Report on the joint ESO/NRAO Conference

Resolving Planet Formation in the Era of ALMA and Extreme AO

held at ESO Vitacura, Santiago, Chile, 16–20 May 2016

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ALMA in its long-baseline configuration, as well as new optical/near-infrared adaptive optics instruments such as SPHERE and GPI, are now able to achieve spatial resolutions considerably better than 0.1 arcseconds. These facilities are enabling us to observe for the first time the regions around young stars where planets form. Already, complex structures including holes, spiral waves and extreme asymmetries are being found in these protoplanetary discs. To discuss these newly-imaged phenomena, and to enable cross-fertilisation of ideas between the two wavelength ranges, a joint ESO/NRAO workshop was held in Santiago. We present here a summary and some highlights of the meeting.

The understanding of how planets form around young stars is an increasingly popular subject, particularly now that that it is appreciated that most stars harbour planetary systems. However, the nearest regions containing stars less than 10 Myr old are generally more than 100 pc distant. This means that typical planet-forming discs subtend an angle of less than 1 arcsecond. Observing these protoplanetary discs requires both sub-arcsecond resolution and the ability to discriminate against the bright stellar photospheric emission. The recent impressive advances in both high-contrast adaptive optics (AO), in particular extreme AO (XAO), and sensitive long-baseline millimetre-wavelength interferometry, in particular using the Atacama Large Millimeter/submillimeter Array (ALMA), are now enabling such studies on angular scales of 0.1 arcseconds or less. This workshop brought together 130 astronomers from both the AO and the millimetre communities to discuss the exciting new results starting to emerge from these facilities.

The workshop was held over one week in May 2016 and both the ESO Vitacura conference room and an overflow 'lounge' in the library were needed to house the audience (see Figure 1). Exemplifying the level of interest and the recent rapid developments in the field, there were 65 contributed talks and 28 posters in addition to the 21 invited talks. A poster session was held on the Monday evening (sponsored by the Centre National de la Recherche Scientifique, CNRS) and the Wednesday afternoon was kept free to give attendees a break from the packed programme. The posters were also judged, and an award was given to Elie Sezestre for a poster entitled "Could the stellar magnetic field explain the structures in the AU Mic debris disc?".

The programme was divided into sessions on: embedded discs; classical "protoplanetary" discs; disc theory; transition discs; disc surveys; planetesimals; disc dispersion and evolution; and finally debris discs and young planets. In addition there was a session focusing more on instrumentation, particularly ALMA and AO facilities including the Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE) on the Very Large Telescope (VLT), the Gemini Planet Imager (GPI) and coronagraphs on the Keck and Subaru telescopes, as well as future XAO instrumentation.

Dust images

Highlighting the meeting were the many high-resolution continuum images recently obtained at submillimetre (sub-mm) and infrared/optical wavelengths. As

Figure 1. Over 130 participants taking the photo break outside during the typical Santiago winter weather.

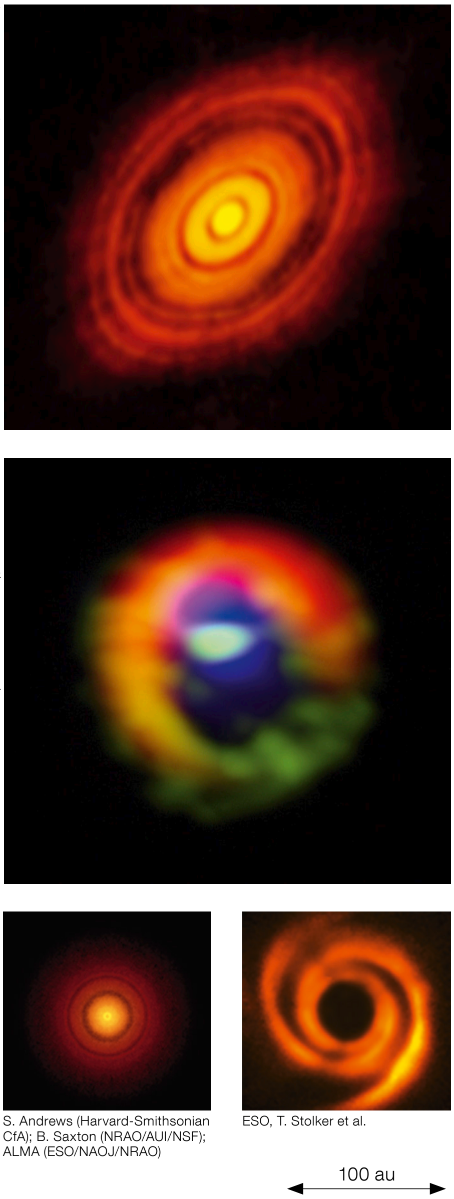

Figure 2. A few examples of protoplanetary discs shown during the meeting, illustrating the wide variety of structures found. Top: HL Tau (ALMA Partnership, 2015); middle: HD 142527 (Casassus et al., 2013; Boehler et al., in prep. using ALMA); lower left: TW Hya (Andrews et al, 2016, using ALMA); lower right: HD 135344B (from Stolker et al., in prep. using SPHERE XAO). All are shown on the same linear scale, except HD 142527, which is compressed by a factor of two.

