area of astrophysics, which is technically very challenging. Another key aspect of this workshop is that it was organised mostly by scientists at an early stage of their career — the only exception being the first author of this report. Similarly, preference was given to inviting young and brilliant speakers, providing them with a chance to shine in the complicated times we currently live in. The conference took place on the Zoom platform and used Slack for discussions, the exchange of files, and social interactions.

Hands-on session

The first two days of the workshop were devoted to a series of hands-on lectures, providing young astronomers with intensive training in how to extract observational data that are useful for exoplanet studies and how to interpret them, using sophisticated theoretical models and advanced methods such as machine learning. To ensure sufficient interaction between the participants and the lecturers, the number of participants in these lectures was limited to 30 — a selection therefore had to be made. The selection was based on the status of the participants, with preference given to early PhD students, and on a short motivation letter they had to write. For the benefit of those who weren't selected, however, and of those who would like to learn these techniques in future, all sessions were recorded and the videos posted on YouTube and linked from the programme page[1]. The material necessary to do the exercises, including the python notebooks, is provided on GitHub, and linked from the programme page[1]. During the lectures themselves, the material was provided to the participants via Google Colab notebooks, making it easier to run the codes without the hassle of installing various items of software.

There were seven hands-on sessions, covering many aspects of the study of exoplanet atmospheres. These were given mostly by members of the organising committee. First, Elyar Sedaghati showed how to remove the signature of Earth's atmosphere from spectra, using the ESO package Molecfit. This is the crucial final step in the data reduction, before one can start to apply specific techniques. Emily Rickman and Elyar then explained how to obtain useful data for atmosphere characterisation from spectrophotometric and direct-imaging observations. The next two lectures were dedicated to one of the most successful techniques used, namely narrow-band transmission spectroscopy using high-resolution spectra. Núria Casasayas-Barris and Julia Seidel demonstrated the general features of this technique and the caveats to be aware of, while Matteo Brogi and Jens Hoeijmakers explained in more detail how to use the cross-correlation method. The following day was devoted to the interpretation of observations. Chloe Fisher and Siddharth Gandhi led a hands-on session on how to interpret the cross-correlation maps, while Eleonora Alei and Evert Nasedkin showed how to use the petitRADTRANS code to perform low- and high-resolution forward models. This also included introducing a retrieval routine that is now part of the suite. Finally, Ryan MacDonald and Natasha Batalha gave the participants an overview of how theoretical atmospheric models are derived and their inputs and limitations.

These lectures were a clear success as evidenced by the feedback provided by the participants, most of whom can be seen in Figure 2. When asked to provide

Figure 2. Most of the participants in the hands-on lectures.

a score between 0 and 10 to rate the general content of the sessions, the average was 8.7, while the ease of the combined use of Zoom/Slack/Google Colab was also deemed excellent. All participants praised the quality of the lecturers.

From the Solar System to exoplanets

The last three days were dedicated to a conference, open to all and free to attend. Besides nine invited review talks, the conference included 19 contributed talks. The first invited talk was by Julia Seidel who gave a summary of what had been discussed during the hands-on sessions. She walked us through the most common complications when building a transmission spectrum and highlighted the most important results of recent years in the realm of narrow-band transmission spectroscopy using high-dispersion spectra, with a focus on the different spectrographs that are capable of this, whether currently or in the future.

Following this, Henrik Melin brought us back to our own neighbourhood, the Solar System, and presented what we currently know about the upper atmospheres of Uranus and Neptune. These two ice giants in our Solar System are excellent analogues for a vast number of exoplanets in the Universe, and their relative proximity to the Earth allows us to perform detailed observations of their atmospheres. One can, for example, study aurorae on these planets, which are capable of injecting large amounts of energy into their upper atmospheres. Observations over almost 30 years of the molecular ion H_3^+ have revealed that the upper atmosphere of Uranus is subject to long-term cooling. The situation of Neptune is even more surprising, as H_3^+ remains undetected in its atmosphere, the upper limit of its ionospheric density being much lower than predicted by models.

