Downloaded from rsta.royalsocietypublishing.org

Young stars with discs

C. J. Clarke and J. E. Pringle

Phil. Trans. R. Soc. Lond. A 2000 **358**, 729-739
doi: 10.1098/rsta.2000.0555

Email alerting service Receive free email alerts when new articles cite this article - sign up in the box at the top right-hand corner of the article or click **here**

To subscribe to *Phil. Trans. R. Soc. Lond. A* go to: **http://rsta.royalsocietypublishing.org/subscriptions**

This journal is © 2000 The Royal Society

Downloaded from rsta.royalsocietypublishing.org

Young stars with discs

By C. J. Clarke and J. E. Pringle
Institute of Astronomy, Cambridge CB3 0HA, UK

T Tauri stars are young pre-main-sequence stars and were first identified because of their variability. They emit excess radiation, relative to normal stars, at both long (infrared) and short (ultraviolet) wavelengths, and also emit at X-ray and radio wavelengths. Early models for both the excess radiation and variability in terms of strongly enhanced magnetic chromospheric/coronal activity were not very successful. Once it was realized that most T Tauri stars lie at the centre of gaseous discs (left over from the process of star formation), it became widely accepted that the UV excess is caused by continued accretion, and the IR excess by radiation from the disc. More detailed investigations of this model have brought the wheel full circle with the realization that T Tauri stars do have strong magnetic activity, and that many of their properties can be accounted for in terms of interactions between the stellar fields and the surrounding discs.

Keywords: magnetic fields; pre-main-sequence; spots; accretion discs; X-rays

1. Introduction

The T Tauri stars, members of a class of stars known originally as the nebular variables, are now recognized as forming part of the chain of events a star goes through between when a dense molecular core undergoes gravitational collapse and when the star (or stars) formed by that collapse arrive at the main sequence and begin to burn hydrogen in their cores. The pre-main-sequence phase of star formation is currently identified loosely as comprising of four classes of object (Lada 1999). The class O objects are heavily obscured, and are visible only at long wavelengths. Their spectra peak typically at *ca.* 100 µm, and do not extend to shorter wavelengths much beyond 30 µm. This is thought to be the main accretion phase of the star-formation process, and is usually also accompanied by powerful and collimated outflows of molecular material (Pudritz, this issue). The class I sources are still heavily obscured, with energy output still peaking at *ca.* 100 µm, but with emission extending to much shorter wavelengths, with perhaps the hint of a black-body source peaking at *ca.* 2 µm. This is thought to be the late accretion phase, in which the cloud core has undergone sufficient collapse that most of the material is now concentrated into a central self-gravitating pressure-supported object. Powerful collimated outflows are still seen to emanate from these objects in the form of molecular gas and/or in the form of highly collimated optical jets (Pudritz, this issue). Once the original dense core has thinned out to the extent that the optical spectrum of the newly formed star is visible, we have the class II objects, or classical T Tauri stars (CTTs). These objects were originally identified as variable stars found in the neighbourhood of dark clouds and obscuring nebular material

© 2000 The Royal Society

Downloaded from rsta.royalsocietypublishing.org

(hence the name 'nebular variables'). The variability takes place on a large variety of time-scales, from *ca.* 5 min (flaring), up to around 100 years, corresponding to the longest time for which such stars have been observed. A large body of data concerning the variability of these stars has been collected together by Herbst *et al.* (1994; see also Vrba *et al.* 1993) and is available at the following Web-site: ftp://sun.astro.wesleyan.edu/pub/ttauri. A discussion of optical flaring activity may be found in Guenther & Emerson (1997). The stars show up on objective prism surveys as displaying strong Balmer line emission, and also show a strong ultraviolet excess (above the photospheric emission—see, for example, the spectra displayed in Gullbring *et al.* (1998) and Hartmann (1998)). The CTTs lie above the main sequence in the HR diagram, on the tracks that stars contracting towards the main sequence would be expected to follow, and are therefore identified as pre-main-sequence stars. Finally, the class III objects lie in similar positions in the HR diagram, are similarly associated with star-forming regions, but show much weaker Balmer line emission. For this reason they are known as the weak line T Tauri stars (WTTs). They appear to show no evidence of accretion, and the inner disc (which emits at near infrared wavelengths) is absent.

