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The B[e] Phenomenon in Pre-Main-Sequence Herbig Ae/Be Stars

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Abstract. In this review I describe the intermediate mass pre-main-sequence Herbig Ae/Be stars and their role in studies of star formation. They play a particularly important part in understanding the differences between the accretion of matter onto low and high mass stars. Once these differences are understood, further progress can be made in high mass star formation. Given that the B[e] phenomenon is a spectroscopic one, I will present recent developments in the spectroscopic studies of the Herbig Ae/Be stars, and then move to the [e] phenomenon in these object. Based on a large sample, it is found that forbidden lines are present for half of the Herbig Ae/Be stars, implying that the "[e]" phenomenon is widespread in Herbig Ae/Be stars. I will describe how the presence and properties of these lines can be used to our advantage in learning about their circumstellar environments, and their disks in particular. I conclude with a forward look.

1. Star Formation Issues

Stars come in many sizes and masses, and the study of their formation and evolution is central to astrophysics. Traditionally and typically, astronomers dedicate studies to either high or low mass objects, as it is often by studying the extreme ends of any distribution that initial progress can be quickly made. As far as star formation is concerned, there are profound differences in both our observational and theoretical understanding of the formation of low and high mass stars. I will outline these issues below and will introduce the intermediate mass Herbig Ae/Be stars, which by their very nature have properties in common with both low and higher mass stars. As such they are extremely well suited to study star formation across the entire mass range.

Stars find their origin in large molecular clouds collapsing under their own gravity. Due to conservation of angular momentum, the contracting core rapidly spins up. As a result, the increasingly strong centrifugal forces lead to the formation of a disk-like structure surrounding the star. Through this disk, mass is channeled from the outer envelope to the stellar surface, allowing the star to continue to grow to its final mass. The mechanism by which the low mass stars (defined at less than 2 $M_\odot$) accrete material via this disk in this stage of their formation is widely accepted due to magnetically controlled accretion (MA). The magnetic field is generated through the dynamo motion of charges in the stars' convective envelopes and truncates the circumstellar disk at a distance of a few stellar radii. The accreting material flows along magnetic field lines onto the protostar (Bertout 1989, see Fig. 1). The material is essentially in free-fall and shocks the stellar photosphere where it crash-lands. The thus released gravitational potential energy is re-radiated at UV wavelengths. The MA paradigm has been tried and observationally tested in the case of low mass stars, for example through magnetic field mapping (Donati et al. 2007) and spectroscopy (Kurasawa et al. 2006). A review on current evidence for MA is provided by Bouvier et al. (2007).

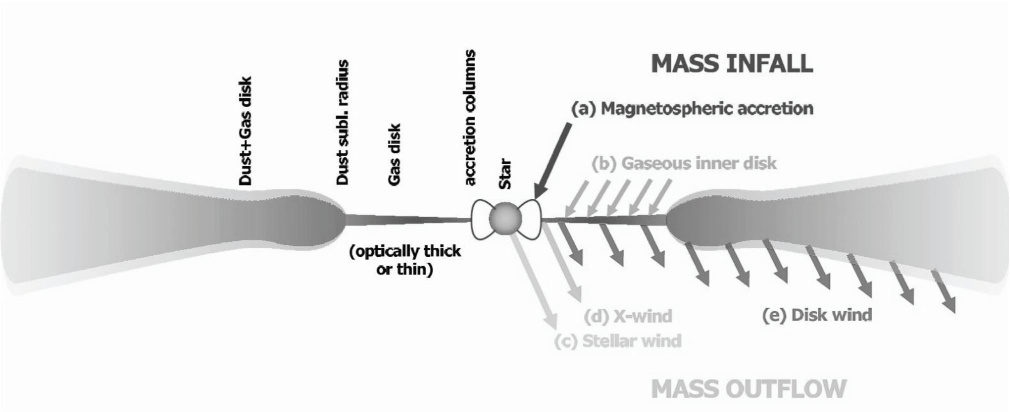

Figure 1. Cartoon of the inner disks of pre-main-sequence stars. Material is channeled through the disk onto the star. Whereas the final accretion onto the star is well-known to be channelled via the magnetic field lines in the case of the magnetic, low mass T Tauri stars, the situation for higher mass stars is still unclear. Figure taken from Kraus (2008, his Fig. 1).

