THE ASTROPHYSICAL JOURNAL, **251**:113–125, 1981 December 1

IUE OBSERVATIONS OF PRE–MAIN-SEQUENCE STARS. I. Mg II AND Ca II RESONANCE LINE FLUXES FOR T TAURI STARS

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Received 1981 February 23; accepted 1981 June 12

ABSTRACT

We present absolute flux measurements of the Mg II and Ca II resonance lines in a sample of T Tauri stars, obtained with the *International Ultraviolet Explorer* satellite and the image tube scanner of the 3 m Lick reflector. We discuss the Mg II *h* and *k* line emission and the Ca II H and K line emission within the context of stellar chromospheres, and we present the corroborative evidence for the chromospheric origin of these particular resonance lines in the T Tauri stars. We derive chromospheric radiative loss rates in the Mg II and Ca II resonance lines. We find that the degree of nonradiative heating present in the outer atmospheres of the T Tauri stars generally exceeds that of the RS CVn systems, as well as the dMe stars and other active chromosphere dwarfs. We infer that the surfaces of these pre–main-sequence stars are extensively covered by regions similar to solar plages, and we estimate the relative filling factors of these active (plage) regions. We find that the chromospheric mass column density at the temperature minimum in T Tauri stars is typically an order of magnitude greater than that of the average quiet Sun, while the mean chromospheric electron density is characterized by $n_e \approx 10^{11}$ cm^{-3}. We also briefly consider the relative importance of mass loss to the energy balance in the outer atmospheres of T Tauri stars by comparing the net chromospheric and coronal radiative loss rates to the stellar wind flux in the specific case of the pre–main-sequence star T Tau.

Subject headings: stars: chromospheres — stars: pre–main-sequence — ultraviolet: spectra

I. INTRODUCTION

The observational criteria utilized in the classification of T Tauri stars according to a variety of spectral line features is given by Herbig (1962). In general, the T Tauri stars exhibit hydrogen Balmer line emission and absorption (Schneeberger, Worden, and Wilkerson 1979), Ca II resonance and infrared triplet line emission (Kuhi 1974; Herbig and Soderblom 1980), as well as Fe I, Fe II, and Ti II emission lines (Strom, Strom, and Grasdalen 1975). The Li λ6707 line is present in absorption, and forbidden emission lines of [Si II] and [O I] are also observed in many T Tauri stars. The T Tauri stars are further characterized by UV and IR excesses (e.g., see Gahm *et al.* 1974; Mendoza 1966) in addition to irregular variations in their general spectral and polarization properties (Imhoff and Giampapa 1980*a*; Schneeberger, Worden, and Wilkerson 1979; Serkowski 1969*a*, *b*; Breger 1974). Radio emission at centimeter wavelengths is also detected (Spencer and Schwartz 1974), while Feigelson and De Campli (1981) observe strong ($L_x \approx 10^{30-31}$ ergs s^{-1}) X-ray emission and X-ray variability as well (see also Gahm 1980; Walter and Kuhi 1981). The stellar class is further delineated by Herbig and Rao (1972) according to the relative optical emission line strength among T Tauri stars. The T Tauri stars are regarded as pre–main-sequence objects that are precursors of spectral types between F5 V and middle M V. The corroborative evidence for the pre–main-sequence nature of the T Tauri stars is discussed by Herbig (1962), Imhoff and Mendoza (1974), Strom, Strom, and Grasdalen (1975), Grasdalen (1973), and Rydgren (1975).

Recently the advent of the *International Ultraviolet Explorer* (*IUE*) satellite has stimulated an extensive observational investigation of the T Tauri stars. The resulting ultraviolet data base consists mainly of low dispersion, short wavelength (1150–1950 Å) and low dispersion, long wavelength (1900–3200 Å) spectra of several T Tauri stars (Imhoff and Giampapa 1980*a*, *b*; Imhoff and Giampapa 1981; Gahm *et al.* 1979; Appenzeller and Wolf 1979; Appenzeller *et al.* 1980*b*; Mundt *et al.* 1981). In addition, high dispersion, long wavelength ultraviolet spectra are now becoming available (Giampapa and Imhoff 1981; Imhoff and Giampapa 1980*a*; Appenzeller *et al.* 1981; Brown *et al.* 1981). These data

[1] Guest Observer, *International Ultraviolet Explorer*.

provide a valuable supplement to current optical data, such as the moderate resolution scanner observations of T Tauri stars by Cohen and Kuhi (1979) and the high resolution Balmer line and Na D line profile sets presented by Schneeberger, Worden and Wilkerson (1979) and Ulrich and Knapp (1981). The observations have dictated and/or suggested various theoretical investigations. Kuan (1975) and Schneeberger (1977) discuss the emergent line spectrum within the context of a spherical, geometrically extended region incorporating velocity field structure. In addition, Ulrich (1976) and Ulrich and Knapp (1979) explore T Tauri line asymmetries as indicators of mass inflow and outflow, while Bertout (1979) constructs theoretical models incorporating mass infall combined with rapid rotation. Moreover, the spectral energy distribution in T Tauri stars is investigated theoretically by Cram (1979) through the construction of nonspecific, plane-parallel chromospheric models constrained by the assumptions of hydrostatic equilibrium and complete frequency redistribution (CRD) in the treatment of the line transfer. Calvet (1981) also computes a grid of single-component, homogeneous semiempirical model chromospheres based upon observed chromospheric line fluxes for several T Tauri stars. Finally, the temperature distribution of the emission measure, an estimate of the electron density and the source of heating in the transition regions of T Tauri stars is discussed by Cram, Giampapa, and Imhoff (1980).

We essentially seek in this investigation, and subsequent studies, to extend the development of semiempirical model chromospheres over an evolutionary time scale by obtaining data sets consisting of well-calibrated, high and moderate resolution spectral line data for a sample of T Tauri stars. The T Tauri stars are a particularly valuable laboratory for the study of the evolution of stellar chromospheres since these stars are not as severely afflicted with uncertainties as to their final main-sequence spectral type, although ambiguity persists with regard to an exact determination of the final ZAMS type of a given T Tauri star (Cohen and Kuhi 1979). By contrast, the giant stars constitute a less homogeneous sample since the main-sequence progenitor of a given giant star is uncertain. The youth of T Tauri stars and their generally rapid rotation rates (Vogel and Kuhi 1981; Herbig 1957), as compared to other late-type stars, may serve to indicate the importance of the dynamo effect and remnant primordial magnetic fields to the generation of nonradiative heating and the driving of stellar winds. The presence of mass outflow will reveal the role of stellar winds in pre-main-sequence and, ultimately, main-sequence evolution. Furthermore, the winds and mass infall may play an important role in the energy balance in the outer atmospheres of T Tauri stars. In summary, the results to be obtained in this series of investigations of pre-main-sequence stars will allow astronomers to begin to address the problem of the origin of stellar chromosphers, ultimately addressing the fundamental questions of how the origin, structure, and evolution of stellar chromospheres depend upon the dynamic and thermal properties of stars.

The primary purpose of the paper is to offer a qualitative assessment of calibrated, moderate resolution Mg II ($h + k$) and Ca II (H + K) resonance line flux data which we will use in subsequent investigations for calculating model chromospheres for T Tauri stars. In § II we describe the observational data, and in § III we discuss systematic trends in the line fluxes and flux ratios as well as evidence which suggests the predominantly chromospheric origin of the Mg II and Ca II line emission. We present a brief summary of our principal results and suggestions for future research in § IV.