For the optically visible pre-main-sequence stars, the T Tauri stars, the original ideas for explaining the ultraviolet excess, and the chromospheric emission lines, were in terms of scaling up the magnetically driven model of chromospheric and coronal emission applied to the Sun. However, even simple scaling up of the solar model had problems in accounting for the strength of the effect. The problem became even more acute with the advent of detectors in the near infrared, and at longer wavelengths, which demonstrated that the CTTs have considerable flux at long wavelengths in excess of that expected from a stellar photosphere.

Because of these problems, this idea was replaced in the 1980s by the currently accepted paradigm for the CTTs which is that they are stars surrounded by accretion discs (Lynden-Bell & Pringle 1974; Hartmann 1998). The infrared excess is interpreted as emission from the disc—either accretion energy, or reradiated emission from the central star. The ultraviolet excess was originally proposed to come from a boundary layer where the accretion disc grazes the stellar surface. For example, Bertout *et al.* (1988) give detailed spectral fits to the spectral energy distributions of a number of CTTs in the wavelength range 200 nm to 60 μm in terms of disc plus boundary-layer emission in addition to the stellar spectrum. These models for the CTTs fit in well with the time sequence of class O–III pre-main-sequence objects, in which the material present in the original molecular core gradually either accretes onto the central stars or becomes dissipated, and with the current realization that discs are commonly found around pre-main-sequence stars. Reviews of protostellar accretion discs, and of accretion disc dynamics, may be found in Lin & Papaloizou (1996), Hartmann (1998), Stone *et al.* (2000) and Brandenburg (this issue).

However, having reached this point in the development of theoretical ideas, the requirement that T Tauri stars be strongly magnetically active objects seemed to have been put to one side. Nevertheless, during the remainder of this paper, we shall hope to convince the reader that T Tauri stars, and indeed perhaps all pre-main-sequence objects, are indeed strongly magnetic, and that a strong stellar magnetic field is necessary for a proper understanding of many of the phenomena associated with them.

Downloaded from rsta.royalsocietypublishing.org

2. Indirect evidence for magnetic fields

There are several lines of indirect evidence which point to the probability that T Tauri stars are magnetically active. We shall discuss each concept in turn, bearing in mind that a number of the ideas are interdependent.

(*a*) *Inner disc holes*

In trying to fit the complete spectral energy distributions from millimetre wavelengths to the ultraviolet it soon became apparent that a simple model in terms of a star plus boundary layer plus standard accretion disc was inadequate. One particular problem was identified by Beckwith *et al*. (1990), and this was that in some stars the energy distribution had two distinct peaks, one at stellar wavelengths and one in the far infrared. The simplest modification to the original idea, which gave reasonable fits to the distribution, was to assume that the disc was truncated at some inner radius which was larger than the stellar radius. The discs fitted by Beckwith *et al*. (1990) had outer radii of *ca.* 100 AU, and inner radii which might be as small as the stellar radius, but needed for some objects to be as large as 0.1–0.3 AU. It is now recognized that inner holes as large as this are most likely caused by the presence of a binary companion which carves out a hole in the disc by tidal interactions (see, for example, Lubow & Artymowicz 1996). However, the need for taking account of the possibility that the disc might not extend down to the stellar surface, and thus that the inner disc radius might be at a few (rather than at one) stellar radii, in modelling near infrared energy distributions has not gone away. Recent papers by Armitage & Clarke (1997), Kenyon *et al*. (1996) and Meyer *et al*. (1997) in accounting for the colours of CTTs in the J, H, K and L wavebands as well as using disc inclination and accretion rate as fitting parameters, also make allowance for the inner disc radius to be in the range 1–6 stellar radii.

(*b*) *Rotation periods*

A certain amount of the photometric variability seen in T Tauri stars is periodic on time-scales of days. This variability is attributed to rotational variations caused by the presence of bright and/or dark spots on the stellar surface (see below). For example, a recent survey of 2279 stars in the Orion region (Stassun *et al*. 1999) found photometric periods in 254 of them with periods in the range 0.5–8 days, with typical amplitudes of 0.1–0.2 mag at I.

