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MODELS FOR THE ATMOSPHERES OF T TAURI STARS

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ABSTRACT. A self-consistent picture of the atmospheres of T Tauri stars based on the solar analogy is gradually emerging. Theoretical models for the structure of these atmospheres indicate that they can be described in terms of a photosphere with a temperature rise above it, similar to the chromospheres found in the sun and other late-type stars, although with higher densities. In addition, the derived temperature profiles and the resulting fluxes, both in lines and in continua, are consistent with early and recent claims that the observed activity is produced by flares, spots and related type of surface inhomogeneities, as it is the case for other active stars. I review these indications, and explore in a preliminary way the energy requirements in the resulting atmospheres.

I. INTRODUCTION

T Tauri stars (TTS) are low mass stars ($M<2.5\ M_{\odot}$) in state of gravitational contraction toward the main sequence. They are identified (Herbig 1962) by characteristics of their optical spectrum, such as emission lines of Ca II, H, and He I, the fluorescent lines 4063 and 4131 of Fe I, and occasionally emission lines of Na I, Fe II, [O I], and [S II]. These emission lines appear superimposed on a late-type absorption spectrum corresponding to spectral types between middle G to middle M, although the absorption spectrum is absent, at least at low resolution, in the so-called "continuum" stars. Additionally, TTS show excess of continuum flux in the ultraviolet and in the infrared, first discussed in detail by Haro and Herbig (1955) and by Mendoza (1966, 1968), respectively. In this work, I will review the models constructed for the atmospheres of TTS, which have attempted to explain these emission characteristics.

II. FIRST MODELS

The composite character of the spectrum of TTS, showing both absorption and emission lines, suggested a model for their atmospheres consisting of a late-type photosphere surrounded by a hot region producing the emission. Accordingly, some of the first models presented included an extended hot region with velocity fields. The region was either in expansion, to reproduce the emission line profiles (Kuhi 1964; Kuan 1975), or static, to reproduce the general emission characteristics (Rydgren, Strom, and Strom 1976), or infalling. This last type of models was motivated by the discovery of the "YY Ori" stars (Walker 1972), which showed inverse P Cygni profiles in the higher lines of the Balmer series. Ulrich (1976) could reproduce observed line profiles with rotating infalling models. However, Ulrich did not include in his calculations the emission from the accretion disk which would necessarily form, and that omission casted doubts on his results (Ulrich 1978). In later years, Appenzeller and collaborators have found a number of examples of the YY Ori phenomenon. They have proposed a model in which the emission comes from the shock region produced by the material falling on the stellar photosphere (Appenzeller and Wolf 1977; Wolf, Appenzeller and Bertout 1977; Mundt 1979). However, no detailed spectrum calculation has been done yet. An appealing feature of this type of model is that it can account in a natural way for the source of energy for the emission with the kinetic energy of the infalling material.

It has been suggested that the YY Ori stars are the youngest among the TTS, still accreting mass from the parent cloud. However, the discovery of a molecular outflow around HL Tau (Calvet, Cantó, and Rodríguez 1983) powered by a stellar wind is not consistent with this hypothesis, since HL Tau is one of the youngest TTS known, as shown by its large infrared excess (Cohen 1973c; Cohen and Schwartz 1976), the presence of ice around it (Cohen 1975), and its position in the HR diagram (Cohen and Kuhi 1979).

Alternatively to the extended region, a type of model involving a region of small dimensions, $R \ll R_*$, was presented. Herbig (1970) proposed a solar chromosphere-like region, but with a deeper temperature minimum than in the solar case. Figure 1 shows schematically the temperature profile in this model. Weak lines form deep in the atmosphere and appear in absorption, while strong lines form in the temperature rise zone and appear in emission. Dumont et al. (1973) used a very schematic chromosphere-type model to reproduce the ultraviolet continuum and the flux in Hα, with some success. They also found that a deep temperature minimum was required. Gahm et al. (1974)

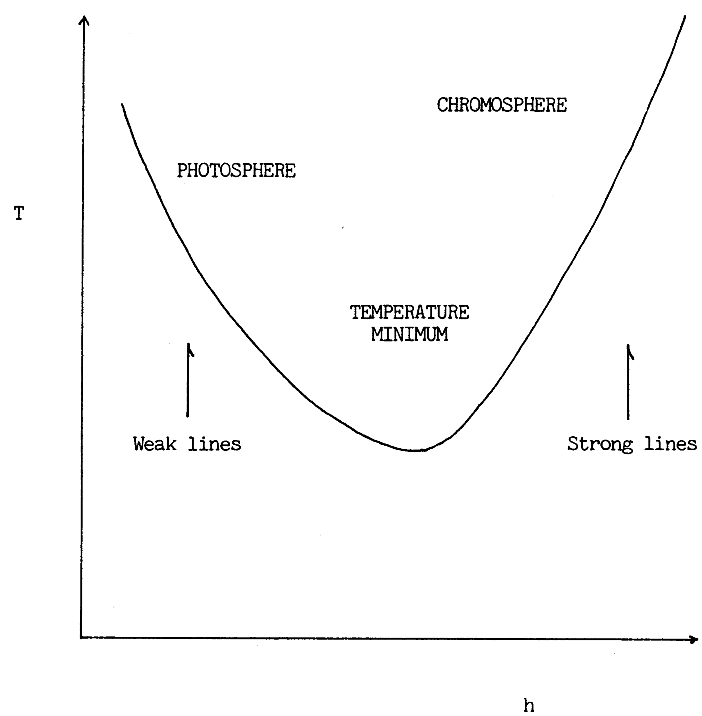

Figure 1. Schematic temperature profile showing temperature rise above the photosphere corresponding to the chromosphere. Arrows show regions where weak and strong lines form.

proposed an optically thin chromosphere with dust to explain the energy distribution of RU Lupi. Cram (1979) calculated model chromospheres in order to reproduce a number of spectral features of TTS. Cram could reproduce in general terms the flux in the Ca II lines, the ultraviolet continuum, and the absorption spectrum. However, he could not reproduce the observed range of flux in Hα and the Balmer decrement. Still, Cram's work demonstrated the feasibility of the chromospheric model for TTS.

