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RECENT ADVANCES IN THE THEORETICAL INTERPRETATION OF T TAURI STARS

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ABSTRACT. Recent developments concerning the theoretical interpretation of the T Tauri phenomenon are briefly summarized: New evolutionary model computations clarified the possibilities and limitations of predicting the basic properties of pre-main sequence stars and their dependence on the initial conditions. Improved computations of the radiative transfer in T Tauri atmospheres and circumstellar envelopes made it possible to reproduce the major spectral properties of these objects. Other model computations resulted in new insights into the causes and mechanisms of the circumstellar mass flows associated with T Tauri stars. Finally, new mechanisms which may cause the observed strong time variability of pre-main sequence stars have been studied.

I. INTRODUCTION

T Tauri stars are defined on the basis of their spectral properties. They are characterized by emission lines similar to those observed in the solar chromosphere and in solar active regions, but with intensities which (relative to the photospheric continuum) may be 10^4 to 10^6 times stronger than in the sun. Most theoretical work on the T Tauri stars has been devoted to the interpretation of this "exaggerated activity". However, although whole research institutes and specialized observatories and many of our most distinguished colleagues devoted decades of work to the explanation of the solar activity, we are still far from fully understanding the physical processes in the emission line producing layers and regions of the sun. Thus, it is not surprising that the theory of the T Tauri stars (where we have much less and much less accurate observational data) is still in a very incomplete and unsatisfactory state, and that many of our present theoretical papers on this subject are of a rather speculative nature. Nevertheless, much hard work has been devoted to this field during the past years, and some progress has indeed been made. Because of the limited space available my review of this work will have to be rather selective and incomplete. It will be restricted to most recent studies and will cover the following details: The more recent evolutionary model computations relevant to T Tauri stars, recent progress in the theoretical interpretation of the observed spectra, the interpretation of the circumstellar mass flows, and new suggestions concerning the physical causes of the variability of T Tauri stars.

II. EVOLUTIONARY MODEL COMPUTATIONS

There seems to be general agreement that T Tauri stars are low mass ($M \lesssim 3\ M_\odot$) pre-main sequence objects. Starting with the pioneering work of Hayashi (1961) many different authors computed numerical models of pre-main sequence stars ("PMS") in this mass range. There are still some uncertainties concerning the low temperature stellar matter opacities, the initial deuterium abundance, and the detailed properties of the convective energy transport. But otherwise conventional hydrostatic PMS models can be computed easily, fast, and cheaply, even with (according to today's standards) small computers, provided the initial conditions are known. Unfortunately relatively little is known on these initial conditions and all published conventional PMS computations were based on arbitrarily assumed initial models. As shown by von Sengbusch (1968) low mass PMSs eventually "forget" their initial conditions (except for the initial mass, rotation, and chemical abundance) and their structure becomes basically independent of the initial values when the models approach the zero-age main sequence. However, the effects of differing initial conditions are known to fade away on a time scale comparable to the PMS evolutionary time scale itself. Therefore, at least the early PMS phases are expected to be determined essentially by the initial values.

In addition to the uncertainties introduced by the unknown initial conditions the truly "stellar" (i. e. purely hydrostatic) structure of the T Tauri stars has also been questioned in the literature. Some authors suggested that part of the T Tauri stars may be mass accreting "protostars" (Walker, 1972) or perhaps accretion disk objects of the type observed in mass exchanging binary systems. These suggestions were motivated by the results of hydrodynamic model computations of the star formation process which predicted for low mass stars that protostellar mass accretion would continue for about 10^6 years after the formation of a hydrostatic core, while hydrostatic evolutionary age estimates resulted for many T Tauri stars in considerably smaller ages (in some cases $< 10^5$ years; see e. g. Cohen and Kuhi 1979). Moreover because of the high specific angular momentum of interstellar matter the contracting protostellar clouds are expected to become rotationally flattened, eventually reaching a ring or disk-shaped configuration. According to all modern scenarios of the formation of our solar system a gaseous disk must once have existed around our sun or protosun to allow the formation of the solar system planets. Hence, the very existence of our planetary system (and our own existence) seems to provide ample proof for the hypothesis that disks do (at least occasionally) play a role during the formation or early evolution of low mass stars. On the other hand we know that most galactic stars appear to be members of binary systems, which are probably formed via ring-shaped (rather than disk-shaped) protostellar clouds (see e. g. Bodenheimer 1978). Hence, although protostellar disks are definitively expected to occur, they may well be the exception rather than the rule.

When disks occur, they obviously must form already during the very early (isothermal) protostellar collapse phases. In principle detailed evolutionary model computations of rotating protostellar clouds should show us, whether such disks survive the early collapse phases and are still present and important during the T Tauri evolutionary stage. During the past years many hydrodynamic model computations of rotating collapsing clouds have been made. Their results have been summarized in various recent reviews (Larson 1978, Bodenheimer and Black 1978, Woodward 1978, Tscharnuter 1980 , 1982, Appenzeller 1982) and will therefore not be described here in detail. Unfortunately none of these computations was continued to the stage where the central object had become a T Tauri star. Hence, the duration of the disk stage still remains unknown and open to speculations. However, the more detailed model computations (by e. g. Cameron 1978, Tscharnuter 1981, Lin and Bodenheimer 1982) indicate that protostellar disks are much larger and in many respects qualitatively different from their counterparts in close binary systems. One of the most important differences may be the fact that binary accretion disks are resupplied by accretion in the symmetry plane of the system, while protostellar disks will experience an essentially isotropic matter infall. As a result, binary disks have "hot spots", while protostellar disks are expected to have a "hot surface". Therefore, results derived for binary disks may not always be applicable to protostellar disks.

As noted already, none of the model computations of rotating protostars has been continued to the T Tauri evolutionary stage. Hence, all our theoretical predictions on the later stages of the protostellar evolution and the initial conditions of the hydrostatic PMS evolution are based on simplified spherically symmetric and non-rotating models. For members of binary systems (which seem to form the majority of all young stars) the non-rotating models may still turn out to be acceptable approximations, since rotational fission (as described by Bodenheimer, 1978) and subsequent tidal effects may lead to protostars with relatively low spin angular momentum. But, as long as detailed non-spherical model computations of the late protostellar stages do not exist, we have no way to estimate the accuracy and reliability of the spherically symmetric models. All quantitative comparisons of these models with observations should therefore be made only with great care and skepticism. But, the spherically symmetric computations produced several important qualitative results, which should remain valid or become even more pronounced when rotation and other so far neglected physical effects are included.