Bouvier *et al*. (1993) identified 25 rotation periods in T Tauri stars in the Taurus–Auriga star-forming region. The periods ranged from about one to about 12 days. Two points of importance emerged from this work. First, all the rotation periods are much longer than the rotation period of about half a day, which corresponds to rotational break-up speed. If all the accretion onto the central star took place through a disc which extended to the stellar surface, then the central stars should be spun-up to close to break-up. This implies that either the disc does not extend down to the surface and/or the stars have some efficient way of losing angular momentum. Second, the CTTs, which made up about a half of the Bouvier *et al*. (1993) sample, were found to have longer rotation periods (mean around eight days) than the WTTs (mean around four days). The simple explanation for this was that the CTTs contain discs which are magnetically truncated by the stellar magnetic field at around the

Downloaded from rsta.royalsocietypublishing.org

corotation radius (radius at which the disc angular velocity is approximately equal to the stellar angular velocity) which for a period of eight days corresponds to a radius of a few stellar radii (see § 2 *a*), and that the disc is able to extract angular momentum from the star at that radius by means of magnetic torques (Königl 1991). In contrast, the WTTs have lost their accretion disc at an earlier stage, and so have begun to spin up as they contract (conserving angular momentum) towards the main sequence (Cameron & Campbell 1993; Armitage & Clarke 1996). In paper IV of their series, Bouvier *et al.* (1997) present rotation periods for post T Tauri stars, i.e. pre-main-sequence stars which have almost reached the main sequence, and demonstrate the continued spin-up as the main sequence is approached.

These proposed ideas would indeed form a neat explanation for the distribution and evolution of rotational periods of pre-main-sequence stars, were it not for the recent survey by Stassun *et al.* (1999) of T Tauri stars in the Orion region, and whose sample is a factor of ten larger than the original Bouvier *et al.* (1993) sample. They find that although the mean rotation rate is still around a tenth of break-up, the period distribution does indeed extend right down to the shortest possible. But more seriously for the Bouvier *et al.* (1993) picture, Stassun *et al.* (1999) find that in the Orion sample the period distributions of the CTTs and the WTTs are indistinguishable. Thus, there is clearly more to be learned in this area.

(*c*) *Starspots*

A discussion of the spot properties and of the origin of photometric period variations in T Tauri stars is given by Bouvier *et al.* (1995). As was remarked in the talk by Rosner (this issue), starspots are a common stellar phenomenon which are closely linked to the presence of stellar magnetic activity.

(i) *Bright spots*

While fitting the spectral energy distribution of the CTT DF Tau, by means of the combination of stellar spectrum, accretion disc and boundary layer, Bertout *et al.* (1988) remarked that, although the fit they obtained for DF Tau was one of the better ones, the star itself displayed a photometric variation with a period of around 8.5 days, which was most simply explained in terms of a rotational modulation caused by bright spots on the stellar surface. They went on to suggest that perhaps, notwithstanding the goodness of fit in terms of modelling the UV excess as a contribution from a boundary layer, the disc was in fact disrupted close to its inner radius by a strong stellar magnetic field (of order a few hundred gauss), and that accretion took place onto the star mainly down the magnetic-field lines onto the magnetic poles, thus giving rise to the observed bright spots. This coincides closely with our current picture of these systems (see, for example, fig. 6.1 in Hartmann (1998)).

The idea that accretion of material onto the CTTs occurs by means of a flow which is closer to being radial infall, rather than rotationally through a disc, received strong support from the work of Edwards *et al.* (1994). In a survey of 15 CTTs they found that 13 of them displayed a significant blue-ward asymmetry in the emission lines of the Balmer series and of Na I, in the form of redshifted absorption minima. The redshift velocities corresponded to *ca.* 200–300 km s^{-1}, equal to the infall velocities onto the stars from a distance of a few stellar radii. They concluded that their results

Downloaded from rsta.royalsocietypublishing.org

suggested an extensive magnetospheric structure which keeps infall zones in our view at all times (see also Muzerolle *et al*. 1998; Calvet & Gullbring 1998).

As discussed by Rosner (this issue), although photometric variability can be interpreted as temperature variations over the stellar surface, coupled with rotation, deriving the actual temperature distribution over the stellar surface is difficult to achieve in a unique way using photometric measurements alone. A much more powerful technique is so-called Doppler imaging, which makes use of spectrophotometric data. By using the variation of line profiles observed as the star rotates, it is possible to use the resultant velocity information to obtain a clearer picture of the positions of temperature variations. For example, Unruh *et al*. (1998) have mapped surface inhomogeneities on the CTT DF Tau using various spectral features caused by lithium, calcium and iron. They report evidence that the stellar surface, at the time of their observations, has hotspots with temperatures in excess of 5000 K, compared with the photospheric temperature of 3750 K. The hotspots appear to cover *ca.* 4% of the stellar surface. In addition, when one of the mapped hotspots crosses the stellar disc, they observe absorption features in the Na D lines, which they interpret as evidence for mass infall associated with this hotspot. They also note that it is well known (Bouvier *et al*. 1993, 1995) that the intrinsic variability of DF Tau is large, suggesting that the geometry of the accretion regions changes on a time-scale of only a few rotation periods.

