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THE ROLE OF ACCRETION DISKS IN ESTABLISHING THE INITIAL ANGULAR MOMENTUM OF LOW MASS STARS

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RESUMEN

Las observaciones revelan que las velocidades de rotación de estrellas jóvenes de baja masa difieren significativamente si muestran características de poseer discos de acreción o no. Las velocidades de rotación menores se encuentran en aquellas estrellas aparentemente rodeadas de discos de acreción, lo que sugiere que el disco puede jugar un papel fundamental como regulador de la velocidad angular de la estrella central, balanceando la tendencia de rotar mas rápido en su contracción hacia la secuencia principal y por acreción de material de alto momento angular específico. Esto implicaría que el momento angular inicial de una estrella en formación es el mismo que posee cuando se disipa su disco de acreción. El intervalo de velocidades rotacionales observado entre las estrellas de edad cero en la secuencia principal y de masa determinada en cúmulos jóvenes, podría en parte ser el resultado de un intervalo de escalas de tiempo de disipación del disco: las estrellas que pierden su disco rápidamente serían los rotadores mas rápidos, mientras que aquellas que conservan su disco un tiempo largo ocuparían el extremo de baja velocidad en la distribución de velocidades rotacionales en estrellas de la secuencia principal de edad cero.

ABSTRACT

Observations reveal that the rotational velocities of young low mass stars differ significantly depending on whether or not they show accretion disk signatures. Slower rotational velocities are found for those stars apparently surrounded by accretion disks suggesting that the disk may play a fundamental role in regulating the angular velocity of the central star, countering the tendency of the star to spin up both from contraction toward the main sequence and from accretion of disk material of high specific angular momentum. This would imply that the initial angular momentum of a forming star is the angular momentum it carries when its accretion disk is dissipated. The observed order of magnitude range in rotational velocities among ZAMS stars of a given mass in young clusters might then result in part from a range in timescales for disk dissipation: stars which lost their disks early would be among the most rapid rotators, while those which retained their disks the longest would populate the low velocity end of the ZAMS rotational velocity distribution.

Key words: **STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

A forming star faces two angular momentum crises in its gravitational collapse from a spinning molecular loud core to the stellar body which finally emerges from that collapse. The first crisis, the classical angular nomentum problem, arises from the considerable discrepancy between the angular momentum of the star orming core and that of the resultant star (at least a factor of 1 000; Bodenheimer 1991). Two likely reservoirs for he angular momentum residing in molecular cores (Goodman et al. 1993) are the formation of binary/multiple systems (Simon 1992) and the formation of centrifugally supported solar-system-sized circumstellar disk (Cassen & Mooseman 1981; Shu, Adams, & Lizano 1987). Recent work on the multiplicity of the youngest low mass stars suggests both that the frequency of binaries is significantly higher than that found for main sequenc stars in the solar neighborhood, and that the frequency of detection of circumstellar disks is comparably higl in binary and single stars (Ghez 1993; Leinert et al. 1993). The high frequency of both binary/multipl systems and circumstellar disks among low mass young stars suggests that both are likely reservoirs for th core angular momentum, and that they are not mutually exclusive options. Significantly, circumstellar disk are likely associated with the formation of most or all stars, independent of their multiplicity status. That al such circumstellar disks are in a state of active mass accretion for much or all of their observable lifetimes is the most likely interpretation of the optical and near infrared excesses and broad blueshifted forbidden lin emission which characterize the spectra of stars believed to be surrounded by disks (Bertout 1989; Hartmanr & Kenyon 1990; Edwards et al. 1993).

The second angular momentum crisis faced by a forming star arises as a result of its central location in ar accretion disk. During the accretion phase, the central star will accumulate both mass and angular momentur from the inner Kleperian disk, at a rate set by the mass accretion rate through the disk

$$\dot{J}_{acc} \sim \dot{M}_{acc}\, \Omega_{Kep}\, R_*^2$$

For the youngest optically visible low mass stars, the T Tauri stars, typical disk accretion rates are $\dot{M}_{acc} \sim 10^{-}$ $M_\odot$ yr^{-1} (Hartigan et al. 1991; Basri & Bertout 1989), which imply an accumulation of high angular momentur material sufficient to spin the central star up to an angular velocity near break-up in a time comparable to th age of the youngest T Tauri stars, $t \sim 1$ Myr (Hartmann & Stauffer 1989). However, the observed v *sin* distributions for T Tauri stars reveal that most have projected equatorial velocities v *sin* $i \leq$ 20 km s^{-1} corresponding to angular velocities $\Omega \leq 0.1\, \Omega_{breakup}$. The modern angular momentum problem in star formatio might be stated thus: *why aren't central stars in accretion disk systems spinning at break-up?*