Based on fairly basic considerations, we can readily identify two issues that indicate that the formation of a massive star (defined as those with masses larger than 8 $M_\odot$) is different from that of a lower mass star. Firstly, these objects are non-magnetic because of their radiative envelopes. As a result, the MA does not apply and requires a different formation mechanism. How the material arrives at the stellar surface in the absence of magnetic fields is still unclear however. The only mechanism suggested so far is the so-called boundary layer accretion, which has been shown to operate in accreting compact objects in binary systems. In this model, the circumstellar disk reaches onto the stellar surface, and the thin layer in which the Keplerian rotating material loses its angular momentum and kinetic energy gives rise to excess UV emission (e.g., Blondel & Tjin a Djie 2006; Mendigutia et al. 2011; Cauley & Johns-Krull 2015). Details have to be worked out for the case of higher mass pre-Main Sequence stars.

A second factor indicating a different formation mechanism for high mass stars has long been recognized: their brightness (the luminosity on the Main Sequence goes roughly as $M^{3.3}$) can halt the accretion of matter onto the stellar surface because of the increased radiation pressure on the infalling material. The upper limit to the maximum possible mass has been estimated to be of order 10-30 $M_\odot$ (e.g., Wolfire & Cassinelli 1987; Zinnecker & Yorke 2007), implying stars more massive than that cannot be formed. However, such stars are commonplace, thus requiring a new mechanism for the formation of massive stars.

After intense debate over the last couple of decades, one of the more popular theories put forward to explain high mass star formation, the merging of two lower mass stars (Bonnell et al. 1998), lost support due to the exceptionally high densities of stars needed to make this mechanism occur (Baumgardt & Klessen 2011). The theories that are now being put forward can be roughly divided into two groups. On the one hand, a mechanism similar to the low mass star formation paradigm is invoked. In this case a star forms through the monolithic collapse of a molecular cloud and is fed through an accretion disk (McKee & Tan 2003; Krumholz et al. 2009). Its main competing scenario requires the presence of clusters. In this model, a number of low to intermediate stars form simultaneously through the gravitational collapse of a cloud. The most massive of the fragments steal material from the other objects and grow more rapidly and to larger final masses. This process has been coined "competitive accretion" (Bonnell et al. 2001; 2004). Both theories indicate that the key to creating a massive star is through an accretion disk. This helps concentrate the material in the equatorial plane so that it may overcome the strong ionizing radiation of the central object and be efficiently accreted (e.g., Kuiper et al., 2010; 2011). Many observational studies have been dedicated to finding and characterizing such disks.

2. Observational Studies

The various types of pre-Main Sequence star fall into three classes. The young low mass stars in the pre-Main Sequence phase are the so-called T Tauri stars (Bouvier et al. 2007), while at intermediate masses, we find the optically bright Herbig Ae/Be stars (Waters & Waelkens 1998). They bridge the gap between the low mass pre-main sequence T Tauri stars and the most massive young stellar objects (MYSOs). The MYSOs are optically invisible whilst still embedded in their native clouds and, as a consequence, only recently a large well-characterized sample could be constructed (the mid-IR Red MSX Source (RMS) survey, Lumsden et al. 2013, www.ast.leeds.ac.uk/RMS).