II. OBSERVATIONS

The Mg II $h + k$ line (λ2800 blend) observations were obtained with the *IUE* satellite in the long wavelength, low-dispersion mode. The satellite, telescope, spectrographs and data reduction procedures are described by Boggess *et al.* (1978*a*, *b*). The spectral resolution corresponding to the low-dispersion mode with the long wavelength (1900–3200 Å) camera is 6 Å FWHM. Observations were acquired with both the large and small apertures in order to verify the consistency of the line flux measurements. We multiplied the observed flux as obtained though the small aperture by a factor of 2.0 in order to deduce the true flux at the earth. Observations acquired through the $10'' \times 20''$ large aperture include essentially all the stellar flux transmitted by the telescope. Table 1A is a log of the observations giving the *IUE* image number, date, and time of the beginning of each observation, aperture (large or small), and exposure time. We also list the measured Mg II ($h + k$) flux at the Earth, and in the final column of Table 1A we display the mean of these observations for each star. We utilize the mean value of the observed Mg II ($h + k$) flux for all subsequent analysis. We find that the internal agreement of the determined Mg II fluxes is typically 10% and never worse than 20%.

We obtained Ca II K line (λ3934) fluxes with the image tube scanner (Miller, Robinson, and Wampler 1976) at the Cassegrain focus of the 3 m Lick reflector. The effective resolution of the system is 7 Å. Details of the data reduction procedure are given by Cohen and Kuhi (1979). Table 1B is a log of the optical observations giving the star, data of the observation, and the observed K-line flux. The fluxes given in Table 1B are integrated fluxes for the K line, with the interpolated continuum subtracted. We estimate an uncertainty of $\pm$ 15%–25% in these measured fluxes, and we adopt the mean value of the observed fluxes for each star in the analysis to follow. We deduce the total Ca II (H + K) resonance line flux by assuming that $f(\mathrm{H+K}) \approx 2f(\mathrm{K})$. Accurate measurements of the Ca II H line (λ3968) flux are difficult to obtain at these spectral resolutions since the H line is strongly affected by the nearby Hϵ line (λ3970). However, the aforementioned method of estimating the total Ca II resonance line flux should be a very good approximation to the true flux. This argument is supported by data given by Linsky *et al.* (1979) for stars throughout the H-R diagram and by Giampapa *et al.* (1981) for the dMe and dM stars (see also Kuhi 1974). We list the inferred values

TABLE 1A

Summary of *IUE* Observations

Star	Image[a] (LWR)	Year	Day	Begin Time (UT)	Aperture	Exposure (min)	f(Mg II)[b]	⟨f(Mg II)⟩[b]
BP Tau	4191	79	94	20:29	large	30	1.0(−12)	1.0(−12)
	4249	79	102	1:21	large	23	1.0(−12)	
T Tau	4248	79	102	0:33	large	3	7.5(−12)	8.0(−12)
	4248	79	102	0:21	small	4	8.4(−12)	
DF Tau	4194	79	94	23:39	large	40	7.1(−13)	5.9(−13)
	4194	79	95	0:21	small	35	4.6(−13)	
DG Tau...............	4193	79	94	21:46	large	30	1.1(−12)	1.2(−12)
	4193	79	94	22:23	small	30	1.3(−12)	
SU Aur	4183	79	92	20:47	large	6	16.(−12)	1.3(−12)
	4184	79	92	22:06	large	20	1.1(−12)	
	4195	79	95	2:49	large	45	1.4(−12)	
	4195	79	95	1:40	small	60	1.2(−12)	
RW Aur...............	4181	79	92	12:23	small	6	1.4(−11)	1.6(−11)
	4182	79	92	19:45	large	2.6	1.7(−11)	
	4182	79	92	19:55	small	2.6	1.6(−11)	
	4223	79	99	21:43	small	3	1.5(−11)	
CO Ori	4225	79	99	23:57	large	20	8.5(−13)	7.5(−13)
	4225	79	100	0:24	small	15	6.4(−13)	

[a] The LWR camera includes the spectral range 1900–3200 Å.
[b] Units: ergs cm^{-2} s^{-1} at the Earth.

of f(Ca II H + K), as calculated from the mean value of f(Ca II K) for each star, in the fourth column of Table 1B.

Table 2 lists the adopted stellar parameters we utilize to convert the observed flux at the Earth to the absolute surface flux at the star. The final column of Table 2 gives the reference from which the listed data are taken. In some cases the given spectral type, extinction, or luminosity is a crude estimate. For example, DG Tau exhibits a strong emission spectrum with no apparent photospheric features. Previous observations in the red of T Tauri stars similar to DG Tau have revealed a photospheric spectrum corresponding to a spectral type of late K (Cohen and Kuki 1979; Herbig 1979). We have consequently assumed a spectral type of K5 for DG Tau. We list conservative estimates of the extinction and luminosity for RW Aur, and, hence, the inferred resonance line surface fluxes are lower limits. In the case of AS 205, the adopted extinction and stellar parameters are a compromise among those values that have been suggested. We infer the effective temperatures from the given spectral types combined with the spectral type $-T_{\rm eff}$ relation of Johnson (1966). Hence, the radii are derived from the inferred values of the effective temperatures and the luminosities as given in the references. For some of the T Tauri stars listed in Table 3, we adopt values of the observed Mg II ($h + k$) line flux given in the literature. In some cases in the literature an actual value of the flux is not given. However, it is evident from the published spectrum of the object in question that the value of the flux we list in Table 3 is a lower limit.

As will be discussed by Imhoff and Giampapa (1981), the inferred values of the resonance line surface fluxes are most sensitive to uncertainties in the adopted extinction. The extinction estimates for the T Tauri stars are often uncertain due to the peculiar spectra the objects exhibit. For example, given $A_v = 1.0$ mag, the corresponding extinction corrections for the Mg II and Ca II line fluxes are factors of 5.3 and 3.7, respectively. A change in the determination of $E(B - V)$ by 0.1 mag corresponds to a change in A_v of 0.3 mag; for $A_v = 1.3$ mag, the Mg II and Ca II flux corrections become 8.7 and 5.5 We note, however, that the *ratio* of the corrections changes from 1.4 to 1.6, or a difference of only 14%. Similarly, for a peculiar extinction law such as that of θ Ori (Bless and Savage 1972), combined with a ratio of total to selective absorption of $R = 6$, the ratio of the corrections changes from 1.2 to 1.3. Thus, *ratios* of the Mg II to Ca II resonance line

TABLE 1B

Summary of Lick 3m Observations

Star	Date[a]	f(Ca II K)[b]	⟨f(Ca II K)⟩[b]	f(Ca II H + K)[b]
BP Tau	1	2.73(−13)	3.15(−13)	6.3(−13)
	2	3.56(−13)		
T Tau	1	7.33(−13)	8.06(−13)	1.6(−12)
	2	8.78(−13)		
DF Tau	1	1.60(−13)	1.33(−13)	2.7(−13)
	2	1.05(−13)		
DG Tau	1	5.05(−13)		
	2	6.41(−13)	4.88(−13)	9.8(−13)
	3	3.18(−13)		
DR Tau	1	4.70(−13)	4.70(−13)	9.4(−13)
RW Aur	1	2.54(−12)	2.82(−12)	5.6(−12)
	2	3.09(−12)		

[a] Dates: (1) night of 1977 Nov 8; (2) night of 1977 Nov 7; (3) night of 1977 Aug 7.
[b] Units: ergs cm^{-2} s^{-1} at the Earth.

