Report on the ESO Workshop

Astronomy at High Angular Resolution

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A workshop took place in Brussels in 2000 on astrotomography, a generic term for indirect mapping techniques that can be applied to a huge variety of astrophysical systems, ranging from planets, single stars and binaries to active galactic nuclei. It appeared to be timely to revisit the topic given the many past, recent and forthcoming improvements in telescopes and instrumentation. We therefore decided to repeat the astrotomography workshop, but to put it into the much broader context of high angular resolution astronomy. Many techniques, from lucky and speckle imaging, adaptive optics to interferometry, are now widely employed to achieve high angular resolution and they have led to an amazing number of new discoveries. A summary of the workshop themes is presented.

Figure 1. Photograph of the participants at the workshop in the entrance hall at ESO Headquarters.

The workshop brought together people from different communities (see the conference photograph, Figure 1), who use various techniques to construct images at very high angular resolution, with the aim of reviewing these methods, the progress in the field, the new harvest of results that have been collected, as well as to prepare the next generation of astronomers to use these tools and techniques. The various techniques used to beat the seeing and the telescope diffraction limit can be roughly distributed as follows:

- single-dish imaging methods have been developed to beat the seeing at the focus of telescopes (e,g., adaptive optics, lucky/speckle/holographic imaging, sparse aperture masking) aiming at sub-arcsecond spatial resolution up to the diffraction limit of single telescopes;
- techniques that allow the diffraction limit to be beaten in order to achieve milliarcsecond angular resolution using direct (optical interferometry) and indirect (e.g., spectro-astrometry) techniques; and
- single-dish tomographic reconstruction methods (astrotomography), with microarcsecond resolution, but applicable only to certain classes of objects.

The workshop was structured to present the various techniques, with extensive reviews, and then to consider the various scientific fields that have profited from these techniques: exoplanets and brown dwarfs, stars, binaries, and large-scale phenomena. We give a very short summary of the material presented; the programme of the workshop is available[1] and the presentations can be downloaded[2].

Beating the seeing: Reaching the diffraction limit

Atmospheric turbulence creates inhomogeneities in the refractive index of air that affects the image quality — the infamous "seeing". To counter this, astronomers have devised a series of techniques, such as lucky imaging, speckle imaging and adaptive optics.

Adaptive optics (AO), which has a long history at ESO, aims at neutralising the atmospheric turbulence by a closed-loop system. As Julien Milli reminded us in his presentation, the first astronomical system ever online was Come-On at the Observatoire de Haute-Provence, which later became operational at the 3.6-metre telescope in La Silla (Merkle et al., 1989). AO is now part of many systems at the Paranal Observatory, as well as in all major observatories, and has led to many of the most important ESO discoveries: the supermassive black hole at the centre of the Milky Way, the first image of an exoplanet and imaging of the young discs around stars. AO comes in many different flavours and can be defined by the total corrected field of view versus the Strehl ratio which the system achieves. These flavours include ground-layer AO (GLAO), multi-conjugated AO (MCAO) and eXtreme AO (XAO). All major telescopes have second generation AO instruments currently in operation, which can reach typically 15–50 milliarcsecond (mas) resolution with high Strehl ratios and have ten times more actuators than the first generation AO systems.

At the Very Large Telescope (VLT), the second generation AO system is SPHERE (an XAO system), which is beginning regular operations (see article on Science Verification by Leibundgut et al., p. 2) and is based on a system with 1600 actuators (see the result in Figure 2, right). A GLAO system (part of the VLT Adaptive Optics Facility [AOF]) is under development at ESO to assist instruments such as MUSE and Hawk-I, combining diffraction-limit imaging and relatively wide-field imaging spectroscopy. Not least, the whole concept of the European Extremely Large

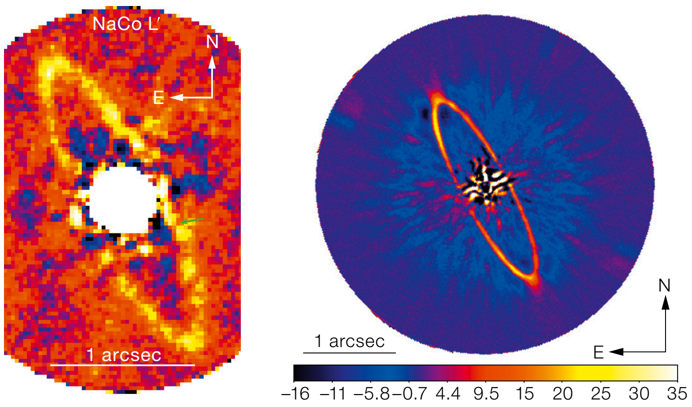

Figure 2. Showing the progress achieved in AO: a comparative study of the disc around HR 4796 A by NACO (left; from Milli et al., 2014) and, more recently, with SPHERE (right; from Milli et al. [2015] in prep.).