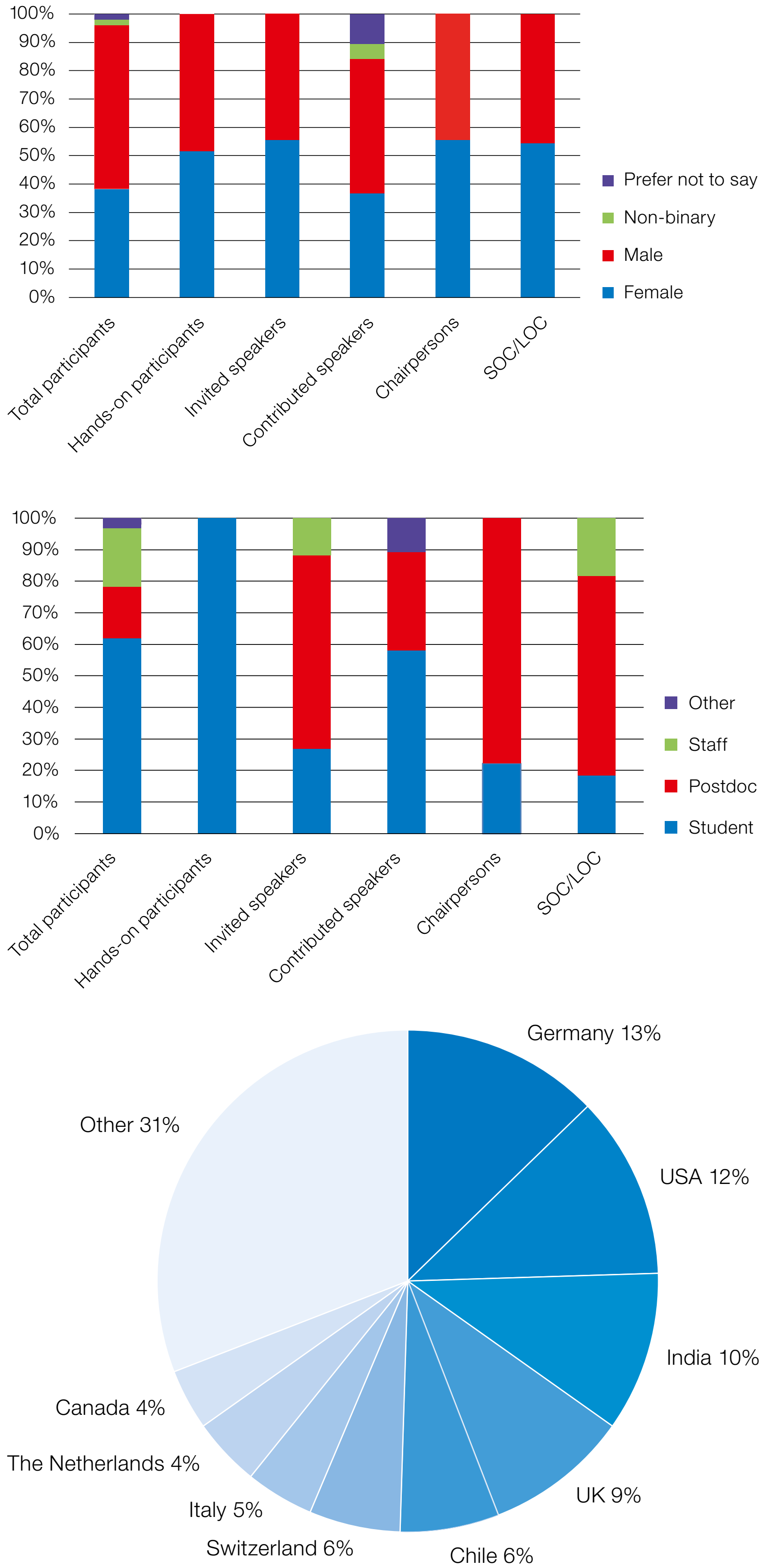


Figure 3. Charts depicting the distributions of gender (top) and career stage (middle) of the participants in the workshop, where we note that the categories shown may not accurately reflect the complex reality. The bottom panel shows the distribution of the registered participants according to their country of residence.

