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ENERGY SOURCES OF T TAURI STARS

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RESUMEN

Hemos estimado empíricamente la pérdida total de energía de las regiones atmosféricas localizadas sobre la fotosfera en estrellas T Tauri. Hemos también estimado la entrada de flujo de energía en la atmósfera en ondas magnetohidrodinámicas (MHD) producidas en la zona convectiva subfotosférica. Dentro de las incertidumbres tanto teóricas como observacionales, este flujo parece representar la entrada básica de energía en la atmósfera, siempre que las estrellas T Tauri posean una alta cobertura superficial de campos magnéticos. Además de esta entrada básica de energía producida en la zona convectiva, las estrellas T Tauri deben contar con otras fuentes de energía, cuyo origen esté localizado en la superficie estelar. Entre estas fuentes están el flujo de energía llevado por ondas de Alfvén, producidas por la acción de movimientos de materia sobre tubos magnéticos, así como disipación y aniquilación de campos magnéticos en eventos ráfaga. El decrecimiento de flujos en líneas de emisión con luminosidad estelar parece indicar que las ondas MHD calientan la cromosfera, mientras que las zonas superiores de la atmósfera requieren de una fuente adicional de calentamiento.

ABSTRACT

We have empirically estimated the total energy loss from the atmospheric regions above the photosphere in T Tauri stars. We have also estimated the flux input into the atmosphere by magnetohydrodynamic (MHD) waves produced in the subphotospheric convection zone. Within the uncertainties of both theory and observations, this flux seems to represent the basic energy input into the atmosphere provided that a large surface coverage of magnetic regions exists. In addition to this basic energy input from the convection zone the T Tauri atmospheres must have other energy sources, originating in the stellar surface. Among those we can include the flux of energy carried by Alfvén waves resulting from the action of surface material motions on magnetic flux tubes, as well as dissipation and annihilation of magnetic fields in flare events. The observed decrease in emission line fluxes with luminosity seems to indicate that MHD wave fluxes heat the chromosphere, while the uppermost atmospheric regions require another source of heating.

Key words: **STARS-T TAURI – STARS-ATMOSPHERES – STARS-CHROMOSPHERES – STARS-FLARE – STARS-PRE-MAIN-SEQUENCE**

I. INTRODUCTION

T Tauri stars (TTS hereafter) have large rates of nonradiative energy input into their atmospheres. Evidence for this fact are the fluxes in the resonance lines of Ca II and Mg II, a factor of 10 higher than those in the most active stars of any other type (Giampapa *et al.* 1981); the large fluxes in the Balmer lines, especially in Hα (Kuhi 1974; Cohen and Kuhi 1979); the ultraviolet line fluxes, which are factors of 10^3 to 10^4 higher than the solar values (Appenzeller and Wolf 1979; Appenzeller *et al.* 1980; Imhoff and Giampapa 1980, 1981); the large ultraviolet continuum excess (Walker 1972; Kuhi 1974; Rydgren, Strom, and Strom 1976); and the X-ray luminosity, low when compared to the luminosity expected from the ultraviolet line enhancement (Gahm 1980; Feigelson and DeCampli 1981; Walter and Kuhi 1981), but still of the same order as that of active K stars (Walter 1981, 1982). The source of this energy in excess to that corresponding to a late-type subgiant photosphere has been discussed only qualitatively. Herbig (1970) proposes that the energy would originate in the stellar convection zone, in analogy with the solar case. Alternatively, other authors favoring the accretion model put the origin of the excess energy in the kinetic energy of infalling matter on the stellar photosphere (Walker 1972; Ulrich 1976; Appenzeller and Wolf 1977; Wolf, Appenzeller, and Bertout 1977; Appenzeller 1977; Mundt 1979; Bertout *et al.* 1982).

In recent years, a great deal of information has been gathered for active stars of late spectral type. A rotation-activity connection has been established observationally (Ayres and Linsky 1980; Walter and Bowyer 1981), and the present consensus favors a magnetic origin for this connection. Rotation interacts with convective motions in late-type stars to give rise to differential rotation (Gilman 1979), which in turn, interacts with the convective motions to generate magnetic fields, according to the dynamo mechanism (Parker 1970). The presence of mag-

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netic fields enhances the energy production in the convection zone, and consequently the energy input and energy losses from the atmosphere.

In non-magnetic regions in the stellar convection zone below the surface, acoustic waves are generated; these waves dissipate in the lower atmosphere accounting for the quient chromosphere energy losses (Ulmschneider *et al.* 1977, 1978; Schmitz and Ulmschneider 1980*a, b,* 1981). In magnetic regions of the convection zone, on the other hand, magnetohydrodynamic (MHD) waves are generated (Stein 1981); their production mechanism is monopolar in nature so that the generated power is considerably higher than that for acoustic waves (Stein 1981; Ulmschneider and Stein 1982). This difference in energy output between magnetic and non-magnetic region has led Stein (1981) and others to suggest that the spread of a factor of 10 in the observed energy loss among stars of similar type (Basri and Linsky 1979) could be accounted for by differences in the surface coverage of magnetic regions.

For TTS to be consistenly described as "an extreme example of the active chromosphere stars" (Giampapa *et al.* 1981), the ultimate origin of their energy output must be similar to that in other active stars, although "amplified" in some manner. We then expect that magnetic field strength and surface coverage play a crucial role in the generation of the radiated energy in TTS. Unfortunately, neither of these quantities is easy to measure, especially in the faint TTS, nor theoretical calculations are advanced enough to allow their determination from first principles. However, a number of indications indirectly suggest that indeed TTS are characterized by large magnetic field strength and surface coverage.

Most TTS are located along the convective path of pre-main-sequence evolutionary tracks (Cohen and Kuhi 1979), and therefore are expected to have deep convection zones. Vogel and Kuhi (1981) find an upper limit of 35 km s^{-1} for the rotational velocities of TTS, although they cannot measure the velocities of the most active TTS and cannot discard the possibility of these stars having large rotational velocities. Even more important, a substantial degree of differential velocity is expected to be present at least in the youngest among the TTS, as a result of the accretion process during the hydrodynamical collapse of a slightly rotating cloud (Terebey, Shu, and Casen 1984; Shu and Terebey 1984). The two basic conditions to strongly amplify the magnetic field present in the star by the dynamo mechanism are a deep convection zone and a large degree of differential rotation. Therefore, we would expect TTS to be characterized by large magnetic field strengths and surface coverage. Similarly to other type of active stars, TTS then may be expected to have a large energy input into the atsmosphere in the form of MHD waves generated in the convection zone. In this paper, we investigate this possibility in a quantitative way, within the uncertainties set by both observation and theory. In section II, we discuss the energy sources in the form of waves available to TTS. In section III, we estimate the energy losses in the outher atmospheres of these stars and compare them with the expected energy input in waves, and finally, in section IV we discuss our results and give conclusions.

