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Magnetospheric accretion and pre-main-sequence stellar masses

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ABSTRACT

We present a method of determining lower limits on the masses of pre-main-sequence (PMS) stars and so constraining the PMS evolutionary tracks. This method uses the redshifted absorption feature observed in some emission-line profiles of T Tauri stars, indicative of infall. The maximum velocity of the accreting material measures the potential energy at the stellar surface, which, combined with an observational determination of the stellar radius, yields the stellar mass. This estimate is a lower limit owing to uncertainties in the geometry and projection effects. Using available data, we show that the computed lower limits can be larger than the masses derived from PMS evolutionary tracks for $M \lesssim 0.5\,M_{\odot}$. Our analysis also supports the notion that accretion streams do not impact near the stellar poles but probably hit the stellar surface at moderate latitudes.

Key words: accretion, accretion discs – stars: formation – stars: luminosity function, mass function – stars: pre-main-sequence.

1 INTRODUCTION

A complete understanding of the star formation process requires the ability to predict how the properties of young stars depend on the initial conditions of star formation. Despite significant observational effort in the last two decades, a key experimental problem remains. This is the reliable determination of the masses and ages of pre-main-sequence (PMS) stars. Stellar masses are needed to investigate how the initial mass function (IMF) varies from region to region as a function of initial conditions (i.e. cloud parameters). With reliable stellar ages in hand, we can begin to address quantitatively important questions of early stellar evolution. Presently, a common method used to determine masses and ages of young stars is to place them in an HR diagram and compare their positions with theoretical evolutionary tracks (e.g. Hillenbrand 1997). Considerable theoretical work has been done recently that has advanced our understanding of PMS evolution (D'Antona & Mazzitelli 1994, hereafter DM94; Swenson et al. 1994). Yet there remain significant differences in the tracks owing to alternative treatments of convection, opacities and the zero-point of the calculated ages. An additional complication is ongoing accretion during the PMS, which can alter the path of a star during its early evolution (Hartman, Cassen & Kenyon 1997; Seis, Forestini & Bertout 1997). Without adequate observational constraints, it is nearly impossible to determine what the correct treatment should be.

The discrepancies in the PMS tracks are largest for the lowest mass stars (Hartigan, Strom & Strom 1994). It is precisely this end of the stellar mass distribution which is the most uncertain both amongst field stars and in star-forming regions (e.g. Kroupa, Tout & Gilmore 1993; Luhmann & Rieke 1998). Bona fide brown dwarf objects have recently been discovered as companions to field stars (Nakajima et al. 1995) and as free-floating members of young clusters (Rebolo, Zapatero-Osorio & Martin 1995). However the frequency of such objects remains unknown. Young clusters found in regions of star formation provide one of the best opportunities to determine the relative contribution of low-mass stars and brown dwarfs to the cluster IMF, because substellar objects cool as they age, becoming extremely difficult to detect when old. Uncovering local maxima or minima in the IMF near the stellar/substellar boundary would point to the existance of characteristic masses in the formation process (Adams & Fatuzzo 1996). Because of the importance of the low-mass end of the IMF in star-formation theory, it is imperative to establish reliable PMS evolutionary tracks and thus PMS masses. To do this, we need independent determinations of PMS masses to constrain the tracks.

The best techniques available for directly determining stellar masses involve the study of binary star systems. Eclipsing binary systems provide the best estimates of stellar masses, as well as radii (Popper 1980). Unfortunately, only a few such systems are known that are sufficiently young to provide a test of the PMS evolutionary tracks (e.g. Casey et al. 1998) and even these do not probe the lowest masses. Astrometric determination of orbital parameters for visual

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PMS binary star systems is another promising technique (Ghez et al. 1995), but useful constraints are still several years away. Dynamical mass ratios can be derived for double-lined spectroscopic binaries and compared with theoretical mass ratios in order to test the PMS tracks (Lee 1992). However most of the known double-lined PMS spectroscopic binaries (SBs) have primary stars with masses greater than the solar mass and mass ratios near 1. We therefore need other constraints, even if they can provide only lower or upper limits on the stellar mass. Such limits can be obtained from the dynamical information available from the material accreting on to T Tauri and other young stars.