pointed out, these superb new results clearly illustrated the fact that protoplanetary discs do not have the simple power-law radial density structures so beloved of theoreticians for the last 20 years or more (see the presentation by Giuseppe Lodato). In reality all discs have complex — and often very different — structures. The examples in Figure 2 illustrate both their similarity and their diversity. Some, such as HL Tau and TW Hya, have smooth, axisymmetric, concentric rings (presentations by Takashi Tsugakoshi and Andrea Isella). Others such as HD 135344 show low-order spiral arms (see the presentations by Henning Avenhaus, Elsa Huby and Matias Montesinos). Yet others, like HD 142527, have extreme asymmetries in their mm distributions, along with large central holes (Yann Boehler).

Continuum observations of these systems tend to trace dust of a size comparable with the wavelength, meaning there is a factor of ~ 1000 difference between the grain sizes traced by XAO and those traced by ALMA. Comparison images were shown which revealed interesting similarities and differences, promising a better understanding of the dust dynamics (Francois Menard). For example, grain size segregation can result from dust trapping induced by embedded planets or radiation pressure from the star (Paola Pinilla). The challenge now is to account for the multi-wavelength data available by combining the results in a self-consistent model.

A point emphasised during the meeting was that care must be taken in interpreting the images. For example, emission from dust can become optically thick in some discs, even at sub-mm wavelengths. Polarisation — often regarded as the way to measure the magnetic field from aligned grains in discs — is also affected by self-scattering of radiation at wavelengths even as long as 1 mm (Akimasa Kataoka, Adriana Pohl and Gesa Bertrang). Moreover XAO scattered light images tend to show the disc surface layers, which may not reflect the structure in the mid-plane. Finally, images were shown which indicated apparent changes in the outer disc structure on timescales of about one year, and these were interpreted as shadows projected from the inner region, and not part of the main disc structure itself (Tomas Stolker).

Gas in discs

Gas mass estimates in discs are still uncertain and, although self-consistent chemical models have improved, deciphering the physical conditions from molecular gas lines is clearly still a complex problem (Michiel Hogerheijde). Nevertheless, evidence is now being found of chemical abundance changes in discs, including global depletion (Megan Ansdell), as well as local depletion, including radial abundance changes, freeze-out in the disc mid-plane, and photodissociation on the surface (Mo Yu, Hideko Nomura and Stephane Guilloteau). Other exciting new results were the images of snow lines, where different molecules freeze out at different radii in the disc. These are regions thought to have enhanced core and planet formation rates — and some real examples were shown (Kamber Schwarz and Dominika Boneberg). As well as the ubiquitous ^{12}CO, instrumental sensitivities now allow imaging of complex molecules, including deuterated or isotopic species and simple organics (Viviana Guzman Veloso). Gone are the days semi-resolved CO blobs! However, it was recognised that spectral line observations of discs are always likely to be more difficult than those for dust continuum.

Transition discs

It was realised early on, from spectral energy distributions, that there exists a somewhat different class of disc with a large central hole, thought to be evolving from a disc to a planetary system. Resolved images presented at the meeting showed that such transition discs have a ring of millimetre-sized grains, with a large central cavity containing predominantly micron-sized dust and gas. This was explained by the trapping and growth of dust in the ring, along with dust filtration — a mechanism allowing small grains and gas through to the centre (for example by Sebastian Perez and Nicolás Cuello). This mechanism can maintain gas accretion onto the star, even with a central hole. Several presentations showed images of these systems in excellent detail, revealing not only the central cavity, but also detailed structures such as spirals, and warps in the ring (see Figure 2, and the presentations by Nienke van der Marel, Gerrit van der Plas, Clément Perrot and Matthias Schreiber).