II. SOURCES OF ENERGY

Stein (1981) among others has discussed the generation of mechanical energy in stellar subphotospheric convection zones. The Reynolds number in these zones is much higher than unity, implying that they are turbulent. In turn, turbulence generates waves, which carry away a small fraction of the energy of the turbulent eddies. The process of generation of acoustic waves in a turbulent uniform medium was originally studied by Lighthill (1952, 1954) and Proudman (1952), while the generation of waves in a turbulent medium in the presence of a magnetic field was studied by Kulsrud (1955), Parker (1964), and Kato (1968). In regions where magnetic fields are absent, the main emission is quadrupolar, because of the isotropic character of the emitted acoustic waves. On the other hand, in regions where strong magnetic fields are present, the emission of Alfvén waves and slow mode MHD waves is mainly monopolar, since these waves are restricted to propagate along the field lines (Stein 1981), resulting in an increase in radiated power relative to the case of acoustic waves. Ulmschneider and Stein (1982) estimate total energy output, and gravity and effective temperature dependences for the mechanical flux in waves generated in the convection zone, and compare them with observations of the energy loss in stars of active chromosphere. Their results suggest that in non-magnetic regions the heating of the chromosphere occurs mainly by acoustic waves, in agreement with previous estimates (Schmitz and Ulmschneider 1981, and references therein). In regions of strong magnetic fields slow MHD waves, which dissipate as acoustic waves, could produce the heating of the chromosphere, while Alfvén waves could be responsible for the heating of the uppermost atmospheric regions. The average wave energy input into the atmosphere depends on the fractional area covered by magnetic fields (Stein 1981). In this section, we will consider the application of the Ulmschneider and Stein results to TTS; first, however, we will make some general comments on the evolutionary stage of TTS.

a) *Evolutionary Considerations*

TTS occupy a region in the HR diagram very similar to that occupied by low mass stars approaching the red giant region. In fact, the question has been asked as to why TTS have emission characteristics so different from those of post-main sequence subgiant stars (Lago 1982). Implicit in this question is the assumption that according to the Vogt-Russell theorem, the similarity of location in the HR diagram of both types of stars would imply identity of internal structure. The Vogt-Russell theorem

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applies to stars which are similar in mass and chemical composition, and are in hydrostatic and thermal equilibrium (Cox and Giuli 1968). TTS are pre-main-sequence stars and as such are chemically homogeneous throughout, meanwhile post-main-sequence subgiants have already gone through the main sequence phase and possess an inert helium core surrounded by a hydrogen-burning shell. Subgiant stars get their energy from the nuclear reactions taking place in the hydrogen-burning shell, while pre-main-sequence stars lack significant nuclear energy sources and the energy they must radiate in order to keep in a state of quasi-static equilibrium comes primarily from gravitational contraction. This, in turn, implies that they evolve in Kelvin time-scales and are not in thermal equilibrium, so that the Vogt-Russell theorem is not applicable to their case.

The question discussed above casts doubt on the applicability of published estimates of mechanical energy output in waves from the convection zone to the case of stars which are not in thermal equilibrium. However, as the following considerations show, these energy calculations are still valid in this case because wave generation occurs in a thin layer at the top of the convection zone (Renzini *et al.* 1977). A typical time-scale in this region is the eddy turn-over time, given by $t_c \sim \ell/v$. With ℓ, a typical scale, taken as the pressure scale height, $\sim 10^9$ cm, and v, the convective velocity, as ~ 1 km s^{-1}, we obtain a time scale for the envelope of $\gtrsim 10^4$ s, much smaller than the Kelvin time, which typically is 10^7 y. Then, the same equations are valid in the outer envelopes of pre- and post-main-sequence stars, having as conditions the constant values of gravity, g, and effective temperature, T_{eff}. Hence, we expect the outermost envelopes of pre- and post-main-sequence stars of comparable g and T_{eff}, in particular the sites where mechanical energy is generated, to be similar. This discussion indicates that mechanical energy generation calculations for stars in thermal equilibrium could also be applicable to the case of TTS. However, we have not taken into account the role that magnetic fields may play in inhibiting convection, and changing the internal structure. Magnetic fields are expected to be different in pre- and post-main-sequence stars because, of the higher differential rotation expected in pre-main-sequence stars among other factors (Shu and Terebey 1984).

b) *Mechanical Flux Input from the Convection Zone*

Ulmschneider and Stein (1981, US hereafter) give approximate expressions for the mechanical flux carried away by waves generated in the convection zone. These include acoustic waves produced by quadrupolar emission in non-magnetic regions Alfvén and slow mode MHD waves generated by monopolar emission and fast mode MHD waves generated by quadrupolar emission in magnetic regions.

The expressions given by US are highly approximate. A comparison between acoustic fluxes given by US and those by Renzini *et al.* (1977) obtained with a detailed envelope calculation but still using the mixing-length theory, indicates that US fluxes are a factor of ~ 50 higher than those of Renzini *et al.* There are other considerations that indicate that the US fluxes are overestimates. US assume in their calculation that convection is very efficient, so that the total flux carried by convection, F_c, is equal to $\sigma\, T_{eff}{}^4$. At the same time, they take $F_c \sim \rho\, v^3$, and equating these two expressions, they obtain the convective velocity. However, convection first sets in the stellar envelope, going inwards, when $\nabla_r \sim \nabla_{ad}$, where ∇_r and ∇_{ad} are the radiative and the adiabatic gradients. Then a "transition region" follows (Cox and Giuli 1968, Chapter 20) where convection is very inefficient. In this region the true temperature gradient ∇ first follows ∇_r, then switches to ∇_a at the end of the region. When $\nabla \sim \nabla_a$, convection becomes efficient and the transition region ends. According to the mixing-length theory, $v \propto (\nabla - \nabla')^{1/2} \sim (\nabla - \nabla_a)^{1/2}$, where ∇' is the temperature gradient in the convective element. The convective velocities will then be large at the beginning of the transition region, and become very small at its end. Correspondingly, the mechanical power will be highest at the beginning of the transition region, where convection is very inefficient and $F_c << \sigma\, T_{eff}{}^4$. The procedure used by US then overstimates the values of convective velocities, and therefore of the mechanical flux. The correct values for the acoustic fluxes are then probably closer to those by Renzini *et al.* (1977). An appropriate calculation of F_c requires application of a theory for convection to each case and will not be made here.

The expressions given by US for the mechanical power carried by other types of waves are also likely to be overstimates for similar reasons. Hence, we will not use the expressions for the absolute mechanical fluxes given by US. Instead, we assume that their temperature and gravity dependences are approximately correct and estimate absolute fluxes scaling from solar values. We also neglect in this work the mechanical flux carried by acoustic and fast mode MHD waves, since they represent a much less efficient energy input into the photosphere than slow mode and Alfvén waves (US).