Accretion on to young stars occurs through a viscous circumstellar disc, where angular momentum transport outwards permits the inward mass transport (Pringle 1981; Lin & Pringle 1990). There is a growing body of observational evidence indicating that the accretion of material on to young stars occurs via magnetospheric accretion columns which extend several stellar radii from the PMS photosphere to the inner edge of a circumstellar disc (Edwards 1997). Material at this point falls freely along the field lines on to the stellar surface. Evidence for this picture comes predominantly from the observed redshifted absorption component (several hundred km s^{-1}) seen in the line profiles of the higher Balmer, Paβ, Brγ, He I and NaD emission lines (Walker 1972; Appenzeller, Reitermann & Stahl 1988; Edwards et al. 1994; Hartmann, Hewett & Calvet 1994; Folha, Emerson & Calvet 1997; Folha & Emerson, in preparation). Models of the IR colours of T Tauri stars imply that the circumstellar discs have inner holes comparable (but slightly interior) to the magnetospheric radius which is typically estimated at 6–8 $R_\star$ (Kenyon, Yi & Hartmann 1996; Meyer, Calvet & Hillenbrand 1997; Armitage, Clarke & Tout 1998). The magnetospheric accretion paradigm also provides an attractive explanation of the relatively slow spin rates of T Tauri stars (Bouvier et al. 1993; Edwards et al. 1993). The stellar magnetic field interacts with parts of the disc that are spinning slower than the star (at radii beyond corotation) and the resulting magnetic braking of those stars with discs [the actively accreting classical T Tauri (CTTS)] can explain why they have longer periods than those [the non-accreting weak-line T Tauri (WTTS)] stars without circumstellar discs (Cameron & Campbell 1993; Armitage & Clarke 1996).

In this paper, we investigate how the observed redshifted absorption components, known as inverse P Cygni (IPC) profiles, can be used as a measurement of the depth of the potential well of the star and hence, combined with an observational determination of the stellar radius, yield an estimate of a lower limit on the stellar mass. Section 2 describes the method while Section 3 provides examples, using available data, of the mass estimates from this method and compares them with published estimates based on the PMS tracks. Section 4 shows how the lower limits on the stellar mass could in principle constrain the accretion stream geometry. A discussion and summary is presented in Section 5.

2 CONSTRAINING PMS MASSES

The IPC profiles in the emission-line spectra of classical T Tauri (CTTS) stars offer a direct measurement of the depth of the potential well of the star. The large infall velocities seen in the absorption profiles are generally assumed to arise from material in free-fall from several stellar radii. This near-radial infall is believed to be caused by the disruption of the accretion disc by the stellar magnetic field (Konigl 1991; Edwards et al. 1994). The velocity of the stream as it impacts the stellar surface then directly measures the difference in potential energy from the radius at which the disc is disrupted to the stellar surface:

$$\frac{1}{2}V_{\rm stream}^2 = \frac{GM_\star}{R_\star} - \frac{GM_\star}{R_{\rm hole}}, \qquad (1)$$

where $V_{\rm stream}$ is the velocity of the accretion stream at impact, $M_\star$ is the stellar mass, $R_\star$ is the stellar radius, $R_{\rm hole}$ is the magnetospheric radius at which the disc is disrupted and G is the gravitational constant. Knowing these quantities, we can evaluate the stellar mass as

$$M_\star = \frac{V_{\rm stream}^2 R_\star}{2G}\left(1 - \frac{R_\star}{R_{\rm hole}}\right)^{-1}. \qquad (2)$$

The rotational energy of the disc matter at $R_{\rm hole}$ is assumed to be dissipated as the disc matter couples on to the magnetic field lines of the star, and is therefore neglected in equation (1). This energy is at most half the potential energy at $R_{\rm hole}$ and thus its contribution to equation (1) is equivalent to the disc being disrupted at $2R_{\rm hole}$. Mass estimates incorporating the rotational energy will therefore lie in between the two limits we calculate below: that the matter falls in (i) from infinity; or (ii) from $R_{\rm hole}$.