Perhaps the most important qualitative result of the hydrodynamic model computations is the strong dependence of the models on the initial conditions. Figure 1 shows the results of the recent, internally very accurate, spherically symmetric computations by Winkler and Newman (1980) together with some older approximate tracks. Both sets of tracks were started with the initial conditions suggested by Larson (1969), which assume that a protostellar cloud has initially the size of a Jeans length and no significant internal density differences or fluctuations. A detailed comparison of the calculations of Winkler and Newman (WN) and Appenzeller and Tscharnuter (AT) shows that the difference in effective temperature during the final (T-Tauri) stages seem to be caused by the fact that at a relatively early stage a smaller hydrostatic core is formed in the WN computations. The initial size of this core is determined by the properties of the low temperature matter as well as by the fine details of the initial conditions. As pointed out elsewhere (Appenzeller 1980) Larson's initial conditions are a limiting case of the various initial values which may be realized in nature. Spherically symmetric 1 $M_\odot$ model computations started with different initial conditions resulted in evolutionary tracks qualitatively similar to those of AT, but with even larger core radii and higher bolometric luminosities. From the scatter of mass values of individual stars and the (unrelated) scatter of the angular momentum values of binary systems it is clear that the initial conditions of the protostellar phase are certainly not uniform but show a large stochastic scatter. Because of this fact and because of the strong dependence of the evolution on the initial conditions it seems difficult to avoid the conclusion that we also have to expect a large scatter of the individual evolutionary tracks of low mass PMS of the same mass. As

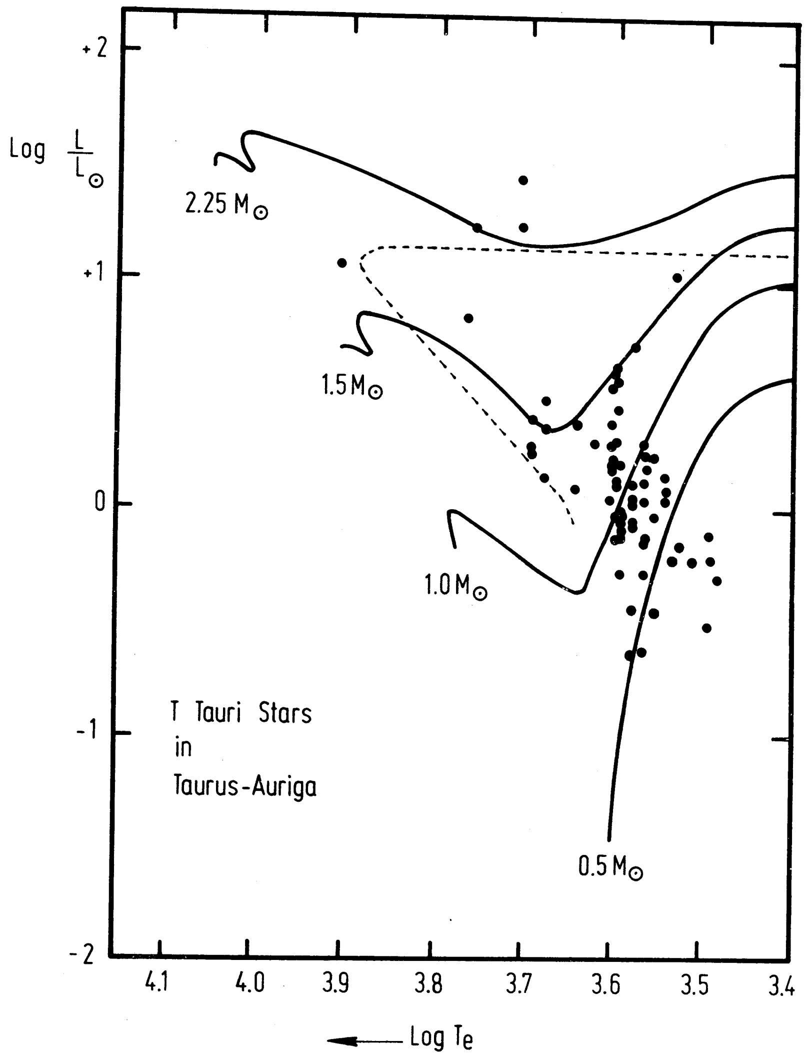

Figure 1: HR diagram of the T Tau stars of the Taurus-Auriga association (adapted from Cohen and Kuhi, 1979). Also included are approximate hydrodynamic PMS evolutionary tracks (solid lines: Appenzeller and Tscharnuter 1975, Appenzeller 1980; broken line: Winkler and Newman 1980).

a result we can (in contrast to the post-main sequence phases) not expect to have for PMSs a unique relation between a star's position in the HR diagram and its mass and age. At least during the earlier T Tauri evolution stars with the same effective temperature and luminosity may have a quite different mass and evolutionary state. Fortunately, since (as noted already) PMS tend to forget their initial conditions on their evolutionary time scale, all calculated 1 $M_\odot$ evolutionary sequences were found to converge at the beginning of the "partially radiative" (i. e. approximately horizontal) part of the PMS tracks. For these relatively "old" T Tauri stars classical hydrostatic tracks are probably reasonable approximations. However, if the T Tauri (and post-T Tauri) stars have surface magnetic fields of the extent estimated from the indirect observations described below, the conventional PMS models may be incorrect even at these stages.

The results described above were obtained by solving numerically the hydrodynamic equations for protostellar models. Stahler, Shu and Taam (1980) recently suggested a different, elegant, and simpler method to study protostellar evolution. In their calculations they compute the evolution of the hydrostatic core separately, using an (arbitrarily) assumed (and adjustable) mass infall rate as a boundary condition. Assuming a constant mass infall rate much larger than the average rate resulting from the earlier hydrodynamic computations (started with Larson's initial conditions) Stahler et al. obtained results which were qualitatively and quantitatively different from those obtained with the conventional hydrodynamic cores. But since there seems to be no physical justification for the mass accretion rate assumption made by Stahler et al., the physically more consistent conventional hydrodynamic computations are probably more reliable.