According to Stein (1981), two cases can be distinguished depending on the importance of the kinetic energy of the turbulent eddies as compared to the magnetic energy. If the kinetic energy of the turbulent motions is higher than the magnetic energy, then in the expression for the power carried by waves is (Stein 1981)

$$P \sim \left(\epsilon\, (k\ell)^{2n+1}\right) / \; \tau \; ; \qquad (1)$$

where ϵ, the energy density of the turbulent motions, is given by

$$\epsilon \sim \rho u^2/2 \quad , \qquad (2)$$

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where u is the mean velocity of the turbulent element and ρ the density. In contrast, in the opposite case,

$$\epsilon \sim B^2/8\,\pi \; . \tag{3}$$

Stein (1981) refers to the two cases characterized by conditions (2) and (3) as of weak and strong fields, respectively. However, strong fields are needed in both cases to channel Alfvén and slow mode waves. Indeed, if $v_A >> v_s$, where v_A and v_s are the Alfvén and sound velocity respectively, then slow mode waves have propagation velocity $v = v_s \cos\theta$, where θ is the angle between the propagation direction and the field direction. Therefore, in this case slow mode waves behave as sound waves restricted to move around the field lines. Cases characterized by equations (2) and (3) are better described, then, as of strong and weak turbulence.

It is to be noticed that in the case of strong turbulence, the conditions $v_A > v_s$ and $(1/2)\,\rho\, u^2 > B^2/4\,\pi$ imply that $u > v_s$. Calculations within the framework of the mixing-length theory, with $\alpha = 1$, indicate that $u < v_s$ for envelope parameters consistent with TTS (Renzini *et al.* 1977). Since the case of strong turbulence appears to describe better the observations, as it is described below, one could argue that a value of the mixing-length parameter α larger than the standard value of 1 would be more appropriate for the case of pre-main-sequence objects.

By equipartition arguments Stein (1981) finds that the background magnetic field scales roughly as $g^{0.3}T^{-1.5}$, so that the Alfvén wave flux and the slow mode wave flux for equipartition fields behave similarly. Scaling from solar values and using values for g and T_{eff} appropriate for TTS, the US expressions for the wave flux can be written in the case of equipartition fields as

$$\frac{F_w}{F_\theta} \sim 0.16 \left(\frac{g}{3.5 \times 10^3}\right)^{-0.2} \left(\frac{T_{eff}}{4\,000}\right)^{6.2} \tag{4}$$

for strong turbulence, and

$$\frac{F_w}{F_\theta} \sim 0.07 \left(\frac{g}{3.5 \times 10^3}\right)^{-0.6} \left(\frac{T_{eff}}{4\,000}\right)^{10.5} \tag{5}$$

for weak turbulence.

These expressions correspond to the flux per unit area produced in magnetic regions on the stellar surface. However, we are interested in the average wave energy flux which gives the average mechanical energy input into the atmosphere, and is to be compared with the observed flux output from the atmosphere. This average flux is the sum of all the possible energy flux inputs per unit area, acoustic or MHD, weighted correspondingly by the fraction of the stellar area free from magnetic fields or covered by them. We will assume that the bulk of the emission comes from magnetic regions, so that we can write $F_{av} \sim f\, F_w$, where f is the fractional surface area covered by magnetic flux tubes, and F_w, given by equations (4) and (5), is the flux carried by MHD waves produced in that area. The average flux is then given by

$$\frac{F_{av}}{F_{\theta,\,av}} \sim 0.16 \,\frac{f_*}{f_g} \left(\frac{g}{3.5 \times 10^3}\right)^{-0.2} \left(\frac{T_{eff}}{4\,000}\right)^{-6.2} \tag{6}$$

for strong turbulence, and

$$\frac{F_{av}}{F_{\theta,\,av}} \sim 0.07 \,\frac{f_*}{f_\theta} \left(\frac{g}{3.5 \times 10^3}\right)^{-0.6} \left(\frac{T_{eff}}{4\,000}\right)^{-10.5} \tag{7}$$

for weak turbulence.

III. APPLICATION TO T TAURI STARS

a) *Energy Losses*

In order to compare the theoretical energy input with observations we need to have an estimate of the energy loss in the atmospheres of TTS. To do this, we need to add the energy lost in all possible forms, which includes emission lines, continuum emission and wind.

It is difficult to obtain a reliable estimate for the total energy lost in the outer atmospheres (above the photosphere) of TTS. The list of problems is long and well known, and includes uncertainties in the determination of stellar parameters and reddening, as well as scarcity of a complete set of data for individual stars and lack of simultaneity of observations in different spectral regions. Despite all these problems, we have attempted to obtain that estimate using data from a large number of stars in the Taurus-Auriga Complex, expecting to reduce the errors by having a large sample. However, we are still forced to make a number of assumptions for which the real justification is that they represent the best we can do at the present stage of knowledge.

We first estimate the flux radiated away by emission lines, which form either in the stellar chromosphere, or in the extended region around the star (Calvet 1981; Giampapa *et al.* 1981; Hartmann *et al.* 1982; Calvet, Basri, and Kuhi 1984). We have taken data from the following sources: (a) fluxes for Hα, Hβ, Hγ, He I λ5876, Fe II λ4923, as well as stellar data from Cohen and Kuhi (1979); (b) Mg II k fluxes from Giampapa *et al.* (1981), reduced to surface fluxes with the adopted stellar values; (c) Ca II K fluxes from Giampapa *et al.* (1981) and from Kuhi (1974); (d) ratios of fluxes for Pγ, Pβ, He I λ10830, and the Ca II infrared triplet to the flux in Hα, measured in the same observing run, from

TABLE 1

ADOPTED STELLAR DATA FOR THE CONTINUUM STARS IN TAURUS-AURIGA

Star	T_{eff}	A_V	log $L/L_\odot$
RW Aur	4 955^a	0.33	0.74
DG Tau	3 960	1	0.88
DL Tau	4 000^b	1.8	0.17
DR Tau	3 960	1.9	0.69
HL Tau	3 960^{b,c}	5^d	0.64

a. Mundt and Giampapa 1982.
b. Herbig (1977).
c. Cohen and Kuhi (1979).
d. Cohen and Schmidt (1982).

Kuhi (1974); (e) *UV* line fluxes from Appenzeller and Wolf (1979), Appenzeller *et al.* (1980), Brown *et al.* (1981), Gahm *et al.* (1979), Gondhalekar, Penston, and Wilson (1979), and Imhoff and Giampapa (1980, 1981). Cohen and Kuhi (1979) do not give information on the stellar parameters of the stars that appeared as "continuum" stars at the time of their observation. Several of the stars classified as "continuum" stars by some observers have had absorption lines visible in their spectrum in another observation. Generally, the corresponding spectral type has turned out to be late, as in the case of CI Tau, DO Tau and XZ Tau. In Table 1, we give the adopted stellar data for the continuum stars. The spectral types are taken from published data (references in the table) when available, or as K7-M0 otherwise. The reddening correction has been determined from published *V–R* colors (Cohen 1973 *a,b,c*; Cohen and Schwartz 1976; Rydgren, Strom, and Strom 1976) and intrinsic *V–R* colors from Johnson (1966). This procedure assumes that the *V* and *R* magnitudes are affected slightly by the chromosphere and nearly correspond to the colors of the stellar photosphere, as suggested by the continuum calculations in theoretical models for the chromosphere and the photosphere of TTS (Calvet 1981; Calvet Basri and Kuhi 1984). For DG Tau we adopt $A_V = 1$, because this procedure gives an abnormally low value for A_V. We also have used $A_V = 1$ for XZ Tau, instead of the value given by Cohen and Kuhi (1979), as indicated by its *V–R* color.