In the following sections, I will discuss the atmosphere of TTS as consisting of a photosphere, a chromosphere, a transition region, a corona, and an extended region created by a wind. In addition, I will assume that TTS are in the quasi-static phase of the pre-main-sequence evolution and are located mostly along the conventional Hayashi track, as suggested by the observational evidence (Cohen and Kuhi 1979). I will summarize some recent developments within the framework of the adopted model for the atmosphere. From the observational point of view, I will mention the discovery of hot gas, indicative of the existence of a chromosphere, a transition region, and a corona. From the theoretical point of view, I will discuss recent model chromosphere and wind region calculations.

III. RECENT DEVELOPMENTS

The discovery of the existence of very hot gas in the atmosphere of TTS has been extremely important. UV spectra of TTS obtained with the IUE satellite have revealed emission lines of metals in high stages of ionization, as well as lines of He II (Appenzeller and Wolf 1979; Appenzeller et al. 1980; Brown et al. 1981; Gahm et al. 1979; Gondhalekar et al. 1980; Imhoff and Giampapa 1980, 1981). Lines of C IV and N V, with approximate temperature of formation of 1 x 10^5 and 2 x 10^5 ,respectively, indicate that gas at least at those temperatures is present in the atmospheres of TTS. The observed value for the UV line fluxes is of the order of 10^4 times the solar value. Cram, Giampapa, and Imhoff (1980) derive emission measures from UV observations, and conclude that the degree of non-radiative heating responsible for the UV emission line spectrum corresponds to that of a solar flare maintained over the whole surface.

Observations with the Einstein satellite have shown that at least for a number of TTS, the atmospheric gas reaches temperatures of order 10^6 K, emitting in X rays (Gahm 1980; Feigelson and DeCampli 1981; Walter and Kuhi 1981). In those stars for which X rays have been detected, the observations imply that the extension of the corona is small compared to the stellar radius. The detected X-ray luminosity is of the order of $\sim 10^{30}$ erg s^{-1}, $\sim 10^3$ the solar value. This enhancement is smaller than the enhancement observed in the UV lines, but it is still comparable to that of the most active K stars.

The question of the existence of 10^6 K gas in the stars with large equivalent width in Hα which, according to Walter and Kuhi (1981), are not detected in X rays still remains. The lack of detection may be an effect of absorption by an extended envelope, as suggested by Gahm (1980). However, it is interesting to notice that the enhancement over solar values is not the same for all

UV lines. Imhoff and Giampapa (1982) and Brown and Jordan (1982) note that the lines with the highest temperatures of formation are weak or absent in the most active TTS. This fact suggests that the maximum temperature in the atmosphere of these stars is $\sim 10^5$ K (Imhoff and Giampapa 1980). On the other hand, stars with a lower degree of activity have an extremely brigth UV emission line spectrum, which indicates that gas at high temperature exists in their atmospheres.

From the theoretical point of view, the determination of atmospheric structural parameters has been important. Semi-empirical homogeneous models have been constructed for the photosphere and chromosphere of TTS, accounting for the observed fluxes in Ca II K, Mg II k, Hα, the UV lines, and the continuum energy distribution (Calvet 1981; Calvet, Basri, and Kuhi 1983). The basic photospheric parameters used are T_{ef} = 4000K and log g = 3.5, which correspond to a typical T Tauri star in the Taurus-Auriga Cloud (Cohen and Kuhi 1979). In the construction of these models, the position of the temperature minimum is adjusted to reproduce the observed width of the Ca II K line. The transition region location, m_{TR}, is in agreement with densities determined from ultraviolet line fluxes (Cram, Giampapa, and Imhoff 1980) and is adjusted to produce fluxes in Ca II K and Mg II k comparable to observations. The most important results from this study are the following:

(1) The photospheric-chromospheric temperature profiles of TTS, shown in Figure 2, are characterized by a deep temperature minimum, in agreement with early estimates for the position of this minimum (Herbig 1970; Dumont _et al_. 1973)