Observational studies have returned a lot of evidence for the presence of disks around young pre-main sequence stars. It has been known for a long time that T Tauri stars are surrounded by accretion disks (e.g., Bertout 1989), but the situation for the intermediate mass Herbig Ae/Be stars is more elusive. After a decade of observational debate on whether Herbig Ae/Be stars are surrounded by disks or not, mostly due to the degeneracies in interpreting the Spectral Energy Distributions (SED), the presence of large disks, hundreds of au in size, around Herbig Ae systems was established by Mannings & Sargent's millimeter imaging studies in 1997. Miroshnichenko et al. (1999) put the SED problem to rest by demonstrating that the data could be represented by the presence of both a disk and a spherical envelope.

The presence of much smaller scale disks, of order stellar radii, around Herbig Ae and Herbig Be stars was established in the late nineties using indirect spectropolarimetric methods (Oudmaijer & Drew 1999; Vink et al. 2002; 2003; Mottram et al. 2007; Ababakr et al. 2016), while modeling of the emission lines also indicated the presence of very small scale disks (e.g., Ilee et al. 2014). The disks' presence was later confirmed using interferometry and imaging techniques, even though these techniques probe larger scales than spectroscopy and spectropolarimetry (see, e.g., reviews by Beltran & de Wit 2016; Grady et al. 2015; Kraus 2015; Quanz 2015; Wyatt et al. 2015), but much smaller scales than those obtained from mm studies in the 1990's.

Observational studies of MYSOs have been challenging due to their optical invisibility and large distances. Thus far, the best direct evidence for disk accretion in a MYSO are the high resolution near-infrared interferometric data of Kraus et al. (2010), which just resolves a disk-like structure of order 15 au in size. Indirect spectroscopic studies on large samples of objects have shown that small scale Keplerian rotating disks around MYSOs are commonplace (e.g., Wheelwright et al. 2010; Ilee et al. 2013), supporting the disk accretion theories.

In summary, it would appear that, at present, based on both observational and theoretical considerations, the commonly accepted scenario for the formation of massive stars requires a circumstellar disk as the agent for the delivery of the material onto the star. However, the actual disk-accretion process is well-accepted as being due to magnetospheric accretion for low mass stars, but is not known for the higher mass stars.

3. Herbig Ae/Be Stars

It is in the mass range spanned by the Herbig Ae/Be objects that the acting star forming mechanism switches from magnetically controlled accretion from disks with inner holes to the as yet unknown mechanism. It turns out that the stars in this mass range not only hold important clues to the formation of stars, but are also important for the formation of planets. To date, several systems have been observed to not only accrete material themselves but also to be orbited by planets in formation (see, e.g., the review by Quanz 2015). The study of Herbig Ae/Be stars is dynamic and for recent reviews on the class, I refer the reader to the Topical Collection on Herbig Ae/Be stars published in 2015 by the Astrophysics and Space Science Journal[1]. In particular I refer to the papers by Kraus (2015) on interferometric results; Grady et al. (2015), Quanz (2015), and Wyatt et al. (2015) who review (protoplanetary) disks; Brittain et al. (2015) on spectroscopy,;Vink (2015, spectropolarimetry – see also these proceedings); Duchêne (2015, binarity), and Beltran (2015) for the earlier phases in their formation.

Traditionally, the transition from magnetic to non-magnetic accretion was thought to occur at comparatively low stellar temperatures, at the G/F to A spectral type boundary where the envelopes become radiative. However, over the past decade or so, a change in this picture has occurred; it appears that Herbig Ae stars are more akin to the T Tauri stars than to Herbig Be stars. The spectropolarimetric signatures observed in both T Tauri and Herbig Ae stars can be explained with accretion hot spots due to magnetically channeled accreting material (Vink et al. 2003; 2005; Mottram et al. 2007). This is suggestive of the notion that Herbig Ae stars may form in the same manner as T Tauri stars. Similar findings have been published since. Magnetic fields have been reported in some Herbig Ae/Be stars (Wade et al 2005; Hubrig et al. 2004; Alecian et al. 2013). Others have reported differences in properties between Herbig Ae and Be stars, but similarities between the Herbig Ae and T Tauri stars (Mendigutia et al. 2012). Grady et al. (2010) deduce that the accretion shock regions in a Herbig Ae star are comparable in size and location to those in the magnetic lower mass objects. Recently, using spectroscopic variability studies, Scholler et al. (2016) provide evidence that a Herbig Ae star is currently undergoing magnetically controlled accretion in the same manner as the T Tauri stars. On the other hand, dedicated modeling indicated that, if present at all, the magnetosphere in a particular Herbig Be star with spectral type B9IV must be small (Kurosawa et al. 2016). It would appear that there is a break at around late B spectral type where the MA star formation mechanism ceases to operate and another mechanism takes over.

