Observational aspects of Herbig Ae/Be stars and of candidate young A/B stars

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GENERAL INTRODUCTION

1. The Herbig Ae/Be stars, observationally defined

The question about the formation of stars has always been a major topic in modern astronomy. One of the main reasons is that the answer could yield the understanding of the origin of the solar system and of terrestrial life.

The study of stars just being formed and evolving towards the main sequence, the so-called pre-main sequence (PMS) objects, began with those of low mass stars of which the evolution is slow. It was even believed that the more massive stars could not be seen in their PMS phase at all due to their fast evolution. However, Herbig (1960) suggested that somewhat higher-mass counterparts of T Tauri stars (TTs) must exist. The disadvantage of the shorter main sequence lifetimes of higher-mass stars is compensated by their higher luminosities, which will make them more easily detectable than T Tauri stars. As explained by Herbig, such stars would then be frequently enough observed, when not too far away. Furthermore, their relatively short PMS lifetimes will make them to be found easily as they can not be far from dark nebulae, their places of birth. It was therefore defined that higher-mass PMS stars should illuminate a reflection nebula. Another criterion for the inclusion to this PMS group is the presence of emission lines in their spectrum. Citing Herbig (1994): “no more than a hopeful analogy to the T Tauri phenomenon”. Finally, being the higher-mass counterparts of T Tauri stars, their spectral type was suggested to be of B or A.

An uncertainty we have encountered in the literature concerns the definition of the mass interval of T Tauri stars. Usually the group is supposed to consist of very young stars of spectral types K–M5. However, a temperature definition from 3,500 to 7,000 K can also be found, which yield stars up to spectral type F. A better qualification is based on the mass, \( M_{\text{TT}} \leq M_0 \), because usually the temperature of a young object undergoes large changes, see Fig. 5. To know the mass of an object, its intrinsic parameters and well determined theoretical evolutionary tracks must be available. In any case, the spectral range of the A/B type PMS stars put them well away from any confusion with T Tauri stars. The A and B emission type PMS objects are known in the literature as the Herbig Ae/Be (HAeBe) stars.

After Herbig’s (1960) suggestion about the HAeBe stellar group not much work can be found in the literature concerning special studies of these stars. Although they were identified by observational studies of young clusters and in star forming regions, the preferred interest of astronomers was star formation and T Tauri stars.

Due to the introduction of new observing techniques, especially in the near-IR, during the early 70’s many peculiar early type emission line stars having large amounts of IR-excess were identified. Although most of these objects were classified as being probably evolved stars, several were recognised as possible HAeBess (Allen & Swings 1976). In the subsequent years, studies on individual cases were made. Photometric variabilities of several HAeBe candidates, most of them located in Orion, were searched in the General Catalogue of Variable Stars (Kukarkin et al. 1985), and further investigated. In the beginning, the IR-excess of several peculiar early type stars could be explained by free-free emission or by the presence of a cool companion. However, the notion that the sometimes large IR-excess can be explained by the presence of large amounts of dust close to the just formed early type star, inspired several astronomers. The early work of the Amsterdam group must certainly not be neglected in the recognition of HAeBess to be genuine PMS objects. The real break-through came in the early 80’s after the redefinition of the HAeBe stellar group by Bastian et al. (1983), and the publication of the first list of HAeBess by Finkenzeller & Mundt (1984), who had studied some of their properties. Although it compromises only 57 HAeBe candidates, in further extended studies the Finkenzeller & Mundt catalogue is basically the source. From these studies, besides the properties defined by Herbig, several new observational characteristics of HAeBess were found.

The present redefinition and known observational characteristics of HAeBess are assembled and discussed in Chapter A1.

2. The theoretical picture of HAeBess

Star formation described in current theory follow a certain scheme (Appenzeller 1994), see Fig. 1, and is based on the classic numerical study of Larson (1969). The compression of massive cool interstellar (IS) clouds is followed by a collapse at a constant or decreasing temperature due to gravitational forces. With increasing density, these clouds will break up as the gravitational forces will grow faster than the counteracting gas and turbulent forces. The survival of fragmentation and building up of a significant density will only proceed if most of the very high initial angular momentum, compared to stars, is removed from the fragments and transformed into orbital angular momentum. The removal occurs by magnetic momentum transport and further fragmentation due to rotation (examples...
Fig. 2. Accretion-induced rotational fragmentation which results in the formation of binaries, from theoretical calculations of Turner et al. (1996). They identified a mechanism for binary star formation in which protostellar disks are fed by accretion flows in which the specific angular momentum increases with time. Consequently the disks may be spun up until they become rotationally unstable and fragment. Two variants of this mechanism are identified:

*Left:* In case the specific angular momentum increases rapidly, the disk becomes unstable, it will cleave into two comparable components, which then may grow and will move apart due to the remaining accretion flow. The components will move apart as they repeatedly intercept the accretion flow and will convert part of, by-now high, angular momentum of the accreting material into orbital motion instead of spin.