(ii) *Dark spots*

If the sun were a useful guide to the association of surface spots with magnetic activity, then we would expect strong surface fields to be associated mainly with dark spots. Thus we might expect the non-accreting T Tauri stars, the WTTs, to have dark spots on their surfaces. This appears to be true for the WTT V410 Tau. Interpretation of the 1.87 day photometric modulation suggests modelling in terms of dark spots covering *ca.* 30% of the stellar surface (Vrba *et al*. 1998). This is confirmed in some detail by Joncour *et al*. (1994) who make use of Doppler imaging techniques in the Li I line. Their model for the observed spectral line variations shows temperature variations between 3000 K and the photospheric temperature of 4800 K, with the large cold spots being located predominantly at one rotational stellar pole. They find little evidence for magnetic dipole field geometry.

However, before concluding that everything makes sense, in that accreting stars (CTTs) have bright spots, while non-accreting stars (WTTs) have dark spots (Bouvier *et al*. 1995), we should note the investigation of the CTT SU Aur by Petrov *et al*. (1996). The conclusions of this investigation are that, while the general line profile variations in the Balmer series, and in He I, are consistent with magnetically channelled accretion, the surface Doppler imaging in the Fe I line profiles shows the presence of cool spots centred on the equator.

(*d*) *X-ray and radio emission*

Reviews of X-ray and radio emission from pre-main-sequence stars are given by Montmerle (1991) and by André (1996).

Downloaded from rsta.royalsocietypublishing.org

(i) *X-ray emission*

Both CTTs and WTTs are strong emitters of X-ray radiation. Indeed, a large fraction of the known population of WTTs has been discovered through their X-ray emission, in particular by the ROSAT All Sky Survey (RASS) (Neuhäuser 1995; Neuhäuser *et al*. 1995). About 10% of CTTs and over 60% of WTTs are detected at X-ray wavelengths (Neuhäuser *et al*. 1995). It is well known (see, for example, Rosner, this issue) that the X-ray fluxes, or to be more precise the X-ray emissivity per unit surface area, of main-sequence stars is inversely correlated with rotation period. The T Tauri stars lie close to, but about a factor of three above, this relation. That is, at a given rotation rate, the mean X-ray emissivity per unit area of T Tauri stars is similar to, but somewhat larger than, that from main-sequence stars (Bouvier 1990). In addition, T Tauri stars show strong flaring behaviour at X-ray wavelengths, with $L_{\mathrm{X}}/L_{\mathrm{bol}}$ being of order a few per cent. Typical flare temperatures are of the order of a few keV, and the temperature is seen to decrease during the flare. The assumption that the decay time-scale of the flares (in the range 1–10 h) is caused by thermal cooling then implies particle densities of order $n_{\mathrm{e}} \sim 10^{10}$–$10^{11}\ \mathrm{cm}^{-3}$. To explain the observed X-ray luminosity, it is then necessary for the size of the flaring region to be around a few stellar radii (see also Stelzer *et al*. 1999). Using the solar analogy, and assuming that the flaring activity is essentially magnetically driven, coupled with the assumption that typical magnetic energy densities are similar to the thermal energy density in the flaring plasma, leads to the requirement that magnetic fields are of order a few hundred gauss.

There has been discussion about whether or not the X-ray properties of CTTs and WTTs differ to a discernible extent. The raw observations indicate that WTTs are in general slightly more luminous and show slightly softer X-ray spectra than their CTT counterparts. However, once allowance is made for the fact that CTTs are surrounded in general by material (discs, winds, outflows) which is able to absorb the lower-energy X-rays, then it becomes hard to disprove the idea that the *underlying* X-ray emission processes in both CTTs and WTTs are identical (see, for example, Neuhäuser 1995). This does indicate, however, that the idea that the disc contributes significantly to the observed X-ray emission can be discounted, for it is the CTTs, which have substantial discs, that display the weaker observed fluxes.