Molecules, molecules...

Molecules in the atmospheres of exoplanets was the topic of the talk by Katy Chubb, who showed how determining molecular spectra at the high temperatures of transiting exoplanets (typically up to 1000–2000 K) is challenging. Ambitious and demanding projects such as ExoMol and HITEMP have been set up in recent years to provide such spectra in the form of molecular line lists, whose computations can sometimes take years, particularly for molecules with more atoms/electrons. These line lists then need to be converted to pressure- and temperature-dependent spectra to be used in retrieval codes for atmospheric characterisation.

Focusing on a subset of these molecules, Aurora Kesseli described how metal hydrides (FeH, CaH, MgH etc.) and metal oxides (TiO, VO etc.) are likely to be important sources of opacity at visible wavelengths in hot and ultra-hot Jupiters and can also cause the temperature inversions that we see in some ultra-hot Jupiters. However, conclusively detecting any of these species has proven extremely challenging and more work is needed to obtain high-resolution line lists of these molecules. If such species can be unambiguously discovered in exoplanets, it will help us understand dayside to nightside temperature contrasts, cold-traps and more, and they could then be used as probes of exoplanet properties like metallicity, weather, and magnetism.

The detection of such molecules is best done with high-resolution cross-correlation techniques, which were reviewed by Matteo Brogi. Spectroscopy at very high resolution (R > 25 000) with telescopes on the ground couples the ability to resolve the dense forest of molecular lines with sensitivity to the changing planet's orbital motion, and it extracts information from spectra via cross-correlation with models. While the cross-correlation method has shown enormous potential to recognise molecular species, exploring families of models and retrieving information about abundances and temperature have proven more challenging, and working solutions have only emerged in the last two years. Matteo also highlighted the complementarity between space- and ground-based observatories, which we are just starting to exploit and which will be fully realised when coupling the JWST to ESO's Extremely Large Telescope.

The following day, Neale Gibson provided convincing evidence that while the "classical" cross-correlation approach is efficient at finding atomic and molecular species, it is quite limited in its inability to recover quantitative information on the atmosphere, such as abundances and temperature profiles; nor can it place statistically robust uncertainties on the quantities it can measure. Recent pioneering efforts have therefore sought to develop likelihood "mappings" from the cross-correlation function, that can be used to directly compare model fits to high-resolution data sets, thereby solving these issues. Such frameworks can be based on a simple Gaussian likelihood, remarkably similar to the techniques that have been applied to transit light curves for over a decade. However, this only works if one can filter out the stellar and telluric lines from the data without losing the signal from the underlying exoplanet. Luckily, Neale showed that much progress has been made on these fronts.

Mornings and evenings

The above methods aim at understanding the atmospheres of exoplanets and inferring more information about the planets themselves. However, as Néstor Espinoza highlighted, care must be taken in the interpretation. During transit, stellar light gets filtered through the terminator region of an exoplanet, allowing us to peek into its atmospheric structure and composition. Because of its complex 3D nature, however, this region is most likely not homogeneous. Hot, highly irradiated and tidally-locked giant planets in particular have been predicted to have different properties around their morning (i.e., night-to-day) and evening (i.e., day-to-night) terminators, implying that they might have distinct temperature, pressure and thus compositional profiles that would give rise to different spectra on each side of a terminator. This can nevertheless be used to our advantage, as constraining those differences might give precious insights into circulation patterns and compositional stratification that might prove to be fundamental for our understanding of not only the weather patterns in the planets under study, but also of planetary formation signatures which might only be possible to extract once these features are well understood. Néstor reviewed the state-of-the-art models predicting this effect and the prospects for their observational detection, with a special focus on the role that high- and low-resolution ground-based spectrographs could have on the quest to constrain the mornings and evenings on these distant worlds.