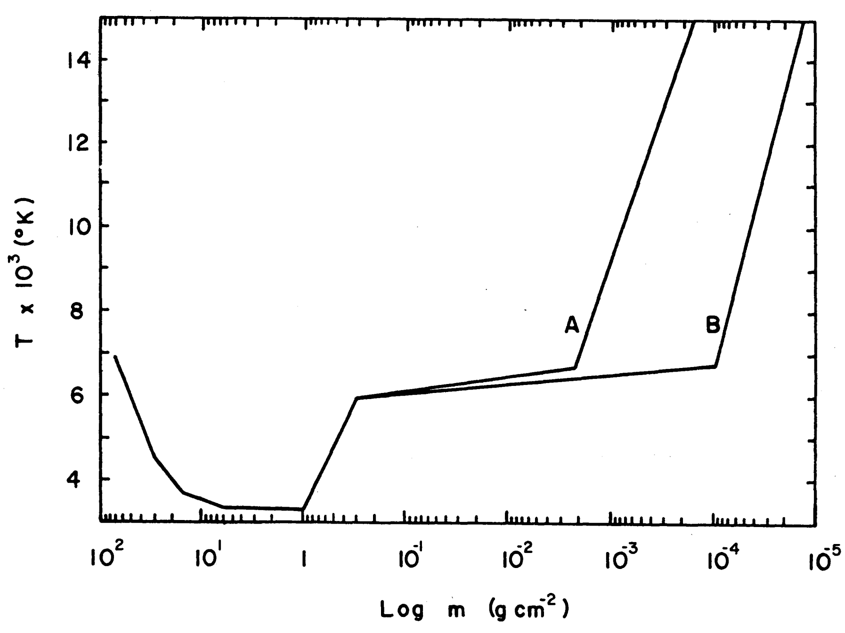

Figure 2. Temperature profiles for the photosphere and chromosphere for models A and B. m is the mass column density.

(2) The chromospheric temperature profile is characterized by a plateau at T~6000K, similar to that found for the sun (Vernazza, Avrett, and Loeser 1981), but less broad and extending to deeper column density. A steep temperature rise, marking the beginning of the transition region, follows this plateau. The semi-empirically determined photospheric-chromospheric temperature profile for TTS is similar to that found for solar active regions (Basri et al. 1979; Vernazza et al. 1981), solar flares (Machado and Linsky 1975), and stellar flares (Cram and Woods 1982).

(3) The continuum energy distribution of TTS is determined by both the photosphere and the chromosphere. A late-type photosphere has its maximum continuum flux at λ>8000A. Accordingly, the photospheric contribution of the flux dominates in the red region of the spectrum, unless the chromosphere has an extremely deep transition region. On the other hand, the photospheric flux in

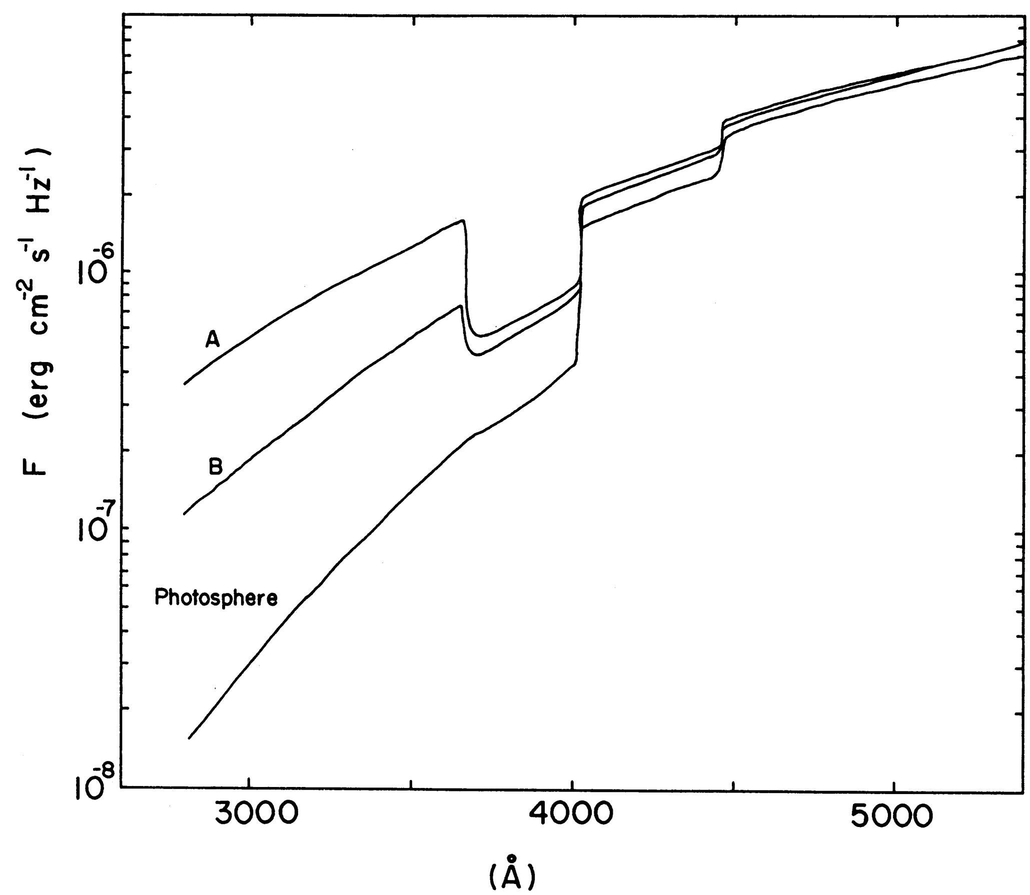

Figure 3. Continuum energy distribution for models A and B of Figure 2. The photospheric flux is also shown for comparison.

late-type stars falls sharply for λ<4500A, because of the effect of line blanketing. For this reason, radiation from the chromosphere becomes increasingly important as the wavelength decreases, creating an excess of flux over the normal photospheric level which could be identified with the "blue excess" observed in TTS. Because of the wavelength dependence of line blanketing, this excess is differential, increasing toward shorter wavelengths. Figure 3 shows this effect. The photospheric flux from

Carbon and Gingerich (1969) shows schematically the wavelength-dependent effect of line blanketing. The increasing importance of radiation from the chromosphere on the energy distribution toward smaller wavelengths is apparent in the fluxes produced by models A and B in the same Figure, with corresponding temperature profiles in Figure 2. This property is in agreement with the observed behavior of the blue excess (c.f. Kuhi 1974).