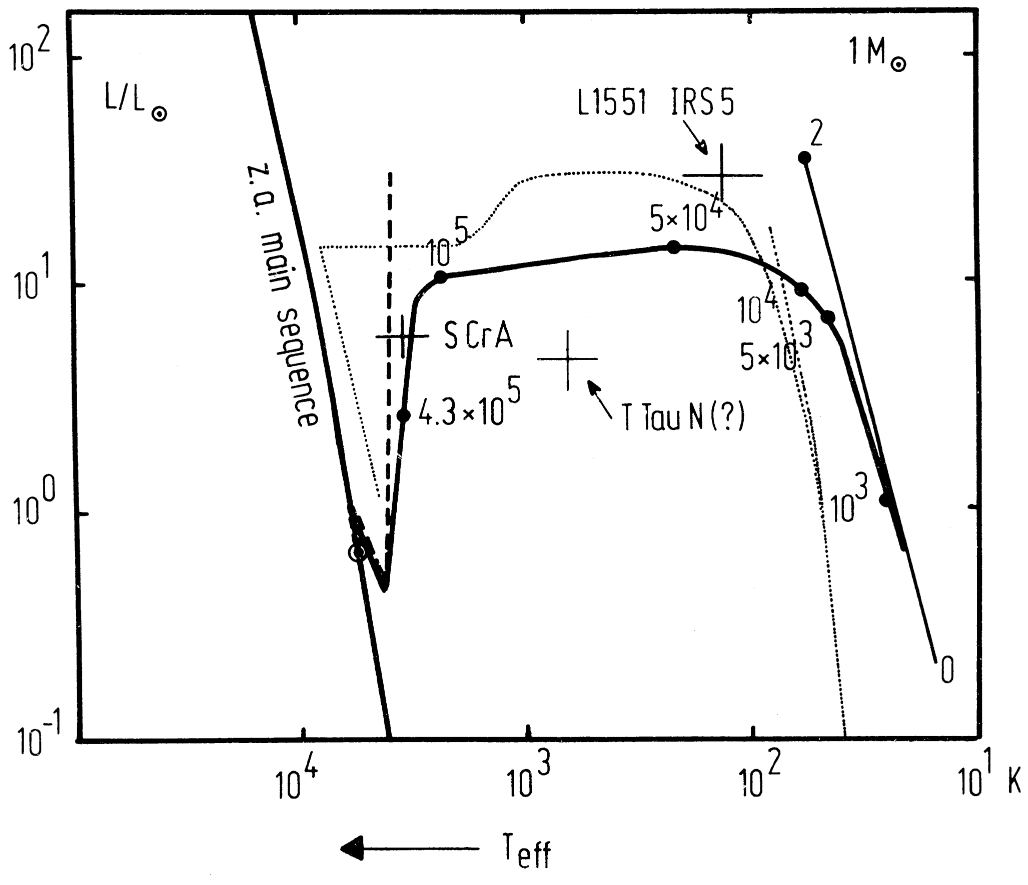

Figure 2: Evolutionary track in the IR-HR diagram of a 1 $M_\odot$ protostar according to Appenzeller and Tscharnuter (solid line) and recent more accurate computations by Winkler and Newman (dotted line). The numbers indicate age in years. The broken line represents a conventional hydrostatic 1 $M_\odot$ PMS track. The crosses give the approximate locations of three objects which have been suggested to be low mass protostars.

As illustrated by Figure 2 the T Tauri evolutionary phase is preceded by a relatively short-lived ($\lesssim 10^5$ years) stage during which the protostar radiates practically only at infrared wavelengths. Because of their relatively low luminosity such "proto-T Tauri stars" are difficult to detect by groundbased IR surveys. But, with IRAS now operating and other cooled space-based infrared telescopes under construction, such objects are expected to become quite accessible within the near future. Even in the past two low-luminosity IR sources (IRS 5 in L1551 and T Tau IR) have been suggested to be proto-T Tauri stars. Their approximate positions in the IR-HR diagram are given in Figure 2, where (following Dyck et al. 1982) the cool companion of T Tau is labeled "T Tau N", although, according to new arguments, it may in fact be the southern component of the T Tau system. In the case of IRS 5 in L1551 (cf. Beichman and Harris, 1981) the true "photospheric" temperature appears still rather uncertain and the strong gas outflow centered on this object may indicate that IRS 5 is in fact a strongly obscured more evolved object, perhaps similar to V1331 Cyg. Bertout (1983) demonstrated that the cool companion of T Tauri (Dyck et al. 1982) may be a much better candidate for a proto-T Tauri star. As shown by Bertout, a protostellar model of T Tau IR provides a better fit of the observational data than the "proto-planet" model of Hanson et al. (1983). But at the time of this writing too little is known on this object to allow a definitive identification.

III. THE CONTINUUM ENERGY DISTRIBUTION OF THE T TAURI STARS

Figure 3 shows the observed continuum energy distribution of the star T Tau between 140 nm and 11 cm. As shown by Bertout (1980), this spectrum is readily explained by a superposition of three components: (a) radiation from a normal late type stellar photosphere, (b) free-free and free-bound emission from a thin ionized circumstellar envelope, and (c) thermal radiation from circumstellar dust.

Although the well investigated "prototype" T Tau is probably a special case, where most of the dust radiation is produced by a cool companion, the presence of the three emission mechanisms (a) to (c) seems to be a general property of the T Tauri stars, and in most cases a superposition of these three mechanisms results in a good fit of the observed energy distribution. However, some T Tauri stars with strong emission spectra and most of the YY Orionis stars show an excess in the blue spectral range, which cannot be explained by a superposition of a normal photosphere and the radiation of an ionized envelope (see e. g. Strom, Strom and Grasdalen 1975). Usually the same stars also show a strongly weakened or "veiled" photospheric absorption spectrum. Two mechanisms have been suggested to explain this phenomenon: (a) an additional absorption line free blue continuum light source, which dilutes the photospheric radiation, (b) the existence of "deep chromospheres", i. e. an atmospheric temperature minimum occurring already at a density and optical depth much (i. e. $\sim$100 times) higher than in the sun. As additional light sources viscous accretion disks or extended hot layers heated by turbulence (Ulrich 1983) have been suggested. The deep chromosphere model has been studied by Dumont et al. (1973), Cram (1979), and Calvet (1980). A temperature minimum at a high optical depth may be caused either by excessive mechanical or magnetohydrodynamic heating from below or (in the case of the YY Orionis stars) by accretion shock heating from above. In my opinion the most important theoretical contribution to the problem of the origin of the blue continuum and

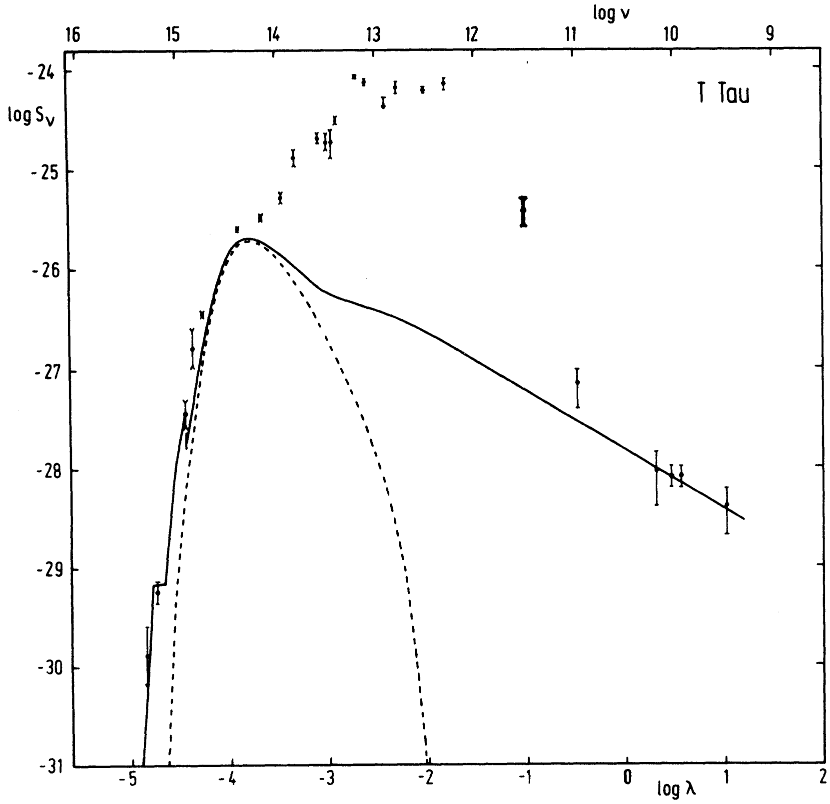

Figure 3: Continuum energy distribution of the star T Tau (according to Bertout 1980). The λ = 1 mm point is a new measurement by Chini et al. (1983). The units of S_ν are $Wm^{-2}Hz^{-1}$, λ is given in cm, ν in Hz. The broken line indicates the contribution of the star's photosphere, the solid line the combined contribution of the photosphere and the ionized part of the circumstellar gaseous envelope. The remaining IR excess is attributed to dust emission.