More interestingly, there has been a recent report of an X-ray flare from a class I pre-main-sequence object (Grosso *et al*. 1997). This is a highly embedded object with a visual extinction in the range $A_{\mathrm{v}} \sim 20$–40 mag. After correcting for extinction, the peak X-ray flux is of order 10–100 times the solar luminosity, and the flare is modelled in terms of a hot bubble of plasma with a size of order 0.1 AU. It should be noted, of course, that had the flare not been this bright, it would not have been seen, and thus that this flare should be regarded as extreme and not necessarily typical of class I objects. Nevertheless, this observation opens the possibility that X-ray activity is present in pre-main-sequence objects, even at the earliest times (Carkner *et al*. 1998).

(ii) *Radio emission*

Radio emission is detected in a significant fraction of T Tauri stars (see, for example, André *et al*. (1992), and the review by André (1996)). In a recent VLA 8.4 GHz survey of ROSAT-selected pre-main-sequence stars (and therefore predominantly

Downloaded from rsta.royalsocietypublishing.org

WTTs) in the Taurus–Auriga region, Carkner *et al.* (1997) report a 32% detection rate. For those stars that are detected, the L_X/L_{radio} flux ratio is consistent with that found for other active stars, such as the RS CVn binaries, and the ultra-fast rotators in the Pleiades. The fact that the detection rate for WTTs is greater than that for CTTs is consistent with the fact that the observed ionized winds present in the CTTs would be able to absorb the radio flux, if it were present.

Radio observations of T Tauri stars indicate substantial circular polarization (in the range 5–20%), and brightness temperatures in the range $T_{\text{br}} \sim 10^7$–10^9 K. Some of the brighter WTTs (at radio wavelengths) have been mapped using VLBI and the radio-emitting regions are found to have sizes of up to approximately 25 stellar radii. The general conclusion from all this (André 1996) is that the radio emission is gyrosynchrotron emission (in order to account for the circular polarization) from MeV energy electrons in a region of size more than about five stellar radii, permeated by a magnetic field of order 1–10 G. For a dipole field, this would imply fields at the stellar surface of several hundred gauss.

3. Direct evidence for stellar magnetic fields

As discussed by Rosner (this issue), the most direct way of measuring the surface field on a star is by means of the Zeeman effect.

(*a*) *Spectrophotometry*

The effect of a magnetic field is to remove the degeneracy of atomic energy levels. This results in an apparent additional broadening of the observed spectral line. The size of the effect, that is the degree of extra broadening, depends both on the strength of the field and on the magnetic sensitivity of the particular transition. Because the spectra of T Tauri stars are already subject to significant, and unknown, broadening (in particular stellar rotation, as well as the usual broadening mechanisms) it might be thought that disentangling the effects of the extra broadening brought about by the presence of magnetic fields would be a hopeless task. However, by judicious choice of photospheric lines of different magnetic sensitivities, and by moving into the near infrared, where the broadening is larger for a given magnetic-field strength, it is possible to make measurements of the surface fields in T Tauri stars by means of spectroscopy alone (Basri *et al.* 1992; Guenther & Emerson 1996). To a first approximation, what can actually be measured is the mean value of the magnitude of the magnetic field over the visible surface, which is written as $f \cdot \mathbf{B}$, the product of the filling factor f and the magnetic-field strength $\mathbf{B}$. To next order in the approximation it should, by detailed analysis of a number of different photospheric lines, be possible to obtain estimates for both f and $\mathbf{B}$ independently, and thus to obtain an estimate of the fraction of the surface covered by strong magnetic features, but this has so far proved difficult. The current state of affairs is summarized in a paper by Guenther *et al.* (1999). For two CTTs, T Tau and LkCa 15, they find values of $f \cdot \mathbf{B}$ of 2.35 and 1.1 kG, respectively, and also estimate that the filling factors f must be approximately larger than 0.5. Measurement of kilogauss fields in WTTs seems at present to be less certain. A field of 1.0±0.5 kG is reported in the WTT TAP35 (Basri *et al.* 1992), and a detection of a magnetic field, but no estimate of its magnitude is claimed in V410 Tau by Donati *et al.* (1997).