At infrared wavelengths, longer than $\sim 3\ \mu$, radiation from the chromosphere is dominant again. However, it cannot account for the IR excess observed in TTS (Mendoza 1966, 1968; Cohen 1973a, b,c,d; Cohen and Schwartz 1976; Rydgren, Strom, and Strom 1976; Rydgren and Vrba 1981). This excess must be due to thermal emission from a dust distribution around the star (Cohen and Kuhi 1979; Rydgren and Vrba 1981), as confirmed by the correlation existing between the IR excess and the degree of polarization (Bastien 1982), and the indication that the polarization arises from a dust distribution located outside the main emission-line region (Bastien and Landstreet 1979).

(4) The energy output from the chromosphere is determined mainly by the location of the beginning of the transition region. Moreover, changes in m_{TR} determine changes in the ultraviolet continuum flux which may account for the observed short-term variability.

(5) Neither the observed flux in Hα nor the steep Balmer decrement observed in TTS can be accounted for by the chromosphere, except in the case of the less active stars.

An important theoretical development has been the calculation of wind models for TTS. DeCampli (1981) has shown that the most viable mechanism for producing winds in TTS is the deposition of energy and momentum of Alfvén waves in their atmospheres. Hartmann, Edwards and Avrett (1982) have calculated the response of a late-type homogeneous atmosphere with parameters appropriate to TTS to the presence of a large flux of Alfvén waves. They found that:

(1) For wave fluxes corresponding to 0.1 to 1 stellar luminosities (assuming isotropy and $R_* \sim 2\text{-}3 R_\odot$) the deposition of energy and momentum of Alfvén waves in the upper atmospheres generates a wind with mass loss rates of the order of $\leq 10^{-8}\ M_\odot\ yr^{-1}$, in agreement with observations, within the uncertainties of the mass loss determination (DeCampli 1981).

(2) Alfvén waves dissipate over a length scale assumed equal to the stellar radius. The temperature in the wind reaches a maximum between 2.5 and 3 stellar radii and then decreases. The wind velocity attains its terminal value, ~ 250 km s^{-1} , at ~ 2 stellar radii. The maximum temperature of the wind decreases as the flux of energy in waves increases, while the mass loss increases. For instance, for values of the surface magnetic field of 500 and 250 Gauss, the maximum temperature reached by the wind is 1.4×10^4 K and 1.5×10^5 K, while the mass loss rate is 4.4×10^{-8} and $2.2 \times 10^{-9}\ M_\odot\ yr^{-1}$, for $R = 3\ R_\odot$.

(3) In contrast to chromospheric models, the wind region can produce equivalent widths and strengths in Hα comparable to observations. The large width in the Balmer lines originate in the fact that in the denser atmospheric regions the waves have large amplitudes, so that turbulent velocities may exceed the expansion velocity.

IV. INHOMOGENEOUS MODEL

In recent years, systematic studies of the photometric variability of TTS have been carried out gathering evidences in favor of an inhomogeneous atmosphere in these stars. I will review these and other evidences next.

Herbig and Soderblom (1980) note that the infrared Ca II triplet lines remain saturated in TTS even when the lines are weak relative to the continuum. They interpret this effect as a result of a varying relative emitting area between stars and not of a varying number of emitters. These results support the suggestion of Petrov and Shcherbakov (1976), Gershberg and Petrov (1976), and Gershberg (1977; 1982) that the surfaces of TTS are covered by spot-like regions and associated active regions.

If indeed the photosphere is covered by spots, we expect their number and size to change with time. In fact, Herbst, Holtzmann, and Phelps (1982) find that the stars they have followed photometrically get redder as they get fainter, for colors redder than U-B, and ocassionally than B-V. As the continuum flux is dominated by the photosphere in red wavelengths, even for the case of homogeneous models, the photometric behavior observed by Herbst et al. is consistent with spots in the surface. The quasi-periodic variability found in other type of stars and interpreted as evidence of the presence of spots in the surface may not be so noticeable in the case of TTS, since the large number of spots and the degree of activity expected may smear out the flux of individual spots.

The active regions would be responsible for the fluctuations in the U band found by Herbst et al. (1982) to be independent from the photometric variability at red wavelengths. In agreement with this interpretation, Worden et al. (1981), analyzing the power spectrum of the short-term fluctuations in the U band, find that these fluctuations can be interpreted in terms of a superposition of many solar-type flare curves, although the flare activity in TTS is more frequent and more energetic than in the sun. Worden et al. indicate that the flare power spectrum in TTS is very similar to that in UV Ceti stars.

We can use the results for the theoretical homogeneous models to interpret the active regions as zones where the bulk of the flux in the resonance lines of Ca II and Mg II, and the ultraviolet continuum are produced. These regions have temperature profiles characterized by deep temperature minimum and transition region similarly to the temperature profiles in flare-occurring regions in the sun and in flare stars, so that they can naturally be identified with flares. This interpretation is in agreement with the results of Worden et al. (1981).