Young planets

Catching planets in the process of formation is clearly an interesting topic and there is a concerted effort to find protoplanets, particularly around the central holes of transition discs. Although proof of a planet is not always straightforward, some candidates were shown during the meeting, along with several interesting predictions of the observational effects of planets on discs (Claudio Cáceres, Anne-Lisa Maire, Stephanie Sallum, Kazuhiro Kanagawa, Elena Sissa and Matías Gárate). At some point or other, planets were blamed for almost all of the structural complexities now being discovered, but it was clear that there were other possible explanations (as suggested, for example, by Sascha Quanz and Munetake Momose). Several authors are starting to use the observed disc structure to estimate planet masses and orbital parameters (Giovanni Rosotti, Judit Szulagyi, Hauyu Baobab Liu, Ilse Cleeves and Valentin Christiaens). Related to this was some discussion of binary systems and their effect on discs (Joel Kastner, Jorge Cuadra and Meredith MacGregor), one example being disc warping and shadowing.

Disc theory

Dust evolution in discs was discussed in terms of grain collisions and their outcomes, and dust transport — including turbulence, settling, and radial drift. Particle trapping was considered as an important and ubiquitous effect, and the contributors described how this could be caused by relatively small pressure bumps, by embedded planets or by rotational instabilities (for example, Paola Panilla, Laura Perez and Giuseppe Lodato). Many images showed evidence of these particle traps, which operate both radially (giving rise to rings and gaps) and azimuthally (resulting in non-axisymmetric clumps). This was something not appreciated until the new images actually showed the evidence. Some examples are shown in Figure 2.

Moreover, with the high dynamic range imaging now possible, spiral structures are also being found (Figure 2). There were presentations of methods to distinguish between spirals induced by planets and those resulting from gravitational instabilities, and the new images are providing the "ground truth" for these debates.

One issue which is still unclear is gas accretion. Observations indicate accretion rates can be $\sim 10^{-7}\ M_\odot$/yr, yet the observations so far are suggesting that discs are not particularly turbulent, implying that models of viscous disc accretion may need to be revised (Phil Armitage, Jacob Simon and Christophe Pinte).

Statistics and disc evolution

It was pointed out that the spectacular resolved images only represent 1 % of all discs. So what about more typical systems? Instrument sensitivities now enable disc statistics to be measured over whole star-forming regions, and the first results of some of these studies were presented, providing estimates of disc lifetimes as a function of stellar mass and binarity (Lucas Cieza, Scott Barenfeld and Megan Ansdell). Disc dissipation and evolution are not yet fully understood, but gas removal mechanisms, including photoevaporation and planet interaction, were discussed (Uma Gorti, Cathie Clarke and Olja Panic). At least one example of a disc caught in the act of dissipating was shown (Emmanuel Di Folco).

Debris discs & planets

Debris discs are somewhat different from protoplanetary discs, in that they are normally dust-dominated and found around older main-sequence stars. It has long been assumed that they are composed of secondary dust released in collisional cascades of larger bodies. Systems were described which may be hybrid between protoplanetary and debris discs, containing mostly dust but with some traces of gas. The origin of their gas is presently unclear; some contributors presented evidence that some disc systems could contain remnant primordial material, and others that they could contain gas released from secondary collisions (Andreas Moór, Luca Matrà, Sebastian Marino and Daniela Iglesias).

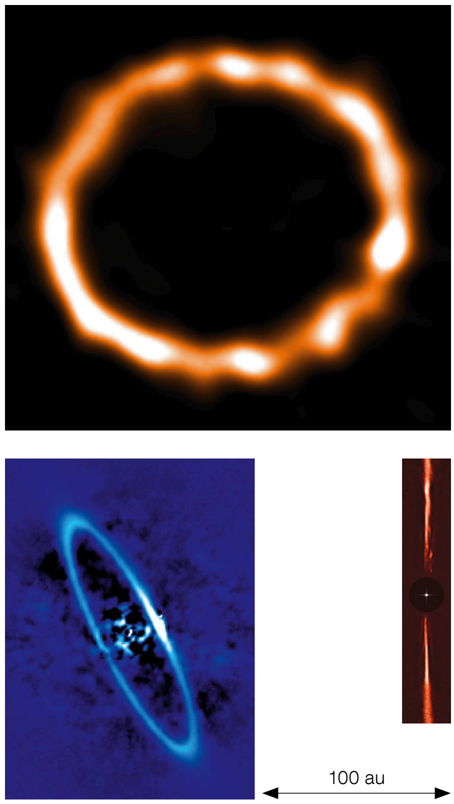

Figure 3. Some examples of high resolution images of debris discs, shown on the same spatial scale. Clockwise from top: the face-on system HD 181327 with ALMA (from Marino et al., 2016); the edge-on disc AU Mic (from Boccaletti et al., 2015) with SPHERE; and HR 4796A with SPHERE-IRDIS (from Milli et al. in prep.).