Downloaded from rsta.royalsocietypublishing.org

(*b*) *Spectropolarimetry*

The lifting of the degeneracy of the energy levels of an atom by the presence of a magnetic field manifests itself in two ways. First, the fact that the different quantum states (with different components of angular momenta in the direction of the field) now have different energies, leads to the atomic transition being apparently broadened, and thus to detection of the field through careful observation of the line profile (as discussed above). Second, however, the different transitions from the different energy states also display different polarizations. If the field line is perpendicular to the line of sight, then each transition is linearly polarized. However, if, say, the magnetic field is pointing towards the observer, then the transition which is shifted with positive $\Delta\lambda$ might display positive circular polarization, and the transition which is shifted with negative $\Delta\lambda$ would display negative circular polarization. If the magnetic-field direction is reversed, the sign of the circular polarization of each transition is also reversed. Thus an observation of the net circular polarization of a photospheric line yields a measurement of the mean value $\bar{B}_z$ of B_z, the component of $\mathbf{B}$ along the line of sight, over the stellar surface.

Johns-Krull *et al.* (1999*a*) report spectropolarimetric observations of the CTT BP Tau. Previous spectroscopic observations of these stars by Johns-Krull *et al.* (1999*b*) yielded a measurement of the average surface field strength of $\mathbf{B} = 2.1 \pm 0.3$ kG. Johns-Krull *et al.* (1999*b*) estimated that if that represented a dipole field aligned with the rotation axis, then spectropolarimetry should have measured a net value of $\bar{B}_z \sim 600$ G. However, lack of detection of net polarization in the photospheric absorption lines enabled them to set a 3σ upper limit to $\bar{B}_z$ of 200 G. On the other hand, strong circular polarization was measured in the He I emission line, indicating a mean longitudinal magnetic field of $\bar{B}_z = 2640 \pm 120$ G in the line-formation region. Since the emission line is thought to come from the region of the surface where radial infall is occurring, the authors conclude that accretion occurs preferentially along large-scale magnetic loops that occupy a small fraction of the stellar surface.

4. Conclusion

It should be evident from the above that observations of pre-main-sequence stars are fully consistent with strong magnetic activity in these stars. In Parker (1979), only a few lines are devoted to the subject of magnetic fields in pre-main-sequence stars. He remarked that it is straightforward for a fully convective main-sequence star to shed itself of any primordial field (due to the enhanced diffusivity caused by convection), and also that a field could be maintained in such stars by dynamo action. While it is clear that nowadays few theorists would disagree with these sentiments, it is also true that our physical understanding of the origin, maintenance and evolution of the fields in pre-main-sequence stars has advanced little in that time.

We have seen, however, that observational techniques have now advanced to the stage where a sustained observational attack on pre-main-sequence stars could begin to yield information of sufficient detail that it can be used to test theoretical models for dynamo activity in these stars. Prolonged observations of spectral-line variations should be able to indicate the nature, position and time evolution of surface features, most of which are caused by the presence of magnetic fields. In addition, a sustained programme of time-resolved spectrophotometry and spectropolarimetry should be

Downloaded from rsta.royalsocietypublishing.org

able to yield direct information about the magnitudes, positions and time evolution of surface magnetic fields. By tying all this information together into a single sustained observing programme, the nature of the magnetic activity, and its dependence on, for example, the stellar rotation rate, the stellar accretion rate and other parameters, can be determined.

On the theoretical side, it is still true to say that models for stellar dynamos are for the most part based on various input assumptions, with various degrees of physical motivation, relating to the feedback processes which enable the dynamo to operate, and to other processes which lead to the limiting and self-regulation of the dynamo process. We have yet to see, in the stellar case, the kind of self-consistent numerical calculations that have been carried out for accretion disc dynamos (Brandenburg, this issue) and which demonstrate, without arbitrary input assumptions, the nature of dynamo action in these objects. Computer power, and numerical techniques, must now be close to the stage where such self-consistent numerical MHD computations could be carried out in the stellar context.

References

André, P. 1996 In *Radio emission from the stars and the Sun* (ed. A. R. Taylor & J. M. Paredes), ASP Conference Series, vol. 93, p. 273.

André, P., Deeney, B. D., Phillips, R. B. & Lestrade, J.-F. 1992 *Astrophys. J.* **401**, 667.

Armitage, P. J. & Clarke, C. J. 1996 *Mon. Not. R. Astron. Soc.* **280**, 458.

Armitage, P. J. & Clarke, C. J. 1997 *Mon. Not. R. Astron. Soc.* **285**, 540.

Basri, G., Marcy, G. W. & Valenti, J. A. 1992 *Astrophys. J.* **390**, 622.

Beckwith, S. V. W., Sargent, A. I., Chini, R. S. & Güsten, R. 1990 *Astronom. Jl* **99**, 924.