Telescope (E-ELT) requires the use of AO. The future lies also in the development of wide-field AO systems (WFAO), as shown by Benoît Neichel in his talk. By using multiple laser guide stars (LGS), WFAO significantly increases the field of view of AO-corrected images. The first such system in routine operation is GeMS, the Gemini Multi-Conjugate AO System, which uses five LGS and provides 87 by 87 arcsecond AO-corrected images in the *H*-band with a resolution of 80 mas. Such wide-field images with uniform point-spread functions over the full field of view are particularly useful for astrometric studies, for example in clusters or at the Centre of the Milky Way. Moreover, such developments are critical, as all the ELTs rely on multi-LGS WFAO systems.

Wolfgang Brandner reviewed lucky imaging, which is often presented as a poor man's adaptive optics. It exploits moments of good seeing, that is, it takes many short exposures and then retains only those images that have the best quality (typically 10 % of the whole). The technique is still quite popular and new projects are being devised, especially since the availability of noise-free detectors such as L3 (Low Light Level, LLL) and extended multiplication (EM) charge coupled devices (CCDs), and the fact that these systems are quite affordable. For example, the AstroLux Sur on the ESO New Technology Telescope (NTT) had a total hardware cost of only 50 000 euros. Lucky imaging is also quite useful as it generally has fainter limiting magnitudes than most AO systems, and it can work in the visible where AO is not so developed. As pioneer and expert, in his presentation, Craig Mackay mentioned that, at the 5-metre Palomar telescope, AO and lucky imaging are combined, leading to the highest resolution image ever taken in the visible on faint targets, with a resolution of 35 mas in the *I*-band and a Strehl ratio of 17 %. Gergely Csépány combined lucky imaging and AO to study a sample of 38 T Tauri multiple systems over a 20-year period, and was able to cover the orbits in several of them. In addition, Mackay presented a proposal for a mosaic of lucky imagers for the NTT. This project, called GravityCam, will consist of no less than 100 CCDs with 70 mas pixels and will mainly be used for exoplanet microlensing surveys, down to below an Earth mass.

Speckle imaging was introduced by Sridharan Rengaswamy, who showed the advantages of the method and its significant contribution to the imaging of binary stars. More details about this technique is given in Rengaswamy et al. (2014). This technique was further developed, as speckle holography, by Rainer Schödel, which he calls "lucky imaging on steroids" to reconstruct images of crowded and "wide" fields of view of several tens of arcseconds, while keeping the instrument sensitivity.

In sparse aperture masking (SAM; or non-redundant masking [NRM] depending on which side of the Atlantic you work), a mask with a few holes is placed in front of the AO system. This transforms the primary mirror into a separate-element, multiple-aperture interferometer and allows diffraction-limited imaging of (bright) astrophysical targets to be reconstructed, such as dust-enshrouded evolved stars. The technique was presented in detail by Mike Ireland. In particular, he pointed out that there are some moderate to high Strehl regimes, where working in the Fourier plane using a non-redundant mask offers improved performance over standard pupil-plane analysis; the example of a putative forming planet in a young disc in LkCa 15 was discussed. As a complement, Makoto Uemura showed how sparse aperture modelling can be applied, in a cross-disciplinary approach, to Very Long Baseline Imaging (VLBI) images, Doppler tomography and gamma-ray Compton imaging. In another vein, Jaeho Choi presented a non-interferometric phase-differential imaging method that uses Foucault knife-edge filtering.

Beating the diffraction limit: The milliarcsecond horizon

In order to reach higher spatial resolutions, different techniques, such as long-baseline interferometry where two or more telescopes are combined to obtain fringes, are required. The technique was reviewed by Jean-Baptiste LeBouquin. The contrast ("visibility") and phase information ("closure" or "differential phases") of the interference fringe packets can be used to retrieve direct information on the observed object brightness distribution. While the technique has been in widespread use in the radio domain for several decades, it is now also becoming a routine technique in the optical domain, in particular at the VLT Interferometer (VLTI) where the angular resolution in the near-infrared is of the order of a few milliarcseconds.

