Report on the Workshop

Herbig Ae/Be Stars: The Missing Link in Star Formation

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The workshop highlighted the many recent advances within the field of Herbig Ae/Be stars and the close links to star and planet formation. Topics such as magnetospheric accretion and the evolution of dust in discs, the structure of circumstellar discs and the role of walls and gaps and their links to planet formation from many observational aspects were covered. The workshop was dedicated to the life and works of George H. Herbig, who sadly passed away at the end of last year.

Introduction

One of the main open questions in star formation concerns the distinct mechanisms by which low- and high-mass stars form. While it is well established that low-mass stars grow in mass by magnetically controlled accretion, the non-magnetic, high-mass stars must grow by another mechanism, as yet unclear. In some critical mass interval, the growth mechanism changes, corresponding to the masses of A- and B-type stars.

Ever since the identification of the Herbig Ae/Be stars (HAeBes; Herbig, 1960) as a class of early-type pre-main sequence objects (Strom et al., 1972), these stars have taken centre-stage in star and planet formation studies. They have masses which place them in the transitional regime between Solar-type stars and high-mass stars. In detail, the change in star formation character between the high- and low-mass stars is the dichotomy between clustered and isolated formation, between boundary layer accretion and magnetospheric accretion, radiative and convective stellar interiors and between fast and slow rotation. Moreover, the discs around Herbig stars are in general brighter than around their low-mass counterparts, the T-Tauri stars. Therefore HAeBes are prime laboratories in which to study the evolution from actively accreting discs towards debris discs and mature planetary systems.

Importantly, the relative proximity of HAeBes in local young star-forming regions allows a detailed view of their evolving environment. As such, they are pivotal for understanding both the formation of stars and of planets. Nonetheless, the last large meeting purely dedicated to Herbig Ae/Be stars took place some 20 years ago and a review on the state of this particular field was overdue. With this scientific motivation in place, and guided by ESO's innovative edge in infrared instrumentation, our proposal to organise an ESO Workshop on Herbig Ae/Be stars was approved. Shortly after approval, the sorrowful news arrived that the founding father of this field, George Herbig, had passed away at the age of 93. George Herbig pioneered the field of star formation, and especially that of young stars and their nebulous surroundings. His legacy includes the identification and first description of Herbig Ae/Be stars. In consultation with the director of his home institute in Hawaii, it was decided to dedicate the ESO Workshop to the life and works of George H. Herbig.

The workshop took place at the ESO/ALMA Vitacura campus with close to one hundred registered participants (see Figure 1). In the spotlight were the results obtained with instruments like the CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES) and X-shooter, and the Very Large Telescope Interferometer (VLTI) spatial imaging capabilities with the MID-infrared Interferometric instrument (MIDI), the Astronomical Multi-BEam combineR (AMBER) and the Precision Integrated Optics Near-infrared. Imaging ExpeRiment (PIONIER). These, and other, instruments have for the first time opened up the milliarcsecond and sub-milliarcsecond spatial scales where the crucial accretion disc physics takes place and planet formation processes occur. In addition, space-based advances by means of the Infrared Space Observatory (ISO), the Spitzer and Herschel satellites have allowed the study of the dust and gas in protoplanetary discs at high sensitivities. The first Atacama Large Millimeter/submillimeter Array (ALMA) observations have recently revealed the ongoing planet formation process in HAeBe discs.

Figure 1. The conference participants in the garden at ESO Vitacura.

