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Report on the ESO Workshop

Take a Closer Look: The Innermost Region of Protoplanetary Discs and its Connection to the Origin of Planets

held at ESO Headquarters, Garching, Germany, 15–19 October 2018

Carlo F. Manara[1]
P. Christian Schneider[2]
Gaitee Hussain[1]
Stefano Facchini[1]
Anna Miotello[1]

[1] ESO
[2] Hamburg Observatory, Germany

About 150 scientists from all over the world convened at the ESO Headquarters to discuss the origin of close-in exoplanets and the properties of the inner regions of protoplanetary discs, where these planets are formed. In a cordial atmosphere, made possible by the collaborative attitude of the very diverse group of attendees, the discussion led to a deeper appreciation of the importance of several observing techniques and of advances in modelling to tackle key open questions. In addition, the participants had the chance to experience a special show at the ESO Supernova Planetarium & Visitor Centre, which highlighted the potential of this facility.

Motivations for the workshop

Radial velocity and transit surveys have discovered an impressive population of close-in exoplanets, but their origin remains unclear. What are the physical and chemical conditions of protoplanetary discs that foster the formation of close-in planets? How are close-in planets related to the inner disc and how can we observe these regions of the disc? How are inner and outer discs connected and what mechanisms drive their evolution?

We now have solid evidence for the existence of a large population of exoplanetary systems, some of which comprise several planets very close to the central star, i.e. at distances of 0.1–1 astronomical units (au), even around late-type pre-main sequence stars that are younger than 5 Myr (called T Tauri stars). These planets are usually slightly bigger than the Earth and can reach the size of Neptune, while Jupiter analogues are rarer. This finding differs from what we observe in our own Solar System and raises the question of how such planets form. From a theoretical point of view, it is still challenging to show that these planets formed in situ, but it is similarly difficult to explain this population of close-in planets as the result of migration through the disc.

To advance our understanding of the formation and migration mechanisms of these planets, it is crucial to know the conditions within the inner parts of their progenitor protoplanetary discs. The innermost disc region is where most of the processes related to star-disc interaction take place. The magnetic field of the central star truncates the disc at a few stellar radii and channels material onto the central star. Magnetic fields also drive the ejection of fast-collimated jets and slow winds. Also, the inner disc region undergoes rapid evolution, as evidenced,

Figure 1. The conference poster.

for example, by both short and long-lasting dimming events. This rapid evolution is likely to impact the formation of planets. Finally, a fraction of discs known as transition discs show a deficit of dust in the inner few au of the disc, which could be related to the mechanisms driving disc evolution in this planet-forming region.

Studies of this key disc region require innovative techniques and a wide range of instrumentation, because radio interferometers, typically used for disc studies, cannot resolve spatial scales smaller than ~ 10 au in most discs. New observations

Figure 2. The conference workshop photograph.

with instruments on the ESO Very Large Telescope (VLT) and the Very Large Telescope Interferometer (VLTI), as well as with other telescopes and radio interferometers, provide us with unprecedented information probing a range of scales relevant to disc evolution and it was this that motivated this workshop (Figure 1). Specifically, this workshop was convened to discuss the current knowledge of: the morphology and composition of the innermost regions of the disc; the star-disc interaction processes; the theories to describe the inner disc evolution; and the formation of close-in planets.

The workshop programme

With these themes defined, the workshop was aimed at scientists working on a number of related topics, including developing planet formation models, performing observations of exoplanets and discs, and working on current and future high-resolution instrumentations. With 150 participants (see Figure 2), 15 invited talks and reviews, 40 contributed talks, and about 70 posters, the workshop hosted a sizeable fraction of the target community[1]. In order to facilitate discussions, we decided to have contributed talks of 15 minutes, followed by five minutes for questions. This was generally found to be a good balance between space for new results and time for follow up questions; it also ensured keeping to schedule. Each session included two invited review talks, one from a theoretical and one from an observational perspective. Four additional invited talks were focused on current and future high-resolution facilities.

Furthermore, we had two dedicated poster sessions that were well attended, with lively discussions. Poster presenters were each asked to provide a single-page PDF slide to promote their main result. These were used to create a slideshow that was shown during the breaks in the main auditorium. Finally, a panel of four judges selected three outstanding posters, one of which was named the "best poster"; all three authors were given prizes from the ESO shop and their posters were further advertised in the auditorium during breaks on the last day.

