Rev. Mexicana Astron. Astrof., **14**, 353-358 (1987)

THE PHOTOSPHERE OF T TAURI STARS

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RESUMEN. Hemos calculado el espectro de absorción en el intervalo de longitudes de onda 4880-5025A para un conjunto de modelos con T_{eff} = 4000 y log g = 3.5, y una subida de temperatura cromosférica, los cuales son considerados representativos de la atmósfera de las estrellas T Tauri. La posición del mínimo de temperatura en estos modelos va de 0.1 a 2 gr cm^{-2}. Las poblaciones se toman en ETL y la función fuente para las líneas se calcula con la aproximación de dos niveles más continuo. Hemos comparado los espectros calculados con espectros de estrellas T Tauri obtenidos para el programa de determinación de velocidades rotacionales de Vogel y Kuhi (1981). Las diferencias entre el espectro de absorción de estrellas T Tauri pueden entenderse en primera aproximación en términos de diferencias en la posición del mínimo de temperatura. En particular, encontramos que en el momento de su observación, el mínimo en BP Tau estaba entre 1 y 2 gr cm^{-2} y en AA Tau entre 0.3 y 0.6 gr cm^{-2}.

ABSTRACT. We have calculated the absorption spectrum in the wavelength interval 4880-5025A for a set of models with T_{eff} = 4000K and log g = 3.5 and a chromospheric temperature rise. These models are considered as representative of the atmosphere of T Tauri stars. The position of the temperature minimum goes from 0.1 to 2 gr cm^{-2} in the models. Populations are in LTE and the two level plus continuum approximation is used for the source function. We have compared the calculated spectra with those observed in the program of rotational velocity determination by Vogel and Kuhi (1981). Differences between the spectrum of T Tauri stars can be understood in first approximation in terms of differences in the position of the temperature minimum. In particular, we find that at the moment of the observation, the minimum in BP Tau was located between 1 and 2 cm^{-2} and in AA Tau between 0.3 and 0.6 gr cm^{-2}.

Key words: STARS-ATMOSPHERES — STARS-T TAURI

I. INTRODUCTION

It is now generally accepted that the outer atmospheric regions of T Tauri stars are heated by the transport and deposition of mechanical energy, and that the observed optical, ultraviolet and X-ray emission arise in those regions. However, neither the characteristics of the transport mechanisms involved nor the details of the resultant atmospheric structure are well known. Principally as a result of the different assumptions and diagnostics used to study each region, the atmosphere has been divided into three regions, the photosphere, the chromosphere, and the wind. The emission lines and continua are supposed to arise in the chromosphere and the wind. To explain the observations, both regions are required and the importance of each varies from star to star (Cram 1979; Hartmann, Edwards, and Avrett 1982; Calvet, Basri, and Kuhi 1984; Hartmann 1986).

The T Tauri photosphere has been scarcely studied. Atmospheric models published so far have assumed that the photosphere is similar to that of the standard star with the same effective temperature and gravity, except for the position of the temperature minimum which is assumed to be deeper in T Tauri stars, as indicated by several considerations (Herbig 1970; Dumont et al. 1973; Giampapa et al. 1981). The range whithin which the minimum can vary in actual stars is not known, although an upper limit around 2 gr cm^{-2} is found from considerations on the H^- continuum emission at the bottom of the chromosphere (Calvet 1982).

The best photosphere diagnostic is the absorption spectrum. Until now only very schematic absorption spectrum calculations in T Tauri stars have been done, showing that the absorption lines become weaker as the importance of the chromosphere increases, as observed (Cram 1979; Calvet, Basri, and Kuhi 1984). The detailed study of the photosphere, on the other hand, is relevant not only to know its structure but also for the eventual study of the mechanisms of energy transport through it, since a basic amount of energy in magnetohydrodynamic waves is expected to arise in the subphotospheric convection region (Calvet and Albarrán 1984).

In this communication, we present results of the calculation of the absorption spectrum in a given wavelength range for a series of T Tauri models, and we attempt a comparison with the spectrum of particular stars with the purpose of estimating the structure of their photosphere. The method of determination of the photospheric structure presented here still has to be refined, so that we will only estimate one parameter, the location of the temperature minimum. However, the application of this method as presented serves to prove the main purpose of this work, namely, that it is possible to distinguish finer details of the photosphere of a given star using as diagnostic the absortion spectrum. In section II we describe the method of calculation, in section III we compare theoretical and observed spectra, and in section IV we give a summary and conclusions.