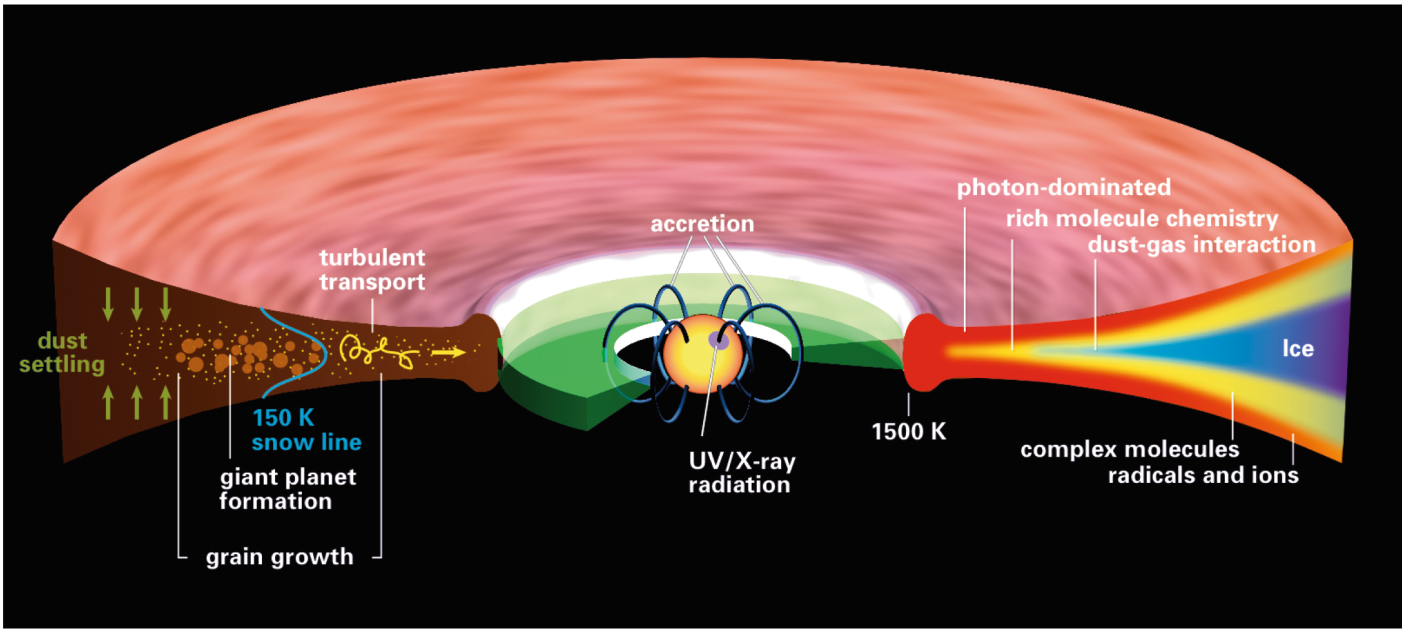

Figure 2. Sketch of the physical and chemical structure of a protoplanetary disc undergoing magnetospheric accretion. From Henning & Semenov (2013).

The scientific programme (available on the workshop webpage[1]) recorded many breakthroughs in the field, established milestones and starting points, and opened new avenues to pushing our understanding of star and planet formation to higher levels. The programme was arranged in sessions according to the physical process, roughly corresponding to increasing length-scale domains. The highest angular resolution traces the inner disc, i.e., the location in the circumstellar environment where there is a strong interaction between the disc material and the star. Longer wavelengths, and lower spatial resolution, preferentially trace the outer parts of the disc, where grain growth, and viscous accretion takes place and giant planets form. In this summary we will reflect on some of the highlights presented at the meeting and work our way from the smallest scales, close to the star, to the physics at larger radii of the HAeBe disc.

Mass accretion at the inner disc

The leading model for accretion onto A- and B-type pre-main sequence stars is magnetospheric accretion. The adoption of this model is partially justified on the grounds that, during the earliest phase of the star formation process, the properties of the intermediate-mass protostars are found to be similar to those of low-mass protostars (contributions by Maite Beltran, Yuefang Wu, Fernando Comerón). In this model, material is guided onto the star via magnetic field lines stretching from the inner disc to one or more regions on the stellar surface. The hot, shocked surface regions generate excess continuum and line emission on top of the star's photospheric spectrum. In this model, the observed excess enables the rate of mass accretion onto the star to be derived. The mass accretion rate is a key physical quantity in star formation as it determines both the timescale and efficiency for star growth, and can be used as a discriminator between different formation models. Figure 2 shows a schematic of a protoplanetary disc.