TABLE 2

STELLAR PARAMETERS

Star	Spectral Type	A_v (mag)	$L/L_\odot$	T_{eff} (K)	$R/R_\odot$	d (pc)	Binary	Reference
BP Tau	K7	0.55	1.6	4000	2.6	160	no	2
T Tau	K1	1.44	28	5100	6.8	160	no	2
DF Tau	M0.5	1.90	5.4	3675	5.7	160	no	2
DG Tau	K5	1.0	7.6	4400	5.8	160	no	2, 10
DR Tau	K5	2.08	4.9	4400	4.7	160	no	2, 5, 9
SU Aur	G2	0.93	18	5770	4.2	160	no	2
RW Aur	K1	0.17	6.0	5100	3.1	160	yes	6
CO Ori	G5	1.08	48	5660	7.2	460	yes	2
GW Ori	G5	0.82	66	5660	8.4	460	no	2
CoD-35°10525	K7	2.0	3	4000	3.6	125	no	1, 7
RU Lup	K5	0.6	2.3	4400	2.6	150	no	3, 4
AS 205	K3	2.6	14	4800	4.1	170	yes	7
S CrA	K2	1.5	5.5	4960	3.2	150	yes	8

REFERENCES.—(1) Appenzeller, Mundt, and Wolf (1978); (2) Cohen and Kuhi (1979); (3) Gahm *et al.* (1974); (4) Gahm *et al.* (1979); (5) Herbig and Rao (1972); (6) Imhoff and Giampapa (1980*a*); (7) Imhoff and Giampapa (1980*b*); (8) Knacke *et al.* (1973); (9) Kuhi (1974); (10) Imhoff (1981).

fluxes are relatively insensitive to the adopted value of the extinction. In this investigation we adopt a normal extinction law. Hence, the Mg II and Ca II resonance line surface fluxes we finally deduce are likely lower limits to the true line surface flux. In conclusion, we estimate that the uncertainty in the surface fluxes is approximately a factor of 2 (Imhoff and Giampapa 1981).

In this investigation we assume that the Mg II and Ca II line emission arises from a "chromosphere," which may be morphologically defined as a hot region immediately above the stellar photosphere which is geometrically thin with respect to the radius of the star (e.g., see Cram 1979; Ayres 1975; Linsky 1980*a*, *b*; Gibson 1973, p. 20). The underlying reasons for the assumption will be discussed in § III*a*. As demonstrated by Linsky and Ayres (1978), the net chromospheric radiative losses due to the Mg II or Ca II resonance lines can be determined by measuring the excess flux in these lines over the expected line flux for a stellar atmosphere in radiative equilibrium. The radiative equilibrium corrections for the Mg II lines are negligible for the late-type stars (Linsky *et al.* 1979). We list our computed values of the Mg II ($h + k$) and Ca II (H + K) line surface fluxes in Table 3 along with their values normalized to the respective value for the mean Sun (Linsky *et al.* 1979). The radiative equilibrium contribution to the Ca II H + K lines as a function of $(V - R)$ color has been computed by Kelch, Linsky, and Worden (1979) for dwarfs and giants. The relationship is graphically presented by Linsky *et al.* (1979; their Fig. 3). If we adopt the $(V - R)$ color corresponding to a given spectral type (Johnson 1966) in Table 1B, then inspection of Linsky *et al.* (1979; their Fig. 3) reveals that the radiative equilibrium contribution to the Ca II (H + K) line flux is negligible compared to the deduced H + K

TABLE 3

TOTAL LINE SURFACE FLUXES

Star	F(Mg II $h + k$)[a]	F(Ca II H + K)	F(Mg II)/$F^{\odot}$(Mg II)	F(Ca II)/$F^{\odot}$(Ca II)
BP Tau	1.9(7)	9.6(6)	15	19
T Tau	1.0(8)	1.1(7)	80	22
DF Tau	2.2(7)	4.7(6)	18	9.4
DG Tau	1.0(7)	5.3(6)	7.8	11
DR Tau	1.7(7)[b]	3.2(7)	14	64
SU Aur	1.8(7)	...	14	...
RW Aur	1.1(8)	3.7(7)	86	74
CO Ori	3.7(7)	...	30	...
GW Ori	$\geq$1.7(7)[c]	...	$\geq$14	...
CoD-35°10525	$\geq$7.8(7)[b]	...	$\geq$62	...
RU Lup	$\geq$1.5(7)[d]	...	$\geq$12	...
AS 205	1.7(8)[b]	...	130	...
S CrA	$\geq$5.4(7)[b]	...	$\geq$44	...

[a] Units: ergs cm^{-2} s^{-1}.
[b] Appenzeller *et al.* (1980*a*, *b*).
[c] Gahm *et al.* (1979).
[d] Gondhalekar *et al.* (1979).

line surface fluxes given in Table 3. We therefore conclude that the line surface fluxes given in Table 3 represent the contribution of the Mg II and Ca II resonance lines to the net chromospheric radiative cooling. In the case of the Ca II resonance lines, the values of the H + K line flux given in Table 3 are lower limits to the true chromospheric emission flux in the Ca II resonance lines because we have subtracted the continuum. A more accurate measurement of the net chromospheric radiative losses due to the Ca II H and K lines will eventually require high resolution, absolute-flux profiles of the Ca II H and K lines in the T Tauri stars.

III. DISCUSSION

a) Line Flux Ratios and the Chromospheric Origin of the Mg II *and* Ca II *Resonance Line Emission*

Theoretical investigations of the origin of the emission line spectrum of T Tauri stars have been conducted within the contexts of a spherically expanding envelope and the resulting geometrically extended region (Kuhi 1964; Kuan 1975; Schneeberger 1977), asymmetric (Ulrich 1976) and symmetric (Bertout 1979) mass infall models followed by an accretion shock in the low chromosphere, or within the context of a static, compact, hot region analogous to the solar chromosphere (Herbig 1970; Dumont *et al.* 1973; Cram 1979; Calvet 1981). We assume in this investigation that the Mg II and Ca II resonance line emission arises from a compact, nonradiatively heated region similar to the solar chromosphere. In the following we present arguments to support this assumption.

The radiative loss ratio F(Mg II)/F(Ca II) may be indicative of optical depths in the emitting region (Linsky and Ayres 1978). Following Herbig and Soderblom (1980), we crudely examine this ratio by considering the emitting region as an isothermal slab. The emergent line flux from an isothermal slab of finite optical thickness is

$$F_l = \pi \frac{B_\lambda(T_e)}{b_\lambda} \Delta\lambda_{\rm D} \int [1 - e^{-\tau(x)}]dx\,, \qquad (1)$$

where $x \equiv \Delta\lambda/\Delta\lambda_{\rm D}$, $B_\lambda(T_e)$ is the Planck function evaluated at wavelength λ and electron temperature T_e, $\Delta\lambda_{\rm D}$ is the Doppler width, b_λ is the ratio of the departure coefficients for the two levels of the particular resonance line transition, and

$$\tau(x) = \tau_{1c} e^{-x^2}\,,$$

where τ_{1c} is the line-center optical depth. If we assume that F(Mg II)/F(Ca II) $\approx F$(Mg II k)/F(Ca II K), then in the optically thick limit of equation (1) we have that

$$\frac{F_{\rm Mg\,II}}{F_{\rm Ca\,II}} = \frac{b_{\lambda 2796}}{b_{\lambda 3934}} \frac{\Delta\lambda_{\rm D}{}^{\rm Mg}}{\Delta\lambda_{\rm D}{}^{\rm Ca}} \frac{\Delta\lambda_k}{\Delta\lambda_{\rm K}} \frac{B_{\lambda 2796}}{B_{\lambda 3934}}\,, \qquad (2)$$

