Circumstellar Disks and Star Formation

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Results from the IRAS satellite showed that many pre-main sequence stars exhibited unexpectedly large fluxes in the infrared spectral region. Several studies have shown that the simplest and most satisfying explanation of this excess emission is that it arises in optically-thick, dusty, circumstellar disks (Rucinski 1985; Adams, Lada, and Shu 1987, 1988; Kenyon and Hartmann 1987; Bertout, Basri, and Bouvier 1988; Basri and Bertout 1989). The masses of these disks are estimated to range between $10^{-3}M_\odot$ to $1M_\odot$ (Beckwith *et al.* 1990; Adams *et al.* 1990), large enough that disk accretion may have a significant effect on the evolution of the central star. Indeed, Mercer-Smith, Cameron, and Epstein (1984) suggested that stars are essentially completely accreted from disks, rather than formed from quasi-spherical accretion (Stahler 1983, 1988).

The importance of disk accretion on stellar evolution must be estimated observationally. The accretion rate is derived from estimates of the accretion luminosity,

$$L_{acc} = \frac{GM\dot{M}}{R} \; .$$

In the standard model of accretion disks, half of the accretion luminosity comes out at long wavelengths, from true disk emission, and the other half of the accretion luminosity is emitted at short wavelengths, in the boundary layer between the star and disk (Lynden-Bell and Pringle 1974). By comparing disk models with observations, estimates of accretion rates for T Tauri (low-mass, pre-main sequence) stars have been derived by several groups of authors (Adams, Lada, and Shu 1987, 1988; Kenyon and Hartmann 1987; Bertout, Basri, and Bouvier 1988; Basri and Bertout 1989; Hartmann and Kenyon 1990; Hartigan *et al.* 1991). Recently, estimates for higher-mass pre-main sequence sta rs have been presented by Hillenbrand *et al.* (1992).

Accretion rates are often difficult to determine for T Tauri stars from analysis of infrared disk spectra. This is because optically thick disks absorb and re-radiate a significant fraction of the central star's luminosity, in the absence of any accretion (Adams and Shu 1986; Kenyon and Hartmann 1987). For many T Tauri stars, the disk luminosity is a fraction of the stellar luminosity, making it difficult to determine whether the radiation

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is truly generated by accretion or is simply reprocessing of incident stellar radiation. More reliable estimates come from analysis of boundary layer radiation (Kenyon and Hartmann 1987; Bertout, Basri, and Bouvier 1988; Basri and Bertout 1989; Hartigan *et al.* 1991). These estimates suggest that many T Tauri stars are accreting at rates $\sim 10^{-7} M_{\odot}\, yr^{-1}$. Adopting typical T Tauri lifetimes of 10^6 yr, the average T Tauri star probably accretes $\sim 0.1 M_{\odot}$ from its disk during optically visible phases.

Estimates of disk accretion rates can also be derived from FU Orionis objects (Hartmann and Kenyon 1985; Hartmann, Kenyon, and Hartigan 1992). The FU Orionis objects are thought to represent T Tauri disks in outbursts of accretion activity. During these outbursts, the disk becomes much brighter than the star, and so disk reprocessing of stellar luminosity is negligible. It is not certain whether all pre-main sequence stars undergo FU Ori outbursts, but event statistics are consistent with $\gtrsim 10$ outbursts per star, with maximum accretion rates $\sim 10^{-4} M_{\odot}\, yr^{-1}$. The total amount of mass accreted during all FU Ori outbursts of the average star is $\sim 0.05 M_{\odot}$, essentially identical to the estimate for T Tauri stars.

The estimates of accretion rates for T Tauri stars, whether in normal states or in FU Ori outbursts, imply that circumstellar disks initially have masses $\gtrsim 0.1 M_{\odot}$, at least at early stages of evolution. These disk masses are larger than the average disk mass found by Beckwith *et al.* (1990) from mm-wave observations; however, the masses depend upon the assumed dust opacity at long wavelengths. The disk masses of Adams *et al.* (1990), who used larger opacities than Beckwith *et al.* (1990), are more consistent with the estimates from accretion rates.

It should be emphasized that the above estimates of disk accretion, amounting to $\gtrsim 10$ % of the final stellar mass, refer only to the optically-visible portion of pre-main sequence evolution. Additional mass could be accreted from disks onto protostars during the earliest

phases of evolution, in which the central object is obscured at optical and near-infrared wavelengths by a surrounding infalling dust cloud. Thus, it is possible that a large fraction, if not most, of a typical low-mass star is accreted from its disk.

The amount of mass accreted and the rate of mass accretion during optically-visible evolution may be sufficient to perturb the central star's evolution away from nominal Hayashi tracks (Hartmann and Kenyon, 1990). K. Strom *et al.* (1992) attempted to test this idea by examining close pairs of T Tauri stars that are probably coeval. Strom *et al.* found that the most rapidly accreting star of a pair tended to appear younger than the other object, suggesting some effect of accretion on HR diagram evolution. Thus, disk accretion might produce stars that appear younger, as judged from conventional Hayashi track isochrones, than they really are. However, it should be pointed out that many weak-emission T Tauri stars, which show no evidence for disk accretion (Mundt *et al.* 1983; Feigelson *et al.* 1987), appear to be just as young as the average accreting T Tauri

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star (Walter *et al.* 1988).

The possibility that T Tauri stars are really older than they appear from standard isochrones would help explain the absence of "post- T Tauri" stars in the Taurus-Auriga molecular cloud. Herbig, Vrba, and Rydgren (1986) pointed out the absence of stars with ages $\sim 10^7$ yr in this region, despite the likelihood that the molecular cloud is at least 10^7 years old. The average age of the T Tauri population is $\sim 10^6$ years for regions separated by crossing or dynamical times $\sim 10^7$ years, and it is difficult to see how star formation could be coordinated over such a large region on such short timescales.

There are observational selection effects which make it difficult to discover older pre-main sequence stars, and Walter *et al.* (1988) found evidence for stars in the region with ages $\sim 10^7$ yr. However, surveys based on proper motion selection show that the space density of older stars is too small to explain the post-T Tauri problem (Hartmann *et al.* 1991; Gomez *et al.* 1992). Walter *et al.* (1988) found some evidence for differences in ages between various regions of Taurus; Gomez *et al.* (1992) estimated that the southern portions of the molecular cloud have ages more typically 2 to 3×10^6 years, but nothing approaching the 10^7 year dynamical time across the region.

If T Tauri stars are actually two to three times older than given by conventional Hayashi tracks, the distribution of stellar ages in Taurus is much easier to understand. In addition, such an increase in T Tauri ages would also help explain the relatively low luminosities of heavily-extincted objects thought to be protostars accreting from freely-falling, quasi-spherical envelopes (Kenyon *et al.* 1990). Increasing the ages of T Tauri stars would also increase the estimated amounts accreted from circumstellar disks.

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