Although the value of $R_\star/R_{\rm hole}$ is uncertain, it can be estimated by comparing the infrared excess emission expected from a circumstellar disc with and without an inner hole. Kenyon et al. (1996) estimate that $R_{\rm hole}/R_\star \approx 4$ (with acceptable values between 3 and 5). Similar results were obtained by Meyer et al. (1997) who estimate that $2 < R_{\rm hole}/R_\star < 6$ for a sample of T Tauri stars located in the Taurus dark cloud. In practice, because we are looking for a lower limit on the stellar mass, and as $R_\star/R_{\rm hole}$ is relatively small, we calculate the stellar mass using equation (2) assuming that the material falls in either from infinity or from five stellar radii ($R_{\rm hole} \approx 5R_\star$). We note that the case of infall from infinity provides a strict lower limit to the mass, resulting in values 0.8 times those obtained in the $5R_\star$ calculation.

We see from equation (2) that we can make an estimate of the stellar mass from just the stellar radius and the impact velocity of the accretion stream. The stellar radius can be calculated directly from the stellar luminosity and $T_{\rm eff}$. It is thus independent of the PMS tracks, but does depend on the ability of observers to correct for reddening, establish the spectral type (i.e. photospheric temperature), and separate stellar from accretion luminosity. The velocity itself can be estimated from the redshifted absorption profile. There is an added complication that the accretion stream is not necessarily parallel to our line of sight so that there is a projection effect in the velocity. The observed IPC velocity relates to the impact velocity as

$$V_{\rm ipc} = V_{\rm stream} \times \cos\theta, \qquad (3)$$

where θ measures the angle between our line of sight and the direction of the stream on impact. This implies that the observed $V_{\rm ipc}$ will be a lower limit on the true impact velocity and again gives us a lower limit on the stellar mass. Furthermore, as the accretion streams most probably rotate with the star, they will be obscured by the star over part of the rotation period (e.g. Smith et al. 1997) and the observed $V_{\rm ipc}$ will be variable (Edwards et al. 1994).

In the above we have not considered the exact mechanism by which the disc matter couples to the magnetic field and the accompanying torques. This simplification neglects any azimuthal motions of the infalling matter as it follows the field lines. Fortunately, any such deviations also ensure that the mass estimates are lower limits. In fact, all of the unknowns involved in measuring the gravitational potential well of the star, the distance from where the material falls, the projection of the stream along our line of

Table 1. Comparison of T Tauri masses from PMS tracks and lower limits from IPC profiles. The radii (in $R_\odot$), and PMS track masses (in $M_\odot$) are taken from Hartigan et al. (1995) using the tracks from D'Antona & Mazzitelli (1994). The IPC profile velocities (in km s^{-1}) are from (1) Edwards et al. (1994), (2) Folha & Emerson (1998) and (3) Appenzeller et al. (1988). Two values of V_{ipc} are used: these are the deepest absorption, V_{ipc}(deep) corresponding to M_{ipc}, and the the maximum velocity in the absorption profile V_{ipc}(max) corresponding to $M_{ipc}{}^*$ (see text). The masses, $M_{ipc}/M_\odot$, are calculated on the assumptions that the matter falls in from infinity, $M_{ipc}(\infty)$, and from $5R_\star$, $M_{ipc}(5R_\star)$. The last three columns list the rotational periods in days, $v \sin i$ in km s^{-1}, and the inclination angles (from Bouvier et al. 1995 adapted to the stellar radii from Hartigan et al. 1995). An inclination angle of 90° is assigned to GM Aur where the above comparison yields $\sin i > 1$.

