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# The formation of stars and protoplanetary disks

The discovery that stars and galaxies evolve, and with them the Universe, is probably the major legacy of twentieth-century astronomy. On the threshold of the new millennium, questions about the origins of the Universe and its constituent galaxies, stars and planets are the main drivers of astronomical research. Answers to these big, fundamental questions will require a timely interplay between ground-based and space-borne observations.

Stars are the main energy sources in the Universe, and their study has always been a central theme in astronomy. In the quest for our origins, stars will continue to play a crucial role. 'Galaxy formation cannot be understood without incorporating a detailed theory of star formation' (Silk 1997). Such a theory also is a prerequisite for understanding the formation of planetary systems in the circumstellar disks with which most stars appear to be born.

While the basic insights into the gravitational instability of molecular clouds date back to Jeans's work (Jeans 1902), the theory of star formation is still far from complete. The formation of structure in the Universe turns out to be a complex process which needs sustained observational efforts to be unravelled. Our present database on star formation is still restricted, since many relevant phenomena occur in regions that are shielded from our view at optical wavelengths. Ground-based and space-borne facilities that are able to probe newly formed stars have been developed only recently. While optical pictures of star-forming regions are often spectacular (Figure 1), one must realize that the spectral energy distribution (SED) of young stellar objects (YSOs) peaks at far-infrared wavelengths, where the Earth's atmosphere is a strong emitter. Consequently, infrared and submillimeter telescopes in space are crucial for unravelling the star formation process observationally and for detecting YSOs which can be observed in adjacent wavelength intervals from the ground. A second window suitable for the detection of YSOs from space is the X-ray window: low-mass YSOs develop convective envelopes, the activity of which generates X-rays that pass relatively unaffected through the molecular cloud material.

Observations from space have, moreover, revealed the existence of circumstellar disks not only of YSOs, but also of stars which already have significantly evolved on the main sequence. Such disks were first discovered from their thermal infrared radiation, and subsequently directly observed in scattered light, in particular by the Hubble Space Telescope. The study of such disks, and the realization that their occurrence is fairly widespread, have triggered very active research on the evolution of such disks towards planetary systems. Only from space can the spectra of these disks and their observational links to Solar System objects be studied in detail. The Infrared Space Observatory (ISO) has highlighted the rich chemistry and mineralogy of the dusty environments of YSOs. Observations from above the Earth's atmosphere can also provide the high angular resolution that is necessary for probing the structure of such disks, with possible links to the presence of planets.

## STAR FORMATION: BASIC SCENARIOS AND TERMINOLOGY

Following Shu *et al.* (1987), star formation can be described as consisting of four stages. The first stage is the formation of dense cores in molecular clouds; these

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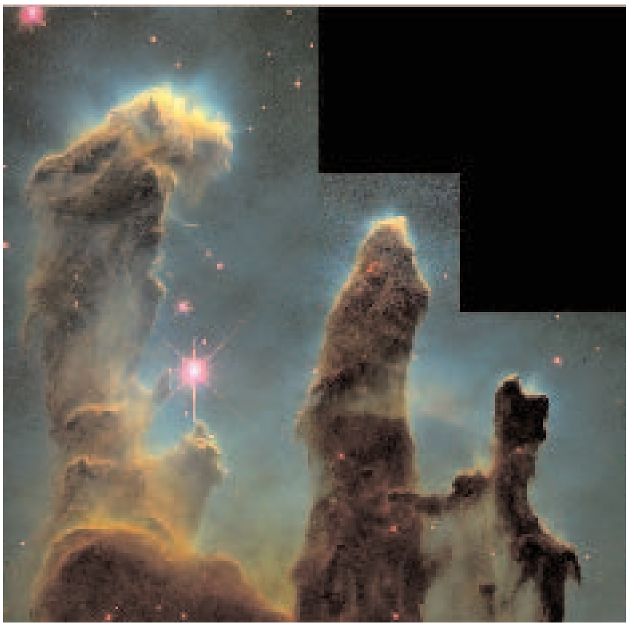