In Table 2 we give a list of the stars studied, the Hα flux values and the ratio of the flux in emission lines to Hα, from the sources mentioned above. For the *UV* lines, we give the ratio of the sum of the flux radiated in all the lines to Hα. We also give the ratio of the sum of the flux in all the Fe II lines to Hα. This value has been estimated from the observed fluxes in all the optical Fe II multiplets scaled to the line λ4923 of multiplet 42 in the spectrum of DG Tau (Cohen and Calvet, unpublished). In order to obtain the total energy loss in emission lines from the outer atmospheres of TTS we use the following procedure. For a given emission line (or sum of emission lines), we take the mean value of the ratio of the line flux to Hα for the stars in Table 1 for which it is available. We then assume that this mean gives us a good estimate for the true ratio in any T Tauri star. Adding up the ratios to Hα for all the emission line fluxes and multiplying this sum by the flux in Hα we get an estimate for the total energy loss in emission lines for each star. The mean values for the ratio of line flux to Hα are given in Table 3. In this procedure, we assume that there is a relationship between the flux in Hα and the flux in

TABLE 2

EMISSION LINE FLUXES^a

		Fluxes relative to Hα									
Star	Hα^b	Hβ	Hγ	Paschen	Ca II *UV*	Ca II *IR*	Mg II	He I 5876	He I 10830	Σ Fe II	Σ *UV*
SU Aur	1.9 + 7	...	...	...	0.05	0.15	0.24	...	...	...	...
T Tau	4.0 + 7	0.18	0.06	0.25	0.15	0.24	6.6	0.01	0.13		1.03
RY Tau	4.6 + 7	...	...	0.61	...	0.22	...	0.01	0.14	...	...
RW Aur	1.2 + 8	0.09	0.03	0.13	0.18	1.50	4.4	0.02	...	0.4	0.11
UX Tau A	7.5 + 6	...	...	0.34	...	0.76	...	...	0.03	...	...
IS Tau	2.0 + 7	...	...	...	...	...	...	...	...	...	...
LKαH 327	7.3 + 7	0.20	0.10	...	...	...	...	0.03	...	...	...
HP Tau	3.9 + 7	0.17	0.05	0.04	...	...	...	0.04	...	...	...
DS Tau	6.7 + 7	0.22	0.13	...	...	...	...	0.02	...	...	...
HN Tau	7.7 + 7	0.21	0.06	...	...	...	...	0.03	...	0.3	...
DR Tau	1.6 + 8	0.20	0.01	1.03	0.03	0.83	0.24	0.05	...	0.04	0.23
UZ Tau F	1.0 + 7	0.15	0.08	0.17	0.77	0.81	...	0.01	0.02	...	...
VY Tau	6.2 + 6	0.19	0.11	...	10.3	5.9	...	...	2.34	...	...
DF Tau	4.4 + 7	0.35	0.31	0.08	0.07	...	1.8	0.04	...	...	...
DO Tau	2.0 + 7	0.15	0.07	...	0.28	...	...	0.01	...	0.20	...
AA Tau	9.1 + 7	0.23	0.09	...	0.78	...	...	0.03	...	0.10	...
DG Tau	1.5 + 7	0.12	0.04	...	0.18	2.8	0.32	0.03	0.14	0.20	...
DK Tau	9.5 + 6	0.17	0.13	...	0.85	...	...	0.04	...	0.10	...

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TABLE 2 (CONTINUED)

Star	Hα[b]	Fluxes relative to Hα									
		Hβ	Hγ	Paschen	Ca II *UV*	Ca II *IR*	Mg II	He I 5876	He I 10830	Σ Fe II	Σ *UV*
GH Tau	4.0 + 6	0.07									
BP Tau	1.3 + 7	0.26	0.20	0.01	0.37	0.04	3.2	0.02	...	0.10	...
HK Tau	2.7 + 7	0.10	0.04								
UY Tau	2.0 + 7	0.23	0.13	...	...	...	...	0.02	...	0.20	...
GO Tau	9.7 + 7	0.26	0.23	...	...	...	...	0.02	...	...	...
GK Tau	8.5 + 6	0.20	0.16	...	...	...	...	0.05	...	...	...
DI Tau	2.0 + 6	0.25	...	...	...	...	...	...	...	...	...
CI Tau	6.0 + 7	0.21	0.08	...	0.28	...	...	0.03	...	0.40	...
HO Tau	3.2 + 7	0.22	0.11	...	...	...	...	0.04	...	0.10	...
CY Tau	1.5 + 7	0.19	...	...	...	...	...	0.03	...	0.10	...
FM Tau	2.8 + 7	0.22	0.12	...	...	...	...	0.01	...	0.04	...
DL Tau	2.0 + 8	0.13	0.05	...	0.24	...	...	0.03	...	0.30	...
CZ Tau	4.1 + 6	...	...	...	...	...	...	...	...	...	...
DP Tau	1.9 + 7	0.15	0.07	...	...	...	...	0.01	...	0.10	...
DH Tau	3.5 + 7	0.32	0.18	...	1.43	...	...	0.07	...	...	...
DD Tau	1.6 + 8	0.25	0.27	...	...	...	...	0.03	...	0.10	...
IQ Tau	2.1 + 6	0.29	0.21	...	...	...	...	...	...	...	...
DN Tau	8.8 + 6	0.22	0.01	...	0.31	...	...	...	...	0.30	...
GG Tau	2.2 + 7	0.23	0.12	...	...	...	...	0.07	...	0.10	...
DM Tau	4.2 + 7	0.10	0.06	...	...	...	...	0.02	...	0.02	...
HL Tau	3.6 + 7	0.21	0.10	...	...	...	...	0.04	...	0.50	...
DE Tau	1.3 + 7	0.20	0.08	...	...	...	...	0.02	...	0.10	...
DQ Tau	2.6 + 7	0.14	0.08	...	0.05	...	...	0.02	0.05	...	...
V410 Tau	6.7 + 6	...	...	...	...	...	...	...	...	...	...
GM Aur	1.0 + 8	0.09	3.-3	...	...	...	...	0.01	...	...	...
LK Hα 266	8.4 + 6	0.20	0.10	...	...	...	...	0.01	...	...	...
FX Tau	2.3 + 7	0.11	...	...	...	...	...	...	...	...	...
LK Hα 328	1.6 + 8	0.14	0.03	...	...	...	...	...	...	...	...
UX Tau B	3.6 + 6	0.15	...	...	...	...	...	...	...	...	...
UZ Tau P	2.5 + 7	0.18	0.10	...	...	...	...	0.02	...	0.30	...
Haro 6-37	9.2 + 7	0.12	0.05	...	...	...	...	...	...	...	...
XZ Tau	1.6 + 8	0.29	0.13	0.44	...	3.5	...	0.02	...	0.20	...
FN Tau	4.5 + 6	0.15	...	...	...	...	...	...	...	...	...
CX Tau	9.9 + 6	0.19	...	...	...	...	...	...	...	...	...
FP Tau	5.9 + 6	...	...	...	...	...	...	...	...	...	...
LK Hα 331	9.3 + 5	...	...	...	...	...	...	...	...	...	...