Two regimes of data analysis were presented. In the first, the measurements are fitted with a parametric model of the object. This is particularly well suited when the number of measurements is limited, the object structure is well understood or the object is only marginally resolved. This was, and still is, the bread and butter of interferometry and is applied to the measurement of precise diameters, binary parameters or simple morphological parameters; it is well illustrated by the spectacular case of the expansion of a nova shell (Schaeffer et al., 2014) or the mass-loss in stars across the Hertzsprung–Russell diagram (e.g., Boffin et al. 2014). In the second case, the object complexity precludes simple modelling. If an object is well resolved (e.g., about 10 mas or more) it is then possible to acquire many measurements in the (*u,v*)-plane in order to carry out image reconstruction. Fabien Baron introduced the art of aperture synthesis and presented some magic tips and tricks for imaging stellar surfaces with interferometry, introducing the SQUEEZE and SIMTOI software. Clearly still an active area of research, it was shown that a large range of priors and model selection methods can be used. It is critical to test the methods and in this respect, the blind interferometric beauty contest plays an important role (Baron et al., 2012; see Figure 3). In the same vein, Christian Hummel presented a novel imaging algorithm that allows the combination of multi-channel interferometric data in a single image.

Interferometry is now coming of age and the VLTI has become a major piece of infrastructure with which it is possible to carry out surveys of hundreds of objects, such as for young stellar objects as part of the Exozodi survey, presented by Steve Ertel (see Ertel et al., p. 24). Gains in sensitivity now allow several dozens of active galactic nuclei (AGN) to be observed and their nuclei to be probed at unprecedented angular resolution. Sebastian Hoenig explained how the VLTI observations challenge the popular dusty torus model and reveal the true complexity of the inner kiloparsecs of AGN, such as its clumpiness and the inflow–outflow connection. This idea was supported by various other talks on interferometric observations that all agreed that there is more structure present in the mass around the black hole than previously assumed (Daniel Asmus, Leonhard Burtscher & Noel Lopez Gonzaga).

Pierre Cruzalèbes showed how to use interferometry to relate deviations from centro-symmetry of evolved stars to the K giant–red supergiant–asymptotic giant branch (AGB) star sequence. Zooming in on one object, Claudia Paladini showed nice results from an imaging project of the carbon-rich Mira R Fornicis, taking data with PIONIER for six half-nights over two weeks with three different quadruplets, leading to 294 visibility points and