Many of the results depend on how well we can model the spectra of planets. This topic, applied also to brown dwarfs, was reviewed by Theodora Karalidi, who showed how we are living in an era where developments in atmospheric models are data-driven. She gave an overview of the intricacies of modelling brown dwarf and exoplanet spectra and how observations have informed our models, and how high-resolution model spectra will help us constrain the 3D structure of brown dwarf and exoplanet atmospheres.

The goal is to gather information on the formation and evolution of exoplanets, and particularly hot Jupiters. This was the subject of the talk by Rebekah Dawson, who started by emphasising how hot Jupiters — the first exoplanets to be discovered around main sequence stars — astonished us with their close-in orbits. They are a prime example of how exoplanets have challenged our textbook, Solar-System-inspired story of how planetary systems form and evolve. More than twenty-five years after the discovery of the first hot Jupiter, there is still no consensus on their predominant origin channel. Three classes of hot Jupiter creation hypotheses have been proposed: *in-situ* formation, disc migration, and high-eccentricity tidal migration. Although no channel alone satisfactorily explains all the evidence, progress is now being made, in particular thanks to the study of atmospheres.

Looking forward

This unique set of review talks was complemented by highly interesting contributions, covering topics such as computing atmospheric models, retrieving atmospheric compositions, and identifying surface features. We don't have space to review all these here, but almost all the presentations have been recorded: copies of the slides and links of the videos are available on the conference's programme webpage[1]. Most slides were also included on Zenodo, allowing them to have a DOI and to be recorded in the ADS.

There is no doubt that the conference highlighted how dynamic the field of atmospheric studies of exoplanets is, a field in which many young scientists are playing a key role. Understanding the processes requires the use of many sophisticated techniques, whether to compute theoretical spectra or to analyse and interpret the data, including the use of machine learning. Things are evolving at an amazing pace, and we hope that with the material provided, even more young astronomers will be encouraged to embark on these amazing studies.

Demographics

In setting up the programme, the Science Organising Committee (SOC) decided to depart from usual practice and to give preference to young scientists who have already demonstrated remarkable achievements in their areas. The quality of the lectures and presentations witnesses that this approach paid off. Thus, most of the lecturers and invited speakers were at the postdoctoral or assistant professor level, with some of them also still about to finish their PhD. It was a further choice of the SOC not to have posters in this conference.

The selection of invited speakers was made to ensure gender and country balance, while the selection of contributed talks was done blindly by the SOC, who were only given the abstracts. This led to 39% of the contributed talks being given by women, higher than the 30% ratio of the submitted abstracts. A large fraction of the contributed talks were given by PhD students.

We had a total of 208 registered participants, even though during the workshop the number of live participants was always around 100–120. This is likely due to the fact that participants came from four continents and 35 countries in total. Live participation was therefore not always easy, given the difference in time zones. However, as most of the lectures and presentations were recorded, and the discussion took place on Slack, we are confident that all registered participants had the opportunity to enjoy the talks and ask questions if necessary.

The distribution of the participants, speakers, and session chairs according to gender, career stage, and countries is shown in Figure 3. A post-conference survey was conducted amongst the participants, which revealed that a large majority were very satisfied with the workshop — the final average rating of the quality of the talks was 9.1 — and that many wished to repeat this conference soon!

Acknowledgements

Many thanks go to all the lecturers and invited speakers for the quality of their presentations. It is a pleasure to thank the ESO librarians for their help with putting the slides of the talks on Zenodo. The title of the workshop is based on a line by Arletty in the 1938 French movie Hôtel du Nord by Marcel Carné. The workshop poster was made by N. Boffin.

Links

[1] Workshop programme webpage: https://www.eso.org/sci/meetings/2021/Atmo2021/program.html


P. Horálek/ESO

Located high on the top of a Chilean mountain, ESO's Paranal Observatory benefits from stunning vistas of the surrounding Atacama Desert and — more importantly! — clear and beautiful skies. This photograph of the site shows an especially colourful scene, as the setting Sun paints the sky with beautiful hues of pink, orange, purple, blue, and yellow.