It is appropriate to mention at this point that for nearly two decades Dr. Haro has suggested that there is a relation between UV Ceti stars, flare stars in young clusters and TTS (Haro 1956, 1968, 1976). As we have seen the observational results and theoretical interpretations that we have discussed so far are in full support of Dr. Haro's suggestion.

As pointed out by Giampapa et al. (1981), the large fluxes in the resonance lines of Ca II and Mg II in TTS imply that the rate of non-radiative heating in the atmospheres of these stars is extremely high, much higher than in any other type of active stars. If we assume that magnetic flux and chromospheric emission are related, as all evidences gathered for the sun and for active late-type stars seem to imply, then the atmospheres of TTS must be almost fully permeated by magnetic fields of variable strength. The evidence in favor of surface inhomogeneities and of flare activity discussed above supports this hypothesis. From the theoretical point of view, magnetic fields are expected to be generated in TTS according to the dynamo mechanism (Parker 1970), since these stars possess the conditions required for this mechanism to be effective, namely, convection and differential rotation. The location of TTS in the HR diagram implies that they are fully convective, according to conventional stellar structure calculations. Additionally, although TTS do not appear to have large rotational velocities (Vogel and Kuhi 1981), they may have a substantial degree of differential rotation left over from the collapse process (Terebey, Shu, and Cassen 1982). Also, TTS may have a large surface coverage of magnetic fields, as suggested by the approximate calculations of Durney and Robinson (1982), in which the relative surface area covered by magnetic regions increases with depth of the convection zone.

The large surface coverage of magnetic fields in TTS has many interesting implications. For instance, Alfvén waves carrying flux in proportion to the magnetic field strength can be generated by surface phenomena, such as granulation and supergranulation (Stein and Leibacher 1980). Depending on the field strength and surface velocities, the fluxes carried by these Alfvén waves could be of the order required by the wind models.

The actual geometry of the field lines is uncertain. Matter could escape along open field lines as a wind. However, hot gas may be trapped in closed field lines, from where most of the emission would arise (Rosner, Tucker, and Vaiana 1978). However, if this was the case, one would expect a large X-ray flux in the stars with higher degree of activity, contrary to observations. Hartmann et al. (1982) speculate that similar phenomena may happen in regions of open and closed field lines. Large amounts of momentum may be deposited in closed field line regions, extending the density distribution. The effect of radiative cooling would result in lower temperatures, as in the case of static chromospheres (Hartmann and MacGregor 1980).

V. ENERGY SOURCES

I want to discuss now briefly what energy sources are available to account for the large energy output in TTS. Herbig (1970) proposes that energy generated in the stellar convection zone could be responsible for the non-radiative heating of the atmosphere, in analogy with the solar case. As mentioned above, another source of energy, the kinetic energy of matter falling on the stellar surface, has also been proposed (Appenzeller and Wolf 1977; Appenzeller 1977; Bertout et al. 1982; Mundt 1979; Ulrich 1976; Walker 1972; Wolf, Appenzeller, and Bertout 1977).

The inhomogeneous model we have described suggests in a natural way an effective energy source. If the surfaces of TTS are almost fully permeated by magnetic fields, then the subphotospheric convection zone generates magnetohydrodynamic (MHD) waves, which are estimated to be a factor of ~100 more efficient in carrying energy than the acoustic waves that heat the quiet solar atmosphere (Stein 1981; Ulmschneider and Stein 1982). The waves that carry more flux into the atmosphere from the convection zone are the slow-mode MHD and the Alfvén waves. Calvet and Albarrán (1983) have estimated the expected flux in MHD waves entering the atmosphere of TTS, using approximate expressions for the wave flux from Stein (1981). Figure 4 compares this flux, calculated under the assumption of full surface coverage of magnetic fields, with energy losses estimated empirically from observations of TTS with different effective temperatures. The estimate of the energy loss from the atmosphere (above the photosphere) includes, in a very crude way, the radiation in ultraviolet, optical, and infrared emission lines, as well as the ultraviolet continuum and the X-ray emission. An estimate of the wind kinetic energy is also included. Theoretical fluxes in Figure 4 are calculated assuming a mean stellar luminosity for a given effective temperature, calculated from observed luminosities