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[1] http://link.springer.com/journal/volumesAndIssues/10509?tabName=topicalCollections

However, the break is not well defined. Various studies have shown differences between low and high mass Herbig Ae/Be stars, but the precise mass has not been established (e.g., Fuente et al. 1998 on mm emission; Testi et al. 1999 on clustering; Baines et al. 2006 on binarity; Millan-Gabet et al. 2007 on near-infrared sizes). Using spectroscopy Cauley & Johns-Krull (2014; 2015) infer that Herbig Ae stars are more likely to have red-shifted absorption than Herbig Be stars, indicating a different infall geometry. In addition, Figure 2 shows the accretion rates derived from the UV excess, and the spectropolarimetric properties. The accretion rates indicate a difference in behaviour around about 2–3 $M_\odot$ (Fairlamb et al. 2015). The spectropolarimetry shows a marked difference between Herbig Ae and T Tauri stars on the one hand and Herbig Be stars on the other hand. When using the width of the polarized line as a quantitative proxy, a trend is present, but the scatter prevents the identification of a clear break (Abakakr PhD thesis 2016, using a larger sample than Vink et al. 2005).

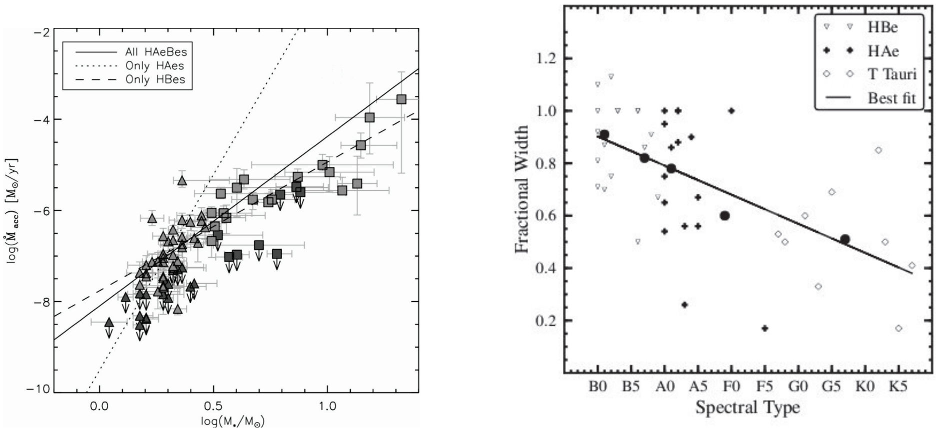

Figure 2. **Left:** Mass accretion rates derived from X-Shooter data as function of mass for a large sample of Herbig Ae/Be stars. The accretion rate increases with mass, but there appears to be a break around 2-3 $M_\odot$, corresponding to the A-B spectral type transition. Reproduction of Fig. 18 published in Fairlamb et al. (2015). The red symbols denote upper limits, whereas the blue symbols represent detections. **Right:** Llinear spectropolarimetric properties of Herbig Ae/Be stars and T Tauri stars using the width of the polarized flux as a proxy. The lines show a trend with spectral type. When looking at the line profiles themselves, the Herbig Ae stars are very similar to the T Tauri stars. Figure from Ababakr's PhD thesis (2016, in prep.), which is an update of Vink et al. (2002; 2005).