**Figure 1** Hubble Space Telescope image of the star-forming region in the Eagle Nebula. (Courtesy of NASA.)

cores are supported by turbulent and magnetic pressure, which gradually decrease due to ambipolar diffusion (Mouschovias 1991). Magnetic pressure is not able to support the more massive cores, which are thought to collapse more rapidly. In the second stage, a central protostar already occurs: it collapses rapidly in its centre, and less so in its outer layers. Matter originating far from the rotation axis has too large an angular momentum to fall onto the protostar and settles in a circumstellar disk; the mass of the latter itself, may, in fact, be higher than that of the central object. The third stage is characterized by a bipolar outflow aligned with the rotation axis. The confinement of the outflow to a narrow cone has led to the suggestion that it is related to magnetic activity, but the occurrence of powerful outflows in massive objects and in the accretion-powered UX Orionis stars is consistent with the hypothesis that accretion energy feeds the outflows. During the fourth stage both infall and outflow are terminated, and a newly formed star with a circumstellar disk emerges. A schematic view of this evolution process was pictured by Hogerheijde (1997) and is shown in Figure 2.

From an observational point of view, YSOs emerge as optically visible, but still heavily obscured, objects during the third stage in the Shu *et al.* (1987) scenario. Younger, still completely embedded, objects have SEDs with a positive spectral index in the far-infrared and are called 'class I' sources in the observational classification scheme proposed by Lada and Wilking (1984; see also Lada 1987, Lada and Shu 1990). This scheme is illustrated in Figure 3. YSOs in stages 3 and 4 are also called 'class II' sources; their SEDs