DOI: 10.18727/0722-6691/5262

Fellows at ESO

Francesca Fragkoudi

Imagine you're flying through space, at breakneck speed, past stars and galaxies, trying to reach the edge of the Universe. Eventually, you make it there! (queue heroic music). After examining it for a moment, you think, "Well, this can't be right. If the Universe is *everything* that exists, it can't just end – what's beyond the edge? It has to keep going!" So, you keep flying on, until even the stunning views get a bit repetitive, and you decide that this darned Universe must, in fact, end *somewhere*. And so the whole process repeats itself, ad infinitum. Or until you fall asleep. This little thought experiment was one of my favourite things to do as a child. My own version of counting sheep, if you will. I had read in a popular science book that the Universe might be infinite, and I tried very hard to figure out — just by thinking about it — whether this could be true and what it would mean. I think you can tell from this story that I was always going to become a theorist.

So how did a theoretical astrophysicist end up working at ESO?

Growing up in Cyprus, I was fascinated from an early age by mathematics and physics and annoyed my teachers by asking "why?" a lot, so I decided to study Physics and Philosophy at the University of Bristol. My love affair with philosophy was rather tumultuous, and while I loved the first-year courses, by the end of the second year we had fallen out. My infatuation with physics, on the other hand, was going strong. I eventually dropped philosophy, and earned myself a BSc in physics. After three beautiful years in Bristol, I needed a break from the English weather, so I moved to Barcelona, Spain, to study for a master's degree in astrophysics & cosmology. There, I got my first real taste of research, working on the dark matter bispectrum of large scale structure with Licia Verde and Raul Jimenez. It was a great experience which solidified my desire to pursue a PhD in astrophysics. However, life sometimes takes unexpected turns; I decided that before embarking on a PhD I wanted to see more of the world, so I took a year off the academic path. I first worked for a few months in a restaurant, saved some money, and then spent half a year travelling around South America. Needless to say, this was one of the most formative experiences of my life.

After returning, I started my PhD at the Laboratoire d'Astrophysique de Marseille, with Lia Athanassoula and Albert Bosma, on the dynamics of barred galaxies. During my PhD I studied the orbital structure of galactic bars and their vertically extended part — called the boxy/peanut bulge — exploring how these structures affect their host galaxies. I also developed a dynamical modelling technique that allowed me to determine how much dark matter is present in the innermost regions of barred galaxies and applied this method to the galaxy NGC 1291. After finishing my PhD, I left Marseille (a city that I will always love dearly) and started a postdoc position at the Paris Observatory, working with two wonderful mentors, Paola Di Matteo and Misha Haywood. During my two years in Paris, I applied my knowledge of bar dynamics to our home galaxy, the Milky Way. I was able to show that N-body models of the Galaxy that are composed purely of a thin and thick disc component can reproduce the properties of stellar populations of the inner Milky Way. I did this by comparing — as accurately as possible — the N-body simulations to observations of the Galactic bulge from a large spectroscopic survey called APOGEE. These findings suggest that the Milky Way's bulge has a mostly *in-situ* origin, which contradicts the classical picture of bulge formation through mergers. During my time in Paris, I also started an educational science outreach project called "Columba-Hypatia: Astronomy for Peace". This project uses astronomy as a tool for peace and diplomacy, to promote a sense of global citizenship, in my divided home country of Cyprus. I could spend this whole article talking about Columba, but instead I'll leave you with a link to the project in case you'd like to find out more (www.columbahypatia-project.org).