II. CALCULATIONS

We have calculated the absorption spectrum using the program ESPECTRO (Calvet 1986). The ionization equilibrium is calculated assuming the populations in LTE. Continuum opacity sources include H, H^-, He^-, H_2^+, C, Si, Mg, and electron and Rayleigh dispersion. Molecules are not taken into account.

Populations are assumed in LTE in the line opacity calculations. Lines have Voigt profiles, and damping constants are taken from Griem (1968) and Cowley (1971) for the Stark broadening of ions and neutrals, respectively, and from Unsold (1955) with enhancement factor by Edmunds (1975a,b) for the van der Waals broadening. The resonant broadening is represented by the classical expression, which approximates the actual value within 30 % according to Peytremann (1972). Line data is taken from the Kurucz and Peytremann (1975) compilation. Microturbulence is included as a depth dependent parameter.

The line source function is represented by a two-level plus continuum approximation. Radiation in the continuum is described by a radiation temperature equal to the effective temperature. The photoionization cross-section for all levels is assumed to be 10^{-18} cm^2. The collisional ionization coefficient is taken from Burgess and Seaton (1964), and the collisional excitation from Van Regemorter (1962). The scattering integral is represented by the Planck function at a radiation temperature given by the temperature of the point where the line optical depth becomes one, for small line optical depths, and by the electron temperature otherwise. The continuum source function is taken as the Planck function.

The absorption spectrum is calculated in the wavelength range 4880 - 5025A for a set of chromospheric models with T_{eff} = 4000K and log g = 3.5. The chromospheric temperature rise is similar to model B in Calvet, Basri, and Kuhi (1984), but the position of the temperature minimum is varied in the models. The position of the minimum is given in Table 1 and the temperature profiles are shown in Figure 1. Microturbulence is taken as 15 km s^{-1} at the top of the chromosphere and decreases to 1 km s^{-1} at the temperature minimum and the photosphere.

One of the problems we have found in this investigation is the inaccuracy of the line gf values, which is more serious the weaker the line. We have tried to correct for this problem by calculating a solar spectrum in the same wavelength range using the VAL model (Vernazza, Avrett, and Loeser 1976) and adjusting the strength of the lines until they fit the observed values. This method of estimating gf values is subject to uncertainties in the assumed model and in the solution of the transfer of radiation.

TABLE 1
POSITION OF THE TEMPERATURE MINIMUM

Model	m_o (gr cm^{-2})
A	0.1
B	0.3
C	0.6
D	1.0
E	2.0

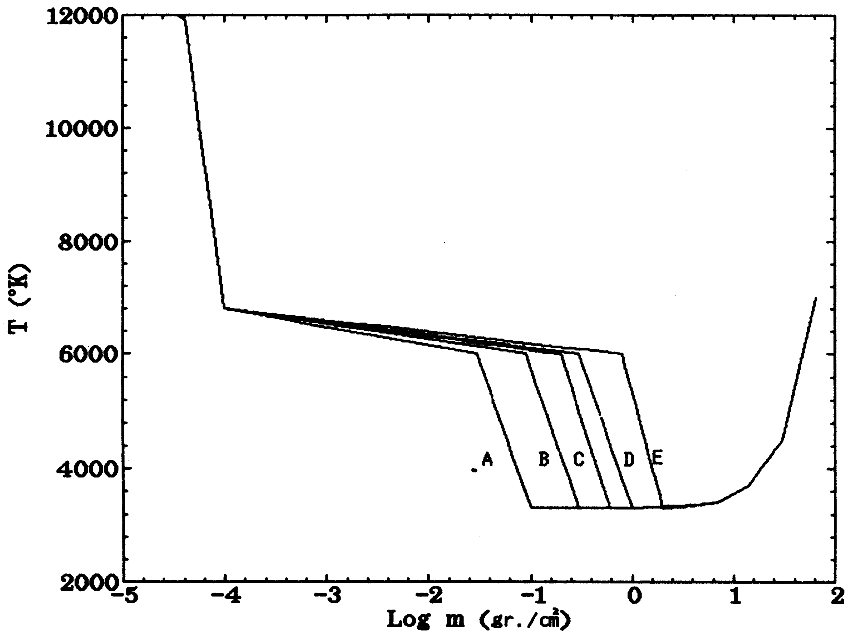

FIGURE 1. Temperature structures for models A to E.