the veiling in T Tauri spectra are the synthetic spectra computed and reproduced by Cram (1979), which clearly support the deep chromosphere hypothesis. Additional purely observational support of this assumption is provided by the time variability of the "veiling": According to Aiad et al. (1983) in the case of the star YY Ori strong variations of the degree of veiling may occur without significant changes of the objects brightness. If the veiling were due to a superimposed line-free light source, veiling and brightness could hardly be uncorrelated. Hence, we may conclude that the observed energy distribution of the T Tauri stars can be explained by a combination of a late type photosphere, a "deep chromosphere" (in some cases possibly resulting from an accretion shock), and a partly ionized and (again at least sometimes) dusty circumstellar envelope. At present there seems to be no compelling evidence for other more exotic contributions, although other mechanisms can of course not be ruled out by the above successful fit.

IV. REMARKS ON THE EMISSION LINE SPECTRUM

The line spectra of T Tauri stars are discussed in detail in Nuria Calvet's contribution to this volume. Therefore, this chapter will be short and restricted to a brief report on some recent unpublished work by my colleague Claude Bertout and his associates in Heidelberg and Paris. In these studies Bertout explains the T Tauri phenomenon by the interaction of a relatively normal late type corona with the relics of the star's cool protostellar cloud. According to Bertout, it is possible, to find solutions for the flow in the resulting thermal stellar wind, where the hot wind material condenses upon contact with the cool cloud material, forming a transition zone with intermediate temperatures and densities. Because of geometric effects this "second transition zone" is expected to contribute more flux to the "chromospheric" emission line spectrum than the star's chromosphere itself. As a result, Bertout (1982) was able to reproduce the observed emission line strengths even of strong-line-emission T Tauri stars with mass loss rates as low as about 10^{-9} $M_{\odot} yr^{-1}$.

In a different but related investigation Wagenblast, Bertout, and Bastian (1983) studied the emission line profiles which are produced by moving circumstellar gaseous shells. (This problem is related to Bertout's "second transition zones", since in his model most line radiation is emitted in thin shell-like regions). In view of the uncertainties concerning the true radiation field in the vicinity of T Tauri stars, Wagenblast et al. did not try to calculate detailed models of the radiative transfer. Instead they computed line profiles <u>assuming</u> certain line source functions S(r). Interestingly even with rather simple functions S(r) the resulting line profiles showed a striking similarity with the observed profiles in strong emission T Tauri stars. Examples are given in Figure 4. The three profiles reproduced in this figure were calculated assuming the same free-fall (i. e. $\dot{r} \sim -r^{-1/2}$) velocity law (probably characteristic of the YY Orionis stars), but with different source functions. As pointed out by Wagenblast et al., these profiles resemble those observed at the H_{α}, H_{γ}, and H_{δ} lines of YY Orionis stars. Interestingly, one of the three profiles of Figure 4 is a pure Type III P Cygni profile, which could also be produced by mass outflow. Type I P Cygni profiles (as observed in the Balmer lines of strong-mass-loss T Tauri stars) could also be produced by assuming a wind flow instead of an accretion flow.

V. CIRCUMSTELLAR MASS FLOWS

As shown by the two examples in Figure 5, some T Tauri stars show conspicuous blueward--displaced or redward-displaced absorption components of certain emission lines. Usually these shifted absorption components are interpreted as evidence for, respectively, mass outflow or mass inflow. While the mechanisms driving the observed outflow are still disputed (see below) the observed inflow is generally assumed to be due to matter accelerated by the star's gravitational field. The origin of the infalling matter is less clear: Walker (1972) suggested that in the T Tauri stars with redward-displaced absorption components (i. e. the "YY Orionis stars") the final phases of the protostellar mass accretion are observed. Grasdalen (1977) proposed that the observed infalling matter is ejected by (undetected) companion stars or has been ejected earlier by the star itself, but with an ejection velocity below the escape velocity, and is now falling back onto the

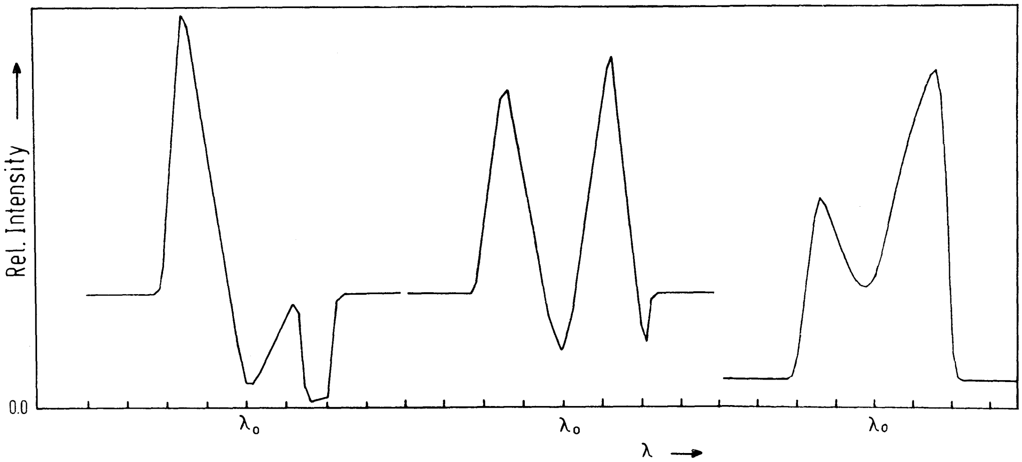

Figure 4: Computed emission line profiles produced by a free falling gaseous shell surrounding a T Tauri star (according to Wagenblast et al. 1983). Note the similarity with observed profiles of the Balmer lines of YY Orionis stars. For all three profiles the same velocity field and matter density distribution, but different excitation conditions were assumed.

T Tauri star's surface. Mundt (1983) recently argued that the presence of blueward-displaced absorption components in the resonance lines of most or all YY Orionis stars (Wolf et al. 1977, Mundt 1983) seems to support the "back-fall hypothesis". However, in at least one T Tauri star (DR Tau, cf. e. g. Krautter and Bastian 1980, Aiad et al. 1983) mass inflow and mass outflow (at least at times) seems to occur simultaneously. Moreover, in many T Tauri stars we have reliable evidence for a highly nonisotropic character of the mass outflow, leaving plenty of room for simultaneous mass inflow. Hence, I see no convincing reason why the presence of escaping matter near a T Tauri star should rule out a net mass accretion flow of the YY Orionis stars. Other astrophysical objects, like the hot components in certain cataclysmic binaries, are also known to show a net accretion flow in spite of a stellar wind (see e. g. Krautter et al. 1981). Unfortunately, in contrast to other objects, our poor knowledge of ionization and excitation conditions in T Tauri envelopes do not allow sufficiently accurate mass loss and mass accretion rate estimates from the observed line profiles to calculate the net rates directly. Therefore further, more reliable observational evidence or an improvement of the theory will be needed before a conclusive statement about the nature and origin of the infalling matter in YY Orionis stars can be made.