Star	Radius	M_{tracks}	line	V_{ipc}(deep)	$M_{ipc}(\infty)$	$M_{ipc}(5R_\star)$	V_{ipc}(max)	$M_{ipc}(\infty)$*	$M_{ipc}(5R_\star)$*	p_{rot}	$v \sin i$	i
AA Tau	1.8	0.38	Hβ	220[1]	0.23	0.28	280[1]	0.34	0.41	8.2	11.4	81
BP Tau	1.9	0.45	Hδ	290[1]	0.42	0.51	400[1]	0.8	0.96	7.6	7.8	38
CW Tau	2.2	1.03	Brγ	170[2]	0.17	0.20	260[2]	0.40	0.48			
DK Tau	2.7	0.38	Hγ	280[1]	0.56	0.67	315[1]	0.70	0.84	8.4	11.4	43
DL Tau	1.9	0.37	Na D	240[1]	0.29	0.34	315[1]	0.50	0.60			
DN Tau	2.2	0.42	Hβ	160[1]	0.15	0.18	205[1]	0.25	0.30	6.0	8.1	27
DO Tau	2.4	0.31	Paβ	175[2]	0.19	0.23	235[2]	0.34	0.41			
DR Tau	2.7	0.38	HeI	225[1]	0.36	0.43	315[1]	0.71	0.85			
			Hδ	330[3]	0.77	0.93						
DS Tau	1.6	1.28	Hδ	265[1]	0.29	0.35	370[1]	0.56	0.68			
FM Tau	1.6	0.15	Paβ	120[2]	0.06	0.07	210[2]	0.18	0.21			
GI Tau	2.5	0.30	Paβ	225[2]	0.33	0.40	350[2]	0.81	0.97	7.2	11.2	40
GK Tau	2.2	0.41	Hβ	250[1]	0.36	0.43	280[1]	0.46	0.55	4.65	18.7	52
GM Aur	1.6	0.52	Paβ	250[2]	0.26	0.31	315[2]	0.41	0.49	12.0	12.4	90

sight, the assumption that the stream impacts radially, and even the assumption that the maximum velocity of the stream is on the stellar surface and not at some distance from the star, make our estimate a lower limit. Therefore we should, in general, underestimate the gravitational potential well of a star. Given an accurate determination of the stellar radius from its luminosity and temperature, the mass determined from this method is a lower limit on the true stellar mass.

3 COMPARISON OF IPC MASS LIMITS AND MASSES FROM PMS TRACKS

In order to ascertain how useful this method is for constraining PMS masses, we compare the masses derived from PMS tracks (M_{tracks}) with the lower limits on the stellar masses calculated with equation (2) (M_{ipc}). Table 1 shows this comparison for 13 CTTS stars chosen from the stars studied by Hartigan et al. (1995). This sample includes all stars with observed IPC profiles (from Edwards et al. 1994, Folha & Emerson, in preparation, and, in one case, Appenzeller et al. 1988) that have also been surveyed and found *not* to have any companions within separations 0.1–2.0 arcsec (Mathieu 1994 and references therein; Simon & Prato 1995). Companions in this separation range are unresolved in the Hartigan et al. (1995) study and hence would introduce errors into the determination of the stellar luminosity and thus the radii and PMS track masses (Ghez, White & Simon 1997). This highlights another advantage of the technique; it can be applied to *single* stars and not just binary systems in contrast to the methods for determining stellar masses directly discussed above. The radii and masses [from D'Antona & Mazzitelli (1994) tracks, adopting Alexander opacities and CM convection] are taken from Hartigan, Edwards & Gandour (1995). These authors have attempted to deredden the stars and remove the effects of accretion luminosity before calculating the stellar parameters.