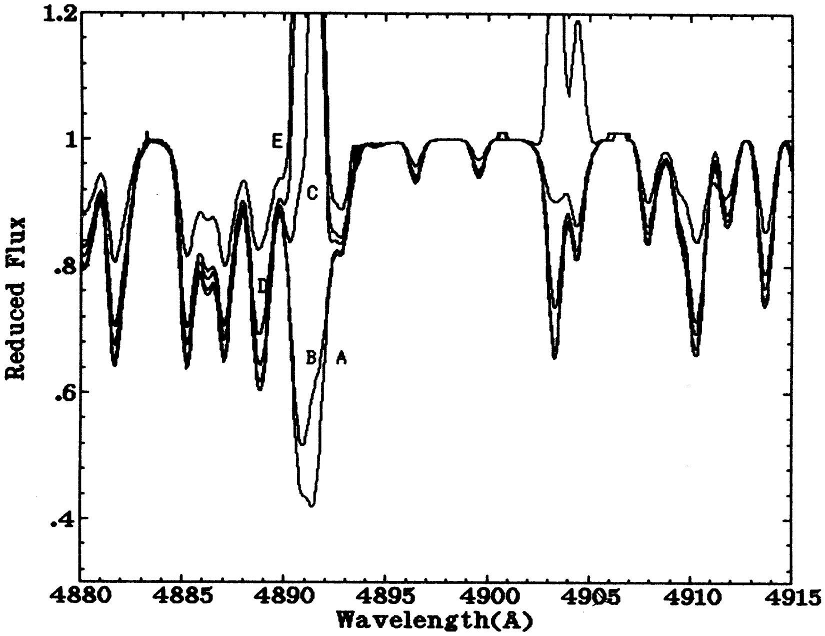

FIGURE 2. A portion of the calculated spectrum for models A to E, convolved with a gaussian of the appropriate width. The photospheric spectrum is also shown. Ordinate shows flux reduced to continuum.

III. RESULTS AND DISCUSSION

We have compared our results with spectra taken for the rotacional velocity program of Vogel and Kuhi (1981). The spectra were obtained in IIIa-J plates at 13 A/mm, so that in order to acomplish the comparison we convolved the theoretical calculations with a gaussian of the appropiate width. A portion of the convolved spectra for all models is shown in Figure 2. The ordinate shows the flux reduced to the continuum. It is apparent that the strength of the lines decreases as the temperature minimum becomes deeper, both because of increased ionization of neutrals and because of the additional contribution to the total source function from chromospheric levels (Calvet, Basri, and Kuhi 1984). Also, as the temperature minimum depth increases the strong lines become into emission in the models. This is mainly a result of the poor treatment of the line radiation, because since optical depth unity occurs in the chromosphere, the line radiation temperature is too high. We are presently working in a better approximation for the radiation transfer in the lines.

Figures 3a and b show the comparison of spectra in Figure 2 with those of the stars BP Tau and AA Tau. Along with the observed spectra, we have plotted the two theoretical models that best enclose them. No shift to account for radial velocity has been done. Observed spectra show more features than the theoretical ones, especially weak ones, probably reflecting the fact the some of the gf values used are inappropriate. Some of the lines are not in the Kurucz-Peytremann list; in particular, we have not been able to identify the feature at 4895.5A. There is a further uncertainty in the determination of the observed continuum. In addition, since the stellar photospheric temperature profiles certainly differ by more than the location of the temperature minimum, we expect to observe more differences between the spectra than just those predicted by our set of theoretical models. However, despite all these problems, it is apparent in Figure 2 that there are differences between the spectra of BP Tau and AA Tau which can be understood, in a first approximation, in terms of a different location of the temperature minimum at the time of observation. Lines in BP Tau are weaker than in AA Tau, and from the comparison one can estimate than the minimum from BP Tau is located between 1 and 2 gr cm^{-2}, while that in AA Tau is located between 0.3 and 0.6 gr cm^{-2}.