A time-slot on Thursday was reserved for special breakout sessions, to allow discussions on particular subjects that may not have been equally relevant to all participants. The main breakout session in the auditorium dealt with a peculiar object, RW Aur. This session consisted of five highly focused five-minute talks which briefly presented recent results, followed by a lively and wide-ranging discussion lasting for more than an hour. This allowed everyone working on this target to get acquainted with the latest results from other groups, and to explore the possible explanations fitting the wealth of observational and theoretical constraints. A parallel session in the Pavo Room was organised by Mihkel Kama on observations of the inner regions of Herbig Ae/Be star discs, and this was also very well attended. Lastly, a group of colleagues took advantage of being together to discuss the reduction and analysis of still proprietary data from GRAVITY, the second-generation VLTI instrument.

The workshop closed with a final discussion led by four Science Organising Committee (SOC) members based on anonymous questions put into a "Magic Box" (Figure 3) by the participants during the week. This allowed more participants to ask any big questions, including questions they may not have had the courage to ask during the workshop. Indeed, several Magic Box questions turned out to be tricky and even provocative (in the most positive sense). The resulting lively discussion revealed a large variety of opinions and constructive answers.

All talks and posters are available via the Zenodo platform[2], where they will be stored and assigned a Digital Object Identifier (DOI). In the following sections, we summarise the subject matter of the workshop, broadly following the various programme sessions.

Exoplanet detection and formation mechanisms

As described in the review by Raphaëlle Haywood, the large number of close-in exoplanets detected to date gives us the possibility to explore the observed lack of planets at orbital periods shorter than ~ 3 days and with sizes ~ 2 $R_\oplus$. It is now possible to try to reproduce these observations with different formation mechanisms, for example based on different chemical properties of the host star, or as the result of the evolution of planetary atmospheres due to photoevaporation driven by ultraviolet radiation coming from their host stars. The latter model seems to explain most of the observations, in particular the "evaporation valley" — a gap in the distribution of planets with sizes of between 1.5 and 2.0 $R_\oplus$. One of the major open issues in this quest is the determination of the masses of these planets, in particular below ~ 2 $M_\oplus$. In this mass range, the magnetic activity of the host star and its rotational modulation contribute a radial velocity signature that has a larger amplitude than the effect due to the planet. A lot of effort is being invested into disentangling these effects; approaches include precisely modelling the physical processes causing the stellar contributions to radial velocity variability — for example, by viewing the Sun as a star — or accounting for these effects by applying robust statistical techniques to well monitored radial velocity time series.

On the other hand, the search for the youngest exoplanets is even more challenging. Radial velocity signatures from stellar magnetic activity are even more

Figure 3. This is the "Magic Box" in which participants could confidentially post their most burning questions over the duration of the workshop. These questions were used to drive the discussion on the last day of the workshop.

pronounced in young stars, as discussed later in the workshop by Gaitee Hussain and Colin Hill. Direct imaging also remains challenging. While the recent discovery of a planetary-mass object in the disc of PDS 70 was reported in a talk by Miriam Keppler, the lack of Hα emission at the location of the claimed planet in the disc of another system LkCa 15 (shown by Ignacio Mendigutía) casts doubts on its existence and highlights the need for careful characterisation and long-term monitoring of these candidate planets. Furthermore, Luca Ricci showed high-resolution ALMA observations of protoplanetary discs, which reveal a large number of gaps and rings (also see p. 19). If these structures are caused by exoplanets, they imply planetary masses smaller than the minimum detectable by current direct imaging instruments. Once those planets are identified, VLTI data provide a new way of retrieving their spectra, as shown by Karine Perraut for β Pic b.

Owing to the difficulty of detecting young exoplanets, the main formation mechanism remains unclear. In his review talk, Chris Ormel reported that there are three main theoretical scenarios that aim to describe the formation of these planets: “in-situ” formation; formation in the outer disc followed by inward migration; and a pebble-driven formation and migration scenario. In the current assessment there are some problematic aspects in all the scenarios under consideration, for example, regarding efficiencies (which can be either too high or too low), and regarding the final composition of the planets. Many of these issues, and some alternative scenarios, were addressed in several theoretical contributed talks on this topic, but it was broadly highlighted that better information on the precise morphology, chemical properties, and evolution mechanisms of discs is necessary to constrain such models.