where we evaluate the temperature-dependent terms at an electron temperature of $T_e = 6500$ K. This value approximately corresponds to the temperature at which Mg II and Ca II thermalize in the chromosphere of the quiet Sun (Vernazza, Avrett, and Loeser 1980). An accurate value of $\Delta\lambda_k/\Delta\lambda_{\rm K}$ requires high resolution line profiles, preferably obtained simultaneously in order to avoid the effects of line profile variability (Schneeberger *et al.* 1979; Ulrich and Knapp 1981; Appenzeller *et al.* 1980*a*; Krautter and Bastin 1980; Mundt and Giampapa 1981). Since such data are currently unavailable we adopt the value $\Delta\lambda_k/\Delta\lambda_{\rm K} \approx 2.5$ as given by Ayres (1979) for effectively thick emission-line cores. An accurate value of the ratio of departure coefficients, $b_{\lambda 2796}/b_{\lambda 3934}$, can only be ascertained through a detailed, non-LTE model atmospheres calculation. Giampapa (1980*b*) finds in the case of the active chromosphere star EQ Vir (dK5e) that $b_{\lambda 2796}/b_{\lambda 3934} \approx 1$ for the temperature regime considered here. We therefore assume for the purposes of this crude analysis that this value of the ratio of the departure coefficients is applicable to T Tauri chromospheres as well. Substituting the aforementioned quantities into equation (2) yields F(Mg II)/F(Ca II) = 1.3. The corresponding value of this ratio in the optically thin limit of equation (1) for an isothermal slab in LTE is F(Mg II)/F(Ca II) = 0.51. Inspection of column 2 of Table 4 reveals that the observed values of F(Mg II/F(Ca II) are more consistent with the optically thick case rather than with the value deduced for the optically thin case. Observed deviations from the ratio calculated according to equation (2) can be attributed to the existence of a steep temperature gradient in the chromosphere (Cram 1979). Moreover, the Mg II resonance lines actually thermalize at a somewhat higher temperature than do the Ca II resonance lines (Linsky and Avrett 1970; Linsky *et al.* 1979). In addition, the Ca II (H + K) surface flux is a lower limit to the true chromosphere emission flux, as discussed in § II. Finally, we note the important caveat that the Mg II data and the Ca II data discussed in this investigation were not acquired simultaneously. Thus, the emergence and decay of stellar surface activity combined with the rotational modulation of these features are likely to cause variations in the observed net chromospheric radiative losses. Therefore, data sets obtained at widely separated times of observation cannot be confidently compared on a star-by-star basis (with the possible exceptions of the "most active" and the "least active" stars). We can, however, partially circumvent this difficulty by comparing the *mean* values of physical quantities for a particular sample of stars. Since the degree of chromospheric activity among stars in a given sample is uncorrelated, the mean values of physical quantities will remain relatively constant. We thus find the mean value of the ratio F(Mg II)/F(Ca II) to be 3.7.

TABLE 4

LINE FLUX RATIOS

Star	F(Mg II)/F(Ca II)
BP Tau	2.0
T Tau	9.4
DF Tau	4.9
DG Tau	2.0
DR Tau	0.51
RW Aur	3.1

This value of the flux ratio is consistent with the assumption that the emission arises from an optically thick region. Furthermore, Giampapa (1980*b*) finds F(Mg II)/F(Ca II) = 2.90 for a sample of dMe and dM stars, while Basri and Linsky (1979) conclude that the ratio of chromospheric radiative loss rates for the Mg II/Ca II resonance lines is ~ 2.2 for a small sample of solar-type dwarf stars. While the results given in Table 4 provide corroborative evidence for the chromospheric origin of the Mg II and Ca II emission, they do not by themselves constitute a proof of this assertion.

Additional corroborative evidence for the chromospheric origin of the Mg II and Ca II resonance line emission is offered by Herbig and Soderblom (1980). These investigators conclude that the Ca II infrared triplet line emission in T Tauri stars arises from an optically thick region that is similar to a solar plage. Hence, the Ca II resonance line emission and, by implication, the Mg II resonance line emission must also originate in the same kind of region. Furthermore, Feigelson and De Campli (1981) report observations of rapid X-ray variability exhibited by DG Tau, thus indicating that the X-ray emission occurs near the stellar surface. A similar conclusion is reached by Gahm (1980) and by Walter and Kuhi (1981) on the basis of the observed behavior of X-ray emission with Hα strength. Moreover, Worden *et al.* (1981) show that observed short-period photometric fluctuations in T Tauri stars can be ascribed to the superposition of many solar-like flare events. In addition, Ulrich and Wood (1981) conclude that the He I recombination lines λ5876 and λ10830 arise from a chromospheric or "probable chromospheric" region in most of the T Tauri stars they considered. Furthermore, Cram, Giampapa, and Imhoff (1980) show that source depths of transition region lines are consistent with the existence of a region analogous to the solar chromosphere and corona. Finally, Cram (1979) and Calvet (1981) successfully synthesize many of the basic features of T Tauri line spectra by assuming that T Tauri stars possess a chromosphere that begins relatively deep in the atmosphere. In summary, the aforementioned observational and theoretical results offer compelling reasons to interpret the Mg II and Ca II resonance line emission as substantially chromospheric in origin. However, the existence of a stellar chromosphere alone cannot account for all aspects of T Tauri spectra (Cram 1979; Heidmann and Thomas 1980; Schwartz 1974; Ulrich 1976; Calvet 1981).

Given the preceding arguments in justification of the assumption of a chromospheric origin for the Mg II and Ca II emission, we now proceed to discuss the line fluxes and flux ratios within the context of stellar chromospheres. According to Kelch, Linsky, and Worden (1979) the degree of chromospheric emission present is correlated with the value of the chromospheric temperature gradient, with the active chromosphere stars having temperature gradients that are steeper than those of the quiet chromosphere stars. If the relative flux in the Ca II and Mg II lines is indicative of chromospheric temperature gradients (Linsky *et al.* 1979), then the results of Kelch, Linsky, and Worden (1979) suggest that the ratio F(Mg II)/F(Ca II) may be correlated with the total chromospheric losses in the Mg II and Ca II resonance lines. The ratio F(Mg II)/F(Ca II) is plotted with respect to the total fluxes, F(Mg II) + F(Ca II), in Figure 1. The data are widely scattered with no apparent physical relationship between the two parameters. Giampapa *et al.* (1981) find a similar result in the case of the dMe and dM stars. Thus, the ratio F(Mg II)/F(Ca II) may really be more diagnostic of chromospheric optical depths and thermalization lengths rather than temperature gradients. In addition, the results of Kelch, Linsky, and Worden (1979) may not be applicable to the T Tauri and M dwarf stars. Interestingly, the results of single-component, homogeneous, semiempirical model chromospheres (Giampapa 1980*b*) and nonspecific model chromospheres (Cram and Mullan 1979) for dMe and dM stars reveal that the temperature gradients are similar among the active and quiet chromosphere stars. Hence, enhanced chromospheric emission is due to enhanced chromospheric density rather than an increased temperature gradient. If this result is applicable to the T Tauri stars (and if F[Mg II]/F[Ca II] is indicative of chromospheric temperature gradients), then we would not expect any systematic trends in Figure 1. However, confirmation of this hypothesis will require a detailed model atmospheres calculation based upon high resolution, well-calibrated line profiles.