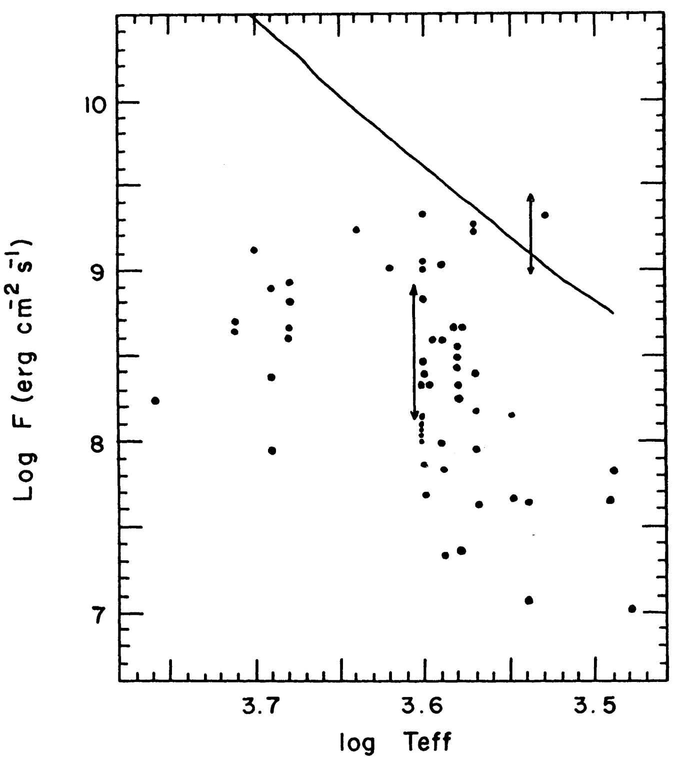

Figure 6. Comparison between energy loss in the outer atmosphere, above the photosphere, of T Tauri stars (dots) and flux input in MHD waves from the convection zone (continuous line). The wave flux is calculated for 1 $M_{\odot}$ and for full surface coverage of magnetic fields. Arrows show typical ranges of variability.

of stars in Taurus-Auriga (Cohen and Kuhi 1979).

Even taking into account that only a fraction of the energy input into the atmosphere is available for heating, the rest being lost by radiative damping, Figure 4 suggests that MHD waves from the convection region could account for the basic level of emission in TTS, if there was a large surface coverage of magnetic fields. Stars with energy loss much below the theoretical line could have a smaller fraction of the surface covered by magnetic regions, while stars with energy loss close to the the theoretical line could have additional sources of energy in surface phenomena, for instance in flares. In this sense arrows in Figure 4 show typical ranges of variability in TTS, in agreement with the hypothesis that transient surface phenomena could be responsible for the additional heating.

VI. SUMMARY AND FINAL COMMENTS

A picture is emerging for the atmospheres of TTS in agreement with claims made by investigators as Guillermo Haro and others during decades. According to this picture, the atmospheres of TTS are highly inhomogeneous with surfaces covered by spots and active regions. The rate of occurrence of flares is high, with flares dominating the emission in the most active stars and determining its large variability. Because of the large surface coverage of magnetic regions there is a substantial energy input into the atmosphere in MHD waves from the convection zone, which probably can account for the basic energy output in TTS. This energy input is accompanied by additional energy sources, including surface transient phenomena as flares.

The general picture presented here can account for the T Tauri phenomenon in a gross way. Nonetheless, many problems still need to be solved. For instance, we still need to determine if spectroscopic changes as the star varies in brightness are consistent with the spotted-surface hypothesis. We also have to understand local velocity fields which very likely are responsible for the line profile variabily, and in particular may explain the inverse P Cygni profiles observed mainly in the higher Balmer lines. In fact, much work still is to be done before one can say that these peculiar stars are fully understood.

REFERENCES

Appenzeller, I. 1977, Astr. Ap., 61, 21.

Appenzeller, I., and Wolf, B. 1977, Astr. Ap., 54, 713.

______. 1979, Astr. Ap., 75, 164.

Appenzeller, I., Chavarria, C., Krautter, J., Mundt, R., and Wolf, B. 1980, Astr. Ap., 90, 184.

Basri, G.S., Linsky, J.L.,Bartoe, J.-D.F., Brueckner, G., and Van Hoosier, M.E. 1979, Ap. J., 230, 924.

Bastien, P.A. 1982, Astr. Ap. Suppl., 48, 153.

Bastien, P.A., and Landstreet, I.D. 1979, Ap. J. (Letters), 229, L137.

Bertout, C., Carrasco, L., Mundt, R., and Wolf, B. 1982, Astr. Ap. Suppl., 47, 419.

Brown, A., Jordan, C., Millar, T.J., Gondhalekar, P., and Wilson, R. 1981, Nature, 290, 34.

Brown, A., and Jordan, C. 1982, in IAU Colloq. No. 71, Activity in Red Dwarf Stars, eds. M. Rodonó and F. Foggi (Catania Astrophysical Observatory).

Calvet, N. 1981, Ph.D. Thesis, University of California, Berkeley.

Calvet, N., and Albarrán, J. 1983 (in preparation).

Calvet, N., Basri, G. S., and Kuhi, L.V. 1983, Ap. J., 268, 739.

Calvet, N., Cantó, J., and Rodríguez, L.F. 1983, Ap. J., 267,

Carbon, D.F., and Gingerich, O. 1969, in Theory and Observations of normal stellar atmospheres, ed. O. Gingerich, (Cambridge: M.I.T. Press), p. 377.