The velocities V_{ipc} are estimates based on the IPC profiles seen in the Balmer, NaD and He I lines (Edwards et al. 1994; Appenzeller et al. 1988), and in the Paschen β and Brackett γ lines (Folha & Emerson, in preparation). The use of different lines to measure the impact velocities is non-ideal as it may introduce uncertainties due to radiative transfer effects, but is necessary because of the paucity of available IPC profiles. For each star, two estimates of the velocity were made, the first from the deepest part of the absorption feature and the second from the maximum velocity of the absorption (taken to be where the absorption profile meets the continuum). These estimates are most probably lower limits on the velocity of the infalling material when it impacts the stellar surface. Modelling of the IPC profile with radiative transfer (Muzerolle, Calvet & Hartmann 1998) shows that the impact velocity typically corresponds to the redmost extreme part of the absorption component. The minimum in the IPC profiles in Muzerolle et al. (1998) generally corresponds to a V_{ipc} that is 10 to 20 per cent lower than the characteristic velocity V_{stream}. We prefer to use both estimates of V_{ipc} (quoted in Table 1) as limits of the true characteristic velocity to avoid any uncertainties in the details of the line formation. For each star, the maximum velocity observed (of each type) was used. In general, IPC profiles are variable (e.g. Edwards et al. 1994; Smith et al. 1997), with higher velocity IPC profiles presumably arising when the accretion stream is most closely aligned to our line of sight. These velocities are therefore lower limits on the actual impact velocity of the accretion stream. In this context it is worth noting the two different estimates of the IPC velocity profile of DR Tau (from Edwards et al. 1994 and Appenzeller et al. 1988) in Table 1. The IPC profile can even disappear completely when the stream is behind the star. This implies that the magnetospheric accretion geometry is complex and is not an axisymmetric ring aligned with the rotation axis. The dynamical mass estimates (lower limits) based on the IPC velocity measurements are given in columns 6 and 7 of Table 1 assuming that the stream velocity, V_{stream}, is given by the position of the minimum of the absorption feature, and that the matter falls in from infinity ($R_\star/R_{hole} = 0$) or from five stellar radii ($R_\star/R_{hole} = 0.2$). The corresponding cases for the maximum velocity seen in the IPC profile are given in columns 9 and 10. The photometric rotation periods, $v \sin i$, and inclinations of the stars, derived by Bouvier (1995), are given in column 10.

It is difficult to quantify the uncertainties in our mass determinations presented in Table 1. First we consider the errors in the stellar radii derived from the observational determination of the stellar

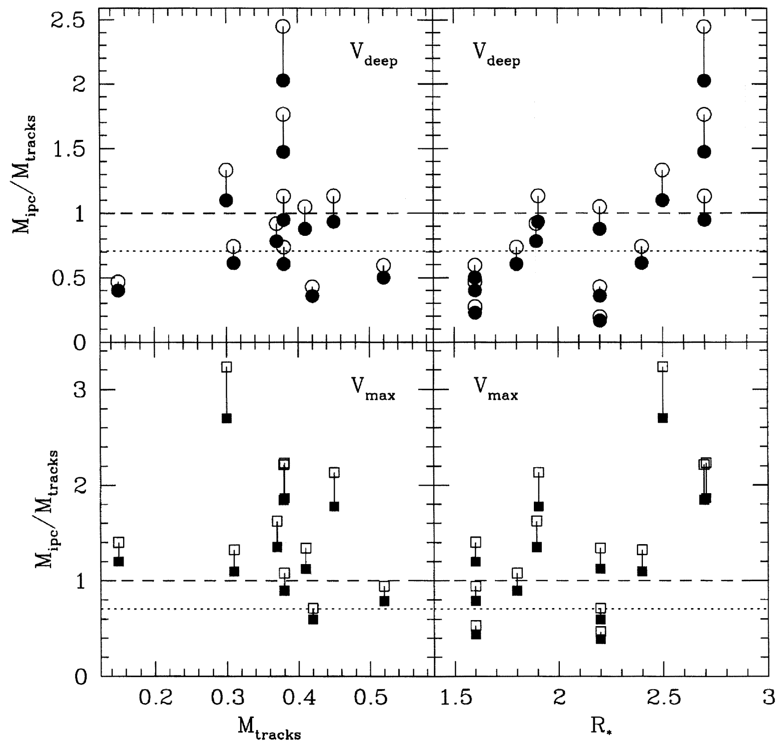

Figure 1. The ratio of the dynamical mass estimate, M_{ipc}, to the mass derived from the PMS tracks, M_{tracks}, is plotted against $M_{tracks}/M_{\odot}$ (left panels) and against the stellar radii in $R_{\odot}$ (right panels). The top panels (circles) use the deepest part of the absorption profile as being the characteristic V_{ipc}, while the bottom panels (squares) assume that V_{ipc} is the maximum velocity in the absorption profile. The filled symbols assume the matter falls in from infinity while the open symbols assume that the mass falls in from five stellar radii. As M_{ipc} is a strict lower limit, the ratio of M_{ipc}/M_{tracks} should always be less than 1 (dashed line) if the PMS track masses are correct. The dotted line represents the expected ratio for a projection of 45 degrees.