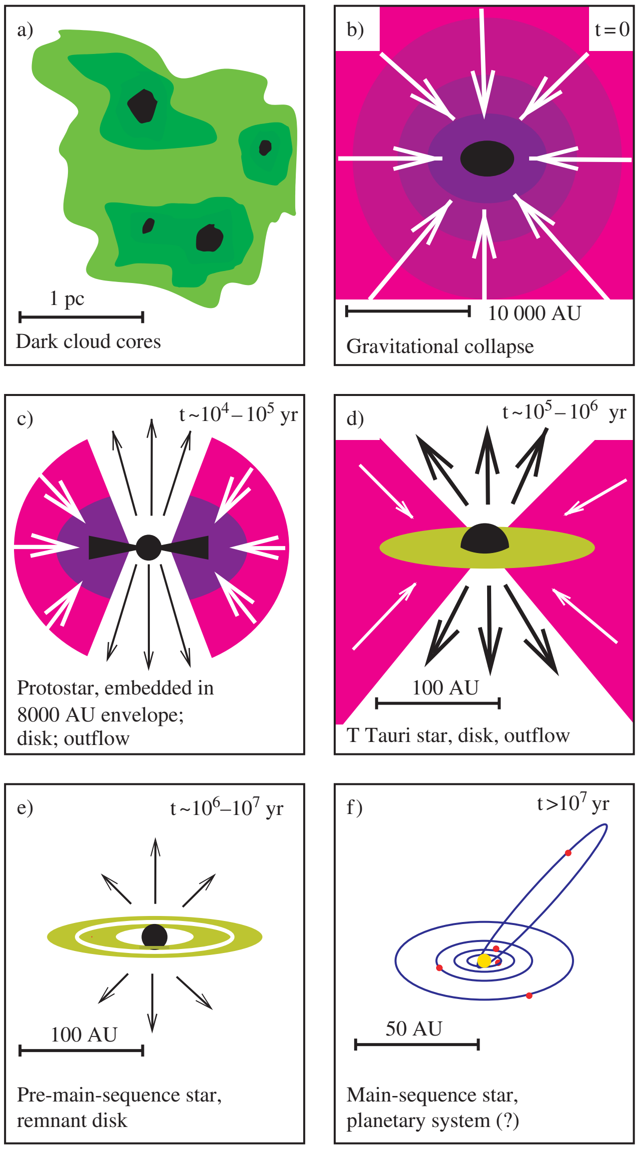


**Figure 2** Schematic representation of stellar formation and early stellar evolution (Hogerheijde 1997). With respect to the original scheme, the third (outflow) phase has been split up in two subphases before and after the evaporation of the envelope, and a sixth phase, where planets have formed in the disk, has been added. (After Shu *et al.* 1987.)

are characterized by a more or less reddened stellar component and an infrared excess. This classification scheme has been extended towards 'class III' YSOs, the infrared excess of which has essentially disappeared, but for which circumstellar gas causes atomic emission lines, and also towards 'class 0' sources, which emit the bulk of their energy in the sub millimetre and millimetre domains (André *et al.* 1993), and even towards 'class-I' sources (Boss and Yorke 1995), where the collapse has just been initiated and which still await detection.

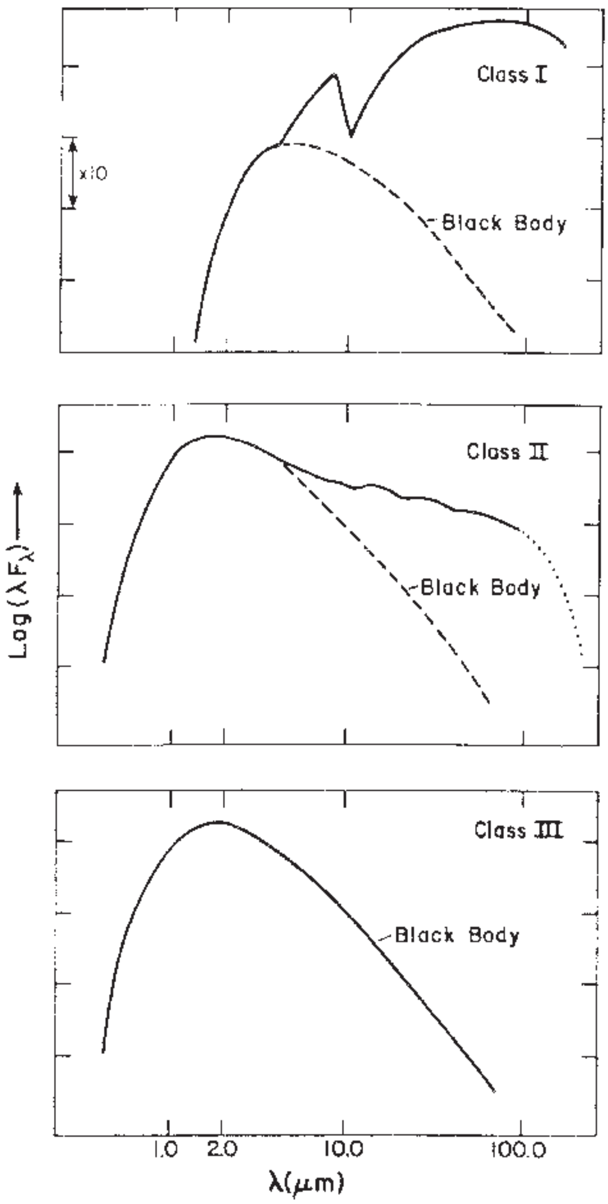


**Figure 3** Observational classification scheme of YSOs. The 'black bodies' in the plots incorporate a correction factor to account for circumstellar reddening. (After Lada and Shu 1990.)