In this review, we will summarize recent evidence which suggests a resolution of this angular momentur crisis: that during the phase of active disk accretion, an effective mechanism acts to regulate the angular velocit of the central star, holding the stellar angular velocity fixed, and consequently resulting in a net *decrease* in th stellar angular momentum as the star contracts toward the main sequence. The initial angular momentum o the star will then be the angular momentum it carries when its regulating accretion disk is dissipated. We wil suggest that a dispersion in initial angular momenta will result for stars of a given mass, due in part to th range of disk dissipation timescales which are known to characterize star formation regions.

2. OBSERVATIONAL BASIS FOR DISK REGULATED ANGULAR VELOCITIES

To understand the role of accretion disks in resolving the modern angular momentum problem it is necessar to examine a sample of low mass young T Tauri stars, selected to have similar masses and ages and thus simila interior structure, where we have both 1) determined precise angular velocities of the T Tauri stars and 2) ca provide unambiguous discrimination between T Tauri stars which are and are not in accretion disk systems.

2.1. Photometric Rotation Periods

Irregular photometric variability is a key observational characteristic of T Tauri stars, and many pioneerin observations searching for periodicities were carried out by E. Mendoza (1966; 1968), among others. The firs photometric periods for T Tauri stars were identified in the 1980's by Rydgren & Vrba (1983). The periodi brightness variations are interpreted as deriving from rotational modulation by cool photospheric spots, an today many tens of such light curves have been identified (Bouvier et al. 1993; Attridge & Herbst 1994) Photometric rotation periods derived from high precision photometric observations of starspot modulated ligh curves provide 1) a direct measure of the stellar angular velocity free from projection effects and 2) the potenti of determining angular velocities for stars with equatorial rotational velocities which lie below the limit c standard spectroscopic techniques.

2.2. Classical and Weak T Tauri Stars

Low mass stars first become optically visible as T Tauri stars at an age $t \sim 1$ Myr, at which tim approximately half are still surrounded by accretion disks (Strom, Edwards, & Skrutskie 1993). The timescale for disk dissipation apparently vary widely among stars of similar mass and age, with some disks persistin or times up to $t \sim 10$ Myr. Diagnostics for accretion disks surrounding T Tauri stars include 1) optical/uv ontinuum excess "veiling") attributed to the "boundary layer" interface between the slowly rotating star and the nner disk regions in Keplerian rotation (Basri & Bertout 1989; Hartigan et al. 1991); 2) forbidden line emission rising from [O I] λ 6300 A, and attributed to formation in an energetic wind powered by accretion related ctivity (Cabrit et al. 1990; Edwards, Ray, & Mundt 1993); and 3) infrared continuum excess from viscous nergy dissipation in a self-luminous accretion disk (Mendoza 1968; Beckwith et al. 1990). Recent observations how that *all* T Tauri stars which exhibit near-infrared color excesses significantly above photospheric levels lso show evidence of veiling and forbidden line emission (Edwards et al. 1993). This result strongly suggests hat all disks which are both optically thick and extend inward to within a few stellar radii of the surface of T Tauri star are in fact, accretion disks, and that near infrared color excesses are an excellent diagnostic of uch disks.

In addition to a population of classical T Tauri stars (cTTS) which show accretion disk signatures, star ormation sites usually show a second T Tauri population, characterized by similar masses and ages to the lassical T Tauri stars, but which lack the optical and near infrared excesses indicative of accretion disks. Both he weak T Tauri stars (wTTS) and the cTTS possess strong x-ray emission attributed to enhanced solar-like nagnetic activity (Montemerle et al. 1993). Indeed, examples of resolved non-thermal radio emission from large nagnetic loops have been detected among both cTTS and wTTS, indicating both groups of stars possess strong nd extended magnetic fields (Phillips et al. 1991; Andre et al. 1992).