luminosity and effective temperature. By propagating errors in the photometry, reddening, distance modulus, bolometric corrections (i.e. luminosity) and spectral types (i.e. photospheric temperatures), we estimate that the radii are accurate to within 20–30 per cent (in agreement with the analysis of Kenyon & Hartmann 1995). We can estimate the systematic uncertainties in the radii by comparing the derived values from different observational determinations of the stellar parameters (Hartigan et al. 1995; Gullbring et al. 1998). Both studies rely on independent spectra and use different corrections for the photometry. The stellar radii derived independently in this way agree remarkably well, with differences at the 10–15 per cent level.

Uncertainties in our estimates of V_{ipc} are approximately 10 per cent. Furthermore, we neglect radiative transfer effects and the errors associated with estimating the maximum absorption velocity in a noisy spectra. Both of these should tend to reduce the observed velocity from the true impact velocity. Thus, as we are deriving lower limits, uncertainties in our estimates of V_{ipc} from the data should be smaller than the difference between our two limits. Combining the errors in the radii with the 10 per cent error in estimating the velocities, this corresponds to a maximum uncertainty in our lower limits of ± 45 per cent.

Of course the errors in deriving the stellar luminosity and temperature also result in uncertainties in the mass estimates from the PMS tracks. Because the mass tracks are generally vertical during the Hyashi contraction phase for late-type stars, errors in spectral type and conversion to effective temperature dominate the errors in estimating stellar masses from PMS evolutionary models. Typical errors of ± 1 spectral subclass translate into errors of ± 0.02 dex in $\log(T_{eff})$, resulting in relative errors of ± 0.1 $M_{\odot}$ in stellar mass estimates for young (< 10 Myr) late-type (K–M) stars for the DM94 tracks (Hillenbrand 1997). Apart from problems with the tracks themselves (which we attempt to probe with this technique), different approaches for placing stars in the HR diagram taken by different groups could be an additional source of systematic error. The masses reported by Gullbring et al. (1998) (derived from the same DM94 tracks) generally agree with those reported by Hartigan et al. (1995) except in those cases where a significantly different spectral type was adopted. Gullbring et al. (1997) adopted a later spectral type for DS Tau than HEG (K5 versus K2) and an earlier spectral type for GI Tau (K6 versus M0).

The ratio of the dynamical mass estimate, M_{ipc}, to the track mass, M_{tracks}, is plotted in Fig. 1 against the PMS track mass and the radius. The ratio is plotted for both mass estimates based on the two characteristic velocities and on the hole size in the disc [matter falling in from infinity (filled) and from five stellar radii (open)]. As the dynamical mass estimates are lower limits on the stellar masses, the ratio plotted should be less than 1 for all stars. We see that this is not the case for some of the stars when we use the lower characteristic velocity (upper panels) and with most stars if we use the maximum velocity seen in the IPC profile (lower panels). The three stars for which this discrepancy is most striking (DK Tau, DR Tau and GI Tau) are all unusual and have larger radii than the other stars. They should be treated with some caution. DK Tau is a relatively wide binary (2.5-arcsec separation) which should, in principle, be uncontaminated by its companion. Contributions from a companion can lead to a larger luminosity (radius) and hence mass using the IPC method while not significantly effecting the mass derived from the tracks. GI Tau has $M_{ipc} < M_{tracks}$ according to the stellar parameters of Gullbring et al. (1998) while the high veiling of DR Tau makes its stellar parameters