The mean ratio, [F(Mg II)/F(Ca II)] = 3.7, indicates that the Mg II resonance lines generally play a more important role in the overall chromospheric energy balance than do the Ca II resonance lines. However, an accurate assessment of the *total* contribution to the chromospheric net radiative cooling by Ca II requires measurements of the chromospheric emission flux in the Ca II infrared triplet lines at λ8498, λ8542, and λ8662. For the specific case of DR Tau, we convert the measured infrared triplet line equivalent widths given by Herbig and Soderblom (1980) to surface fluxes by multiplying the

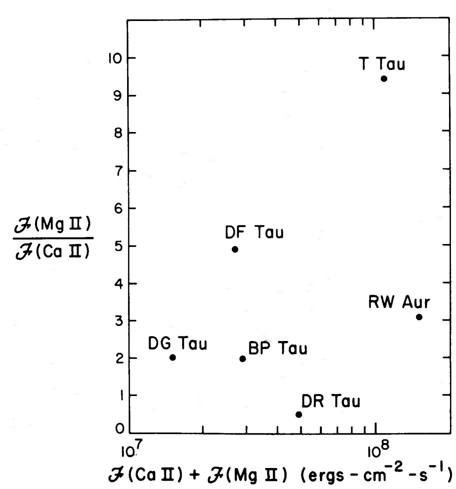

FIG. 1.—Ratios of the flux in the Mg II resonance lines to that of the Ca II resonance lines is plotted with respect to the sum of the Mg II and Ca II chromospheric line flux. See § III*a* for a discussion.

equivalent widths by the local Planck functions at the adopted effective temperature given in Table 2. In all other instances we utilize the observed, unreddened continuum flux measurements at $\lambda 8540$, as given by Kuhi (1974), combined with the radii and distances listed in Table 2 to convert the equivalent widths given by Herbig and Soderblom (1980) to line surface fluxes. For some objects Herbig and Soderblom (1980) present more than one measurement of the infrared triplet line equivalent widths. In these cases we adopt the mean value of the given measurements. The results are listed in Table 5 for a small sample of T Tauri stars for which both the Mg II and Ca II data are available. Inspection of Table 5 appears to indicate that the Ca II resonance and infrared triplet lines in T Tauri stars are generally more important contributors to chromospheric radiative cooling than are the Mg II resonance lines. Vernazza, Avrett, and Loeser (1980) also find that for the average quiet Sun the largest integrated cooling rates are due to the Ca II infrared-triplet and resonance lines, followed in order by the Mg II resonance lines, H^-, and Lα. However, the results in Table 5 are tentative in view of the (1) lack of simultaneous observations, and (2) the crude estimate of the infrared triplet line surface fluxes given in this study. An accurate assement of the contribution by the Ca II infrared triplet lines of the total chromospheric net radiative cooling will require well-calibrated line flux measurements combined with an estimate of the expected line flux for a T Tauri stellar photosphere in radiative-convective equilibrium.

Finally, we plot in Figure 2 the quantities F(Mg II) and F(Ca II) versus effective temperature, where, as before, we adopt the mean values of F(Ca II) for T Tauri stars which have more than one measurement of this quantity. We also plot the sum of the chromospheric radiative losses in the Mg II and Ca II resonance lines in Figure 2. According to Table 3, the T Tauri stars exhibit values $F(\text{Mg II})/F_{\text{Mg II}}{}^{\odot} \gg 1$ and $F(\text{Ca II})/F_{\text{Ca II}}{}^{\odot} \gg 1$, while the corresponding ratios for dMe and dM stars are generally less than unity (Giampapa *et al.* 1980; Giampapa 1980*b*). Furthermore, Figure 2 appears to show a trend of decreasing total resonance line emission flux with decreasing effective temperature for the T Tauri stars considered here. Lastly, we note that our estimates of surface flux are lower limits to the true flux in a line since we assume that the emission arises from the entire stellar surface.

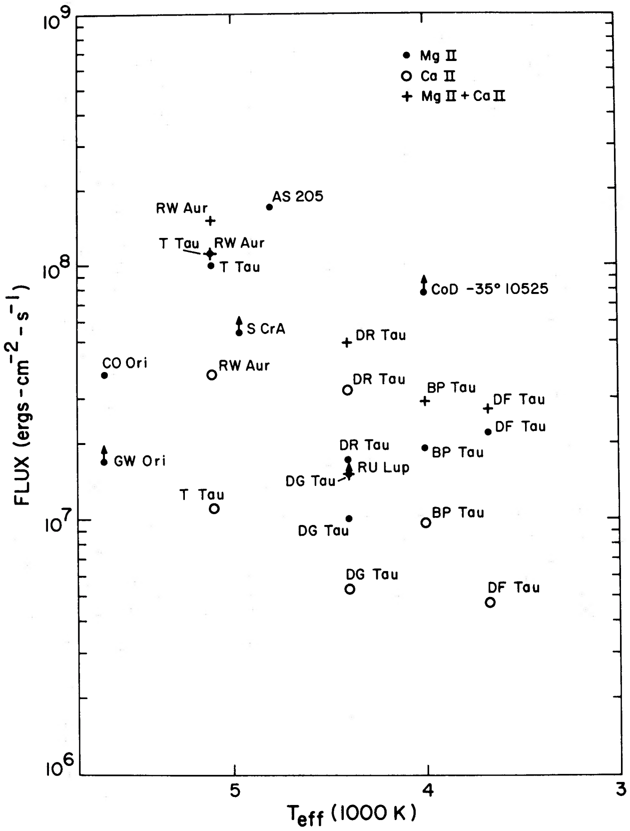

FIG. 2.—Net chromospheric radiative loss rates in the Mg II and Ca II resonance lines are plotted with respect to effective temperature. The sums of the radiative loss rates in these lines are also included. See § III*a* for a discussion.

b) *Chromospheric Radiative Loss Rates*

The importance of chromospheric nonradiative heating present in this sample of pre-main-sequence stars can be readily intercompared through the ratio

$$R_{hk} \equiv F(\text{Mg II } h + k)/\sigma T_{\text{eff}}{}^4 ,$$

where the index R_{hk} represents the chromospheric radiative loss rate in the Mg II resonance lines normalized to the total stellar surface flux. The values of R_{hk} are listed in the second column of Table 6, and we display a plot of R_{hk} versus T_{eff} in Figure 3. We also include in Figure 3, for comparative purposes, dMe and dM stars from Giam-

TABLE 5

ESTIMATED FLUXES FOR THE Ca II INFRARED TRIPLET LINES[a]

Star	$F(\lambda 8498)$[b]	$F(\lambda 8542)$[b]	$F(\lambda 8662)$[b]	$\sum F$	F(Mg II) / F(Ca II H + K + IR triplet)
DG Tau	8.3(7)	8.5(7)	5.9(7)	2.3(8)	0.04
DR Tau	3.8(7)	4.4(7)	3.4(7)	1.2(8)	0.11
RW Aur	1.7(8)	1.5(8)	1.1(8)	4.3(8)	0.23
T Tau	1.8(6)	2.2(6)	1.5(6)	5.5(6)	5.9

[a] Data from Herbig and Soderblom (1980) and Kuhi (1974).
[b] Units: ergs cm^{-2} s^{-1}.

TABLE 6

IMPORTANCE OF NONRADIOACTIVE HEATING IN T TAURI STARS

Star	$R_{hk} \equiv \frac{F(\text{Mg II } h + k)}{\sigma T_{\text{eff}}^4}$	$R_{HK} \equiv \frac{F(\text{Ca II H + K})}{\sigma T_{\text{eff}}^4}$
BP Tau	1.3 (−3)	6.6(−4)
T Tau	2.6 (−3)	2.8(−4)
DF Tau	2.1 (−3)	1.2(−4)
DG Tau	0.47(−3)	2.5(−4)
DR Tau	0.80(−3)	15.0(−4)
SU Aur	0.29(−3)	...
RW Aur	2.9 (−3)	9.3(−4)
CO Ori	0.64(−3)	...
GW Ori	≥0.29(−3)	...
CoD-35°10525 ..	≥5.4 (−3)	...
RU Lup	≥0.71(−3)	...
AS 205	5.6 (−3)	...
S CrA	≥1.6 (−3)	...

papa (1980*b*), active chromosphere dwarf stars given by Kelch (1978) and Linsky *et al.* (1981), the RS CVn systems HR1099, UX Ari, α Aur and λ And (Basri and Linsky 1979), and a solar plage region (Kelch and Linsky 1978). Inspection of Figure 3 clearly reveals that the degree of nonradiative heating present in T Tauri atmospheres is greater than that present in the dMe stars, the active chromosphere dwarf stars ξ Boo A and 70 Oph A, or in solar active (plage) regions. Moreover, the mechanical energy dissipation presumably occurring in these pre–main-sequence stars generally exceeds that which is present in the RS CVn systems. Observations of the Mg II *h* and *k* lines during solar flares are not yet available. However, extensive observations of the Ca II resonance lines during solar flares do exist, and we find that the mean value of the Ca II (H + K) lines flux for the stars considered here, $[F(\text{Ca II H + K})] = 1.7 \times 10^7$ ergs cm^{-2} s^{-1}, is comparable to that of a solar flare of importance 3B (Machado and Linsky 1975). This is similar to the result given by Cram, Giampapa, and Imhoff (1980) who find that the degree of nonthermal heating in the transition regions in active T Tauri stars corresponds (in terms of energy requirements) to that of a solar flare permanently maintained over the entire stellar surface.