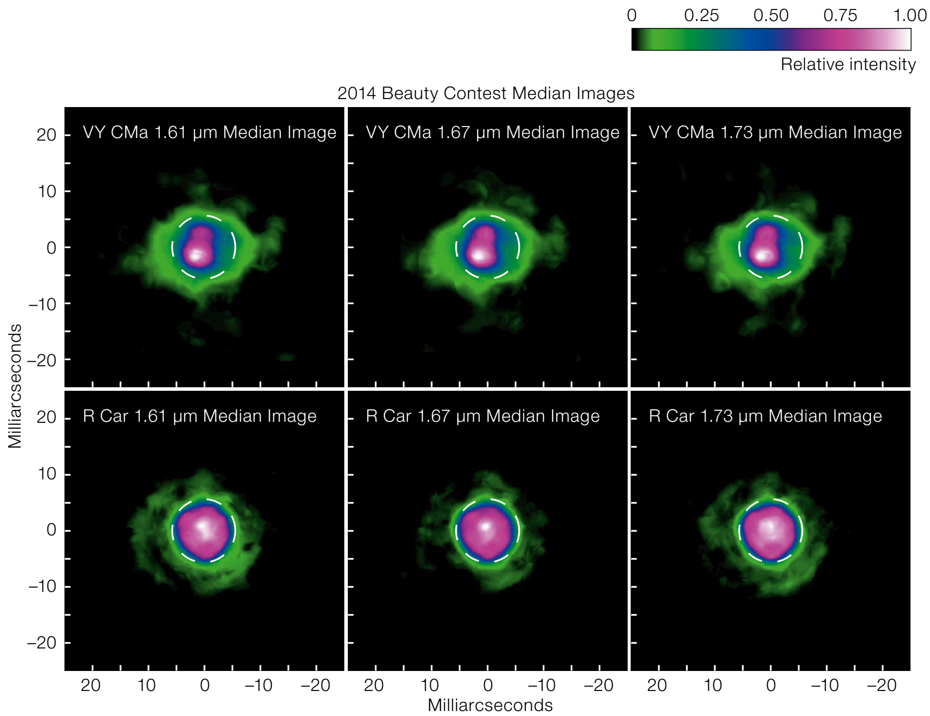

Figure 3. Results from the 2014 image reconstruction contest (see Monnier et al., 2014) based on data recorded with VLTI PIONIER. Upper: The VY CMa supergiant. Lower: The Mira star R Car.

201 closure phases. The resulting image is clearly aspherical, and shows that the surface is partially obscured by a mixture of dust and molecular opacity, similarly to R Coronae Borealis. The case was made that the combination of image reconstruction and spectral resolution should, in the future, become a major development at the VLTI, since it should allow astronomers to peer through the molecular layers in the complex stellar atmosphere. Michel Hillen looked at even more evolved stars using interferometry to study the discs around post-AGB stars and to constrain their vertical structure and dust distribution.

New instruments will soon be available, such as GRAVITY (Eisenhauer et al., 2011) and MATISSE (Lopez et al., 2014) at the VLTI. Jean-Philippe Berger showed in particular how GRAVITY will be useful for exoplanet detection. The increase in sensitivity through the use of efficient fringe tracking was discussed by Jorg-Uwe Pott, while Romain Petrov provided a detailed analysis of the possibility of more sensitivity gains.

Often, it is necessary to use many complementary techniques to gain the necessary knowledge. This was most evident in Stephan Gillesen's review on the already legendary observations of the Galactic Centre: many years of AO observations have resolved the stars of the central cluster and revealed the orbits of the inner stars around the Galactic Centre. These observations have proved the central object to be a supermassive black hole. Gillesen reported on follow-up observations that were taken to address more details and a campaign to follow the periastron passage of the star S2 in 2017 with several AO instruments. Future observations with GRAVITY in the Galactic Centre will be able to test whether Einstein's theory of general relativity holds in the vicinity of a black hole.

Stefan Kraus discussed the long-term plans to build a planet formation imager with the goal of studying the formation process and early dynamical evolution of exoplanetary systems on spatial scales corresponding to the Hill sphere of the forming planets. This requires angular