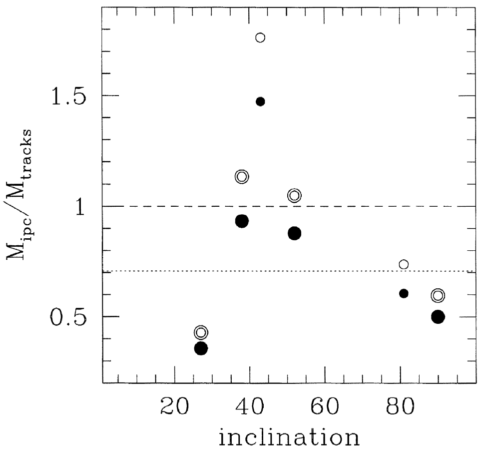

Figure 2. The ratio of the dynamical mass estimate, M_{ipc}, to the mass derived from the PMS tracks, M_{tracks}, is plotted against the star's inclination to the line of sight (pole-on corresponds to 0 degrees). The dynamical mass, M_{ipc}, is calculated from the lower characteristic velocity representing the deepest absorption and the assumption that matter falls in from infinity (filled circles) or from five stellar radii (open circles). The smaller symbols indicate an uncertainty in the inclination of less than 10 degrees while the larger symbols represent an uncertainty in the inclination of less than 5 degrees. The highest point corresponds to DK Tau (a 2.5-arcsec binary). GI Tau has not been plotted because of the large difference in radii between Hartigan et al. (1995) and Gullbring et al. (1998), which leads to a large uncertainty in the inclination.

somewhat uncertain. The other stars commonly have mass limits that are similar to or lower than the track mass when the lower estimates for V_{ipc} are used. If we use the maximum velocity seen in absorption, then almost all the derived dynamical mass limits have $M_{ipc} \gtrsim M_{tracks}$.

Furthermore, some of the stars should be seen with relatively large projection angles, so we would expect them to have $M_{ipc} \lesssim 0.7 M_{tracks}$ (for a projection of 45 degrees). Thus, from the fact that most of the stars with masses $M_\star \lesssim 0.5\,M_\odot$ have $M_{ipc} \gtrsim 0.7 M_{tracks}$, even when the velocity is estimated from the deepest part of the absorption, we deduce that the DM94 tracks potentially underestimate the true stellar masses. This problem is aggravated if the disc is truncated at smaller radii, resulting in higher estimates of M_{ipc}. Therefore, we can conclude that the dynamical mass estimates provide a useful lower limit on the stellar mass and thus a constraint on the PMS evolutionary tracks.

Other PMS tracks give different results. For example, the tracks of Swenson et al. (1994) give systematically higher masses (see Hillenbrand 1997 for comparison) which would compare more favourably with our upper limits. However this technique can in principle only reject a set of tracks for which the predicted masses were too low. As long as the track masses are comfortably above the lower limits set by M_{ipc} we cannot prefer one set of tracks over another. None the less, a direct comparison of different PMS track masses (including the effects of accretion) with mass limits derived using the method described here for a statistically significant sample of PMS stars will assist in discarding unviable PMS evolutionary tracks.

4 INCLINATION AND ACCRETION STREAM GEOMETRY

The dynamical mass estimate of equation (2) can also tell us something about the geometry of the magnetospheric accretion streams. The mass estimate uses the observed infall velocity along our line of sight and so can constrain the orientation of the stream. Once reliable masses are available from the PMS tracks we can combine the mass estimate from the IPC velocity with the knowledge of the inclination of the star to our line of sight and constrain where on the star the accretion stream impacts. Fig. 2 plots the ratio of the dynamical mass estimate, M_{ipc} (using the lower velocity corresponding to the deepest part of the absorption profile), to the mass derived from the PMS tracks, M_{tracks}, against the inclination angle of the star for those stars with both measured rotation periods and $v \sin i$ determinations (from Bouvier et al. 1995). The star GI Tau is excluded from the plot because of the uncertainty in its radius (between Hartigan et al. 1995 and Gullbring et al. 1998) and hence the inclination. The inclination angles are also listed in Table 1. GM Aur is assigned an inclination of 90° because the apparent $\sin i > 1$. From Fig. 2, we see that stars oriented pole-on (0° inclination) and equator-on (90° inclination) have dynamical mass estimates significantly lower than those derived from the PMS tracks. In contrast, stars with moderate inclination angles (30° to 60°) have dynamical mass estimates approximately equal to or greater than those derived from PMS tracks.