As far as the matter ejected from T Tauri stars is concerned, there is no dispute about its origin, but the mechanisms driving the flow are not (or at least not reliably) known. In the past it has usually been assumed that the T Tauri winds are simply scaled-up versions of the thermaly driven solar wind. However, as pointed out by DeCampli (1981) and others, in this case the coronal densities corresponding to the high mass loss rates of T Tauri stars quoted in the literature would result in impossibly high coronal radiation losses and X-ray fluxes much higher than the observed values. Therefore, DeCampli (1981) and Hartmann, Edwards and Avrett (1982) suggested that T Tauri winds are driven by the magnetic pressure of Alfvén waves. As shown by these authors, this

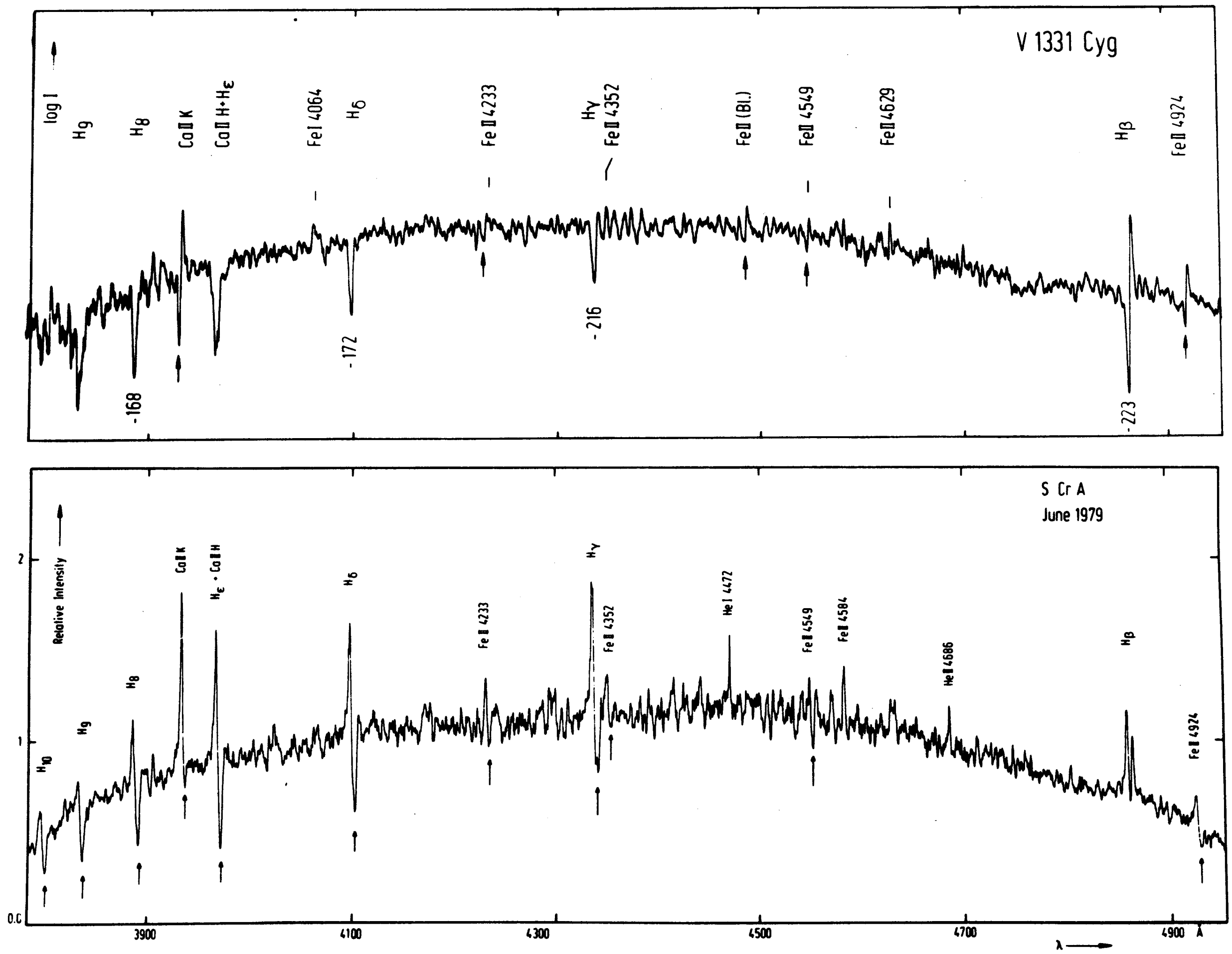

Figure 5: Examples of P Cygni (V 1331 Cyg) and YY Orionis (S CrA) line profiles in spectra of T Tauri stars.

mechanism may lead to mass loss rates up to about 10^{-8} $M_{\odot}yr^{-1}$ and the escaping matter can remain relatively cool (~10^4 K). At present little is known on the T Tauri magnetic fields and there exist neither theoretical predictions nor direct observational evidence for the presence of a suitable and adequately efficient generator of Alfvén waves at the surface of the T Tauri stars. But, the compression of matter and the differential rotation effects expected for the protostellar stage of pre-main sequence objects make it rather likely that strong surface magnetic fields are present in these objects. Therefore, the Alfvén wave acceleration mechanism (and other magnetic mechanisms) obviously provide a plausible and highly attractive alternative to the thermally driven wind hypothesis. On the other hand, it may be too early to completely rule out thermally driven winds in the T Tauri stars: If the mass loss rates are as low as derived by Bertout (1982), a thermally driven wind may still be adequate and no problems with excessive coronal heating and X-ray emission are encountered.

One of the most important recent observational developments concerning the T Tauri stars is the rapidly growing evidence for a highly nonisotropic character of the mass outflow from T Tauri