In a systematic X-shooter study of a large number of systems, the relation between excess emission, line luminosities and mass accretion was investigated across a wide mass range of young objects: from brown dwarfs to classical T-Tauri stars to Herbig Ae stars (talk by Ignacio Mendigutía). Although the magnetospheric accretion model works well for Herbig Ae stars, it is not able to explain the strong observed ultraviolet (UV) excesses in early B-type stars (talk by John Fairlamb). Further support for the magnetospheric accretion model comes from other observed similarities between Herbig Ae stars and classical T-Tauri stars, such as linear polarisation measurements in spectral lines (talk by Jorick Vink), the geometry of the rotating disc and the location of the inner disc radius. Finally, the hydrogen line profiles are also consistent with what is expected for magnetospheric accretion (contributions by Sean Brittain, Alicia Aarnio, Ricardo Ramírez, Monika Petr-Gotzens and Mario van den Ancker).

Despite the success of extending the formation scenario of low-mass stars into the intermediate-mass regime, some fundamental problems are lurking around the corner. One serious problem came to the fore during the meeting. The systematic searches for stellar magnetic fields demonstrate the presence of weak or non-existent magnetic fields in all but a small fraction (~ 6 %) of the HAeBes. For reference, a kiloGauss magnetic field is required in order for the magnetospheric accretion model to work (review talk by Evelyne Alécian). Possibly connected to the dearth of strong magnetic fields, the closely connected phenomenon of jet formation in Herbig Ae/Be stars appears to be rare (although selection effects cannot yet be excluded). Nonetheless when they are found, their properties are found to be similar to those in low-mass young stars (talk by Catherine Dougados). Soft X-rays emanate from these jets (Christian Schneider) and they can produce (soft) cosmic rays (talk by Tom Ray).

This situation is markedly different for the T-Tauri stars, in which the observed strong fields generated in the outer convective layers are capable of supporting magnetospheric accretion (talk by Gaitee Hussain) and where jet action has a very high incidence. Looking for alternatives to explain the strong UV excess, options were explored in which the excess comes from the gas in the inner disc. However, in the models presented at the meeting, the temperature of this gas seems to be too low to explain the observations (contributions by Stefan Kraus, Catherine Dougados and John Ilee). On the observational side, a hot inner disc seems to be detected in some systems and the CO emission may be explained by UV fluorescence (Sean Brittain, Giuseppe Lodato).

Dust walls and gaps

Cross-fertilisation between long-baseline interferometry and stellar astrophysics has been especially successful for the field of study of the Herbig stars. Probing the bright emission by warm and hot dust particles for nearby stars, milliarcsecond imaging reveals that the HAeBe disc displays a near vertical inner dust wall directly irradiated by the central star. This discovery solved one of the long-standing open questions regarding the hot thermal dust emission in Herbig stars. The dust in the wall is at the sublimation temperature and the observed relation between the star's luminosity and the distance between star and inner dust wall is consistent with this finding (review by Stefan Kraus).

Recent advances in infrared interferometric instrumentation, like PIONIER, now allow for efficient synthesis imaging at milliarcsecond resolution of the inner dust disc and also provide evidence for a puffed-up inner rim (talks by Jacques Kluska and Wing-Fai Thi). Related to the warm dust component, located further downstream from the inner dust wall, an extensive MIDI dataset provides evidence for flaring and gaps in discs; together with information from the spectral energy distribution, it shows that many discs have asymmetries (talks by Jonathan Menu and Narges Jamialahmadi). In a new development, interferometric data at a range of wavelengths is now combined to probe different regions of the disc. Near-infrared, mid-infrared and millimetre-wave interferometry probe different disc radii, and a variety of spectral tracers are used to characterise both the surface layers and the interior of the disc with the aim of achieving a global, yet detailed, understanding of the disc.