The RS CVn stars are close binaries with orbital periods of 2^d–17^d (Hall 1976). Since tidal forces induce synchronism of rotational and orbital periods on evolutionary short time scales (Zahn 1977), the active secondary stars in these systems are characterized by large ($\geq$ 30 km s^{-1}) rotational velocities (Linsky 1980*a*, *b*). If

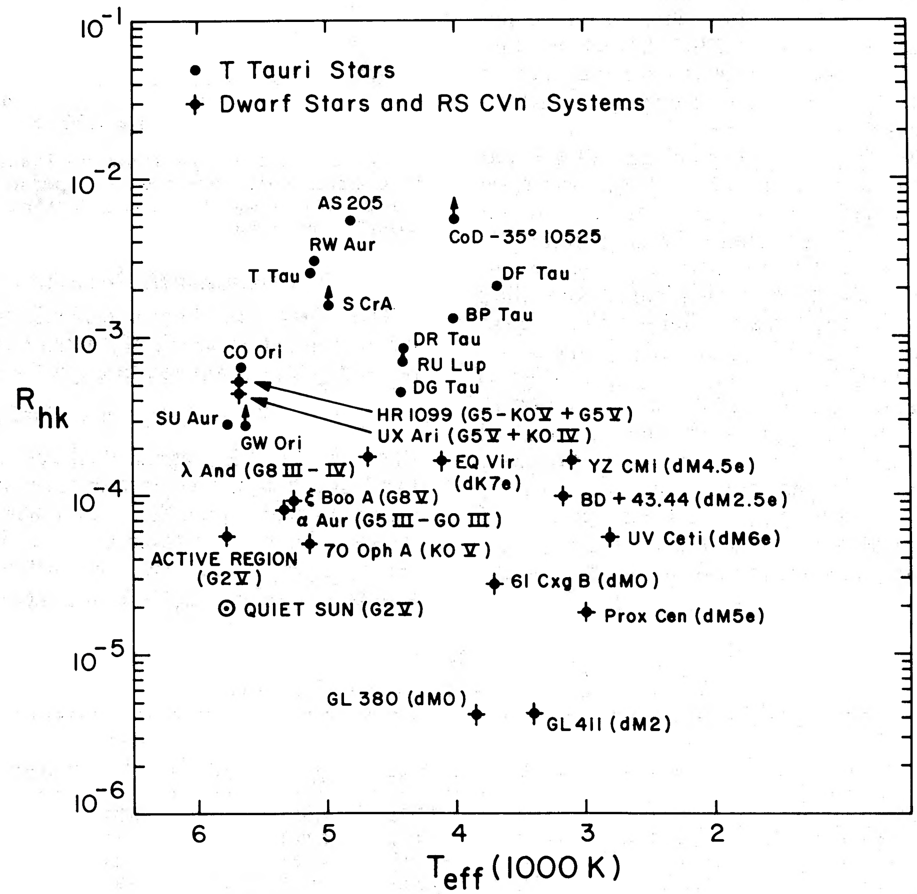

FIG. 3.—Values of R_{hk}, the ratio of the chromospheric radiative loss rates in the Mg II *h* and *k* lines to the total surface flux of the star, are plotted with respect to effective temperature. Additional objects are also included for comparative purposes. Arrows indicate that the plotted value is a lower limit. See § III*b* for a discussion.

the degree of chromospheric activity present is directly correlated with rotational velocity (Kraft 1967; see also Pallavicini *et al.* 1981), then Figure 3 implies that the T Tauri stars generally have higher rotational velocities than those of the components of the RS CVn systems. Hence, the T Tauri stars may possess the highest rotational velocities within the class of late-type, single stars.[2] Furthermore, the importance of nonradiative heating in the T Tauri stars exceeds that of the active chromosphere stars ξ Boo A (G8V) by more than an order of magnitude in some cases. Robinson, Worden, and Harvey (1980) report the detection of 2.7 kilogauss magnetic fields covering 20%–45% of the surface of ξ Boo A. This result combined with Figure 3 implies that the T Tauri stars are characterized by even larger values of magnetic field flux, assuming that magnetic flux and chromospheric emission are correlated (e.g., see Skumanich, Smythe, and Frazier 1975).

In addition to the intense chromospheric emission, the T Tauri stars are characterized by high X-ray luminosities ($L_x \approx 10^{30-31}$ ergs s^{-1}) as well (Feigelson and De Campli 1980). The relative importance of the X-ray emission as a mechanism for atmospheric cooling is reflected in the ratio $F_{\text{X-ray}}/F_{\text{Mg II}}$. The ratio is listed in column 4 of Table 7 and plotted with respect to effective temperature in Figure 4. The values of $F_{\text{X-ray}}$ follow from Feigelson and De Campli (1980) and have a stated accuracy of within a factor of 2. The value of $F_{\text{X-ray}}$ for BP Tau follows from Walter and Kuhi (1981). As in Figure 3 (R_{hk} vs. T_{eff}), there are no apparent trends with effective temperature in Figure 4. Thus, the fraction of the total stellar luminosity that provides chromospheric and coronal heating is not dependent on T_{eff}, but on another physical parameter presumably related to the magnetic field (e.g., see Rosner 1980; Rosner and Vaiana 1980; Golub *et al.* 1980). Moreover, the mean value $[F(\text{X-ray})/F(\text{Mg II})] = 0.22$ indicates that chromospheric line emission generally plays a more important role than X-ray emission in the overall atmospheric energy balance in the T Tauri stars. However, it is important to realize that strong X-ray and chromospheric emission are directly related. For example, the median value of L_x for the sample of T Tauri stars considered here is log $L_x = 30.5$, as compared to a (preliminary) median value of log $L_x = 27.30 \pm 0.15$ for the M dwarf stars (Topka 1980).

[2] While Vogel and Kuhi (1981) do find a few large rotational velocities, most pre-main-sequence stars in the sample they consider have only an upper limit of ~ 30 km s^{-1}. However, the most probable candidates for high rotation rate are strong line emission stars for which the lack of absorption lines prevents any such measurement.

TABLE 7

CHROMOSPHERIC AND X-RAY EMISSION

Star	F(Mg II)[a]	F(X-Ray)[a]	F(X-Ray)/F(Mg II)
T Tau	1.0(8)	1(6)	1.0(−2)
DF Tau	2.2(7)	>5(5)	2.3(−2)
DG Tau	1.0(7)	4(6)	4.0(−1)
SU Aur	1.8(7)	3(6)	1.7(−1)
GW Ori	≥1.7(7)	1(7)	≤5.9(−1)
BP Tau	1.9(7)	2(6)	1.1(−1)

[a] Units: ergs cm^{-2} s^{-1}.