*Right:* In case the specific angular momentum increases more slowly, the disk repeatedly forms spiral arms. If sufficiently massive, the spiral arms may detach and condense to form initially small secondaries. Such secondaries merge with the primary or with each other and move away from the primary as described above. In some cases the components can become of comparable mass.

of the latter mechanism and the possible products are given in Fig. 2). Furthermore, the high magnetic flux of the interstellar gas must be removed since the observed magnetic fields of stars is low.

![Image](image.png)

**Fig. 3.** A centrifugally driven disk wind, as observed above and below the disk, drives accretion flows through the underlying accretion disk as it carries off disk angular momentum (from Pudritz 1985).

Although the fragmentation phase is less understood and depends highly on a complex interaction of different effects (Appenzeller 1994, see also Fig. 2), it is certain that the final fragments have stellar masses and have lost most of their initial spin angular momentum and magnetic flux. Such objects are called “protostars”, as they have stellar masses, but have not yet established a hydrostatic equilibrium (Larson 1969). Independent from detailed assumptions or initial conditions, the protostellar clouds form hydrostatic cores, surrounded by rotationally flattened disks near the center, while accretion from their less flattened envelopes still occurs (Bodenheimer 1993), see also Fig. 3.

The disk and core will form after about $3 \times 10^5$ years, i.e. 1.5 times the free-fall time scale, in case of an initially uniform envelope with typical protostellar densities. The infall continues until the envelope is completely depleted. Within about $10^6$ years 99% of the envelope is gathered into the core and disk.

In Fig. 4, the above described star formation scenario is visualized. The different phases of the formation are characterized by the spectral energy distributions of Fig. 4.

The cores follow their “own” evolution as soon as they are formed. This is due to the radiative energy loss from their surfaces and the quasihydrostatic PMS contraction. The time scale of the latter depends strongly on the core mass, which is shorter with increasing mass. For low mass cores, between 0.5 and $3 \ M_\odot$, the PMS time, that is the time between core formation and the onset of core hydrogen ignition on the ZAMS, lies between $10^4$ and $10^5$ years.
It will be clear that for sufficient massive protostars, the cores evolve faster than the envelopes. Objects, more massive than the critical mass, $M_C$, start their core hydrogen burning already in their main-mass accretion phase. Such objects evolve directly from the embedded infrared protostar to the zero-age-main sequence without having a hydrostatic PMS phase. Consequently, for low mass stars, with $M < M_C$, the contracting cores can be observed as hydrostatic PMS stars.

The transition mass $M_C$, which separates low-mass and high-mass star formation, is estimated to be between 3 and 6 $M_\odot$ (Larson & Starfield 1971; Appenzeller 1980). As remarked by Appenzeller (1994), this coincides with the mass range of the HAeBes stellar group. It must be noticed here that beside the fact that star formation can be triggered under different conditions, the theoretical picture is far from complete. This give rise to uncertainties within the time scales involved with the implication that $M_C$ may well differ for each star forming region and even from object to object.

An example of a mechanism interfering with the above given estimation of $M_C$ is the presence of a stellar wind. Observations show that young stellar objects start to process a wind which interacts with their envelopes even during the protostellar age. Therefore, the mass accretion rate will not decrease with time to zero until the envelope mass has been depleted. Stahler (1980) suggested to use a universal mass accretion rate independent of the protostellar mass and constant during the complete accretion phase. Accretion stops only when the core has reached its final stellar mass and will even be reversed by the onset of the stellar wind. With these assumptions and a mass accretion rate of $10^{-5}$ $M_\odot$yr$^{-1}$, low-mass stars appear in the Hertzsprung-Russell diagram along a well defined birthline (Stahler 1983). This picture can be extended to the intermediate-mass stars, as shown by Palla & Stahler (1992), see Fig. 5a. Although the qualitative difference between massive and low-mass protostellar evolution is not affected by this "birthline scenario", the transition mass $M_C$ is now up to 10 $M_\odot$ and depends on the different accretion rates as shown in Figs. 5a - b (Palla & Stahler 1993).

Illustrated by the above described scenario of stellar formation, is that without improving the theoretical picture, it has been logical that there was some scepticism to find or observe HAeBes at all. Furthermore, since so many massive stars are observed in star forming regions, and so many different observed properties are involved, it is questionable if a single theoretical scenario can predict what the upper limit of $M_C$ might be.

Although high-mass star evolution is very short, the theoretical scenario illustrates that, in general, a disk is formed close to the core. It can be understood that the disk lifetime is short due to the strong wind, and the destructive UV radiation will certainly not allow dusty disks. It is clear, however, that there might be a mass range where main sequence stars still have a left over gaseous (accretion) disk. This is not studied yet, because the main interest is on dusty disks.
Fig. 5. The pre-main sequence evolutionary tracks and birthlines, dotted, from Palla & Stahler (1992, 1993).
Left: In case of an accretion rate of $10^{-5}\,M_\odot\,\text{yr}^{-1}$ onto the protostar. Note the ages: The PMS contraction phase of T Tauri stars will consist in general most significantly of a nearly vertical "Hayashi track", characterized by a fully convective structure, while for HAeBes the short PMS contraction phase is almost purely a horizontal "Henney track", where the protostar has developed a radiative core.
Right: The upper birthline shows the effect of an increased accretion rate of $10^{-4}\,M_\odot\,\text{yr}^{-1}$. The early type PMS stars are now still visible at their younger stage.