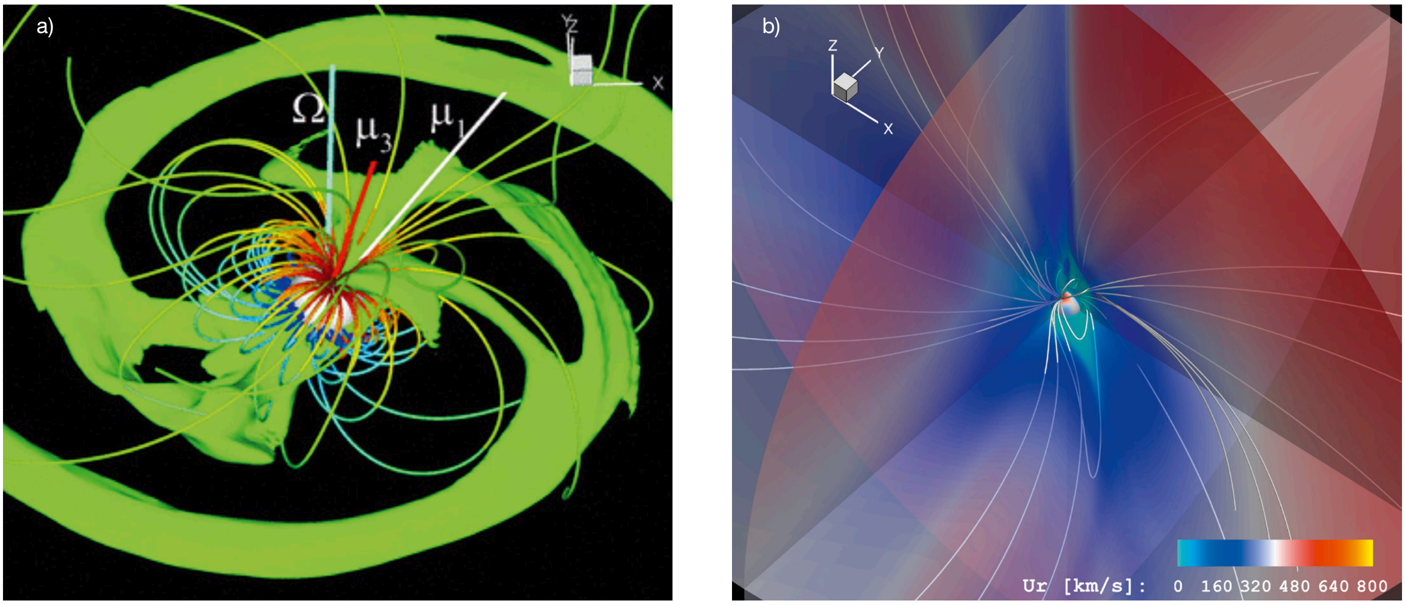

Figure 4. Large-scale magnetic field maps obtained using Zeeman Doppler imaging are key inputs for numerical simulations of their coronae and extended environments. a) In pre-main sequence stars that are still accreting from their circumstellar discs, magnetic field maps have been used to test magnetospheric accretion scenarios (Romanova et al., 2011). b) In main sequence stars they can be used to model stellar winds, and the conditions in interplanetary environments (from Alvarado-Gomez et al., in prep.).

resolution of 0.03 AU, or 0.2 mas, which clearly points to a whole new facility.

While interferometry provides direct information with milliarcsecond resolution, Klaus Pontoppidan presented spectro-astrometry, an inexpensive method for measuring spatial properties of line-emitting gas far beyond the diffraction limit, and particularly powerful in determining the position angles and sizes of rotating and jet-like compact objects on scales as small as 0.1 mas. The rather simple idea is to measure the centroid on a spectrum as a function of wavelength, giving two-dimensional information. The technique has been applied to a wide range of astronomical objects, from protoplanetary discs, binary stars, discs around massive stars to AGN. Although it can be carried out with most spectrographs, AO-fed high dispersion echelle spectrographs allow much higher spatial resolution to be reached and this is why instruments such as the CRyogenic high-resolution InfraRedEchelle Spectrogrph (CRIRES) or NIRSPEC with AO are ideal for this technique. Miwa Goto described spectro-astrometry with CRIRES at the VLT to study the anomalies in discs around stars, Mónica Blanco Cárdenas looked at the cores of planetary nebulae, while on another scale, Jonathan Stern used the same technique to spatially resolve the kinematics of 0.1 mas wide quasar broad-line regions.

Luca Pasquini presented a new method, tachoastrometry, which aims at doing astrometry with radial velocities, and is particularly adapted for double-lined spectroscopic binaries, leading to a precision of better than two mas.

Microarcsecond resolution

The last set of techniques, allowing astronomers to reach microarcsecond spatial resolutions, are known together as astrotomography, and consist of indirect imaging techniques from observations of projections, that are obtained through eclipses, Doppler shifts, and/or time delays (Boffin et al., 2001). These techniques have been used to probe the orbits of exoplanets, map the surfaces of a variety of stars and the structure of accretion discs in binary systems.

Andrew Cameron showed how the distinctive signature from transiting exoplanets in time series of high-resolution spectra could be used to recover details of the system's spin–orbit alignment through the Rossiter–McLaughlin effect. Measuring these spin–orbit alignments is important for understanding the origins of the system. In rapidly rotating stars, similar studies are important for exoplanet validation and for breaking degeneracy between v sin *i* and spin–orbit misalignment for low impact parameters. Tilted and retrograde orbits have been recovered for a number of systems, pointing to a number of different migration pathways. Studies of time series of near-infrared spectra have been employed to detect the transmission spectra of exoplanets themselves, enabling the masses of both the planet and star to be computed. The recent detection of the dayside spectrum of the hot Jupiters, τ Boo b, 51 Peg b and HD 189733b show that non-transiting planetary atmospheres can be detected; with β Pic b found to spin significantly faster than any planet in the Solar System. These are key pathfinder studies for the ELT.