a. Sources given in the text.

b. Hα fluxes in erg cm^{-2} s^{-1}

TABLE 3

ADOPTED RATIOS OF EMISSION LINE FLUXES TO Hα

Feature	Mean value
Σ Balmer	1.24
Σ Paschen	0.27
Ca II	2.7
Mg II	2.8
He I	0.16
UV lines	0.46
Σ Fe II	0.15

any emission line. In fact, Cohen and Kuhi (1979) find linear relations between the logarithm of line fluxes and the logarithm of the flux in Hα with a slope close to unity for all the emission lines in the spectra of the TTS in their sample. A point to notice is that these line fluxes were obtained simultaneously. Still, the lines for which the linear relations are observed are formed in different layers of the atmosphere. This suggests that a similar type of relationship may exist for all lines formed in the atmosphere, although this relationship may not always be apparent because of the lack of simultaneity of the observations. Given all the uncertainties associated to the determination of absolute fluxes in TTS, and the order of magnitude estimate we are looking for, this approach appears sufficient at the present moment. Stars in Table 2 are arranged in groups in decreasing order of effective temperature. No systematic differences among the different groups are apparent. Adding all the different contributions, we obtain that the total energy

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radiated away by emission lines in TTS is of order $\sim 8F(H\alpha)$.

The energy lost by continuum emission is more difficult to estimate. In the infrared, the total luminosity sometimes is of the same order or greater than the optical luminosity. In the near infrared, a large part of the contribution is photospheric (Calvet 1981). For $\lambda \gtrsim 5\mu$, the infrared flux is largely due to thermal emission from a dust distribution around the star (Cohen and Kuhi 1979, Rydgren and Vrba 1981), interpretation that has been corroborated by polarization studies (Bastien 1981, 1982) and radio continuum observations (Felli *et al.* 1982). The star must be responsible for the heating of the dust distribution, although it is not clear what the actual heating process is. It is interesting to notice that for a typical value for the infrared flux of $\sim 5 \times 10^{-23}$ erg cm^{-2} s^{-1} Hz^{-1} for a star in the Taurus cloud, (which amounts to $\sim 6 \times 10^{-4}$ erg cm^{-2} s^{-1} Hz^{-1}) between $\sim 5\ \mu$ and $10\ \mu$, we obtain a total infrared flux of $\sim 3 \times 10^{9}$ erg cm^{-2} s^{-1}, which amounts to $\sim 60\%$ of the stellar surface flux σT_{eff}^{4} (for $T_{eff} = 4\,000$K). This, in turn, roughly corresponds to the total energy removed from the optical region by the scattering process characterized by the standard reddening law for $A_V \sim 1$, typical of TTS (Cohen and Kuhi 1979). This suggests that the IR excess does not represent an energy loss from the upper atmosphere, but instead it corresponds to reemitted photospheric radiation.

The large *UV* excesses found in TTS (Walker 1972); Kuhi 1974; Rydgren *et al.* 1976) are mostly due to chromospheric emission, since the intrinsic photospheric fluxes of TTS, corresponding to those of late type stars, are low (Calvet 1981; Calvet, Basri, and Kuhi 1983). The *UV* flux then, represents an energy loss from the upper atmospheric layers. It is difficult to estimate the absolute magnitude of this loss, because of the scarcity of observations. We have used the narrow-band photometry of Kuhi (1974) for those stars in the Taurus-Auriga Complex included in his program. For these stars, we have integrated the flux between λλ3320 and 3620, corrected for reddening and reduced it to surface flux. Table 4 gives the value of this integration for a number of stars in several dates of observations. A fraction of this flux is photospheric in origin, and this fraction increases for increasing stellar effective temperature. We have used the monochromatic fluxes from the blanketed models of Carbon and Gingerich (1969) with corresponding values of T_{eff} and g to estimate the photospheric contribution, also given in Table 4. The difference between the surface flux and the photospheric flux gives a lower limit to the total energy loss in *UV* continuous emission. We note that in some cases the photospheric contribution is larger than the stellar surface fluxes, although still of the same order of magnitude. Given the uncertainties in the determination of the stellar parameters, we consider that the agreement is good and that in the later cases the chromospheric contribution in the *UV* is negligible compared to the photospheric flux. In Figure 1 we plot the energy loss in the *UV* calculated by this procedure against the flux in Hα measured simultaneously with the *UV* flux, from Kuhi (1974). A correlation seems to exist between the *UV* energy loss and the flux in Hα, such that $F_{UV} \sim F(H\alpha)$. Since F_{UV} is a lower limit for the total loss in the *UV*, we arbitrarily adopt a value of $\sim 2\ F(H\alpha)$ for this loss.

TABLE 4

UV CONTINUUM FLUX[a]

Star	Date	Stellar flux[b]	Photospheric flux[c]	*UV*
BP Tau	9095.79	1.4 + 8	9.6 + 7	4.8 + 7
	9153.67	1.2 + 8	...	2.7 + 7
	9879.64	1.8 + 8	...	8.0 + 7
RY Tau	9095.91	4.4 + 8	5.4 + 8	...
	9153.65	4.2 + 8	...	...
T Tau	9095.72	3.7 + 8	5.4 + 8	...
	9153.68	1.2 + 8	...	...
	9476.81	1.4 + 8	...	...
	10869.90	1.7 + 8	...	...
DF Tau	9153.69	1.8 + 8	9.6 + 7	8.6 + 7
	9476.88	1.9 + 8	...	9.2 + 7
	9877.80	1.6 + 8	...	6.3 + 7
DG Tau	9095.93	9.6 + 7	9.6 + 7	2.0 + 5
	9153.70	1.1 + 8	...	1.7 + 7
	9476.89	1.2 + 8	...	1.9 + 7
	9880.67	1.1 + 8	...	1.4 + 7
UX Tau	9095.83	2.5 + 8	5.4 + 8	...
	9153.71	5.8 + 7	...	...
XZ Tau	9095.83	2.6 + 8	< 9.6 + 7	> 1.6 + 8
	9153.71	2.7 + 8	...	> 1.7 + 8
UZ Tau	9095.78	6.0 + 7	< 9.6 + 7	...
SU Aur	9095.95	9.4 + 8	1.1 + 9	...
RW Aur	9095.96	5.8 + 8	5.4 + 8	3.0 + 7
	9153.76	5.4 + 8	...	...
	10869.92	7.3 + 8	...	1.9 + 8

a. Data from Kuhi 1974; b. = $\int F_\nu d_\nu$, integrated from λλ3320 to 3620, in erg cm^{-2} s^{-1}. c. Models from Carbon and Gingerich (1969).

