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Disks around young stellar objects

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Abstract. By 1939, when Chandrasekhar's classic monograph on the theory of *Stellar Structure* was published, although the need for recent star formation was fully acknowledged, no one had yet recognized an object that could be called a star in the process of being born. Young stellar objects (YSOs), as pre-main-sequence stars, were discovered in the 1940s and 1950s. Infrared excess emission and intrinsic polarization observed in these objects in the 1960s and 1970s indicated that they are surrounded by flattened disks. The YSO disks were seen in direct imaging only in the 1980s. Since then, high-resolution optical imaging with HST, near-infrared adaptive optics on large ground-based telescopes, mm and radiowave interferometry have been used to image disks around a large number of YSOs revealing disk structure with ever-increasing detail and variety. The disks around YSOs are believed to be the sites of planet formation and a few such associations have now been confirmed. The observed properties of the disk structure and their evolution, that have very important consequences for the theory of star and planet formation, are discussed.

Keywords. Star formation; young stellar objects; circumstellar disks; exoplanets.

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1. Introduction

S Chandrasekhar's classic monograph [1] on the theory of *Stellar Structure* was published in 1939. In it, he restricted his study to stars that were in equilibrium and were in a steady state. Questions regarding the origin of stars and pre-stellar objects and their structure were not considered. In the early 1930s it was still not clear whether star formation was taking place at the present time. Only by 1938, with the work of Bethe and others on thermonuclear burning of H into He as the energy source for main sequence stars [2], did it become clear that massive OB stars cannot survive for more than a few million years on hydrogen fusion reactions and therefore must have been born recently. The coexistence of lower-mass stars together with OB stars in some star clusters implies that these low mass stars are also of recent birth. While the need for recent star formation was fully acknowledged, no one had yet recognized an object that could be called a star in the process of being born.

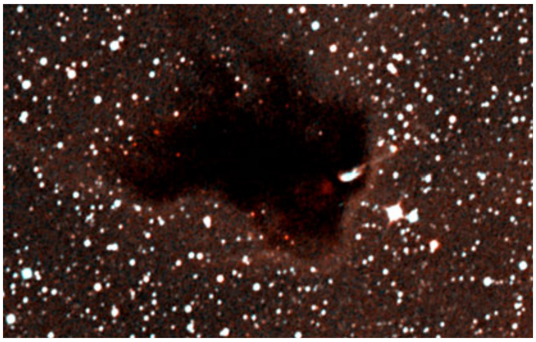

Figure 1. A dark globule in Vela (image taken from the digital sky survey (DSS)).

2. The birth of stars

2.1 *Where are the stars born?*

Where are the stars born? The interstellar medium (ISM) is the only large enough reservoir of material required for current star formation. Whipple [3] and Spitzer [4] first suggested that dust grains in the ISM could be compressed into denser clouds by interstellar radiation, which could then collapse under gravity to form protostars and stars. Therefore, one may expect to find protostellar and young stellar objects in and around interstellar clouds like the dark globules pointed out by Bok and Reilly in 1947 [5], an example of which is shown in figure 1.

2.2 *Discovery of candidate young stars*

The emission-line variables like T Tauri, discovered by Joy in the early 1940s [6,7], associated with dark clouds of Taurus, Auriga and other regions of the Milky Way, were recognized as young stars in expanding stellar associations by Ambartsumian [8]. That, expanding stellar associations are also the birth sites of massive stars was suggested by Ambartsumian [8] and Blauuw [9]. Emission-line stars of type Ae/Be, associated with nebulosity in regions of dark clouds, were identified later by Herbig [10], as young, more massive counterparts of T Tauri stars.

3. Observational characteristics of pre-main-sequence stars

Protostellar and young pre-main-sequence stellar objects in the process of formation from dense interstellar clouds by contraction under gravity could be expected to have the following characteristics:

1. They would be cooler and larger in size as compared to normal stars on the main sequence. Theoretical work by Salpeter [11] on the reactions of light nuclei (D, Li, Be, B) in young contracting stars and stellar evolutionary tracks for such objects by Henyey *et al* [12] predicted that they would occupy positions to the right (lower

temperature) and above (higher luminosity) the main-sequence in the Hertzsprung–Russell (HR) diagram. This was confirmed by Walker [13] for lower mass stars, including the T Tauri variables, in the young cluster NGC 2264, from a photoelectric colour-magnitude diagram.