And this finally brings me to the Munich part of the story, which in fact started across the street from ESO, at the Max Planck Institute for Astrophysics (MPA). There I spent three fantastic years with an MPA fellowship, during which time my scientific horizons really expanded. I was able to continue my research on barred galaxies like the Milky Way, now using cosmological simulations. I showed that cosmological simulations corroborate our previous findings, i.e., that the Milky Way has a bulge that is compatible with being formed *in-situ*, and that it has had an unusually quiet merger history. While at MPA, I applied for an ESO fellowship, as I wanted to bridge the gap between the theory and observations being done across the street from each other. As my research has always been at the interface with observations, moving to ESO felt like a natural next step. I've now been here for just over a year, and I can safely say it was a great decision. Even in these odd pandemic times, ESO is a vibrant place to work, and there are few places where one can experience such a broad range of astronomy-related topics, while learning from the inside what it's like to run one of the world's leading observatories. I have had the opportunity to be involved in projects related to developing the new MUSE exposure time calculator and projects related to mitigating the effects of satellite constellations on astronomy, and I've helped organise the ESO Summer Research Programme, all while mentoring and supervising some fantastic students.

I'll be leaving ESO earlier than expected (to take up a faculty position in the UK), but I feel grateful for having had the opportunity to be a part of this organisation that is pushing the frontiers of astronomical research. I can't wait to see the new heights ESO will achieve with the ELT, and to say proudly when that day comes, "You know, I used to work there".

Alejandro Santamaría Miranda

I was a fortunate child who gazed at the Milky Way during the summer in rural Spain. Like many other astronomers, I grew up in a big city where lights prevented me from seeing the starry sky. Still, I used to spend the summer months in a small village near the mountains in Extremadura, and this was partly what started my vocation to discover the Universe. Even so, I must confess that if there was a defining moment in my life, it was a television interview with the first (and only) Spanish astronaut. At that time, I was about 7 years old, and it was undoubtedly a crucial moment for my future; that was when I decided I wanted to understand the Universe and try to make that my profession. Indeed, in my case, it is pretty clear that having influential figures in early childhood can totally change your life.

Then the path was clear: first a career in physics and afterwards studying astrophysics. But life is not as easy as expected. I have little natural talent for mathematics and physics; it is the memory skills, especially remembering dates and events, where I excel intellectually, so getting my physics degree required a lot of effort on my part. Still, this was the way, and I persevered with it. During my bachelor's degree, I spent two summers working at the Observatorio de Javalambe (Teruel, Spain), while it was still under construction, I studied sky brightness and had my first contact with professional astronomy. These internships kept the flame alive.

I studied physics and a master's degree in astrophysics at the Universidad Complutense de Madrid. My master's thesis, under the supervision of Patricia Sánchez-Blázquez, focused on studying the stellar populations of bulges of spiral galaxies using 70 000 galaxies from the Sloan survey. We obtained an age and metallicity for each of them. Our main results showed no difference in the stellar populations of classical bulges and pseudobulges if classified by purely structural parameters.

While I was studying for my master's, I did a trainee project at the European Space Agency supervised by Norbert Schartel and María Santos-Lleó, where I learned the daily work of an astronomer. This experience was a keystone in my career for two main reasons. The first is that I realised that I love working in an international environment. The second is that I decided that I wanted to work with ground-based telescopes and be involved in the whole process. ESO is ultimately fulfilling both requirements.

Finding a PhD scholarship in Spain in 2015 was a titanic mission. Unfortunately, the country was still suffering the effects of the economic crisis, so there were few options. However, I found in Chile the opportunities that were not available in my own country. I used to think (and I still do) that if you want to be an excellent observational astronomer, you will do well to work here for a while and use one of the telescopes.

I arrived in Valparaíso, Chile, in August 2015 to start my PhD under the supervision of Matthias Schreiber. Our original project was to work on protoplanetary discs. However, in the end I worked on wide substellar companions around T-Tauri stars. And that is how my project ended up focusing on the origin of brown dwarfs to understand their primary formation mechanism. To accomplish this goal, it was necessary to study the brown dwarfs in their early stages, only visible in the submillimetre range of the spectrum. Therefore, I needed to learn how to work with ALMA, and it was at this point when I applied for the ESO studentship to work with Itziar de Gregorio, an expert in both the formation of brown dwarfs and ALMA. I would like to warmly thank Itziar for her guidance during my PhD. Itziar has been a fundamental pillar during my scientific career, and without her wisdom and support I would not have been able to continue in the scientific field.