Notable progress was presented regarding the observational diagnostics of the presence of dust-depleted gaps in the radial density distribution of certain discs (the known as transitional discs), a relatively new discipline with repercussions for planet formation. The shape of the spectral energy distribution (displaying an absence of dust within a certain temperature interval) and the absence of the 10 μm silicate feature was addressed in a number of contributions. It appears that all sources with discs, which are strongly flared, also have dust gaps. Nonetheless, some material is still present within these gaps. For example, the infrared spectrum of polycyclic aromatic hydrocarbons (PAHs) may be a good tracer for the material in these gaps. Ionised PAHs appear to be present in low density, optically thin gas flowing through the gap, whereas the PAHs are neutral in the optically thick disc (talks by Carol Grady, Koen Maaskant).

Versatile carbon monoxide

Valuable information on the inner disc (≤ 10 au) can be retrieved by high spectral resolution, in particular in the near- and mid-infrared using the CO to trace the physics. In this way the disc is probed in a region where planet formation is suspected to occur. Observations with CRIRES show that some transitional discs (e.g., around HD 100546) seem to have gaps (≥ 10 au) devoid of CO, which may indicate a disc gap both devoid of gas and dust. Yet, for other HAeBes, the width of the observed CO line profiles seems consistent with formation within ~ 2 au, as in HD 163296, HD 250550 and Hen 2-80 (talks by Sean Brittain, Gerrit van der Plas and Rosina Hein Bertelsen). The CO observations are extremely fertile and versatile and may even provide hints of circumplanetary discs around accreting planets located within the gaps (invited talk by Sean Brittain). What is currently lacking is a systematic CO survey for sources with discs in different evolutionary phases, i.e., primordial, pretransitional and transitional.

At longer wavelengths, probing the cooler parts of the disc, CO continues to make its mark. Observations with the Photodetector Array Camera & Spectrometer (PACS) and Spectral and Photometric Imaging Receiver (SPIRE) on Herschel have detected the entire CO ladder in many flared gaseous discs and several non-flared systems (talks by Matthijs van der Wiel, Gwendolyn Meeus and Peter Woitke). Detailed modelling demonstrates that the disc scale height at a radius of 100 au needs to be higher for the gas than the dust in order to explain the observed weak CO line emission (talks by Vincent Piétu and Carol Grady). However, it remains difficult to simultaneously explain the bright [O I] emission detected by Herschel (talks by Peter Woitke and Christophe Pinte). Other gas diagnostics which were explored at the meeting include OH, warm H_2O and H_2 (talk by Davide Fedele). NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) may add to this inventory of detected lines in the near future (talk by Hans Zinnecker).

Intriguing disc structures from direct imaging

What is revealed indirectly by spectroscopy of the accretion and planet formation processes has found a resounding confirmation arising from advances in direct imaging techniques. Polarimetric differential imaging (PDI), as pioneered by the Strategic Explorations of Exoplanets and discs with Subaru (SEEDS) survey on the Subaru telescope, and systematic

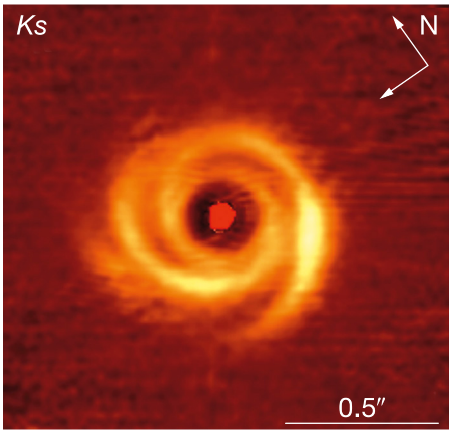

Figure 3. Polarised light emission in *Ks*-band from the disc around the Herbig star HD 135344B. These NACO polarisation differential image data clearly resolve a double spiral arm structure and an inner cavity around the central star (from Garufi et al., 2013).

work done with the NACO camera have shown direct evidence for the existence of gaps, spiral arms and asymmetries in many discs around HAeBes (review talks by Carol Grady and Sascha Quanz; see Figure 3 for an example). Indeed, the diversity in disc substructure, perhaps typified as somewhat overwhelming, was considered as one the milestones presented at the meeting.