A fraction of TTS have measurable luminosities in X-rays, typically of the order of 10^{30} erg s^{-1} (Gahm 1980; Feigelson and De Campli 1981; Walter and Kuhi 1981). The total flux of energy lost in X-rays, assuming isotropic emission, is of order

$$F_X \sim 4 \times 10^{6}\ (2\ R_\odot/R_*)^2 \quad \mathrm{erg\ cm^{-2}\ s^{-1}} \quad ,$$

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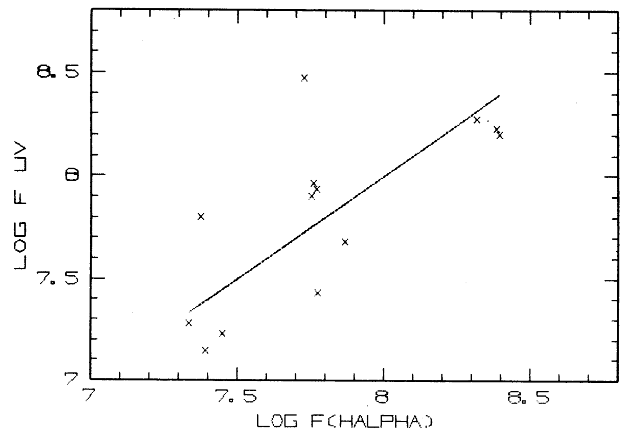

Fig. 1. Ultraviolet flux excess versus flux in Hα for stars in Taurus-Auriga. The slope 1 line is shown as reference.

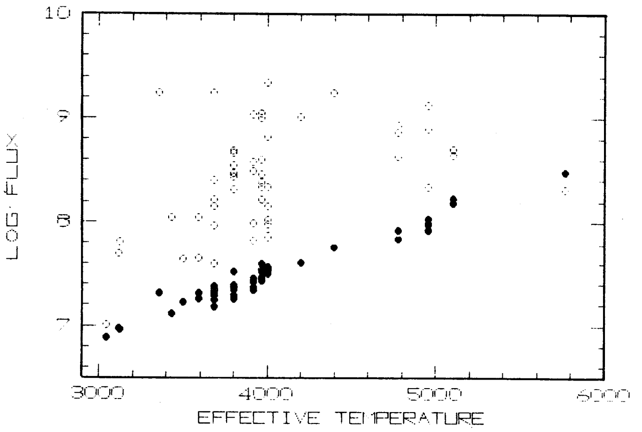

Fig. 2. Energy loss from the outer atmosphere (above the photosphere) in T Tauri stars (open circles). Theoretical MHD fluxes from convection zone in the case of strong turbulence (filled circles). Flux in erg cm^{-2} s^{-1}.

lower than other estimates for the energy loss.

Finally, we consider the energy lost in the wind. The existence of a wind in TTS has been amply proven by spectroscopic optical observations (Hartman 1982; Mundt 1983) radio continuum observations (Felli *et al.* 1982), and observations of the molecular ambient around TTS (Kutner *et al.* 1982; Edwards and Snell 1982; Calvet, Cantó, and Rodríguez 1983). Additionally, theoretical studies indicate that a wind can be generated in TTS by momentum and energy deposition of Alfvén waves in the upper atmosphere (Hartmann, Edwards, and Avrett 1982). However, the specification of wind parameters for individual stars is not available yet. Hartmann *et al.* (1982) show that most of the flux in the lower Balmer lines is produced in the wind, so we expect the flux in Hα and the flux of energy in the wind to be correlated. For expected T Tauri parameters, we can write

$$F_{\rm wind} \sim 2.7 \times 10^{7} \left(\frac{2R_\odot}{R_*}\right)^{2} \left(\frac{\dot{M}}{10^{-9}\ M_{g}\ y^{-1}}\right)$$

$$\times \left(\frac{v}{100\ {\rm km\ s^{-1}}}\right)^{2} \quad {\rm erg\ cm^{-2}\ s^{-1}} \quad .$$

We note that the order of magnitude for this flux is the same as that of Hα. Since we lack a better alternative, we take as an estimate for the flux of energy lost in the wind that $F_{\rm wind} \sim F(H\alpha)$.

At this point, we can add the estimates for all the mechanisms of energy loss that we have considered. With the admittedly crude procedure we have used, we find the total outer atmosphere (i.e., non photospheric) energy loss in TTS to be of the order of ∿ 11 F(Hα).

b) *Comparison with Theoretical Estimates*

In Figure 2 we have plotted as open circles the total energy loss from the outer atmosphere of TTS determined by the procedure described in §IIIa for stars in Table 2, versus stellar effective temperature. In addition, for each star in Table 2, we have obtained a value for its gravity, using its luminosity and effective temperature to estimate its radius, and its position in the HR diagram to stimate its mass in comparison with standard evolutionary tracks. Given the gravity and effective temperature, we can calculate the flux in MHD waves from the convection zone, using expressions (6) and (7). In Figure 3 we plot as filled circles the calculated fluxes in MHD waves for the case of strong turbulence (equation (6)). We have assumed $f_* = 1$, namely, full surface coverage of magnetic regions. We have used $f_\odot = 0.01$ (Stein 1981) and $F_{\odot,\rm av} \sim 2 \times 10^{6}$ erg cm^{-2} s^{-1} (Linsky *et al.* 1982). The actual energy available for heating the outer atmosphere, which is the quantity that should be compared with the energy loss, is lower than that given by expression (6). A large amount of radiation damping occurs in the photosphere (Schmitz and Ulmschneider 1980*a*, *b*), which results in a decrease by a factor of 5 to 10 in the flux available for heating the outer atmosphere. Detailed wave propagation calculations are needed to assess the magnitude of this effect. Also, as discussed previously, there are large uncertainties associated with both theoretical and observational data. However despite these deficiencies, Figure 2 is very suggestive. Two facts can be pointed out. First, that the effective temperature dependence of the MHD wave fluxes seems to agree with that of the lowest observed fluxes, justifying our choice for the strong turbulence case. Second, that no TTS is found below the region determined by the MHD wave energy input.

The fact that no observed fluxes fall below the theoretical line could be interpreted as implying that the