Although the sample size is small, Fig. 2 hints that the accretion streams may impact preferentially at moderate latitudes. This argues against scenarios of magnetospheric accretion where the accretion streams are assumed to impact on, or near, the poles. In contrast, Muzerolle et al. (1998) adopt a dipolar geometry where the accretion stream impacts at moderate latitudes, but that implies small magnetospheric radii such that $R_{hole} \approx 2R_\star$. Kenyon et al. (1994) derive a similar model based on extensive multicolour observations of the rotating 'hotspot' observed on DR Tau. A pure aligned dipolar field implies a relation between the inclination at which the accretion stream impacts (ϕ, measured from the pole) and the ratio of $R_{hole}/R_\star$, given by (Hartmann et al. 1994)

$$\frac{R_{hole}}{R_\star} = \sin^{-2}\phi. \tag{4}$$

As the observed V_{ipc} for the accretion stream should have a maximum where the inclination i of a star is equal to this angle ϕ, then we would expect the inclination angles of 40° to 60° (as seen in Fig. 2) to correspond to disc truncation radii of $R_{hole} = 1.33$ to $2.4R_\star$, much smaller than the $5R_\star$ used here. These smaller values would in turn imply significantly larger values of M_{ipc}. This may imply that accretion geometry is complex, and not a pure, aligned dipole. Using the method described here, with a large enough sample, it should be possible to constrain the geometry of the accretion region.

5 DISCUSSION AND CONCLUSIONS

Determining accurate masses for large ensembles of pre-main-sequence (PMS) objects is presently impossible owing to our inability to constrain the PMS evolutionary tracks adequately. This limitation is a major obstacle in determining the low-mass end (0.05–0.5 $M_\odot$) of the IMF in regions of recent star formation (Hillenbrand 1997). Here, we have shown that lower limits on the stellar masses can be determined by measuring infall velocities on to these objects.

In summary, the presence of redshifted absorption profiles in the emission-line spectrum of PMS stars indicates near-radial accretion. In the magnetospheric accretion model, the stellar magnetic field disrupts the circumstellar disc at several stellar radii from where the matter falls freely in along the field lines on to the stellar surface. The velocity of the infalling matter (from the IPC profile) measures the potential energy at the stellar surface which, when combined with a determination of the stellar radius, yields an estimate of the stellar mass.

For a collection of 13 stars (Hartigan et al. 1995), 11 have lower limits which are comparable to or greater than the track masses and thus can act as significant constraints on the stellar mass. Using the deepest part of the absorption profile as the impact velocity, and assuming the disc is truncated at five stellar radii ($R_{hole} \approx 5R_\star$), five of the 13 stars have $M_{ipc} > M_{tracks}$. If the disc is truncated at infinity, three of these five stars still have $M_{ipc} > M_{tracks}$. If we model the impact velocity as the maximum velocity seen in absorption, then 10 of the 13 stars have lower limits $M_{ipc} \gtrsim M_{tracks}$, eight of which have $M_{ipc} > M_{tracks}$ if the disc is truncated at infinity instead of at $5R_\star$. Truncation radii smaller than $5R_\star$ result in larger dynamical mass limits such that if $R_{hole} \approx 2R_\star$, none of the lower limits would be compatible with the PMS tracks. From this we can conclude that (i) the method described here is a useful method for estimating PMS masses and thus constraining the PMS evolutionary tracks, and (ii) that there are potentially significant problems in the DM94 tracks.

In addition, this method for setting lower limits on the stellar mass can also help us to constrain the geometry of the magnetospheric accretion. Using information on the inclination of a star to our line of sight, we find that stars seen at moderate inclination appear to suffer less from projection effects. This implies that the accretion stream probably impacts on the star at moderate latitudes.

Although this technique appears promising, additional work is required before quantitative tests of the available PMS tracks can be undertaken. Specifically, we require (i) more extensive collections of IPC profiles, (ii) improved estimates of stellar radii based on careful photometric and spectroscopic observations and (iii) additional modelling efforts to determine the appropriate velocity to adopt from the IPC line profile, in order for this method to become a powerful tool in the constraint of the masses of PMS stars. With these data, we can then begin to examine the PMS evolutionary tracks and study the geometry of the accretion streams.

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