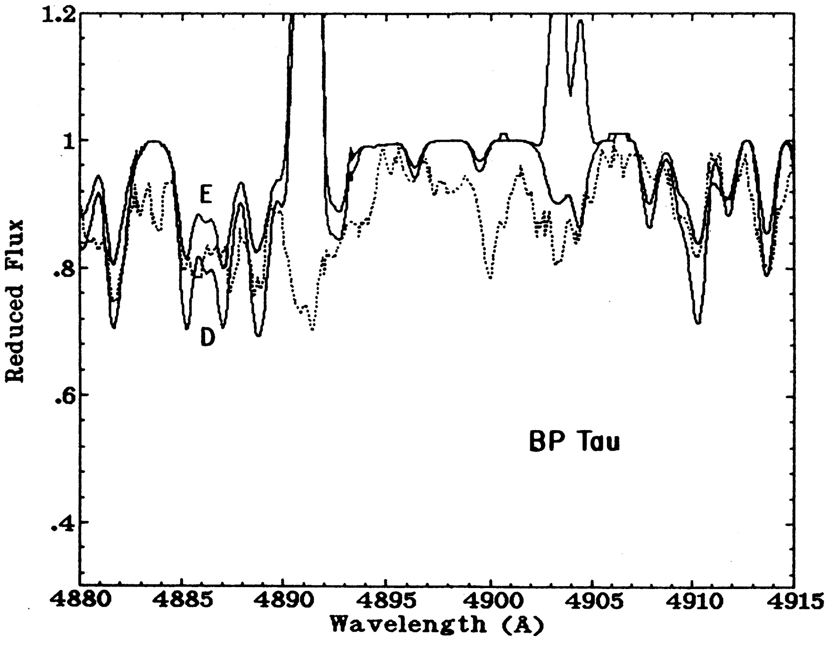

FIGURE 3a. Spectrum of BP Tau (dotted line) and theoretical spectra of models E and D in Figure 2. (continuous lines).

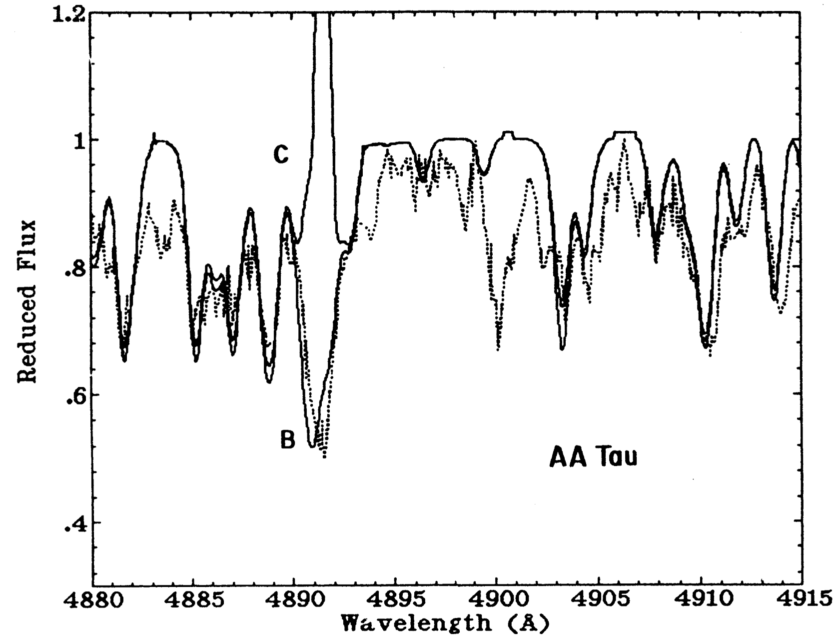

FIGURE 3b. Spectrum of AA Tau (dotted line) and theoretical spectrum of models C and B in Figure 2. (continuous lines).

IV. SUMMARY AND CONCLUSIONS

We have shown that differences between the absorption spectrum of T Tauri stars can be understood in a first approximation by a change in the location of the temperature minimum. For the particular stars studied, the estimated difference between their minimum is almost of an order of magnitude. Other differences between the spectra are probably due to differences in the structure of the upper photosphere which we have not taken into account in this work. This investigation must be considered as a preliminary exploration of the method which, as better atomic parameters become available, a better treatment is given for the strong lines, and high resolution calibrated observations are used, can become a powerful tool for the study of the atmosphere of active stars,as a complement of other spectral indicators.

ACKNOWLEDGEMENTS

We acknowledge the travel support given by the Smithsonian Directorate of International Activities, by CONICIT grant S2-1115, and by the Instituto de Astronomía, UNAM, México.

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DISCUSSION

PEIMBERT: ¿Existen predicciones teóricas de estos modelos para las regiones ultravioleta yx del espectro?

CALVET: No se han publicado hasta ahora predicciones de emisión en el ultravioleta y en rayos-x con modelos de atmósfera de estrellas T Tauri, excepto para líneas en el ultravioleta. Estas últimas se supone que provienen de la zona densa y caliente (Brown et al. 1983).

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