2. Infrared excesses due to the circumstellar matter: Observations of T Tauri stars and related objects like R Mon at infrared wavelengths up to 5μ by Mendoza [14] and 20μ by Low and Smith [15] showed a large flux excess above that expected from a stellar photosphere. The infrared excess was interpreted by Low and Smith [15], and, Davidson and Harwit [16] as emission from protostellar cloud dust that still surrounds the central young stellar object (YSO), as it absorbs light from the central YSO, gets heated and re-radiates at longer wavelengths.
3. The circumstellar dust must be in a flattened disk: If the circumstellar dust were spherically distributed around the central YSO, then the mass of dust required to produce the observed infrared fluxes would lead to very large extinction along the line of sight to the central YSO at optical wavelengths, which is generally not observed. Therefore, the infrared emitting dust must be distributed in a flattened disk-like geometry [17] and it should also cause polarization when viewed more nearly edge-on due to departure from spherical symmetry. Intrinsic polarization was detected in several pre-main-sequence stars in NGC 2264 by Breger and Dyck [18].

Thus the nature of the observed infrared excess emission and the intrinsic polarization of the pre-main-sequence stars strongly indicated the presence of circumstellar disks around these YSOs. Disk formation had indeed been expected as a rotating protostellar cloud contracts under gravity. For a cloud with initial rotation, conservation of angular momentum prevents contraction of the body as a whole. As suggested by von Weizsacker [19], the cloud is flattened and a disk is formed. A flattened protoplanetary disk had indeed been a part of the Solar Nebula models, first proposed and developed by Emanuel Swedenborg (1734), Immanuel Kant (1755) and by Pierre-Simon Laplace (1796) in the 18th century.

4. The circumstantial evidence for circumstellar disks

Till around early 1980s, the evidence for the existence of circumstellar disks around YSOs had been indirect, based on the interpretation of optical-infrared spectral energy distributions (SED) and observations of intrinsic polarization of pre-main-sequence stars. Such studies of SEDs, now extending to far-infrared, sub-millimeter, millimeter and radiowavelengths [20–23] and polarization [24–26] of a large number of YSOs have shown that they are commonly surrounded by disks with a great diversity in their properties.

5. Direct evidence for disks: Imaging

The first direct optical image of a circumstellar disk was obtained in 1984 by Smith and Terrile [27] by 'coronagraphic imaging' of the young (∼10 Myr) main-sequence star β Pictoris. Figure 2 shows a recent infrared image of the β Pictoris disk. The disk around β Pictoris is seen nearly edge-on and extends to about 500 AU from the star. A circumstellar

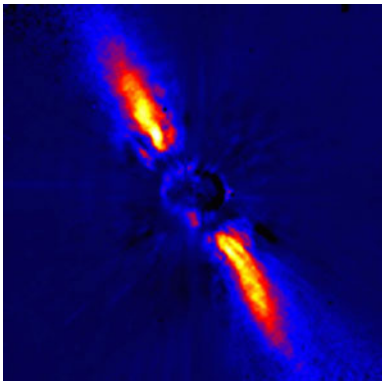

Figure 2. Disk around β Pictoris. Source: European Southern Observatory.

disk around a very young ($\sim 10^5$ yr) pre-main-sequence star, HL Tau, was imaged in the near-infrared (1–3 μ) with an infrared camera in 1988 by Monin *et al* [28].