Fig. 6. A qualitative picture of the evolution of the gas-dust disk, as presented in a schematic sequence of eight stages by Levin (1964). After the molecular cloud collapsed and turbulence is driven away, particles precipitated towards the central plane will grow due to sticky collisions. This is a mechanism to separate dust from gas (only 1% of the mass of interstellar clouds are in the form of solid bodies). During $10^3 - 10^4$ periods of revolution around the central star, a dense dust layer, called the subdisk, forms near $z = 0$. The subdisk will become gravitationally unstable when the density will reach a certain critical value (Safronov & Ruskol 1994). As the major part of the subdisk mass is expected to be distributed in different particle sizes, axisymmetric ringlike perturbations, instabilities and disintegration are prevented. Numerous condensations will then appear which after collisions will transform into kilometer-sized bodies. However, due to Keplerian rotation a gas lag will appear, resulting in a large vertical gradient of the dust density near the upper and lower boundaries of the layer. This causes a vertical gradient of rotation velocity. As shown by Safronov & Ruskol (1994), this will make collisions more frequent and will accelerate the growth of subdisk bodies.
As the envelope of the protostar accretes onto the core and disk, the outer region of the disk of a low-mass star might accumulate enough material to form dense and inhomogeneous structures. Shielded from the relative hot core this material could be dusty which might be the origin to speculate about the presence of proto-planetary disks around such objects. It must be mentioned here that even for T Tauri stars, ten years ago, models did not even invoke such disks at all (Bertout 1984). A reason is that, observationally, jets and outflow features associated with T Tauri stars are much more conspicuous than circumstellar disks.

As recent theory of proto-planetary disks can provide most welcome circumstances to form planetary systems, mainly by collisionally grown bodies, of which a simplified picture is given in Fig. 6, observations are highly necessary to trigger theory. As illustrated above, also for a better theoretical understanding of the first phases of stellar evolution, observational pictures are highly needed.

3. Herbig As/Be stars as seen in a modern prospective

The attention of the astronomical world for the study of young stars and the possible existence of proto-planetary disks around such objects is indeed something of the last decade and is triggered by the many recent discoveries. It is for this reason that new techniques were developed and used in the study of regions in which star-formation has been, or still is, in process and in which stars that are just born are present.

Some beautiful results are the recent “advertising” pictures made with the Hubble Space Telescope (HST). These images show clearly the star formation and that young stars are surrounded, by thick circumstellar disks where formation of planets might occur, see Fig. 7.

Indeed, planets around other stars are not yet imaged, besides the “brown-dwarf/planet companion” of Gliese 229 (Fig. 8), although frequently there are reports of direct or indirect evidences for the existence of extrasolar planets, mainly around very evolved objects. As it will be very spectacular to have direct images of (terrestrial) planets, the indirect evidences of planets orbiting young stars might be much more worthwhile to go for. Examples for this will be given in this thesis. A good result of such a recent discovery is the recent discovery of a candidate planet at 51 Peg, a solar type star, by Mayor & Queloz (1995) by obtaining a spectroscopic monitoring programme for one year.

The main reason to put more attention on the indirect evidence is that planet formation will take place relatively close to the central star in a region most probably well obscured by the more outer parts of the circumstellar disk, as shown in Fig. 7 for some objects. Because most spectacular (HST) discoveries cover only examples of possible young stars in certain evolutionary phases, they are an important guide for our ideas and knowledge of star and planetary formation. A more sophisticated understanding of this topic needs a wider and more fundamental study (i.e. young objects of different masses in a variety of evolutionary phases in crowded or empty fields or being part of multiple systems studied from the X-ray, far-UV, to the far-IR and radio wavelengths). Such studies might yield more information on the possible formation of planetary systems, e.g. are they common or are special circumstances necessary, than information from spectacular images alone.

References

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Fig. 7. HST images of McCaughrean & O'Dell (1995) of an edge-on protoplanetary disk in the Orion nebula. This disk is the largest of the ones detected in Orion and has a diameter 17 times the one of our own solar system. As the disk is seen edge on, the star is hidden inside. 

Left: A three-colour composite image, taken in blue, green and red emission lines. These lines occur from the glowing gas in the nebula. 

Right: The presence of the central star is made visible indirectly. Seen are the nebulosities above and below the plane of the central disk by making use of a filter that blocks the bright emission lines of the disk.

Fig. 8. Discovery of a brown dwarf around Gliese 229. 

Left: The brown dwarf Gliese 229B was first observed by Nakajima & Durrance (1994) in far red light on October 27, 1994 with adaptive optics. The separation with the primary is at least $6 \times 10^3$ km, comparable to Pluto's orbit around the sun. 

Right: An improved image made with the HST by Durrance & Golimowski (1995), also taken in the far red, on November 17, 1995. It is still in discussion whether the mass, between 0.02 and 0.05 $M_\odot$, temperature (900 K) and orbit of Gliese 229B fulfil the brown-dwarf criteria, or that it is more like a "super-planet".