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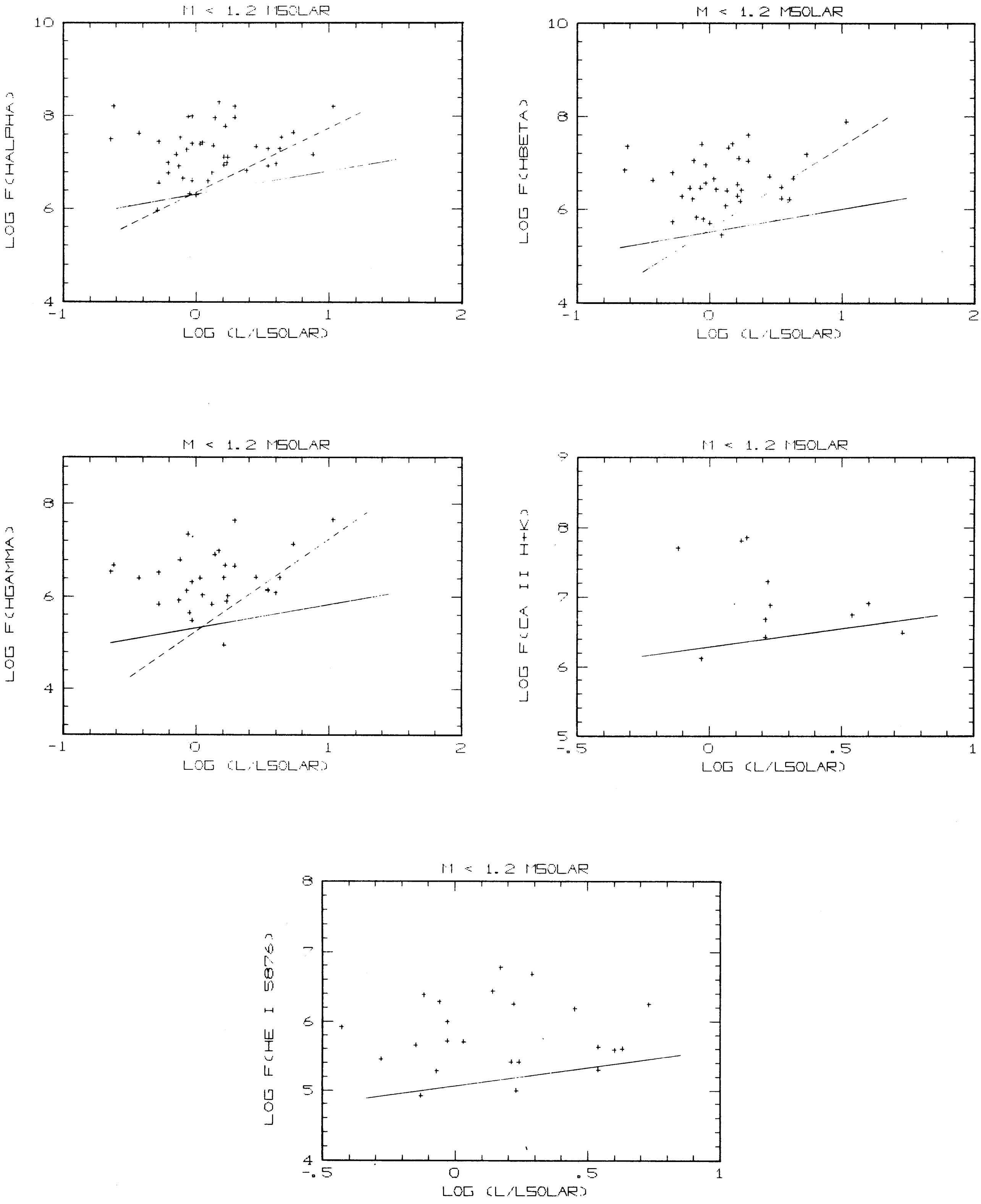

Fig. 3. Dependence of emission line fluxes with luminosity for stars with $M < 1.2\ M_{\odot}$: (*a*) Hα, (*b*) Hβ, (*c*) Hγ, (*d*) Ca II H + K, (*e*) He I 5876. The continuous line has slope calculated by least-squares fitting to the MHD wave flux expected for individual stars. The dashed lines roughly represent the lower limit to the observed emission line flux dependence with luminosity. Flux in erg $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

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basic energy input into the outer atmospheres of TTS comes from waves generated in the convection zone. Otherwise, some of the observed fluxes would be lower than the theoretical flux. Besides this basic energy input, additional sources of energy must be present, which must account for fluxes of the order of 10^8 to 10^9 erg cm^{-2} s^{-1}.

We note that the "continuum" stars are among those with the largest energy loss. These stars, in turn, also have the largest degree of variability observed. In fact, all of the TTS are variable, both in emission lines and in continua, with time-scales that vary from feature to feature (Kuhi 1978). Several lines of evidence seem to indicate that the origin of this variability lies in flare activity. Worden *et al.* (1981) have followed and analyzed the short-period photometric fluctuations in the *U* band for a number of TTS. They interpret these fluctuations as produced by a superposition of solar-like flare events, occurring continuously. Flare activity has been reported in X-rays for the star DG Tau (Feigelson and DeCampli 1981), which emitted 10^{34} erg in a few minutes, and for a number of stars in the ρ Ophiuchi dark cloud, among which the strongest stellar X-ray flare ever recorded has been observed, in which $\geqslant 8 \times 10^{35}$ erg were released (Montmerle *et al.* 1983), Kilyachkov and Shevchenko (1976) observed an optical flare in the star T Tau that lasted for 20 minutes, releasing an average flux of 8×10^9 erg cm^{-2} s^{-1}. In support of these observations, theoretical chromospheric temperature models constructed to reproduce observed fluxes in Ca II K and Mg II k for TTS are similar to those for solar and stellar flares in the case of the most active TTS (Calvet 1981, 1983; Calvet, Basri, and Kuhi 1984), It is reasonable then to expect that similar mechanisms, to those acting in stellar flares are also active in the atmosphere of TTS, for instance, local magnetic field dissipation by reconnection, where large amounts of energy are released in short time-scales (Vaiana and Rosner 1978; Ayres, Mastad, and Linsky 1981). This flare activity occurring continuously on the stellar surface would be responsible for the energy in excess to the MHD wave fluxes in Figure 2. One would expect then that those stars found near the theoretical fluxes were observed in a quiet state in which no large flares were occurring at the surface.

Besides flare activity, other type of surface phenomena can also generate and deposit energy at the expense of the magnetic field. For instance, Alfvén waves generated from buffeting of flux tubes by granules and supergranules can generate fluxes of the order of 10^9 erg cm^{-2} s^{-1} (Stein and Leibacher 1980).

Cohen and Kuhi (1979) have shown that the flux in emission lines decreases with stellar luminosity for stars in Taurus-Auriga. Since most of the TTS in this complex are located along the convective path of pre-main-sequence evolutionary tracks (Cohen and Kuhi 1979), and this evolution occurs at roughly constant effective temperature, Cohen and Kuhi interpret the mentioned effect as evidence of decreasing activity with age. It would be interesting to investigate if the line flux decrease is consistent with a decrease in the basic energy input in MHD waves from the convection zone. To investigate the age effect, we have restricted our considerations to stars with $M < 1.2\ M_{\odot}$, which are located along convective pre-main-sequence tracks (c.f. Cohen and Kuhi 1979, Fig. 2). Therefore, we have compared the behavior of individual line fluxes with luminosity for stars for which fluxes are available with that of the theoretical flux. As we are interested at this point in rates of change rather than in absolute fluxes, we have compared surface line fluxes corrected for reddening with a line whose slope is calculated by least-squares fitting to the relation between theoretical fluxes for individual stars and their luminosities. Emission line fluxes are calculated from data in Cohen and Kuhi (1979). Figure 3 shows this comparison for (*a*) Hα, (*b*) Hβ (*c*) Hγ (*d*) Ca II H + K and (*e*) He I λ5876. The sample of line fluxes used to construct Figure 3 is in some cases too small to allow drawing firm conclusions from its analysis. However, data shown in Figure 3 apparently indicate that line fluxes can be divided into two categories: those for which the lower fluxes observed roughly decrease as the MHD wave flux does, as the Ca II lines and He I λ5876, and those for which the lower fluxes decrease faster than predicted by the decrease of the MHD wave flux, as Hα, Hβ, and Hγ. It is interesting to notice that these two groups of lines are also differentiated as to the atmospheric region in which they are thought to form. The observed strength of Hα for the strongest-line TTS cannot be explained by deep chromospheric models (Calvet 1981; Basri, and Kuhi 1984), so that an extended region is required for this line to form. In fact, wind models for TTS calculated by Hartmann, Edwards, and Avrett (1982) indicate that enough Hα is produced in the wind region to account for the observations. We expect Hβ and Hγ to form in this region also. On the other hand, the Ca II lines and He I λ5876 are expected to form in the deep chromsphere (Calvet, Basri, and Kuhi 1984; Calvet 1984). The disparity of behavior between the two sets of lines could be taken as indicative of different heating mechanisms for the atmospheric regions where the lines form. While the chromosphere appears to be powered by MHD waves from the convection zone, the outermost region seems to require a different energy source that declines more steeply with luminosity.