During my doctorate, I worked on the early stages (pre-stellar cores to Class II) of brown dwarfs using optical and infrared observations to study the accretion processes and radio observations to study molecular outflows and the dust (disc or envelopes) surrounding brown dwarfs and very low mass stars.

After finishing my thesis in 2019, I immediately started working as an ALMA Fellow, thanks to my acquired knowledge of submillimetre interferometry. Working at ESO has given me the freedom and opportunity to collaborate with several people on various projects outside my main scientific path. For example, my area of interest has expanded to water masers, planet formation in brown dwarfs, and high-mass star formation.

I want to end by talking about my pandemic hobby. I began to brew beer at home at the worst time of the lockdown in Chile. Although I started doing this to avoid working on weekends, it became a regular hobby after brewing several batches. This activity opens a new world to me with different styles, colours, and flavours. Feel free to knock on my door to talk about brown dwarfs, low mass stars, outflows, jets, and beer varieties.

ESO Launches Visitor Programme for Scientists Working in Ukraine

Owing to the war in Ukraine, to support our colleagues in the scientific community and their families, ESO is announcing a Special Visitor Programme[1] for scientists working in the country to visit one of the ESO premises (Garching, Germany or Vitacura, Chile) to conduct scientific or technical projects. Grants will be provided in support of these scientific visits, and travel and accommodation will be covered for the full duration of the project. All ESO Member States have condemned the military invasion of Ukraine ordered by the Russian leadership, which blatantly violates the most fundamental human rights and is entirely incompatible with our values at ESO.

Links

[1] Special Visitor Programme for Scientists working in Ukraine: https://www.eso.org/sci/activities/questions.html.html

The Sun rises behind Cerro Armazones in this image from 2016, with the sunlight marking the flat silhouette of the mountain top and Venus witnessing the beginning of a new day from just above the mountain itself. The mountain top was flattened to become home to the Extremely Large Telescope (ELT), ESO's next flagship observatory currently under construction. This picture taken from Paranal, is a stunning example of crepuscular rays, occurring when objects such as clouds or mountains block part of the incoming sunlight, a phenomenon typical at sunrise and sunset when the Sun is low on the horizon or below it.

Annual Index 2021 (Nos. 182–185)

Subject Index

The Organisation

Instrumentation

Astronomical Science

Astronomical News

Author Index

A

B

C

D

G

H

I

K

L

M

Q

R

S

T

V

W

Z

Solar System Science with the **ELTs**

Extremely big eyes on the solar system conference series

Technical presentations on the ELTs, their instruments and relevant ESA space missions

28 April 2022 (half day)
Virtual attendance
Registration deadline: 15 April 2022

Science workshop on the use of the ELTs for solar system research

13–15 June 2022 (3 full days)
Hybrid attendance (ESO Headquarters, Garching, Germany)
Abstract deadline: 15 May 2022
Registration deadline: 15 May 2022

Scientific Organising Committee

Olivier Hainaut (co-Chair, ESO)
Rosita Kokotanekova (co-Chair, IA BAS, BG)
Benoit Carry (OCA, FR)
Michele Cirasuolo (ESO)
Luigi Colangeli (ESA)
Leigh Fletcher (Leicester, UK)
Luisa Lara (IAA, ES)
Agustín Sánchez-Lavega (UPV/EHU, ES)
Alessandra Migliorini (INAF, IT)
Bin Yang (ESO Chile)

Local Organising Committee

Michele Cirasuolo (ESO)
Rosita Kokotanekova (IA BAS, BG)
Olivier Hainaut (ESO)
Stella Chasiotis-Klingner (ESO)
Paolo Padovani (ESO)

#SolSysELTs2022

Contact: solsyselts_loc@eso.org

https://www.eso.org/SolSysELTs2022