Cohen, M. 1973a, M.N.R.A.S., 161, 85.
______. 1973b, M.N.R.A.S., 161, 97.
______. 1973c, M.N.R.A.S., 161, 105.
______. 1973d, M.N.R.A.S., 169, 257.
______. 1975, M.N.R.A.S., 173, 279.
Cohen, M., and Schwartz, R.D., M.N.R.A.S., 174, 137.
Cohen, M., and Kuhi, L.V. 1979, Ap. J. Suppl., 41, 743.
Cram, L.E. 1979, Ap. J., 234, 949.
Cram, L.E., Giampapa, M.S., and Imhoff, C.L. 1980, Ap. J., 238, 905.
Cram, L.E., and Woods, D.T. 1982, Ap. J., 257, 269.
DeCampli, W.M. 1981, Ap. J., 244, 124.
Dumont, S., Heidmann, N., Kuhi, L.V., and Thomas, R.N. 1973, Astr. Ap., 29, 199.
Durney, B.R., and Robinson, R.D. 1982, Ap. J., 253, 290.
Feigelson, E.D., and DeCampli, W.M. 1981, Ap. J. (Letters), 243, L89.
Gahm, G.F. 1980, Ap. J. (Letters), 242, L163.
Gahm, G.F., Nordh, H.L., Olofsson, S.G., and Carlborg, N.C.J. 1974, Astr. Ap., 33, 399.
Gahm, G.F., Fredga, K., Liseau, R., and Dravins, D. 1979, Astr. Ap., 73, L4.
Gershberg, R.E. 1977, Highlights of Astronomy, 4, 407.
______. 1982, in IAU Colloq. No. 71, Activity in Red Dwarf Stars, eds. M. Rodonó and F. Foggi, (Catania Astrophysical Observatory).
Gershberg, R.E., and Petrov, P.P. 1976, Sov. Astron. Lett., 2, 195.
Giampapa, M.S., Calvet, N., Imhoff, C.L., and Kuhi, L.V. 1981, Ap. J., 251, 113.
Gondhalekar, P.M., Penston, M.V., and Wilson, R. 1979, in First year of IUE, ed. A.J. Willis (London: University College), p. 781.
Haro, G. 1956, Bol. Obs. Tonantzintla y Tacubaya, 1, No. 14, 3.
______. 1968, in Stars and Stellar Systems, Vol 7, eds. B.M. Middlehurst and L.H. Aller (Chicago: University of Chicago Press), p. 141.
______. 1976, Bol. Inst. Tonantzintla, 2, 3.
Haro, G., and Herbig, G.H. 1955, Bol. Obs. Tonantzintla y Tacubaya, No. 12, 33.
Hartmann, L., and MacGregor, K.B. 1980, Ap. J., 242, 260.
Hartmann, L., Edwards, S., and Avrett, E. 1982, Ap. J., 261, 279.
Herbig, G.H. 1962, Adv. Astr. Ap., 1, 47.
______. 1970, Mem. Roy. Soc. Sci. Liège, Ser. 5, 9, 13.
Herbig, G.H., and Soderblom, D.R. 1980, Ap. J., 242, 628.
Herbst, W., Holtzman, J.A., and Phelps, B.E. 1982, A. J., 87, 1710.
Imhoff, C.L., and Giampapa, M.S. 1980, Ap. J. (Letters), 239, L115.
______. 1981, in The First Two Years of IUE, ed. R.D. Chapman, (NASA: Goddard Space Flight Center), p. 185.
______. 1982, SAO Special Report No. 392, p. 175.
Kuan, P. 1975, Ap. J., 202, 425.
Kuhi, L.V. 1964, Ap. J., 140, 1409.
______. 1974, Astr. Ap. Suppl., 15, 47.
Machado, M.E., and Linsky, J.L. 1975, Solar Physics, 42, 395.
Mendoza V., E.E. 1966, Ap. J., 143, 1010.
______. 1968, Ap. J., 151, 977.
Mundt, R. 1979, Astr. Ap., 74, 21.
Parker, E.N. 1970, Ap. J., 160, 383.
Petrov, P., and Shcherbakov, A. 1976, in Stars and Galaxies from the Observational point of view, ed. E.K. Kharadze, (Tbilisi: Abastumani Astrophysical Observatory), p. 163.
Rosner, R., Tucker, W.H., and Vaiana, G.S. 1978, Ap. J., 220, 643.
Rydgren, A.E., Strom, S.E., and Strom, K.M. 1976, Ap. J. Suppl., 30, 307.
Rydgren, A.E., and Vrba, F.J. 1981, A. J., 86, 1069.
Stein, R.F. 1981, Ap. J., 246, 966.
Stein, R.F., and Leibacher, J.W. 1980, in Stellar Turbulence, eds. D.F. Gray and J.L. Linsky (Berlin: Springer-Verlag).
Terebey, S., Shu, F.H., and Cassen, P.M. 1982, B.A.A.S., 14, 639.
Ulmschneider, P., and Stein, R.F. 1982, Astr. Ap., 106, 9.
Ulrich, R.K. 1976, Ap. J., 210, 377.
______. 1978, in Protostars and Planets, (Tucson: University of Arizona Press), p. 716.
Vernazza, J.E., Avrett, E.H., and Loeser, R. 1981, Ap. J. Suppl., 45, 635.
Vogel, S.N., and Kuhi, L.V. 1981, Ap. J., 245, 960.
Walker, M.F. 1972, Ap. J., 175, 546.
Walter, F.M., and Kuhi, L.V. 1981, Ap. J., 250, 254.
Wolf, B., Appenzeller, I., and Bertout, C. 1977, Astr. Ap., 58, 163.
Worden, S.P., Schneeberger, T.J., Kuhn, J.R., and Africano, J.L. 1981, Ap. J., 244, 520.

DISCUSSION

Rydgren: *(Comment)* The combined photometry of well-observed T Tauri stars show that colors such as *B-V* and especially *V-I* correlate quite well with V magnitude. However, the color versus V magnitude slopes are very different in different T Tauri stars. Our preliminary results suggest that the slopes tend to be smaller in the stars with stronger chromospheric emission. This seems to be understandable in terms of a differing mix of photosphere and plage regions.