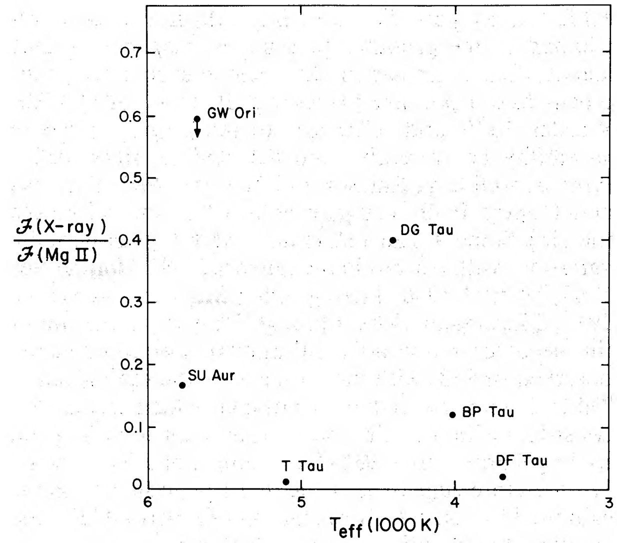

FIG. 4.—Ratios of the X-ray surface flux to the Mg II ($h + k$) surface flux are plotted with respect to effective temperature. See § III*b* for a discussion.

Finally, we consider the relative importance of mass loss to the energy balance in the outer atmospheres of T Tauri stars. Utilizing data given in this investigation and by Imhoff and Giampapa (1981) and Feigelson and De Campli (1980) approximately yields the net radiative chromospheric and coronal losses for the specific case of T Tau, or

$$\begin{aligned} F_R[&\text{Mg II } (h+k) + \text{Ca II } (H+K+IR \text{ triplet}) \\ &+ \text{transition region lines} + \text{X-ray}] \\ &\approx 2 \times 10^8 \text{ ergs cm}^{-2} \text{ s}^{-1} . \end{aligned}$$

The stellar wind flux is

$$F_\omega = 1/2mv_\infty{}^2/4\pi R_*{}^2 \approx 2 \times 10^8 \text{ ergs cm}^{-2} \text{ s}^{-1} ,$$

for $m = 3.5 \times 10^{-7} M_\odot$ yr^{-1} and $v_\infty = 225$ km s^{-1} (Kuhi 1964). Thus, the net radiative losses and stellar wind losses are comparable, although we add the caveat that we do not include the contribution of continuum processes, Lα, and the Balmer lines to our estimate of the net chromospheric and coronal radiative cooling.

c) *Extent of Active Regions on T Tauri Stars*

An approach to account for the degree of chromospheric emission exhibited by stars is to assume that the "quiet" and "active" chromosphere stars fundamentally differ from each other in terms of the fractional area of their surface which is covered by active regions. Such an approach is suggested by the inhomogeneous nature of the solar atmosphere and photosphere, and the results of the previous section. Furthermore, the dMe stars often exhibit quasi-periodic variability which has been attributed to the probable presence of magnetic surface activity that is similar in character to such solar phenomena as sunspots and plages (e.g., Pettersen *et al.* 1980; Worden 1975, and references therein). Quasi-periodic variability has recently been detected in other stellar types as well (e.g., Ramsey and Nations 1980; Baliunas and Dupree 1980; Vaughan *et al.* 1981, and references therein). Some T Tauri stars also exhibit quasi-periodic variations with periods in the range of 3^d–8^d (Hoffmeister 1965; Wenzel 1956; Herbig 1962; Mauder and Schulz 1978; Plagemann 1970, although Plagemann attributes this behavior to nonradial pulsations). If we combine the observed periods with the estimates of the radii given in Table 2, then we deduce rotational velocities that are consistent with the $v \sin i$ measures and upper limits given by Vogel and Kuhi (1981) for a sample of T Tauri stars. We therefore suggest that the quasi-periodic variations exhibited by some T Tauri stars can be attributed to the rotational modulation of surface features that are similar to solar active (plage) regions and sunspots.

In order to estimate the active region filling factor for each of the T Tauri stars shown in Figure 3 we make the following assumptions (Giampapa 1980*a*, *b*; Giampapa *et al.* 1980): (1) the T Tauri star with the largest R_{hk} value has a filling factor of $A \equiv 1$, and the star with the smallest R_{hk} value, the quiet Sun, has a filling factor of $A \equiv 0$; (2) the character of an active region is the same for all the stars; and (3) the center-to-limb behavior of the Mg II (or Ca II) chromospheric resonance line emission can be ignored. The third assumption is an excellent approximation for both the dMe stars (Giampapa 1980*b*) and the Sun (Zirin 1966). The first and second assumptions are entirely *ad hoc.* The combination of these crude assumptions leads to the following expression for the chromospheric radiative losses in the Mg II (or Ca II) lines for a star (Giampapa 1980*a*):

$$F = AF_a + (1 - A)F_Q ,$$

where A is the dimensionless ratio of the area of the active region to the area of the visible quiet stellar surface. The symbols F_a and F_Q represent the particular resonance line surface flux for an active and quiet region, respectively. The values of A based upon the Mg II ($h + k$) lines are given in Table 8. We also estimate values of A based upon the Ca II (H + K) lines, and we list these estimates, along with the corresponding values of $A_{\rm Mg\,II}$, in Table 9 (the estimates of $A_{\rm Mg\,II}$ listed in Table 9 differ somewhat from those given in Table 8 because the two samples of stars given in Tables 8 and 9 are not identical). The estimates of the *relative* filling factor given in Tables 8 and 9 imply, but do not prove, that the surface of the T Tauri stars are extensively covered with active (plage) regions (see also Kuan 1976, 1975). The mean value of $A_{\rm Mg\,II}$ implied by Table 8 is $\langle A_{\rm Mg\,II} \rangle = 0.24$, where we have excluded the assumed extreme values of $A \equiv 1$ and $A \equiv 0$. Inspection of Table 9 indicates that $A_{\rm Mg\,II}$ and $A_{\rm Ca\,II}$ differ for a given T Tauri star, although the mean values $\langle A_{\rm Mg\,II} \rangle = 0.30$ and $\langle A_{\rm Ca\,II} \rangle = 0.33$ are similar. Thus, the discrepancy between the inferred values of $A_{\rm Mg\,II}$ and $A_{\rm Ca\,II}$ for a given T Tauri star in Table 9 may be due to intrinsic variability. However, Giampapa *et al.* (1980) and Giampapa (1980*b*) claim that such apparent discrepancies arise naturally from considerations of line formation in magnetic flux tubes composed of diverging magnetic field lines. Verification of the hypothesis may require a two-dimensional radiative transfer calculation since the assumed magnetic flux tubes are in radiative exchange with their surroundings (Giampapa *et al.* 1980; Giampapa 1980*b*).