4. Optical Spectroscopy

As the [e] phenomenon is a spectroscopic classification, I will now discuss some recent projects on optical spectroscopy of Herbig Ae/Be stars.

From spectroscopic studies of low mass pre-main-sequence T Tauri stars and intermediate mass Herbig Ae/Be stars respectively, Edwards et al. (2006) and Cauley & Johns-Krull (2014; 2015), derive critical properties of the accretion and inner winds of these objects. The detection statistics of the various types of line profiles give important clues on the geometry of the accreting and outflowing material. This can be understood as follows. Typically, accretion takes place in the equatorial plane through a disk, while the accretion powered wind flows from the polar regions. When an accreting object is seen edge-on in the line of sight, predominately red-shifted absorption lines (inverse P Cygni profiles) due to infalling material are seen, while a pole-on sightline results in predominately blue-shifted absorption (regular P Cygni profiles) as we see a wind emerging from the star. The ratio of objects with inverse P Cygni to P Cygni profiles gives direct information on the opening angle of the disk - outflow system. Cauley & Johns-Krull (2015) find that red-shifted, inverse P Cygni absorption is much less prevalent in the Herbig Be stars than the Herbig Ae stars, which means that the disk accretion has a different nature, suggested to be a boundary layer between disk and stars rather than accretion funnels.

A recent study uses data from X-Shooter, mounted on ESO's 8m-class VLT telescope. Its unprecedented and complete wavelength coverage from 0.35 - 2.4 μm includes many lines of astrophysical interest. Fairlamb et al. (2015) presents X-Shooter spectra for 91 Herbig Ae/Be objects, the largest such sample to have been investigated spectroscopically. Twenty five of these are Herbig Be stars, which are massive in their own right and the most massive ones potentially in a more advanced evolutionary state than the MYSOs (Ababakr et al. 2015). An initial study already indicated that the helium 1.08 μm line is a good tracer of accretion in Herbig Ae/Be stars (Oudmaijer et al. 2011, confirmed by Cauley & Johns-Krull 2014). The X-Shooter data extend the wavelength coverage to important diagnostic lines, such as the CO first overtone at 2.3 μm, a key disk tracer (Ilee et al. 2014). Fairlamb et al. (2015) determined the stellar parameters such as temperature and gravity of these stars in a homogeneous fashion by fitting the spectra with stellar atmospheric models and derived the accretion rates from the UV excess following the methodology of Donehew & Brittain (2011) for all these objects (see Fig. 2). Interestingly, all emission lines measured by Fairlamb et al. (2015) have line luminosities that correlate well with the accretion luminosity as measured by the UV excess, and therefore the accretion rate (Fairlamb et al. 2016, MNRAS in press). Although it is not clear whether this correlation is intrinsically due to accretion or some other effect (Mendigutia et al. 2015), they provide an easy way to derive the accretion rate of an object without having to resort to the rather cumbersome process of measuring the UV excess.

5. The Herbig Ae/B[e] Phenomenon

The presence of forbidden line emission in the spectra of Herbig Ae/Be stars has long been known (e.g., Böhm & Hirth 1997 or Lamers et al. 1998), but it has never been considered in a statistical manner. Oudmaijer et al. (2006) posed the "to B[e] or not to B[e]" question for Herbig Ae/Be stars and found that based on his then available spectra, around half of the known Herbig Ae/Be stars exhibit the B[e] phenomenon (see Fig. 3). With a much larger sample, we now find from Fairlamb's X-Shooter data that 48 out of the 91 observed objects, i.e. more than half, display the forbidden oxygen line. Forbidden lines in Herbig Ae/Be stars are thus commonplace.