2.3. Observational Comparision of Rotation Periods and Accretion Diagnostics

When T Tauri stars with known photometric periods and accretion disk diagnostics are examined, a clear istinction in the distribution of rotation periods between stars with and without accretion disk signatures is pparent. This is shown in Figure 1, for a sample of 52 T Tauri stars with spectral types $\geq$ K5, assembled rom papers by Edwards et al. (1993) and Bouvier et al. (1993). The spectral type selection is made to ensure hat all stars lie on their fully convective pre-main sequence tracks and thus have similar interior structure (see Edwards et al. 1993). This figure reveals

- T Tauri stars still surrounded by accretion disks (cTTS) have a narrow range of rotation periods, with a nean period of approximately 8 days.
- T Tauri stars which are not surrounded by accretion disks (wTTS) have a much wider range of rotation eriods, including many which have rotational periods up to 4 times shorter than those of the cTTS.

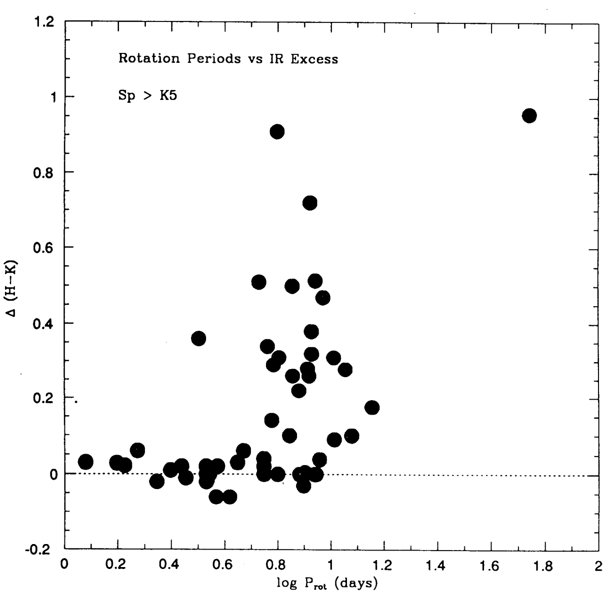

Fig. 1. A plot of the reddening corrected near infrared color excess in the H (1.65 μm) and K (2.2 μm) ands against the logarithm of the stellar rotation period for the combined sample of 52 T Tauri stars of spectral ype $\geq$ K5 from Edwards et al. (1993) and Bouvier et al. (1993). An infrared color excess ≥ 0.1 is considered o be a diagnostic of an accretion disk.

3. DISK REGULATION MECHANISMS

The observations demonstrate that fully convective pre-main sequence stars surrounded by accretion disk not only have angular velocities an order of magnitude smaller than predicted from their inferred disk accretio rates, but they also have systematically slower angular velocities than stars of similar mass and age which hav already dissipated their accretion disks. These observations strongly suggest that the accretion disk acts as a agent in countering the spin-up torque expected from the contracting star and the accumulation of high angula momentum material from the disk. Moreover, the relatively small range of observed rotation periods amon the cTTS suggest that the regulation of the angular velocity is both uniform and efficient among all opticall visible stars surrounded by accretion disks.

Two classes of theoretical ideas offer a potential explanation for this disk regulation mechanism, both c which rely on strong magnetospheres. In one case, closed field lines of the stellar magnetosphere couple t the disk, truncating the inner disk and enforcing co-rotation. A balance between the dynamical pressure c the accreting material and the magnetic pressure from the stellar field acts to determine the regulated stella angular velocity and the corotation radius, and following the formalism established by Ghosh & Lamb (1979 the stellar angular momentum is removed through field coupling beyond the co-rotation radius (Konigl 199 Cameron & Campell 1993; Ghosh 1994). Alternatively, open field lines, rooted in either the star or the disk, a envisioned to channel mass and angular momentum outward in a magnetized, centrifugally driven wind. Th accretion driven wind, with a mass loss rate proportional to the disk accretion rate, would act to remove th angular momentum from the central regions of the disk or from the central star (Shu et al. 1988; Lovelace e al. (1991); Konigl & Ruden (1993); Pudritz & Ouyed (1993).

Recently, a model incorporating some of each the above mechanisms has been developed by Shu et a (1994). Here, shielding currents in the disk are invoked to prevent penetration of the closed stellar field lin everywhere except very near the corotation radius. Just inside co-rotation, where the field lines bow inwar accreting gas is channeled onto the star and angular momentum is transferred back out to the disk. Just outsid co-rotation, where the field lines bow outward, material is lifted off the disk and forces the field lines to ope resulting in a magnetocentrifugally driven wind. This model has far reaching implications, offering a potenti explanation not only for stellar angular momentum regulation in the presence of an accretion disk, but also f the simultaneous presence of accretion-powered T Tauri winds and warm, dense material infalling at free-fa velocities known to characterize T Tauri spectra (Calvet & Hartmann 1992).