Morphology of the inner disc

The theoretical review by Stefano Facchini, the observational review by Stefan Kraus, and the invited talk by Andrea Banzatti all presented evidence for the rapidly evolving inner regions of protoplanetary discs; this is challenging to observe directly and to describe via theoretical models. A particularly striking new result is the evidence from spectroscopy (mainly from the ultraviolet and infrared), from near-infrared interferometry, and from scattered light observations, that many discs appear to have a misalignment between the inner and the outer disc. In extreme cases the inner disc can be close to edge-on, whereas the outer disc is almost face-on. Systems known to have dips in their light curves, possibly caused by extended disc material close to the star, are observed with a range of different inclinations of the outer disc. Megan Ansdell and Paola Pinilla discussed how some of these “dipping” stars have shadows that appear to be cast by the inner disc onto the outer disc. Megan Ansdell cautioned that non-accreting systems could also have “dipper” lightcurves, so a number of mechanisms may be responsible for the “dipping” observational phenomena.

From this point of view, it is crucial to model what can cause misalignments between the inner and outer discs. The effects of binaries and of misaligned planets are being studied, as shown by Stefano Facchini, Rebecca Nealon and Hossam Aly, but other processes can also play a role. In the breakout session about the peculiar dipping star RW Aur, there was extensive discussion of the idea that winds arising from the inner disc regions could lift dust and cause dips as well as explaining other observables, for example, an increase in polarisation and the emission of strong iron lines in the X-ray regime. Whether this process could happen in other objects and somehow mimic the effects of a misaligned inner disc has yet to be understood.

Evolution of the inner disc

The question arises of what processes cause the rapid evolution of the inner disc. For a few years there has been a growing consensus that magnetically induced winds can be responsible for the observed evolution of discs (as described by Giovanni Rosotti in his review talk, and by Jake Simon). However, to constrain mechanisms such as this, further effort must be invested into understanding the properties of the gas in the inner disc regions and of the related interaction between the disc and the star. A number of observing campaigns have been planned to tackle this problem, bringing together complementary techniques, such as mapping the stellar magnetic field and tracing the accretion geometry, while simultaneously intensively monitoring lightcurve variability (as discussed during talks by Paola Pinilla and Silvia Alencar).

From an observational point of view, it is currently possible to probe the properties of the gas in the inner au or so only with spectroscopy, mainly in the infrared, as shown by Melissa McClure and Andrea Banzatti, or by observing the accretion process. Indeed, Laura Venuti explained in her review talk that current data can place strong constraints on the evolution of the accretion processes in time, on both short and secular timescales. Moreover, Rebecca García López discussed how near-infrared interferometric observations of possible tracers of accretion (for example, Brγ) could constrain the emitting regions of the line, and thus the origin in either accretion stream or winds. The modelling of these observables is still under way, mainly from the wind/outflows perspective, as discussed by Somayeh Sheikhnezami.

The inner disc is evolving both physically and chemically. In particular, Arthur Bosman and Richard Booth showed how chemical tracers and metallicity in the very inner disc could be used to help constrain the radial transport of both gas and solids in protoplanetary discs. The need for more sophisticated (in particular 2D) models was clearly highlighted.

Main conclusions and ways forward

This workshop demonstrated spectacularly how our knowledge of the properties of the inner disc is currently evolving from a picture of a quasi-static environment to one of a highly dynamic region, with rapid changes in morphology, chemical composition, and emission properties. In this context, the workshop revealed an impressive wealth of diagnostic methods encompassing X-ray, ultraviolet, optical, infrared, millimetre and even centimetre, wavelengths — with the need for multi-wavelength observations increasingly being recognised by the community.