Bertout, C., Basri, G. & Bouvier, J. 1988 *Astrophys. J.* **330**, 350.

Bouvier, J. 1990 *Astronom. Jl* **99**, 946.

Bouvier, J., Cabrit, S., Fernández, M., Martín, E. L. & Matthews, J. M. 1993 *Astron. Astrophys.* **272**, 176.

Bouvier, J., Covino, E., Kovo, O., Martín, E. L., Matthews, J. M., Terranegra, L. & Beck, S. C. 1995 *Astron. Astrophys.* **299**, 89.

Bouvier, J., Wichmann, R., Grankin, K., Allain, S., Covino, E., Fernández, M., Martín, E. L., Terranegra, L., Catalano, S. & Marilli, E. 1997 *Astron. Astrophys.* **318**, 495.

Calvet, N. & Gullbring, E. 1998 *Astrophys. J.* **509**, 802.

Cameron, A. C. & Campbell, C. G. 1993 *Astron. Astrophys.* **274**, 309.

Carkner, L., Mamajek, E., Feigelson, E., Neuhäuser, R., Wichmann, R. & Krautter, J. 1997 *Astrophys. J.* **490**, 735.

Carkner, L., Kozak, J. A. & Feigelson, E. D. 1998 *Astronom. Jl* **116**, 1933.

Donati, J.-F., Semel, M., Carter, B. D., Rees, D. E. & Cameron, A. C. 1997 *Mon. Not. R. Astron. Soc.* **291**, 658.

Edwards, S., Hartigan, P., Ghandour, L. & Andrulis, C. 1994 *Astronom. Jl* **108**, 1056.

Grosso, N., Montmerle, T., Feigelson, E. D., André, P., Casanova, S. & Gregorio-Hetem, J. 1997 *Nature* **387**, 56.

Guenther, E. W. & Emerson, J. P. 1996 *Astron. Astrophys.* **309**, 777.

Guenther, E. W. & Emerson, J. P. 1997 *Astron. Astrophys.* **321**, 803.

Guenther, E. W., Lehmann, H., Emerson, J. P. & Staude, J. 1999 *Astron. Astrophys.* **341**, 768.

Gullbring, E., Hartmann, L., Briceno, C. & Calvet, N. 1998 *Astrophys. J.* **492**, 323.

Hartmann, L. 1998 *Accretion processes in star formation.* Cambridge University Press.

Herbst, W., Herbst, D. K., Grossman, E. L. & Weinstein, D. 1994 *Astronom. Jl* **108**, 1906.

Downloaded from rsta.royalsocietypublishing.org

Johns-Krull, C. M., Valenti, J. A., Hatzes, A. P. & Kanaan, A. 1999*a* *Astrophys. J.* **510**, L41.

Johns-Krull, C. M., Valenti, J. A. & Koresto, C. 1999*b* *Astrophys. J.* **516**, 900.

Joncour, I., Bertout, C. & Ménard, F. 1994 *Astron. Astrophys.* **285**, L25.

Kenyon, S. J., Yi, I. & Hartmann, L. 1996 *Astrophys. J.* **462**, 439.

Königl, A. 1991 *Astrophys. J.* **370**, L69.

Lada, C. J. 1999 In *The origin of stars and planetary systems* (ed. C. J. Lada & N. D. Kylafis). Dordrecht: Kluwer.

Lin, D. N. C. & Papaloizou, J. C. B. 1996 *A. Rev. Astron. Astrophys.* **34**, 703.

Lubow, S. H. & Artymowicz, P. 1996 In *Evolutionary processes in binary stars* (ed. R. A. M. J. Wijers, M. B. Davies & C. A. Tout), p. 53. Dordrecht: Kluwer.

Lynden-Bell, D. & Pringle, J. E. 1974 *Mon. Not. R. Astron. Soc.* **168**, 603.

Meyer, M. R., Calvet, N. & Hillenbrand, L. 1997 *Astronom. Jl* **114**, 288.

Montmerle, T. 1991 In *The physics of star formation and early stellar evolution* (ed. C. J. Lada & N. D. Kylafis), p. 675. Dordrecht: Kluwer.

Muzerolle, J., Calvet, N. & Hartmann, L. 1998 *Astrophys. J.* **492**, 743.

Neuhäuser, R. 1995 ROSAT Durchmusterung der Taurus–Auriga T Assoziation. PhD thesis, Ludwig-Maximilians-Universität, München.