Since then, high-resolution optical imaging with HST, near-infrared adaptive optics on large ground-based telescopes, mm and radiowave interferometry have been used to image and resolve disks around a large number of YSOs revealing disk structure with ever-increasing detail and variety. Narrow-band imaging with the HST revealed a number of protoplanetary disks in the Orion Nebula silhouetted against the bright nebular background [29]. Edge-on protoplanetary disks that occult the central star are seen as dark lanes separating two scattering surfaces that often show flaring and, in some cases, are accompanied by highly collimated bipolar jets as in HH 30 [30]. Non-axisymmetric structures in more nearly face-on disks, e.g. a spiral pattern in the case of the Herbig Ae star AB Aur [31] have been found in near-infrared coronagraphic images using adaptive optics for some YSOs. Millimeter-wave interferometric observations have not only imaged the flattened disks, but also shown that they are in Keplerian rotation around their central stars [32].

6. Disk models and structure

The circumstellar disk around a YSO consists of gas and dust. The dust absorbs the short-wavelength (UV, optical) radiation from the central star, gets heated and re-radiates at longer (infrared, millimeter) wavelengths. Viscous processes lead to angular momentum transport (outward) and accretion of disk matter radially inward and onto the central star. Gravitational energy released due to accretion heats the disk and is radiated away. The relative contributions to disk heating by the central star luminosity and the accretion energy depend on the mass of the central star and the accretion rate. The disk heating is termed ‘passive’ if it is dominated by the stellar luminosity, or ‘active’ if the accretion energy dissipation in the disk dominates the heating.

The spectral energy distribution (SED) of the observed radiation from the disk depends on the distribution of temperature, opacity, accretion rate and inclination of the disk. The disk luminosity L_ν as a function of frequency ν integrated over the disk surface can be calculated from

$$L_\nu = 4\pi D_\nu^2 F_\nu = 4\pi \cos\theta \int_{R_\mathrm{i}}^{R_\mathrm{o}} \nu B_\nu(T(r))(1 - \exp(-\tau_\nu(r)))2\pi r \, \mathrm{d}r,$$

where F_ν is the flux density at a distance D from the source, R_i and R_o are the inner and outer disk radii respectively, angle θ is the inclination of the disk to the line of sight, $B_\nu(T(r))$ is the Planck function corresponding to the temperature $T(r)$ at a radial distance r in the disk. The optical depth is given by $\tau_\nu(r) = \kappa_\nu \Sigma(r)/\cos\theta$ with κ_ν the opacity and $\Sigma(r)$ the surface density of matter in the disk.

For optically thick and geometrically thin disks that are passively heated, the temperature structure is given by [33]

$$T^4(r) = T^{*4}[\sin^{-1}(R^*/r) - ((R^*/r)\sqrt{(}1 - (R^*/r)^2)]/\pi$$

which for large radii (compared to the stellar radius R^*) tends to $T(r) \propto r^{-3/4}$. T^* is the surface temperature of the central star.

For a flat, actively heated disk accreting at a rate $\dot{M}$ around a star of mass M^* the temperature distribution is given by [34]

$$T^4(r) = 3GM^*\dot{M}[1 - \sqrt{(}R^*/r)]/8\pi\sigma r^3$$

which again, for large radii, tends to $T(r) \propto r^{-3/4}$.

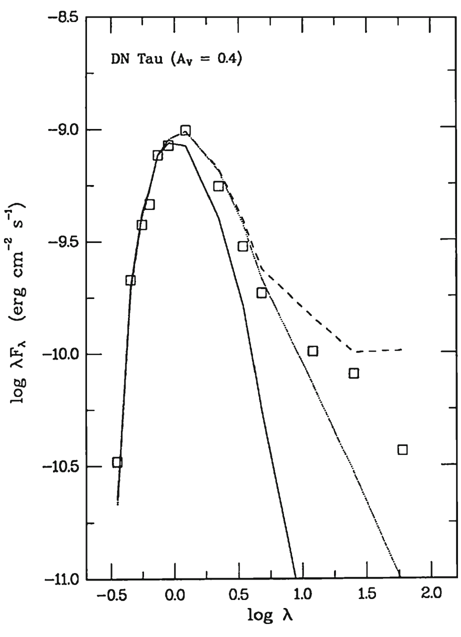

Figure 3. SED of the young star DN Tau. Log *wavelength* in μ is plotted on the x-axis. Solid line represents the stellar contribution, the dotted line corresponds to thin reprocessing model disk and the dashed line a flared disk model from Kenyon and Hartmann [35].