Stellar surface-imaging techniques, Doppler imaging, Zeeman Doppler imaging and Roche tomography exploit the information in time series of intensity and polarised spectra to reconstruct detailed maps of stellar photospheres. In the brightest, most rapidly rotating systems, these maps can achieve a latitudinal spatial resolution close to two degrees. Oleg Kochukhov, Julien Morin and Chris Watson reviewed the application of inversion techniques to reconstruct surface brightness maps, inhomogeneities in chemical elements and the large-scale magnetic fields on stars in systems including: brown dwarfs; G–M-type main sequence and pre-main sequence stars; Ap and Bp stars; B-type HgMn stars; and late-type stars in cataclysmic variable binaries (CVs) and X-ray binaries (examples in Figure 4). These maps probe fundamental processes including surface differential rotation, timescales of flux emergence and diffusion processes, and in CVs may explain the properties and timescales of accretion outbursts.

Julian Alvarado Gomez presented a robust criterion to prevent over/underfitting in maps obtained with Doppler imaging techniques. He demonstrated how the large-scale magnetic fields reconstructed for cool stars can be used to model the extended environments and mass loss properties using three-dimensional magnetohydrodynamic models that have been developed for the Sun. Colin Hill reported the first measurement of differential rotation at the surface of the K4-type secondary of the CV, AE Aqr in contrast to predictions of tidal locking causing solid-body rotation. The timescales of the variability of activity implied by the measured differential rotation rates may contribute to the observed mass-transfer variations in the CV.

Tom Marsh introduced the technique of Doppler tomography, reviewing how structure within accretion discs and flows can be recovered from well-sampled spectroscopic time series. Results were shown for a range of accreting systems, showing how different diagnostics can allow more detail to be reconstructed. Axel Schwope showed how Doppler tomography can be applied to polars (cataclysmic binary stars) to map the detail of magnetic accretion spots on white dwarfs. Petr Hadrava showed how Fourier disentangling of the spectra of binaries can be used to study various phenomena, including pulsations, and can be applied to CVs. Jan Cechura described how hydrodynamic simulations can be used to construct synthetic Doppler tomograms of the high-mass X-ray binary, Cyg X-2, in both hard and soft states. These can be directly compared with observations and aid the conversion of tomograms, which are in velocity space, into spatial coordinates.

Raymundo Baptista reviewed how the detailed structure in accretion discs can be probed using eclipse mapping techniques including the white dwarf, mass donor, disc and outflowing gas. He also demonstrated how the time evolution of discs can be used to follow changes during outburst events and changes in disc viscosity during flickering (using light curves of HT Cas spanning two years). Stephen Potter showed how photo-polarisation light curves could be inverted to create images of accretion shocks and detail in the structure near the white dwarf photosphere in magnetic CVs. Genetic optimisation is found to be effective in finding robust fits to the Stokes parameters. The models used for these reconstructions employ realistic stratifications of the accretion column structure based on radiation hyrdrodynamic simulations. The latest results of tomographic studies of polars, covering consecutive half-orbits for two systems and revealing the variability in the structure of the magnetic accretion flow in V834 Cen and HU Aqr, were presented by Enrico Kotze.

Misty Bentz introduced the technique of AGN reverberation mapping (or echo mapping), where time delays between signals in the continuum and in various broad lines are transformed into spatial information on the broad-line region (BLR). This allows the measurement of the mass of the black hole and, together with velocity delays of the lines, also gives a detailed picture of the BLR itself. As shown by Suvendu Rakshit, combining the angular sizes of the interferometric measurements with the reverberation maps yields geometric distances to the AGNs, which is necessary for the calibration of black-hole masses as well as for general cosmology.

As is most fitting for an ESO workshop, the final session was devoted to current and future instrumentation. Suzanne Ramsay presented the current and future ESO instruments that may be used for high angular resolution, and the list is quite long: MATISSE, GRAVITY, the future AO Facility, ERIS, as well as many instruments to come with the E-ELT. Ulli Kaeufl presented the recent VISIR upgrade (see Käufl et al., p. 15).

The workshop was purposely limited to the optical and infrared domain, but of course high angular resolution astronomy can also be done in other wavelength ranges, and the recent, amazing images coming from ALMA (Atacama Large Millimeter/submillimeter Array) are a perfect demonstration. If the workshop has shown how much progress is evident on many fronts, it has also highlighted how very bright the future is!

Acknowledgements

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Links

[1] Workshop programme: http://www.eso.org/sci/meetings/2014/hires2014/program.html
[2] Workshop presentations available: http://bit.ly/1y4WR4W