Neuhäuser, R., Sterzig, M. F., Schmitt, J. H. M. M., Wichmann, R. & Krautter, J. 1995 *Astron. Astrophys.* **297**, 391.

Parker, E. N. 1979 *Cosmical magnetic fields*. Oxford University Press.

Petrov, P. P., Gullbring, E., Ilyin, I., Gahm, G. F., Tuominen, I., Hackman, T. & Lodén, K. 1996 *Astron. Astrophys.* **314**, 821.

Stassun, K., Mathieu, R. D., Mazeh, T. & Vrba, F. J. 1999 *Astronom. Jl* **117**, 2941.

Stelzer, B., Neuhäuser, R., Casanova, S. & Montmerle, T. 1999 *Astron. Astrophys.* **344**, 154.

Stone, J. M., Gammie, C. F., Balbus, S. A. & Hawley, J. F. 2000 In *Protostars and planets. IV*. University of Arizona Press. (In the press.)

Unruh, Y. C., Cameron, A. C. & Guenther, E. 1998 *Mon. Not. R. Astron. Soc.* **295**, 781.

Vrba, F. J., Herbst, W. & Booth, J. F. 1988 *Astronom. Jl* **96**, 1032.

Vrba, F. J., Chugainov, P. F., Weaver, W. B. & Stauffer, J. S. 1993 *Astronom. Jl* **106**, 1608.

Discussion

T. G. Forbes (*EOS Institute, The University of New Hampshire, USA*). You very briefly mentioned stellar winds in T Tauri stars. Do observations of the properties of these winds provide a way to constrain models of the stellar magnetic field or the accretion process?

J. E. Pringle. The strongest outflows are seen to come from the Class O and I objects and are discussed by Ralph Pudritz in the next talk. CTTs also show outflows (winds) as evidenced by blue-shifted absorption seen in the P Cygni profiles of the optically thick permitted spectral lines, and by high-velocity blue-shifted forbidden-line emission. WTTs do not show such evidence. Thus it is clear that the strong outflows are associated mainly with the accretion process. The next speaker will explain the role of magnetic fields in driving and collimating winds from the disc.

R. E. Pudritz (*McCaster University, Canada*). Do you have any thoughts on why young stars rotate so slowly in the presence of accretion and magnetospheres? As an example, do you believe that the magnetospheric coupling is responsible for slowing the spin of stars or do you have another view on that?

Downloaded from rsta.royalsocietypublishing.org

J. E. Pringle. I don't know that my beliefs are relevant or my calculations either. The story of slowing it down with a disc seemed to be consistent in Taurus and now seems not to be consistent in Orion. You could argue—Cathie Clark did so—that Orion is younger than Taurus and maybe that's the main difference. I think that story hasn't gone away; it's just that the plot has got thicker if you like. Certainly, stars are likely to spin down due to magnetic fields as well as strong winds and magnetically driven winds. That process must be there, but the balance between the two isn't clear as yet.

I. W. Roxburgh (*Queen Mary and Westfield College, UK*). Could I put a question to the solar people who have always believed that you needed to go beneath the convective zone to drive a dynamo? Evidence from small-mass main-sequence stars and now from T Tauri stars is that you can do it within the convective zone itself. Should you all re-examine your premises?

E. R. Priest (*University of St Andrews, UK*). Although there has been a lot of emphasis over the past few years on the suggestion that the large-scale solar dynamo (associated with the sunspot cycle) is operating just below the base of the convection zone, there may well be part of the Sun's magnetic field generated throughout the convection zone and another part near the solar surface by granulation.

L. Mestel (*The University of New Hampshire, USA*). I think one should add to that that one just doesn't know much about these stars. Some of them have big dark spots which move around. It might well be that they have cycles where the polarity flips and the dark spots go away. We don't have enough data on that.

W. Lawson (*Australian Defence Force Academy, Australia*). Two points to note. (i) In the post-ROSAT era, weak-line T Tauri (WTT) stars are known to outnumber classical T Tauri (CTT) stars by at least 3:1, and the WTT and CTT populations appear intermixed. Thus it appears WTT stars can be born without a significant proto-star or CTT phase. (ii) The scatter of stars in the $L_{\mathrm{X}}/L_{\mathrm{radio}}$-plane occurs because most T Tauri stars are observed in radio only during flares, also accounting for the low detection rate.