Recent results have provided evidence for the fact that many stars, if not all, are formed as binaries. Inventories of binary objects in star-forming regions (SFRs) indicate a larger fraction of binaries than for main-sequence stars in the field and in evolved clusters (Mathieu 1994). Some studies suggest that in low-mass SFRs nearly all stars are born as binaries: for the Taurus SFR, Leinert *et al.* (1993) and Ghez *et al.* (1993) find that some 85% of the objects are binaries, that is, much more than the 53% found among G dwarfs in the solar neighbourhood (Duquennoy and Mayor 1991). In high-mass SFRs an excess of binaries is still observed, but it is less marked. Prosser *et al.* (1994) derive a 'normal' binary frequency for the Orion Trapezium cluster, but current data are felt to be insufficient for firm conclusions. The two main scenarios for binary-star formation are fragmentation (where the cloud cores fragment before rapid collapse is initiated), and gravitational instability in the massive circumstellar disk. It is possible that the inventories of binaries in SFRs teach us that binary-star formation is the natural outcome, and that single stars are either disrupted binaries, following dynamical interactions which indeed are more common in the denser high-mass SFRs, or objects whose disks have been rapidly photoevaporated.

Dynamical interaction in SFRs clearly also influences the evolution of the circumstellar disks, as does the interaction with the ionized winds of already formed stars. In various clusters it has been noted that for stars which occur close to each other in the Hertzsprung–Russell diagram, and thus are of about the same mass and age, the infrared excesses – which directly probe the mass of the disk – widely differ (for example, NGC2244; Pérez *et al.*, 1987). The highest fraction of infrared excesses are found for low-mass SFRs (e.g. Hillenbrand *et al.* 1995), where dynamical interactions are less frequent and the ionizing flux is small. The dynamical evolution of the disks and their ablation by the ionizing radiation may thus indeed contribute to the lower binary fraction in high-mass SFRs. In addition, infrared excesses as well as X-ray surveys, as tools for detecting YSOs, have revealed a surprisingly high number of putative YSOs that occur outside known SFRs, suggesting the possibility of almost isolated star formation, with relatively long-lived disks.

In the Hertzsprung–Russell diagram, the 'stellar birthline' (Stahler 1983) is defined as the locus of points at which a protostar no longer accretes mass, and thus initiates its pre-main-sequence phase. For galactic stars more massive than about eight solar masses, the circumstellar environment is still optically thick when the central object initiates core hydrogen burning and thus arrives on the main sequence; in more metal-deficient and therefore less dusty galaxies, this mass limit is higher. High-mass pre-main-sequence stars are thus not observable at optical wavelengths. YSOs with masses between two and eight solar masses, which emerge before having reached the main sequence, are called Herbig-Ae/Be stars, hereafter called Haebe stars. During their quasi-static contraction towards the main sequence, they have radiative envelopes. YSOs of lower mass are called T Tauri stars and have convective envelopes, with associated activity which causes intense emission of X-rays. Class-II T Tauri stars are also called 'classical T Tauri stars' (CTTs), and class-III T Tauri stars correspond to 'weak-lined T Tauri stars' (wTTs) or 'naked

T Tauri stars' for which the circumstellar material has almost disappeared.

## DETECTING THE YOUNGEST STELLAR POPULATIONS

The cool and embedded nature of YSOs implies that infrared, sub millimetre, millimetre and radio techniques, from the ground and from space, are needed to detect and study these objects. All techniques are plagued with their own selection effects, involving sensitivity as well as angular resolution, so that a suitable combination is required in order to obtain a complete picture. The all-sky survey in the 12 to 100 $\mu$m region by the Infrared Astronomical Satellite (IRAS) led to the detection of a large number of YSOs of classes I and II, but was hampered by both relatively low sensitivity and low spatial resolution. A significant improvement has been obtained with ESA's Infrared Space Observatory (ISO), especially from the ISOCAM surveys. Nevertheless, all space surveys so far are confusion limited except for the few nearest SFRs, so that an unbiased picture will probably not emerge before the surveys foreseen by the Herschel satellite, to be launched in 2007, are available. Overcoming the confusion limit in surveys is essential for a proper understanding of the initial mass function (IMF) in various environments.