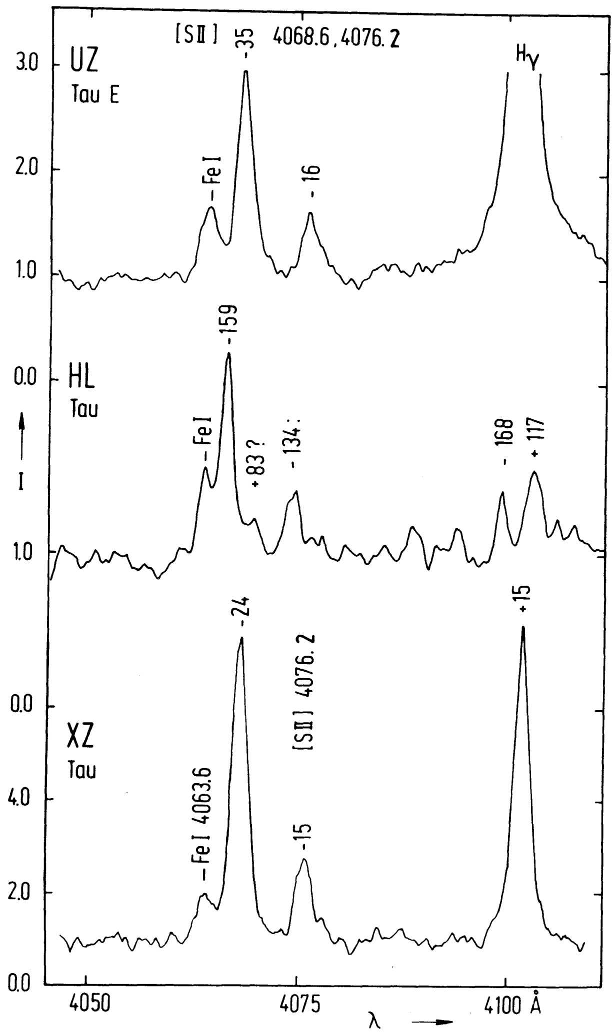

Figure 6: The [S II] (F1) λλ4068.6, 4076.2 doublet in the spectra of three T Tau stars. The numbers indicate heliocentric radial velocities of the emission features which are due to or (probably) dominated by [S II] emission. Note the differing velocities of the forbidden lines in the three stars. In contrast, the photospheric absorption lines and metallic emission lines of the three stars show a uniform (slightly positive) radial velocity.

stars. In the optical spectral range we see H-H objects clearly moving away from T Tauri stars (Herbig and Jones 1981, 1982), bipolar flows and well collimated "jets" (Mundt, Stocke, and Stockman 1983, Mundt 1983a). At radio wavelengths we find evidence for bipolar flows of cool molecular matter, which presumably has been accelerated by the nonisotropic T Tauri winds (Snell et al. 1980, Snell and Edwards 1982, Edwards and Snell 1983, Calvet et al. 1983 ; see also Bally and Lada 1983). As pointed out in Chapter II, T Tauri stars are expected to form as cores of rotationally flattened protostellar clouds. In such an environment even an initially isotropic wind is easily transformed into a (depending on the symmetry properties of the matter distribution) bipolar or unipolar flow by the classical "hydrodynamic focussing" mechanism usually proposed for radio sources (Sakashita 1971, Möllenhoff 1976, Königl 1982) or by the different but related Cantó mechanism (Cantó 1980).

On the other hand, as noted above, there are good reasons to assume that magnetic fields (through Alfvén waves, field reconnection, or other MHD processes) are responsible for the observed mass ejection from T Tauri stars. As we know from our sun, such magnetic field related processes may result in outflow patterns which are intrinsically highly nonisotropic. In our sun such collimated outflows are known as "coronal transients", "plasma clouds", and coronal "bullets" and "jets" (see e. g. Karpen et al. 1982 and the extensive earlier literature quoted therein). Although none of these solar phenomena are theoretically well understood, they are definitively observed and apparently play a major role in the solar wind mass flow. The much more massive flows near T Tauri stars may well have the same origin if (as expected) the magnetic activity in these objects is correspondingly stronger. Hence, on the basis of the presently known facts it is difficult to decide whether (or to what fraction) the collimated flows observed near T Tauri stars are caused intrinsically (by magnetic effects) or externally by hydrodynamic mechanisms.

However, regardless of the focussing mechanism, there are observational results which seem to indicate that many T Tauri stars are indeed surrounded by extended flattened, disk or sheet -like gas and dust clouds (of presumably protostellar origin) which at least in principle could provide the density gradients required for the hydrodynamic mechanisms. One of these observational results are the peculiar radial velocities of the forbidden lines in the spectra of T Tauri stars. As illustrated by the examples given in Figure 6 and as noted in the literature for several individual T Tauri stars (HL Tau, RU Lup, DG Tau; see, respectively, Strom, Grasdalen, and Strom 1974, Lago and Penston 1982, Mundt 1983) in T Tauri spectra the forbidden lines (of [O I], [O II], [S II], [N II], and occasionally [Fe II]) sometimes show radial velocities significantly different from those of the photospheric absorption lines and chromospheric emission lines. (Rydgren (1977) reported this effect also for S CrA, but in S CrA, like in other strong-emission T Tauri stars with weak forbidden lines, blending makes the identification of shifted lines difficult and uncertain, and other authors were not able to confirm Rydgren's results for S CrA). Interestingly, as indicated already by the three T Tauri stars mentioned above, the forbidden lines appear to be predominantly blueshifted relative to the photospheric and permitted lines. In a new unpublished study by I. Jankovics, J. Krautter and myself this effect has recently been investigated more systematically. For this investigation we used spectrograms in our files but considered only T Tauri stars with strong forbidden lines, to exclude spurious effects due to misidentifications or blends with permitted features. Unfortunately, this severely decreases the number of usable spectrograms, since in most T Tauri stars the forbidden lines are weak. So far we were able to obtain reliable measurements for 14 objects. Of this sample 7 T Tauri stars show forbidden line velocities in the range $-40 < v_{\odot} < +40$ km s^{-1}, while for the other half of our sample we have $-160 < v_{\odot} < -40$ km s^{-1}. There is a tendency that the objects with stronger forbidden lines have more negative radial velocities, while stars with weaker forbidden lines tend to show no significant shift. The average velocity of the whole sample is $v_{\odot} = -43 \pm 14$ km s^{-1}. Interestingly the distribution of the individual forbidden line velocities shows some resemblance to the velocity distribution of the Herbig-Haro objects (cf. Strom, Grasdalen, and Strom 1974). This obviously supports the assumption that in the forbidden line regions of T Tauri stars and in H-H objects the same effect is observed, only at different (angular) distances from the central stars. As outlined in Figure 7, the predominantly negative radial velocities of the forbidden lines in T Tauri spectra (and the radial velocity distribution of H-H objects as well) is easily explained if the T Tauri stars are located in optically thick flattened clouds: If the symmetry planes of these clouds are randomly distributed in space, in most cases we view these clouds obliquely, as indicated in Figure 7. Since the forbidden lines can be formed only in the thin outer regions of the wind (typically outside 10^2 AU, cf. Mundt 1983), the receding part of the forbidden line emission region will normally be obscured by the flattened cloud, and we receive only the blueshifted radiation from the approaching part of the forbidden line producing volume.

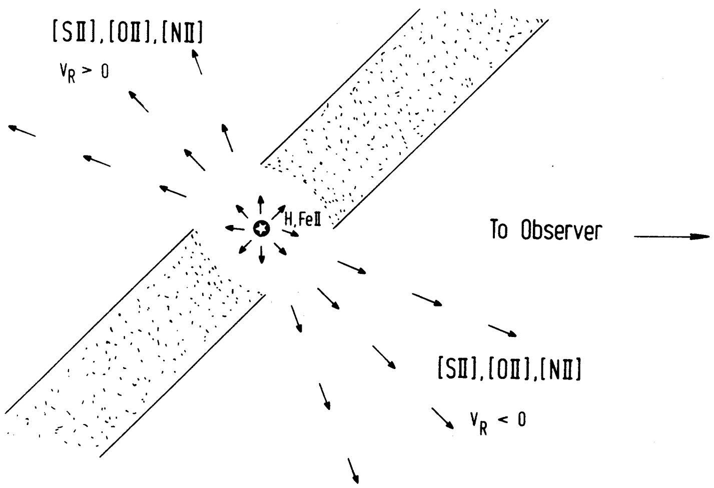

Figure 7: Schematic representation of the geometric obscuration scenario used to explain the predominantly negative radial velocities of the forbidden lines in T Tauri spectra.