Several spectacular new images, both from the ground and from space, of debris systems were shown during the meeting (some examples are shown in Figure 3 and see also Anne-Marie Lagrange, Katherine Follette, Thayne Currie and Mark Booth). These high-resolution data commonly show rather narrow rings of dust — sometimes eccentric, warped, or asymmetric. Such structures are thought to be caused by secular perturbations, resonances and/or scattering by unseen planets (Mark Wyatt and Virginie Faramaz). Encouragingly, the number of scattered light discs detected (and resolved) with new XAO systems (as well as with improved data reduction of archived Hubble Space Telescope data) is now providing a first look at the statistics of their morphology (Markus Kasper, Elodie Choquet and Maud Langlois).

The big picture

Interspersed throughout the conference were summary reviews of the established planet formation mechanisms invoked to describe the formation of the Solar System and known exoplanets, and how they are both challenged and supported by the new results (Hilke Schlichting, Ruth Murray-Clay and Benjamin Bromley). Overall, it was clear from the superb images, the models, and the discussions held during the meeting that the new high-resolution facilities are transforming our understanding of the field. An audience vote on the newly discovered disc structures favoured their being caused by a combination of protoplanets as well as complex disc physics and chemistry. We can expect many more fascinating high-resolution results in the next few years. The challenge is to link these results with planet formation models as well as with the zoo of exoplanets now being discovered.

Most of the talks and posters are available on the conference website[1]. They are also available through Zenodo[2] and linked through the Astrophysics Data System (ADS[3]).

References

ALMA Partnership: Brogan, C. L. et al. 2015, ApJ, 808L, 3
Andrews, S. M. et al. 2016, ApJ, 820, L40
Boccaletti, A. et al. 2015, Nature, 526, 230
Casassus, S. et al. 2013, A&A, 553, 64
Marino, A. et al. 2016, MNRAS, 460, 2933

Links

[1] Workshop website: http://www.eso.org/sci/meetings/2016/Planet-Formation2016/
[2] Zenodo: http://zenodo.org/
[3] ADS: http://adsabs.harvard.edu/

Report on the ESO Workshop

Very Large Telescope Adaptive Optics Community Days

held at ESO Headquarters, Garching, Germany, 20–21 September 2016

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The future of adaptive optics (AO) instruments at the VLT was discussed during a two-day workshop. Three major directions emerged from these discussions: adaptive optics in the optical; multi-object adaptive optics (MOAO); and extreme adaptive optics (XAO). The science cases for these three options were presented and the discussions are summarised. ESO is now planning to provide detailed science cases for an optical AO system and to prepare upgrade plans for XAO and MOAO.

Introduction

ESO is planning the future of adaptive optics with the Very Large Telescope (VLT). With the Adaptive Optics Facility (AOF; Arsenault et al., 2010, 2014, 2016), the VLT will deploy a powerful tool for correcting the distorting effects of the Earth's atmosphere. As part of the AOF, the GRound layer Adaptive optics Assisted by Lasers module (GRAAL) will provide a wide-field (7 × 7 arcminute) ground-layer adaptive optics imaging system for the High Acuity Wide field *K*-band Imager (HAWK-I). Also part of the AOF, the Ground Atmospheric Layer Adaptive optiCs for Spectroscopic Imaging module (GALACSI) will provide two modes of optical corrections for the Multi Unit Spectroscopic Explorer (MUSE), one providing a doubling of the encircled energy over the 1 × 1 arcminute field-of-view of MUSE, and the other with a narrow field (7.5 × 7.5 arcseconds) with at least 5 % Strehl ratio at 650 nm for the MUSE narrow field mode. The Enhanced Resolution Imaging Spectrograph (ERIS) will complement the instrument suite on Unit Telescope 4 (UT4) offering *J*-, *H*- and *K*-band integral field spectroscopy and *J*- to *M*-band imaging with a single-conjugate AO (SCAO) system with high Strehl ratio.

The VLT AO Community Days provided an opportunity to discuss the future of AO at the VLT. The aim was to explore the scientific goals of a new instrument to make good use of the AOF, ideally while complementing the European Extremely Large Telescope (ELT) capabilities. There were 54 registered participants at the Community Days and the programme, with links to the presentations, is online[1].

The VLT AO Community Days started with an overview of the existing and planned AO instrumentation on the VLT (see Table 1). Major development paths for multi-conjugate adaptive optics (MCAO), multi-object adaptive optics (MOAO) and extreme adaptive optics (XAO) were presented. MCAO corrects more than one turbulent layer in the atmosphere and can achieve corrections over a larger field-of-view than single-conjugate adaptive optics systems, like NAOS-CONICA (NACO) and ERIS, are able to. ESO deployed an MCAO test instrument in 2007 (the Multi-conjugate Adaptive optics Demonstrator — MAD; Marchetti et al., 2007). In MOAO several non-contiguous fields are corrected individually so as to permit observing over a wider area. XAO reaches the highest density of correction over a small