The leading contender for the creation of these intriguing disc substructures is ongoing planet formation within the disc. Impressive ALMA Cycle 0 results were presented providing further evidence for disc substructures and ongoing planet formation (talks by François Ménard, Sebastián Pérez, Simon Casassus and Valentin Christiaens). ALMA has also started to provide evidence for the existence of dust traps, caused by a radial pressure bump within the gas once a planet has grown sufficiently massive to open up a gap within the disc (talk by Nienke van der Marel). Transitional discs may be the observational signature of the existence of such dust traps.

The dust in a primordial circumstellar disc which evolves to a planetary system would pass through the following four evolutionary steps: (1) the generation of a dust depletion gap; (2) removal of the millimetre-sized dust; (3) depletion of dust from the inner regions; and (4) concentration of the planetesimals in a ring. The order of these four steps is still unclear (review talk by Mark Wyatt). Infrared spectroscopic and spectro-interferometric studies of dust in these discs show clear differences between pristine and secondary dust and may be able to offer more insights into the order of this evolution (contributions by Thomas Henning, Roy van Boekel, Rodrigo Vieira). For debris discs around A-type stars, the evolutionary successors of the HAeBes like β Pic, the gas appears to be secondary, whereas in the 30-Myr-old system HD 21997 the gas must still be primordial (Mark Wyatt, Agnes Kóspál).

Although disc lifetimes are shorter for intermediate-mass stars than for low-mass stars, no mechanism has yet been identified to explain this mass dependence (contributions by Chikako Yasui, Massanobu Kunimoto). However, the role of binarity on stellar and disc evolution has so far been neglected. Searches for companions around Herbig Ae/Be stars show that single Herbig stars are rare: statistically speaking, for every star there is a companion at some separation (review by Gaspard Duchêne, contributions by Cesar Bricẽno, Gergely Csépány and Bernadette Rodgers). There also appears to be a dependence of metallicity on the accretion rate (Giacomo Beccari). Surveys for new Herbig Ae/Be and intermediate-mass T-Tauri stars are underway in the Magellanic Clouds and in Orion which may enable us to investigate these questions in more detail in the near future (contributions by Blesson Mathew, Jesús Hernández).

Outlook

The workshop in Vitacura highlighted the remarkable progress which has been achieved in the field of Herbig Ae/Be stars in recent years. Imaging at sub-arcsecond down to milliarcsecond scales has given us a new view on the nature of the discs around HAeBes. The sources with flared discs may all have cavities or gaps, and much structure is present in the outer discs. Dust traps may be a signpost of planet formation in these discs. However, so far we have mainly seen snapshots of individual systems. In the coming years, as statistically meaningful samples of Herbig stars will be observed with the new generation of instrumentation, it will be possible to link together the observed disc morphologies in a more systematic way.

An unsolved problem remains whether early Be stars are to be included within the class of Herbig Ae/Be stars. Whereas there is ample evidence that HAes and late-type HBes are indeed young stars in the process of forming planetary systems, the observational evidence for the early-type HBes is still absent. Future facilities, such as the next generation of extremely large telescopes, will offer large gains in spatial resolution which should enable us to tackle this problem for the more distant HBes as well.

The enigmatic issue which came to the fore at the workshop is what drives accretion in the HAeBes. The observed line profiles, spectral excesses and outflows show that HAeBes are accreting, but they appear to have only weak, multipolar magnetic fields. Observational progress in this area may come in the near future from large monitoring programmes on accretion within HAeBes, but further theoretical effort is needed to come up with plausible alternatives to the magnetospheric accretion model.

Acknowledgements

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Links

[1] Workshop web page: http://www.eso.org/haebe2014.html