Mundt: (*Comment*) I want to make a comment on the YY Orionis phenomenon. Among the T Tauri stars I found mass loss indications in the Na D lines about 70% (out of 11 stars) showed occasionally YY Ori profiles. Thus it seems that YY Ori phenomenon is most common among the high mass loss T Tauri stars. This might be interpreted in the following way: the descending material we see occasionally in T Tauri stars is matter ejected by the star (and not remnant star formation material).

Praderie: (*Comment*) The deep chromosphere model, originally suggested by Herbig, applies up to the range of Herbig Ae stars, as shown in the graduate work of Catala in Paris. By modelling the expanding envelope of the 10 000 K star AB Aur, Catala succeeds to reproduce the Mg II resonance lines P Cygni profile, but the emission part of the profile can be accounted for only if one assumes a chromosphere whose temperature reaches 15 000°K, and which is deep. The expanding chromosphere/envelope is very similar to the model of Bertout quoted by Appenzeller, except that no corona is requested in AB Aur. The mass loss rate is of the order of $10^{-9} M_{\odot}\,yr^{-1}$. Of course, the model has spherical symmetry. But we have observed large variabilities in the Mg II profile for AB Aur; this 2.5-3 $M_{\odot}$ star is very similar to T Tauri stars.

Herbst: A prediction of the spot model, I believe, would be that spectral types of T Tauri stars should be composite and become increasingly later as one moves further to the red spectral region. Is there any evidence for this?

Calvet: There has been some discussion in the literature on the difficulties of classifying T Tauri stars. In fact, systematic differences have been found among spectral types assigned by various authors working in different spectral regions, but I am not certain right now in what sense these differences go. It is a very interesting point worth pursuing.

S. Strom: Note that Joy and later Herbig noted for T Tauri stars a discrepancy between H-line (absorption) and metal absorption-line type. This suggests to me significant evidence for temperature inhomogeneities. Also, do you really wish to explain extreme cases such as RW Aur and HL Tau with a chromosphere model? If so, how do you put MHD "luminosity" equal to or greater than the photospheric luminosity?

Calvet: It is not very likely that extreme cases as those you just mentioned can be explained in terms of a plane-parallel chromosphere of small dimensions compared to the stellar radius, but a region with an extended density distribution should be invoked for them. In any case, for all the stars for which we calculated the energy loss from the atmosphere above the photosphere in the approximate empirical manner that I described, we found that this energy loss was smaller than the photospheric luminosity σT^4_{ef}.

Liseau: 1) What does a spot on a cool photosphere look like? 2) Would not regions consisting of dark spots block a substantial amount of flux due to molecular absorption, since the filling factors needed to explain the T Tauri variability by missing flux due to spots are fairly large? 3) How would you expect the chromospheric/TR emission to respond to spot activity? If you expect it to increase, then I want to mention the observation with *IUE* of the star RY Lupi (suspected "spot star" by Appenzeller in previous talk), where the star did not show this correlation, but rather was very faint in the FUV when faint in the V band.

Calvet: 1) A spot in a cool photosphere is a region on it, with lower effective temperature, in analogy with the solar case. Star spots have been reported before to explain the photometric variability, for instance, in RS CVn stars, which as a group include stars substantially cooler than the Sun. In these stars it has been suggested that spots from 400°K to 1200°K cooler than the surrounding photosphere can explain their light curves (Eaton and Hall 1979, *Ap. J.*, 227, 907). 2) Indeed, surface spots are expected to block a substantial amount of flux. As in the polar case, it may happen that this energy is transported out in a form different from convection or radiation, for instance, in waves. 3) In general terms, it is expected that spots would be associated with active regions and flares. However, the actual mechanism relating them is uncertain and no definite correlation exists. Even for the Sun, it is not clear if there is a physical mechanism connecting spots and flares, or if they appear related because both originate in regions of strong magnetic fields.

Walter: (*Comment on question on spots*) Spots are well established in RS CVn stars (K0) and BY Dra stars (K7-M0). Spots are ∿ 1000°K cooler than the photosphere. Spots on T Tauri stars probably look similar.

Appenzeller: You mentioned a relation according to which the fully convective T Tauri stars are expected to be totally covered by magnetic fields. In this case, I see two problems: 1) You do not have spots as the surface will be uniformly darkened. 2) I find it difficult to imagine a field geometry where the whole surface is covered by flux tubes. How certain is the above prediction?

Calvet: 1) Even in the case of full surface coverage of magnetic fields the stellar surface will not necessarily be uniformly darkened, as one expects a distribution of spot sizes and temperatures related to a distribution of magnetic field strength. 2) I mentioned in the talk the derivation of Durney and

Robinson (1982), according to which the fractional surface coverage of magnetic fields increases with depth of the convection zone. These calculations are very approximate and are only suggestive of the real situation. In particular, the field geometry is not known at all.

Basri: Filling factors are determined either by scaling different activity diagnostics from quiet and active Sun data (Giampapa *et al.* 1982) or more directly through magnetic field observations with the Robinson technique (Marcy 1982). A filling factor one is usually meant to indicate almost complete coverage of the star by active regions -such regions may themselves only have true flux tube filling factors of 50%.

Giampapa: (*Comment*) I have observed M dwarf stars, later than M 5.5, and therefore fully convective yet do not see any Hα emission or only weak absorption. Thus the onset of full convection does not guarantee a high level of magnetic field-related chromospheric activity.

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