The SED for such thin disks, for long wavelengths (λ), should have the form $\nu F_\nu = \lambda F_\lambda \propto \nu^{4/3}$. The observed SEDs of YSOs, however, generally show longer wavelength emission at a level higher than predicted in the flat disk models (figure 3).

The observed SEDs are better fit by models in which the scale height of the disk increases with radius (flared disks; Kenyon and Hartmann [35]) and the temperature structure is less steep than $T(r) \propto r^{-3/4}$ for flat disks. Real disks, in fact, will have not only a radial temperature structure, but also a vertical temperature gradient with the top surface of the disk being the hottest due to stellar irradiation and the temperature falling with depth into the disk interior. For active disks, midplane of the disk may get hotter due to accretion [36]. Observations covering a wider spectral range with higher resolution have shown that YSO disks may have inner holes, hot rims and also gaps. The inner edge of the dust disk may be located at the dust destruction radius where the dust is evaporated due to absorption of radiation from the central star [37], leading to emission excess in the near-infrared and puffing-up of the disk due to heating [38]. Inner holes and gaps, indicated by emission deficits in the infrared [39], in the disk may be produced by photoevaporation [40] and gravitational torques due to massive protoplanetary bodies [41] that may have formed in the disk.

7. YSO Disks and planet formation

The general characteristics of the observed disks can be summarized as:

1. Sizes: 0.1–20 arcsec; 10^1–10^3 AU (typical 10^2 AU)
2. Masses: 10^{-3}–$1 M_\odot$ (typical $10^{-2} M_\odot$)
3. Temperature: 10^3–10^1 K with gradients

The typical disk mass (obtained from measurements of mm-wave emission by dust and assuming a gas-to-dust ratio of 100) is similar to that of the minimum mass solar nebula (MMSN) models (disk mass $\sim 0.01 M_\odot$, see e.g., [42]). The YSO disks are thus potential sites of planet formation and, as mentioned earlier, the observed inner holes and gaps in the disks have been interpreted to have been caused by such bodies formed in them.

Sub-stellar and planetary-mass bodies have indeed been discovered in a number of YSO disks in recent years. Young stars GQ Lup [43] and CT Cha [44] host rather massive companions, $21.5 M_J$ and $17 M_J$, respectively; 2M1207 [45,46], a brown dwarf, hosts a $4 M_J$ mass planet; UScoCTIO 108 [47] with a $14 M_J$ mass planet; β Pic [48,49] has an $8 M_J$ mass planet. AB Pic [50], HR 8799 [51], SCR 1845 [52] and Fomalhaut [53] are older planetary systems with ages of about 30 Myr, 60 Myr, 100 Myr and 200 Myr.

The first exoplanet around the sun-like star 51 Peg was discovered in 1995 by Mayor and Queloz [54] and currently more than 300 exoplanetary systems are known. In a Spitzer-based survey, ten new debris disks around stars with planets have been found [55].

Now there is a general consensus that planets and planetary systems form in the circumstellar disks around YSOs. The planet formation processes have been discussed by a number of authors [56–58]. Sedimentation of dust grains, their growth in size by coagulation upon collisions, accretion of gaseous material and gravitational instabilities play important roles in the process. Beginning with sub-μ to μ size dust grains, progressively larger objects are formed in several stages of growth requiring various timescales.

(a) Dust grain growth and sedimentation (size up to cm range on 10^4 yr time-scale)
(b) Planetesimals ~0.1 to ~1 km size, 10^5 yr (during this stage the mechanism to prevent inward radial drift due to viscous drag is still unclear)
(c) Planetary cores ~1000 km to ~earth ($\oplus$) size, 10^6 yr (by gravity-assisted growth)
(d) Giant planets (Jupiter mass M_J and larger) can form in the outer disk in two ways: (i) $10M_\oplus$ core formation followed by accretion requiring $\sim 10^7$ yr, or (ii) by gravitational instabilities on much shorter time-scales, less than $\sim 10^6$ yr, but require very massive disks.