The above statistical result obviously has to be verified using a larger and statistically more meaningful sample. But, if the predominance of negative forbidden line velocities can be confirmed from such a larger sample it may provide the most direct evidence for flattened dust and gas clouds surrounding T Tauri stars.

VI. VARIABILITY MECHANISMS

T Tauri stars are known to show irregular or (in some cases) "quasiperiodic" or "cyclic" brightness variations. The time scales or these variations range from minutes (see e. g. Kilyachkov and Shewchenko 1976) to at least a century (see e. g. Chavarría 1979). The amplitudes may reach up to $\Delta m_V \approx 6$. The "periods" of the cyclic variations are known to range between about half a day and several weeks. Although for a given star a well defined period length can be determined, these variations are not strictly periodic, since the amplitude varies greatly and the phase of the minima (or maxima) is not conserved over extended periods of time. Such quasiperiodic variations in (what we call today) T Tauri stars were already discovered in the last century from visual observations (see e. g. Schmidt, 1871) and have been investigated and discussed by many different authors (including most recently Schaefer (1983) and Rucinski (1983)). Hoffmeister (1965) suggested that these cyclic variations are caused by the presence of large "star spots" on the surface of rotating T Tauri stars. These star spots are assumed to be of the same (magnetic) origin as the sun spots of the solar photosphere. A finite lifetime of individual spots provides a plausible explanation for the absence of truly periodic variations over extended time intervals. The cycle lengths in Hoffmeister's scenario simply corresponds to the stars' rotation periods. Recent direct derivations of rotational velocities of T Tauri stars (Vogel and Kuhi 1981) are in reasonable agreement with the required rotational velocities. Hoffmeister's suggestion later was worked out in some detail by Friedman and Gürtler (1975), who also showed that a rather large fraction of the stellar surface area must be covered by spots to produce the observed amplitudes of the brightness variations.

As alternative explanations of the cyclic variations of T Tauri stars Mauder (1977) suggested stellar pulsations and Poveda (1965) suggested orbiting dust clumps or "planetesimals" as possible causes. However, these suggestions both encounter difficulties: The stellar pulsation hypothesis requires unrealistically low stellar mass values, and sufficiently large planetesimal dust clouds, if orbiting close enough to the star to produce the observed short periods, would probably be destroyed by tidal effects. Therefore, Hoffmeister's suggestion still appears the most likely explanation for the cyclic components of the light variations of T Tauri stars.

A reliable derivation of the causes of the <u>irregular</u> components of the T Tauri variability is more difficult: In the case of the very short time scale variations (in the order of minutes, cf. e. g. Kilyachkov and Shewchenko, 1976, Montmerle et al. 1982) we probably observe "flares" of a similar nature as those seen in the sun and in flare stars. However, the very long time scales of some of the variations and the character of the observed spectral variations seem to rule out that all irregular variations are caused by flare activity. Joy (1945) suggested variable circumstellar dust extinction or obscuration as a source of the T Tauri variability. As demonstrated by Gahm et al. (1974), Walker (1978, 1980), Gahm and Petrov (1982) and others, this mechanism may explain the variations of certain T Tauri stars, if suitable dust properties are assumed. However, many T Tauri stars show emission line spectrum variations correlated with the brightness variations, which is difficult to explain by a variable dust extinction scenario. (In strong emission T Tauri stars, the emission line equivalent widths tend to increase with brightness (Joy 1945), while in weak emission line objects the emission line equivalent widths normally decrease with increasing brightness, cf. Herbst et al. 1982). Hence, at least part of the irregular variations must be due to some mechanism operating in the star or its surface itself. A possible process of this kind may be variable surface magnetic fields: As noted above, it seems very likely that extended magnetic fields are present in T Tauri stars, and if Hoffmeister's interpretation of the cyclic variations is correct, a large fraction of the surface of at least some T Tauri stars must be covered by magnetic fields. The amplitude changes and phase shifts of the cyclic variations and the occurrence of flares indicate that the magnetic fields are variable with time. As pointed out by Dearborn and Blake (1982) magnetic fields in parts of the surface of late type stars influence the stars' convection zones and may result in significant changes of the stellar radii, effective temperatures and of the bolometric luminosity, even if the convective energy flux suppressed below the magnetic surface area is fully redistributed to the spot-free areas. These structural changes are caused by the presence of an additional (magnetic) pressure component in the hydrostatic equilibrium of the outermost layers and by the thermal adjustment of the non-adiabatic part of the convection zone to the redistributed energy flow. If the changes of the magnetic field take place on time scales much shorter than the Kelvin-Helmholtz time of the convection zone (in the order of $10^{5\pm1}$ years for T Tauri stars), thermal equilibrium will never be established and the outermost layers may alternate in consuming (and storing) or releasing (thermal and gravitational) energy, which in turn will result in variations of the surface luminosity. Dearborn and Blake (1982) showed that this effect may produce measurable variations of the solar constant although in the case of the sun never more than a tiny fraction of the surface is covered by spots. In gravitationally contracting PMS with large adiabatic parts of their convection zones, even larger effects are to be expected, since the energy flow and the local energy generation is strongly influenced by the outer boundary conditions. In such stars, decreased radiation losses due to surface fields will simply slow down the contraction and move the star in the HR diagram.

In order to investigate the effect outlined above quantitatively D. Dearborn and myself recently computed PMS models with rapidly changing surface magnetic fields (Appenzeller and Dearborn 1983). For a 1 $M_\odot$ PMS with initial parameters B = O, R ≈ 2.7 $R_\odot$, L ≈ 2.65 $L_\odot$, T_{eff} = 4527 K we found magnetic field induced brightness variations of up to 1.5 magnitudes in the apparent bolometric luminosity and up to 3.5 magnitudes in the visual brightness, if a maximum of 50 % of the stellar surface was covered by the field. The maximum apparent effective temperature change was about 1300 K, while the radius changes were minimal. The effect of the field was found to increase with increasing surface gravity. Therefore, we expect that more evolved T Tauri stars and post-T Tauri stars will probably react even more strongly if magnetic field changes occur.

Various authors suggested that in the case of the YY Orionis stars variable accretion shock heating may cause or contribute to the particularly strong variability of this subclass of the T Tauri stars. If the mass accretion rates estimated from line profile calculations (according to Bastian (1982) in the order of 10^{-7} $M_\odot yr^{-1}$) are correct, direct shock heating may indeed be an important effect. In addition, like magnetic fields, shock heating of the surface layers can also temporarily suppress the convective energy flow near the surface and trigger brightness variations due to internal structure changes.