The question is on the nature of the property decreasing with stellar luminosity, or equivalently with age, and which determines the strength of the emission lines which we have characterized as produced in the extended region. Theoretical models indicate that a chromosphere alone *can* account for the flux in Hα in the case of the weak-emission TTS (Calvet 1981; Calvet, Basri, and Kuhi 1984). This suggests that the property

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that is actually decreasing is the density of the extended region, which determines the importance of the emission of this region over the intrinsic chromospheric emission. A measure of this quantity is the mass loss rate $\dot{M}$, which in our hypothesis should decrease with age. Wind models for TTS, although calculated for only one set of stellar parameters g and T_{eff}, can give some insight at this point. In these models, a wind can be generated in the uppermost atmospheric regions by deposition of energy and momentum by Alfvén waves (Hartmann, Edwards, and Avrett 1982). These waves are assumed to carry a flux

$$F_0 \propto B_0^3 \rho_0^{-1/2} \quad ,$$

where B_0 is the magnetic field strength at the surface, and therefore they are supposed to be generated by surface phenomena, rather than by turbulence in the convection zone. Calculations done with different B_0, or equivalently F_0, indicate that as B_0 decreases, the mass loss rate $\dot{M}$ also decreases. At the same time, as the effectiveness of radiative cooling decreases with $\dot{M}$, the maximum temperature attained in the atmospheric layers increases. This theoretical indication could be related to the observational suggestion that the onset of a corona occurs during the T Tauri phase (Imhoff and Giampapa 1982). In this respect, Walter and Kuhi (1981) have found an anticorrelation between the equivalent width of Hα and the luminosity in X-rays, which could be due to an effect of absorption (Gahm 1980); alternatively, it could indicate that the stars with strongest emission, and therefore more luminous, lack coronae. The latter alternative is supported by the weakness or absence in active stars of ultraviolet lines formed in high temperature regions (Imhoff and Giampapa 1981, 1982). The argument presented so far then is that as low mass TTS evolve, the strength of the surface magnetic field decreases, and consequently the importance of the extended region, as measured by $\dot{M}$, decreases. This could explain the sharp decline of surface line fluxes with luminosity. As the star evolves, the outer atmospheric structure changes from that consisting of a cool wind region to that containing a high temperature region, corona, consistently with the structure with which these stars arrive on the main sequence. This argument is only speculative, however, since most of the intrinsically faint low-mass, weak-emission TTS have been observed neither in the ultraviolet nor in X-rays.

The question remains on why the magnetic field strength would decrease with age. According to Shu and Terebey (1984) and Terebey, Shu, and Cassen (1984), however, this could be expected. These authors have calculated the collapse of a slightly rotating molecular cloud, and propose that strong stellar winds should exist in young TTS as a consequence of the high strength magnetic field resulting from the combined effects of convection and the strong differential rotation induced by the collapse in the protostar. As the star evolves, it tends to move toward a state of uniform rotation, the state of minimum energy. The amplifying effect of the dynamo, then, would tend to decrease with time, and so the magnetic field strength.

IV. SUMMARY

We have compared the energy losses from the outer atmospheres (above the photosphere) in T Tauri stars (TTS) with the flux in MHD waves produced in their turbulent convection zones. We have found that the MHD wave flux produced in regions of strong turbulence closely determines a lower limit for the observed energy losses. We interpret this result as indicating that the MHD wave flux represents a basic energy input for the atmospheres of TTS, in addition to which other energy sources due to surface transient phenomena must exist to account for the energy output and its variability. The most likely candidate for this additional energy source is the flare activity that many lines of evidence indicate occurs at the surface of TTS. Originally proposed by Haro (1976), Gershberg and Petrov (1976), Gershberg (1977, 1982), and Gurzadyan (1980), among others, the suggestion that intense flare activity is characteristic of the surfaces of TTS has received a great deal of support in recent years. Flare activity could explain the observed variability in the ultraviolet (Worden *et al.* 1981) and in X-rays (Montmerle *et al.* 1983). Additionally, the temperature profiles of the Ca II and Mg II resonance line formation region resemble that of solar and stellar flares (Calvet 1983; Calvet, Basri, and Kuhi 1984).

Alfvén waves produced at the surface could also represent another important source of energy for the upper atmospheric layers. For instance, phenomena similar to solar granulation and supergranulation acting upon magnetic flux tubes can produce large energy fluxes, which depend directly on the surface magnetic field strength (Stein and Leibacher 1980).

In order for the MHD wave flux from the convection zone to account for the basic energy input in the atmospheres of TTS, an almost complete coverage of magnetic regions is required. This does not seem to be a very restrictive condition for TTS, since it is strongly suggested by both observational and theoretical arguments.

Observationally, the inhomogeneous nature of the surface is indicated by studies of the Ca II infrared triplet (Herbig and Soderblom 1980), of the Ca II and Mg II resonance lines (Giampapa *et al.* 1981), and of the light variability (Herbst, Holtzmann, and Phelps 1982; Rydgren and Vrba 1983*a*, *b*). Moreover, the observed rate of flare occurrence could be due to a high density of magnetic flux tubes at the surface. Theoretically, strong magnetic fields are expected in stars just appearing in the pre-main-sequence phase, resulting from the combined effects of both convection and the strong differential

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rotation induced in the protostar by the collapse process (Shu and Terebey 1984).

We have also compared the behavior of the MHD wave flux with luminosity with that of the flux for individual emission lines. We find that the decrease in MHD wave flux is consistent with the observed decrease in flux for lines that arise in the chromosphere. In contrast, it cannot explain the steeper decrease observed in lines formed in higher atmospheric regions. We interpret this fact as implying that the chromosphere is powered by MHD waves from the convection zone, while the outermost regions require another heating mechanism. We speculate that the steep decrease in extended-region indicators may be related to the fading of this region as the star evolves. A possible suggestion is that as the star adjusts itself toward the more stable state of uniform rotation, the surface magnetic field decreases. Consequently, the flux of energy and momentum in Alfvén waves probably responsible for driving the wind (Hartmann, Edwards, and Avrett 1982) also decreases. As this flux decreases, it would tend instead to heat the upper atmospheric layers (Hartmann *et al.* 1982); thus we could expect in this scenario to witness the birth of coronae during the T Tauri, state, as previously suggested (Imhoff and Giampapa 1982).

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