8. Disk evolution and constraints on planet formation

Planets are formed in the circumstellar disks around young stars. Observations show that the planets, of the solar system and the exo-planets, and the disks around YSOs exhibit a large range in their physical properties like mass, size, orbits etc. The YSOs and their disks evolve with time, the disk accretion rates and disk masses decrease with age, and eventually the disk is dispered. Any planet formation in the disk must take place within the disk lifetime. From an infrared L-band (3.4μ) survey of the intermediate-age (2.5–30 Myr) star clusters, Haisch *et al* [59] found that the frequency of disk occurrence in young clusters decreases with cluster age and inferred an overall disk lifetime of ~6 Myr. Manoj *et al* [60] studied the evolution of H_α emission-line (a measure of accretion rate; e.g.

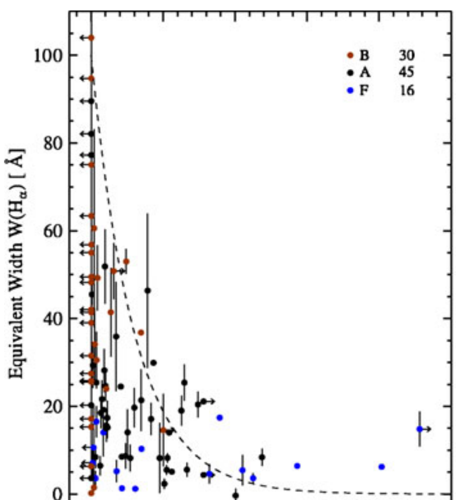

Figure 4. H_α equivalent widths of HAeBe stars plotted against the derived stellar ages. The dashed line is of the functional form $W(\mathrm{age}) = W(0)\exp(-\mathrm{age}/\tau)$, with $W(0) = 100$ Å and $\tau = 3$ Myr (figure taken from [60]).

Muzerolle *et al* [61]) activity in a large sample of intermediate-mass young stars for which age determination could be done individually and found that the accretion rate declines on a time-scale of ∼3 Myr (figure 4). From a more recent survey of pre-main-sequence stars in young clusters and associations, Fedele *et al* [62] estimated an accretion time-scale of 2.3 Myr and a dust (based on near-to-mid infrared excesses) dispersal time-scale of 2.9 Myr.

The disk lifetimes (∼3 Myr), as estimated above, put strong constraints on models for planet formation in disks around young stars. The two main models, originally proposed to explain the characteristics of the solar system, are: the core-accretion hypothesis [42,56,63] and the disk instability scenario [64,65]. While the planetesimals and planetary objects of the size typical of planets in the terrestrial zone of the solar system can form within the lifetime of the disks in both the models, the formation of massive gas giants faces serious difficulties. The core-accretion process is uncomfortably slow (time-scale ∼10 Myr), especially for the formation of super-Jupiters with masses $\sim 10M_{\rm J}$. The disk instability process is fast but requires high mass density in the disk and efficient cooling. In this model the disks need to be ∼10–30 times more massive than the MMSN mass which is only rarely observed.

9. Conclusions

Recent research has conclusively established that the process of star formation in the dense and cold interiors of molecular clouds also produces planets orbiting the young stars. Gravitational collapse of a rotating protostellar cloud leads to the formation of a flattened disk around the central young stellar object and planets form in these disks by processes that involve growth of dust grains and their sedimentation, collisions and coagulation of planetesimals, accretion of gaseous material and gravitational instabilities on various time-scales as proposed in different models. Observations of disks around the YSOs and exoplanets provide very strong constraints on the models. The observed disk dispersal time-scale is ∼3 Myr. The formation of Jupiter-like gas giants in the standard core-accretion models needs ∼10 Myr, and super-Jupiters would require much longer time. Massive gas giants can be formed rapidly in the disk instability models, but require disks that are ∼10–30 times more massive than the minimum mass solar nebula and the average mass of the observed YSO disks. The YSO disks do succeed in forming planets with a range of masses and orbital characteristics and may be following different routes to produce them in different disk environments.

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