Summarizing this chapter I conclude that very likely there are several different mechanisms which contribute to the brightness variations of the T Tauri stars: There is fairly direct evidence for the occurrence of star spots and flares. If the spots and flares are of magnetic origin (as on the solar surface) the global effects of the surface magnetic fields on the convection zone will cause additional variations of the bolometric luminosity and effective temperature. In the YY Orionis stars the accretion shocks produced by the observed supersonically infalling matter can produce brightness variations either directly or, again, by influencing the convective energy transport. But at present the mass infall rates in YY Orionis stars cannot be determined with sufficient accuracy to estimate the relative importance of this effect. Variable circumstellar dust obscuration may also contribute, but the available evidence for this suggestion is less direct and conclusive than for the processes listed above. Other more exotic mechanisms (like instabilities in circumstellar disks or internal rotational instabilities) certainly cannot be ruled out, but the observational or theoretical arguments for such processes are even less obvious.

The lower spectrogram of Figure 5 (S CrA) was kindly made available by Dr. J. Krautter. Figure 6 is based on observations acquired at the Multiple Mirror Telescope Observatory (MMTO). The MMTO is a joint facility of the University of Arizona and the Smithsonian Institution. Part of this review was written during a stay at the Steward Observatory, University of Arizona. I wish to express my sincere thanks to Professor P. A. Strittmatter and the staff of the Steward Observatory for their hospitality. This paper is based on research supported by the Deutsche Forschungsgemeinschaft (SFB 132).

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DISCUSSION

Herbst: (*Comment*) I like your spot explanation for the variability of some T Tauri stars. I would like to point out, however, that some Ae stars (e.g., BF Ori and UX Ori) behave photometrically in a manner nearly identical to that of some T Tauri stars (e.g., SU Aur and CO Ori), so if magnetic effects are involved in the latter we will probably have to accept that the Ae stars can have strong magnetic fields as well.

S. *Strom:* We should be careful about the kind of variability we are attemping to explain. Flaring and "spottedness" can explain fluctuations of 0.01 to perhaps 1.0 mag. However, *some* stars show variations of more than 10 times and are roughly steady before and after an "outburst" or "decrease". It seems to me that we can exclude flaring and spots as the causes; simple changes in the interior structure seem ruled out as well. I wonder whether this drives us to models where the large-scale variability derives from changes in accretion rates? We must establish whether these changes in luminosity reflect changes in photospheric effective temperature or changes in envelope emission.

Appenzeller: The prominent flare observed in T Tau by Kilyachkov and Shevchenko (1976) reached about $\Delta V_V \simeq 1.3$ mag. The model computations of PMS stars with variable surface magnetic fields by Dearborn and myself indicate that the "global" magnetic effects may result in at least $\Delta V_V \simeq 3.5$ mag. But I agree that the largest variations observed in T Tauri stars ($\Delta V \simeq 6$ mag.)

probably cannot be explained by magnetic effects. As pointed out, e.g. by Larson this morning, accretion may produce very large variations. But except for the YY Ori stars we have little direct evidence for accretion and even in the YY Ori stars accretion rates cannot be determined accurately enough to predict expected variation effects. As far as the correlation between the variations in brightness and effective temperature is concerned, I fully agree that observational efforts should be made to establish this relation and that this is a very important criterion for the theoretical interpretation of the variations.

Mundt: (*Comment*) I want to make a short comment on the predominant negative radial velocity of the forbidden lines in T Tauri stars. You made the suggestion that this is due to collimated (bipolar) outflows. I like this idea. However, we have to keep in mind that the negative velocities you reported can also be obtained in a expanding emission region containing dust (which absorbs the red part of the emission). This question should be in principle solvable by high resolution spectra of the forbidden lines.

Pismis: (*Comment*) I like to comment on the bipolar mode of mass ejection from stars that are for more massive and of much higher absolute luminosity, as compared to T Tauri stars being discussed here. I shall mention three stars, two of which are WN and one is an Of star. All three are the ionizing central stars of the symmetrical nebulae: NGC 6164-5, NGC 2357, and M 1-67. Our detailed velocity fields obtained by Fabry-Pérot interferometry together with the morphology have provided evidence that the nebulae were formed essentially from matter ejected by the central star and that the ejection has not been isotropic: matter has been ejected from active regions located at opposite hemispheres on the star. These regions are approximately at the extremities of a diameter (which may mark the direction of a magnetic dipole) oblique to the rotation axis of the star. At present this mode of ejection is termed "bipolar". We have suggested that if the stars have ejected mass in a bipolar fashion in the past, the present outflow from those central stars, observed through their spectra, may also be occurring from localized regions, in a bipolar manner. In other words, the stellar wind known to operate in the WN and Of stars may also have a bipolar configuration. Thus in general we should keep an open mind and expect stellar winds to have structure and not necessarily be isotropic.

These suggestions were put forward and developed by myself and my group since 1974. A summary of these ideas was presented at *IAU Symposium* No. 83 (in the Proceeding, page 43) with the title "Evidence for Non-Isotropic Mass Loss from Central Stars of some Emission Nebulae". A list of the references to our earlier work is given in that summary.

Königl: First, a comment in response to Dr. S. Strom. I suppose that the best test for the influence of accretion on variability would be to check for for large-scale variability in isolated "field" T Tauri stars. *A priori*, however, it is conceivable that such variability could be caused also by internal redistribution of angular momentum. Now the question is: how is a bipolar outflow pattern consistent with a "spotly" magnetic field configuration on the surface of the star?

Appenzeller: If the collimated outflows have an intrinsic (magnetic) origin for bipolar flows, obviously some bipolar symmetry in the field (and spot distribution) would be required.

Krautter: (*Comment*) TW Hya, the T Tauri star far from any dark cloud shows -on the basis of 12 nights photometry- a relative low brightness variation of 0.5 mag in V.

Bastien: What is the order of magnitude of the magnetic field locally, and of its longitudinal component integrated over the stellar disk?

Appenzeller: Of the order of 10^3 Gauss. The local field is such that the magnetic pressure is equal to the gas pressure near the surface, as for the Sun.

Harvey: In the energy distribution of T Tauri it is important to remember that the dust producing the emission at wavelength longer than 30-50 μm is cool enough that it must be farther from T Tau and its infrared companion than the separation between the two. In addition, since T Tauri's emission peaks at shorter wavelengths than its companion, T Tau itself is likely to be the dominant heat source for the cool, far -infrared- emitting dust.

Kuhi: I would like to make a comment about your devastating remarks about pre-main sequence evolutionary tracks. I am just a simple old observer and all that Cohen and I were trying to do was to locate observationally the T Tauri stars on the HR diagram. We used the convective-radiative tracks as a convenient frame work in which to discuss the observations. When you can provide a similar set of calculated dynamic tracks for a range of masses we will be happy to rediscuss our observational results in a dynamical framework.

Immo Appenzeller: Landessternwarte, Königstuhl, D-6900 Heidelgerg, Federal Republic of Germany.