4. EVOLUTIONARY CONSEQUENCES

If accretion disks do provide an efficient mechanism for regulating stellar angular velocities of pre-mai sequence stars, then the initial angular momentum of a star will be established when its accretion disk dissipated. The observations in Figure 1 suggest that regulation of the stellar angular velocity is absent i stars which lack accretion disks, as would be expected if these stars dissipated their disks at an earlier tim and, released from the regulation mechanism, are free to spin up in response to changes in moment of inert as they gravitationally contract down their Hayashi tracks toward the main sequence. Of course, other facto will certainly influence their angular momentum evolution as well, such as tidal locking in close binaries a evolution of their interior structure.

A consequence of the observed range in disk dissipation timescales from low mass stars from less than 1 M up to 10 Myr would be that the initial angular momenta of a set of stars with identical mass, magnetosphere and disk accretion rates would differ considerably depending on their age, and thus radii, when the disk w dissipated. The observed wide range in ZAMS equatorial velocities for low mass stars in young clusters such α Per (($t \sim 30-50$ Myr) and the Pleiades ($t \sim 100$ Myr) (Stauffer 1991), from less than 10 km s^{-1} to in exce of 100 km s^{-1}, could in principle be accounted for by the observed range in disk dissipation timescales foun for T Tauri stars. Stars which dissipated their disks early would be among the most rapid rotators, while tho which retained their disks the longest would populate the low velocity end of the ZAMS rotational veloci distribution.

5. SUMMARY AND FUTURE PROSPECTS

The classic angular momentum problem in star formation, how to account for the angular momentum of t star-forming molecular core, is likely solved by the formation of dual reservoirs of binary/multiple star syste and centrifugally supported circumstellar disks. Since most if not all binary/multiple stars also appear to for disks, the accretion of high specific angular momentum material from a circumstellar disk presents all formi stars with their second angular momentum crisis. The observations show that low mass young stars on their convective tracks have distinctly different rotational velocity distributions depending on whether or not they have dissipated their accretion disks. Since the more slowly rotating stars are those which still possess their disks, it is possible that the presence of the disk around a magnetically active star is responsible for regulating the angular velocity of the star as long as the disk is present. If so, then the dissipation of the accretion disk would signify the termination of the regulation and the star would be free to spin up in response to its internal changes in moment of inertia. The observed range in disk dissipation timescales for low mass T Tauri stars could in principle account for the observed large spread in angular momenta among low mass stars just arriving on the main sequence in young clusters.

In order to test the validity of this hypothesis, large statistical samples of rotational velocities of young solar mass stars from T Tauri ages up to the ZAMS need to be acquired. In addition, the role of accretion disks in regulating the angular velocities of young stars of higher mass needs to be investigated. Several factors might cause disk regulation mechanisms to operate differently in high mass stars. For example, in higher mass stars, internally generated stellar dynamos are likely to be different from, or even non-existent, in comparision to fully convective pre-main sequence stars. Additionally, the Lyman continuum photon luminosity of higher mass stars can significantly affect the structure and evolution of their surrounding accretion disks (Hollenbach et al. 1994). Ultimately star formation scenarios must be able to account for the distribution of the initial angular momentum for stars of all masses, which in turn must be reconciled with the angular momentum distribution for main sequence stars outlined by Kraft (1970) many decades ago.

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DISCUSSION

Koenigsberger: What determines when a star loses its disk?

Edwards: If one looks at the youngest optically visible stars in a particular star formation association, such as Taurus-Auriga, one finds that about half the T Tauri stars have observational signatures we interpret as due to the presence of disks, such as infrared excesses. One then concludes either that only half the stars ever had disks, or that half of the stars dissipated their disks on timescales less than a million years. By an age of 10 million years, all stars have dissipated their disks. We have no observational clues to tell us why this happens. The frequency of disks around binary and single stars, for example, appears to be the same. We do know that the disk dissipation occurs very rapidly, since we see only a few objects which might be in a disk-dissipation stage, with no near infrared excess, but still with a sizable far-infrared excess, as though the disks are clearing from the inside. It is tempting to associate disk dissipation with planet building, but that is only a speculation!

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