Large-scale, ground-based continuum surveys are sensitive to the small amounts of ionizing gas occurring in YSOs of several classes, but often miss the low-mass YSOs for which such radiation is faint. However, X-ray surveys have proved rather efficient in detecting the population of young, often naked, objects in which vigorous stellar activity takes place. After initial successes in this field with the Einstein observatory (Vaiana *et al*. 1981), substantial progress has been made with the ROSAT all-sky survey. Optical follow-up of the ROSAT survey in various SFRs has impressively increased the amount of – mostly weak-lined – known T Tauri stars (for a review, see Neuhauser 1997). In the Taurus region, Neuhauser *et al*. (1995) detected with ROSAT 43 out of 65 wTTs, but only 9 out of 79 CTTs; they found that the larger detection rate in weak-lined objects was intrinsic, being related to, among other parameters, a higher rotation rate. Interestingly, the X-ray technique has also proved useful for detecting objects in the brown dwarf mass range (Neuhauser and Comeron 1998).

A somewhat surprising result of the IRAS and ROSAT all-sky surveys – that is, surveys not limited to known SFRs – and their follow-up, has been the detection of several YSOs which appear isolated in the sky or as small associations (Gregorio-Hetem *et al*. 1992, Kastner *et al*. 1997). The relative importance of such a mode of small-scale star formation is currently not very clear, one possible bias being the fact that the isolated nature of an object may imply a less disturbed and therefore longer evolution for its circumstellar structures. The so-called Bok globules, which are small, dark clouds and are easily detected from the obscuration they cause to the background, appear to be the natural sites for isolated star formation (Bok and Reilly 1947).

Some 10 or even 25% of the known giant molecular clouds appear devoid of current star formation (Blitz 1993). Though for distant clouds this apparent absence of star formation may be due to the limited sensitivity of current surveys, Mooney and Solomon (1998) argue that the case for quiescent molecular clouds is genuine. Detailed mapping of these clouds with future instrumentation should reveal whether they represent an early stage in molecular cloud evolution or whether star formation is inhibited in them. It is clear that we are currently still lacking a definitive theory for understanding the processes of fragmentation and core formation in molecular clouds (André 1997).

## CIRCUMSTELLAR DISKS REVEALED

Disks appear to be a natural byproduct of star formation, but direct confirmation of the disk-like structure of the matter close to young stars has had to await the recent advances in high-angular-resolution observing techniques. With the Wide Field and Planetary Camera on the Hubble Space Telescope (HST), Burrows *et al*. (1996) for the first time were able to resolve the vertical structure of a YSO disk, for the Herbig-Haro object HH30 (Figure 4). The object, viewed nearly edge-on, appears as a circumstellar disk, the equatorial part of which is optically thick, and which shows a vertical decrease in density so that scattered light from the central object can emerge. Perpendicular to the disk, highly collimated bipolar jets are observed. ISOCAM and ISOPHOT observations of this object (Stapelfeldt and Moneti 1999) reveal a double-peaked SED, where the scattered light peaks around 2 $\mu$m and the thermal emission from the disk peaks in the far-infrared.

In the youngest stellar objects, circumstellar disks are strongly affected in their appearance by their surroundings. The so-called 'proplyds' (Figure 5) are flattened circumstellar clouds of gas and dust which are rendered visible as a result of the ionizing radiation of hot stars in a H II region to which they belong, or close to which they are located. In some cases (Figure 5) the optically thick dusty inner disk can be seen in absorption against the background, but the optical appearance of proplyds is most often dominated by recombination radiation from their outer parts. Such objects were detected in the central parts of the Orion Nebula as emission-line sources (Laques and Vidal, 1979) and as compact radio continuum sources (Churchwell *et al*. 1987, Garay *et al*. 1987), and were resolved spatially with

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