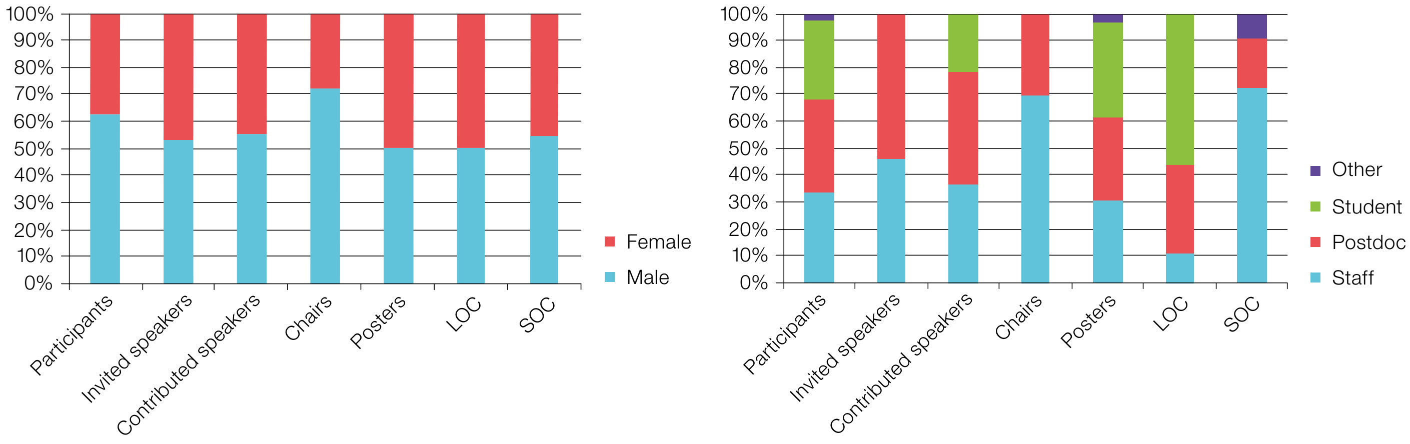

Figure 4. This shows how the distribution of the gender and career level of the participants compared with the corresponding distribution of speakers and organisers.

We also saw an equally impressive rate of progress in the theoretical understanding of the evolution and properties of discs. These models must contend with a wealth of new observational constraints that are continuously coming in. It is now evident that static models need to be replaced by dynamic ones, which include magnetic fields and disc misalignment. These should provide clearer observational predictions to further guide the efforts of observers, ultimately leading to planet formation theories stringently constrained by observations.

The dedication and constructiveness showcased at this workshop prove that the community is clearly ready for this challenge. The diverse audience included many early career scientists, clearly demonstrating the growing nature of this field and the intense interest in the inner regions of protoplanetary discs, their evolution and the role they play in planet formation. During this timely workshop, it also became clear that ESO is providing the current and future instrumentation that will help scientists stay at the forefront of this study for some time to come.

Demographics

Our workshop was organised with the goal of being inclusive and encouraging as diverse an audience as possible to attend. In order to limit the amount of weekend travel — at least for European participants — the workshop started on Monday after lunch and finished at lunchtime on Friday. The Local Organising Committee (LOC) also organised child care in the ESO child-parent room for the children of two participants, who could then attend the whole workshop. The costs of this service were also partially covered by the workshop funds. The workshop funds also covered the costs of lodging for four participants and provided financial support to ten participants.

The selection of SOC members and, in turn, of invited speakers was based solely on scientific merit and the relevance of the research activity for the workshop. The SOC comprised six male and five female scientists. Also, the selection of invited and contributed talks based on scientific excellence resulted naturally in an even gender balance (see Figure 4), demonstrating their success in overcoming unconscious biases.

For our workshop, we were keen to quantitatively evaluate the distribution of participants, both in terms of gender and career stage. In order to monitor this, we requested permission from participants to collect the corresponding information; the response was extremely positive and the results are shown in Figure 4. These confirm a good gender balance amongst the speakers, and amongst the participants overall, suggesting that this research area has close to an even gender balance. The "academic age" distribution of the invited and contributed speakers was also aimed at promoting the work of early-career scientists, with about 40% of the talks given by staff in tenured or tenure-track positions, about 50% of the invited talks given by post-doctoral scientists, and 20% of contributed talks given by PhD students. These statistics further underline what was generally noted during the workshop — that the diversity of the participants and the efforts made by the organising committees to ensure everyone was encouraged to actively participate both helped to drive engaging discussions, and to provide a platform on which to build future productive collaborations.

Acknowledgements

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Links

[1] The workshop programme: https://www.eso.org/sci/meetings/2018/tcl2018/program.html
[2] Zenodo link: https://zenodo.org/communities/tcl2018/