TABLE 8

ACTIVE REGION FILLING FACTORS BASED UPON THE Mg II ($h + k$) FLUXES

Star	A
BP Tau	0.10
T Tau	0.58
DF Tau	0.12
DG Tau	0.05
DR Tau	0.09
SU Aur	0.10
RW Aur	0.64
CO Ori	0.21
GW Ori	≥0.09
CoD-35°10525	≥0.45
RU Lup	≥0.08
AS 205	≡1.00
S CrA	≥0.31
Sun	≡0.00

d) Chromospheric Mass Column Densities and Mean Electron Densities

We may estimate typical values of the mass column density in the temperature minimum region of a T Tauri star through application of the chromospheric scaling laws proposed by Ayres (1979) for effectively thick chromospheric resonance lines formed in a stellar atmosphere that is in hydrostatic equilibrium. While the condition of hydrostatic equilibrium may not be strictly applicable to the T Tauri stars, we may still utilize the scaling laws given by Ayres (1979) as a reasonable first approximation, especially in view of the moderate success attained by Cram (1979) and Calvet (1981) in the construction of T Tauri model atmospheres based upon the assumption of hydrostatic equilibrium (i.e., the gas pressure P_G and

TABLE 9

ACTIVE REGION FILLING FACTOR ESTIMATES BASED UPON BOTH Mg II ($h + k$) AND Ca II (H + K)

Star	$A_{\rm Ca\,II}$	$A_{\rm Mg\,II}$
BP Tau	0.25	0.16
T Tau	0.29	0.93
DF Tau	0.12	0.20
DG Tau	0.13	0.08
DR Tau	0.88	0.15
RW Aur	≡1.00	≡1.00
Sun	≡0.00	≡0.00

mass column density m are related by $P_G = gm$, where g is the stellar gravity). According to Ayres (1979) the mass column density at the temperature minimum, m_*, is

$$m_* \approx \tilde{A}_{\rm Fe}^{-1/2}\tilde{F}^{1/2}\tilde{g}^{-1/2}\tilde{T}_{\rm eff}^{7/2 \pm 1} .$$

In this expression $\tilde{g}$ is the gravity, $\tilde{T}_{\rm eff}$ is the effective temperature, and $\tilde{A}_{\rm Fe}$ is the iron abundance, each normalized to the solar value. In this study we assume $\tilde{A}_{\rm Fe}$ to be unity. $\tilde{F}$ is a scale factor which is proportional to the chromospheric heating rate. The quiet Sun would be characterized by $\tilde{F} \approx 1$, while $\tilde{F} \approx 10$ would represent the so-called active chromosphere stars (Linsky 1977) or solar plage regions. The index $\tilde{F}$ is given by (Ayres 1979, eq. [4])

$$\tilde{F} = F_*^{\rm tot}/7 \times 10^6 \tilde{T}_{\rm eff}^{6} ,$$

where $F_*^{\rm tot}$ is the total heating above the temperature minimum estimated for this sample of stars by scaling from the measured total *solar* chromospheric losses. Hence,

$$F_*^{\rm tot} = F_*^{h+k} F_\odot^{\rm tot}/F_\odot^{h+k} ,$$

where F_*^{h+k} is the measured chromospheric loss rate in the Mg II h and k lines and $F_\odot^{h+k}$ is the same quantity for the Sun. $F_\odot^{\rm tot}$ is the total solar chromospheric loss rate in H^- and important spectral lines (Ayres 1979). We list the value of the index $\tilde{F}$ in Table 10 for the sample of T Tauri stars considered in this investigation. We note that the values of $\tilde{F}$ for the T Tauri stars are typically greater than that considered representative of solar active regions (i.e., $\tilde{F} \approx 10$) or even the dMe stars (Giampapa *et al.* 1981). The values of $\tilde{g}$ can be obtained from estimates of the stellar radii and masses. The masses can be estimated by interpolation among the evolutionary tracks given by Cohen and Kuhi (1979). In the specific case of the pre–main-sequence star T Tau, this procedure yields $\tilde{g} \approx 0.06$, where we have adopted the value of the radius given in Table 2 for T Tau. Substituting this estimate of the stellar gravity, $\tilde{F} = 78$, and $\tilde{T}_{\rm eff} = 0.88$, into the expression for the mass column density at the temperature minimum yields

$$m_* \approx 23\, m_*^{\odot} ,$$

TABLE 10

THE CHROMOSPHERIC ACTIVITY INDEX $\tilde{F}$

Star	$\tilde{F}$
BP Tau	19
T Tau	78
DF Tau	24
DG Tau	9
DR Tau	15
SU Aur	12
RW Aur	86
CO Ori	26
GW Ori	≥12
CoD-35°10525	≥78
RU Lup	≥14
AS 205	142
S CrA	≥44

where $m_*^{\odot}$ is the corresponding value for the average quiet Sun, or $m_*^{\odot} = 6.5 \times 10^{-2}$ g cm^{-2} Vernazza, Avrett, and Loeser 1980). In the specific case of RW Aur we have that $\tilde{F} = 86$, $\tilde{T}_{\rm eff} = 0.88$, and $\tilde{g} \approx 0.36$, thus yielding $m_* \approx 10\, m_*^{\odot}$. Hence, the initial chromospheric temperature rise begins deep within the T Tauri atmosphere, thus corroborating the original suggestion by Herbig (1970). Further evidence for the existence of a dense temperature minimum region in the T Tauri stars is offered by Cram (1979) through the construction of a series of *nonspecific* T Tauri model chromospheres. Cram (1979) finds that a model chromosphere with $m_* = 0.65$ g cm^{-2} (thus corresponding to $m_* = 10\, m_*^{\odot}$) successfully reproduces many aspects of a so-called "advanced" T Tauri spectrum. In addition, Calvet (1981) finds typical values of m_* in the range 3 to 20 $m_*^{\odot}$ for a series of semiempirical model chromospheres based predominantly upon observed continuum and Ca II K line *fluxes*. Hence, verification of the existence of a dense temperature minimum region in the T Tauri stars will eventually require the development of semiempirical model chromospheres based upon the cores and wings of *observed* chromospheric resonance lines such as the Mg II h and k lines.

The mean electron density in a stellar chromosphere should scale approximately as (Ayres 1979)

$$n_e \approx \tilde{F}\tilde{T}_{\rm eff}^{6 \pm 2} m_*^{-1} ,$$

or $n_e \approx 1.6\, n_e^{\odot}$ for the specific case of T Tau, while for RW Aur we obtain $n_e \approx 4\, n_e^{\odot}$. According to Vernazza, Avrett, and Loeser (1980) the electron density in the average quiet Sun at $T_e = 6500$ K is $n_e^{\odot} \approx 5.6 \times 10^{10}$ cm^{-3}. Thus, our results imply that the mean chromospheric electron density in T Tau (and RW Aur) is $n_e \approx 10^{11}$ cm^{-3}. This is similar to the chromospheric electron densities deduced for the relatively high gravity dMe stars (Giampapa 1980*b*).

IV. CONCLUSIONS

We find that the degree of nonradiative heating present in the outer atmospheres of the T Tauri stars generally exceeds that of the RS CVn systems, as well as the dMe stars and other active chromosphere dwarfs. Thus, the T Tauri stars are the extreme examples of the so-called "active chromosphere" stars. Assuming that the chromospheric emission arises from active regions similar to solar plage regions, we infer that the surfaces of these pre–main-sequence stars are extensively covered by active regions. We also find that the initial chromospheric temperature rise must begin deep within the atmosphere, as proposed by Herbig (1970) and corroborated by recent model chromospheres computations (Cram 1979; Calvet 1981). Moreover, the T Tauri chromospheres are characterized by mean electron densities of $n_e \approx 10^{11}$ cm^{-3}. However, verification of these atmospheric parameters will require the following observational and theoretical programs which we intend to pursue; namely, the acquisition of high resolution, well-calibrated profiles of the cores and wings of chromospheric resonance lines (such as the Mg II h and k lines) followed by the detailed computation of model atmospheres which incorporate micro- and macroscopic velocity fields. Other spectral diagnostics formed at various heights in the atmosphere would also be valuable, but these kinds of data must be obtained simultaneously in view of the spectral variability exhibited by the T Tauri stars. Eventually, rotation measures and magnetic flux measurements must be acquired in order to relate the inferred atmospheric structural details to the underlying dynamics. Hence, this program will enable astronomers to address the problem of the origin of stellar chromospheres and discern the effect of chromospheric regions on the subsequent evolution of the stars.

We are grateful to the staff of the *IUE* Observatory for their assistance during the acquisition of the ultraviolet observations discussed in the investigation. This work is supported in part by the National Aeronautics and Space Administration under grant NSG-5235 to the University of Arizona, and by the National Science Foundation via grant AST 79-02866 to the University of California.

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