We might naively expect that the forbidden lines arise in low density material. As a consequence, their only use would then simply be that the lines trace the nebulous material that Herbig Ae/Be star inevitably are associated with. This association with nebulosity was one of Herbig's original selection criteria in 1960. However, Acke et al. (2005) and Acke & van den Ancker (2006) demonstrated convincingly that the

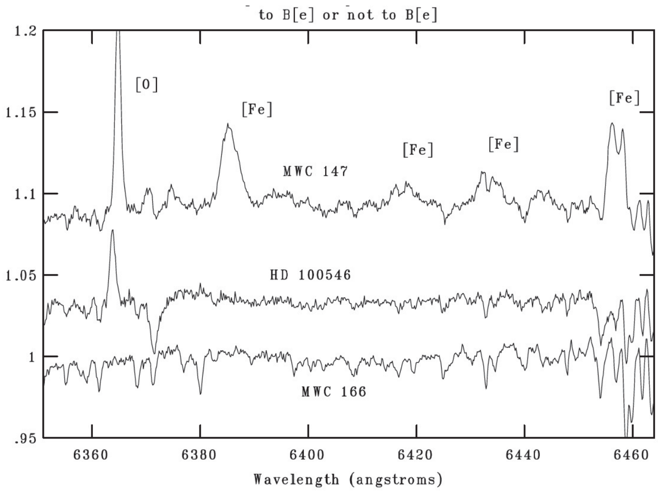

Figure 3. To Herbig Ae/B[e] or not to Herbig Ae/B[e]. Spectra of several Herbig stars with or without forbidden emission lines. Figure taken from Oudmaijer et al. (2006, their Fig. 1).

[OI] 6300 Å line is an excellent tracer of the circumstellar disk's atmosphere. Atomic oxygen is present due to the dissociation of OH molecules in the outer parts of the disk, where the densities and further conditions are such that they favour the emission of the forbidden oxygen lines. The data can be modelled, and by both spatially and spectrally resolving the [O I] λ6300 Å line, Acke & van den Ancker (2006) were even able to infer the presence of a planet-induced gap in the circumstellar disk.

The forbidden lines are thus a powerful diagnostic of the circumstellar material. This is amplified by the fact that they are optically thin, tracing all the emitting material, while the various lines can have different excitation energies and critical densities. They can therefore probe many different parts of the circumstellar environment. Recently, the forbidden lines have begun to be used as diagnostics in further understanding the B[e] phenomenon. A good example where this is applied to B[e] objects is provided by Aret et al. (2016) who use the forbidden [Ca II] $\lambda\lambda$7291, 7324 Å lines as high density tracers to probe the circumstellar matter. Other developments are reviewed in Kraus (these proceedings), and the newly developed diagnostic tools will prove very useful in studies of the circumstellar disks and material around Herbig Ae/Be stars as well.

6. Final Words

Let me conclude this brief overview by looking forward to the future. We are already in the ALMA era and exciting results on Herbig Ae/Be stars are streaming in (e.g., Walsh et al. 2016; Boneberg et al. 2016), while future facilities such as MATISSE and JWST are close on the horizon and the era of the 40 m–class optical telescopes such as the E-ELT is just around the corner.

The astrometric satellite GAIA is revolutionizing astrophysics at the moment. It will offer a great opportunity for the study of Herbig Ae/Be stars. With distances known and spectroscopy available, we will be able to routinely and systematically select Herbig Ae/Be stars from the vast numbers of stars available and begin statistical studies of such well-selected samples. They also allow us to characterize the possible clusters in which these objects are located. This will not only give insights into the role of clusters in the formation of massive stars (Sect. 1 and Testi et al. 1999). They also help to study individual targets. Mehner et al. (2016; see also these proceedings) provide an excellent preview on how we can study young and evolved stars alike by fitting isochrones to the members of a small cluster of stars, and determine the nature of the thus far elusive B[e] star, MWC 137. The recently started Leeds' EU-ITN network STARRY project is intended to do just that. It will tackle this issue by searching for and characterizing new Herbig Ae/Be stars and will then study the presence of the clusters in which they may have formed. Next time there is a B[e] stars conference, I am sure many new results on the Herbig Ae/Be stars and their [e] phenomenon can be expected.

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