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COMMENTS ON THE He I IONIZATION IN T TAURI STARS

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RESUMEN

Las predicciones de un modelo aproximado de ionización por radiación XUV para He I en las atmósferas de estrellas T Tauri se comparan con observaciones de la luminosidad en 5876 de He I y en rayos X. Esta comparación muestra que la ionización XUV no puede reproducir las observaciones. Se infiere entonces que los mecanismos dominantes en la excitación e ionización del He en las atmósferas de estrellas T Tauri deben ser procesos colisionales. De acuerdo a estos argumentos, la ausencia de 1640 de He II no puede usarse como evidencia de que algunas estrellas T Tauri no poseen coronas. El hecho de que no exista una diferencia sistemática en luminosidad en 5876 de He I entre estrellas con y sin detección en rayos X parece indicar que ambos tipos de estrellas poseen estructura cromosférica similar hasta T $\sim$ 50 000 K.

ABSTRACT

The predictions of an approximate model for XUV ionization of He I in the atmospheres of T Tauri stars are compared with observations of the luminosity in He I λ5876 A and in soft X-rays. The comparison shows that XUV ionization cannot account for the observations. Collisional processes are then indicated to be the dominant mechanism determining the excitation and ionization of He in T Tauri atmospheres. The absence of He II 1640, therefore, cannot be used as an argument for the lack of coronae in T Tauri stars. The fact that there is no systematic difference in luminosity in He I 5876 between stars with and without X-ray detection argues for a similar chromospheric structure in T Tauri stars up to T $\sim$ 50 000 K.

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

I. INTRODUCTION

The He I lines in emission are among the secondary characteristics that define the class of T Tauri stars (TTS hereafter) (Herbig 1958). In optical-red spectra, the He I 5876 emission line is present in TTS of almost all degrees of activity (cf. Cohen and Kuhi 1979). A typical time-scale for variability of a few days is characteristic of He I λ5876 A (Kuhi 1978), and together with He I 10830, these lines emit in average a flux of the order of 10% the flux emitted in Hα (Calvet and Albarrán 1984).

IUE spectrograms of a number of TTS indicate the presence of the He II 1640 line, with strength of 10^3 times the solar value (Imhoff and Giampapa 1982); this amounts to a flux of 10^6 erg cm^{-2} s^{-1}, that is, of the same order as the flux of the He I lines. However, there are TTS for which He II 1640 is weak or absent. In turn, these are stars that in general show signs of high activity, such as strong emission in the Balmer lines and in the resonance lines of Ca II and Mg II, as well as extreme variability. Additionally, most of the stars in this sample have not been detected in X-rays, indicating that their luminosity in this bandpass is $\lesssim 10^{-2}$ times the luminosity of the detected stars, $\sim 10^{30}$ erg s^{-1} (Gahm 1980; Feigelson and DeCampli 1981; Walter and Kuhi 1981). Even this luminosity is weak compared to the value expected from the transition region line enhancement, but still $L_X/L_{bol} \sim 10^{-3} - 10^{-2}$, comparable to that in active K stars (Walter 1981) and dMe stars (Vaiana 1980; Linsky 1980). Walter and Kuhi (1981) have found an anticorrelation between the equivalent width in Hα and the X-ray luminosity. Two possible interpretations have been given to this anticorrelation. On the one hand, it has been attributed to an effect of absorption (Gahm 1980; Walter and Kuhi 1981). In this interpretation, all TTS have similar coronae, but the density in the surrounding extended envelope in which Hα arises (Calvet 1981) varies from star to star. The most active stars would have the densest envelope, which would absorb the X-rays emitted by the thin corona near the star. Calvet, Cantó and Rodríguez (1983) did find that stars with strong activity showed the effect of a wind in the molecular environment surrounding the star, while the quiet TTS showed almost no effect. This evidence supports the hypothesis of a higher $\dot{M}$ in the most active stars, since the wind velocity (interpreted as the velocity of the blueshifted absorption component on the emission lines) is of the same order in all stars (Herbig 1977).

Alternatively to the absorption hypothesis, it has been proposed that stars that only have upper limits for L_X lack hot gas in their atmospheres that could produce the emission (Imhoff and Giampapa 1980, 1982). Several indications have been discussed in support of this hypothesis. Theoretical wind calculations (Hartmann, Edwards, and Avrett 1982) show that a wind can be generated in the uppermost layers of the atmosphere of TTS by deposition of energy and momentum of Alfvén waves created in the surface. Hartmann *et al.* find that, depending on the total energy flux in waves, high temperature regions can be generated in the atmosphere. Furthermore, there is an anticorrelation between the maximum temperature the gas reaches and the $\dot{M}$ of the generated wind. These calculations suggest that stars with strong winds have a smaller fraction of their surfaces covered by high-temperature regions; this, in turn, implies for these stars weaker average fluxes in ultraviolet high-temperature transition region indicators and weaker L_X. This correlation is observed; for instance, stars which lack X-ray detection generally do not show emission at N V λ1240 A (Imhoff and Giampapa 1980, 1982).

It has been argued that another evidence in favor of this second alternative comes from the weakness or absence of He II 1640 in those stars that lack X-ray detection (Imhoff and Giampapa 1982; Calvet 1983*b*). It has been argued that the solar He chromospheric spectrum could be reproduced if the He ionization equilibrium was controlled by XUV radiation from the uppermost hot regions of the atmosphere (Goldberg 1939; Hirayama 1971; Zirin 1975). The weakness of the He spectrum in coronal holes (Tousey 1967; Tousey *et al.* 1973; Harvey *et al.* 1974) supports these arguments. If a similar mechanism was relevant in the upper atmospheres of TTS, then the weakness or absence of He II 1640 would indeed imply the absence of X-ray ionizing radiation and therefore of coronae. However, it has been discussed qualitatively (Calvet 1983*a*) that the large fluxes in He I 5876 point to a He ionization mechanism different from XUV ionization. In this work, we discuss this argument in a more quantitative way, and corroborate the previous conclusion. The general and simple approach taken in this paper must be considered as preliminary to a detailed calculation of the He atom excitation and ionization in an appropriate model atmosphere. In §II, the predictions of an approximate model for the He ionization equilibrium based solely ou XUV ionization are presented and compared with the existing observations. The implications of such a comparison are discussed in § III.

II. AN APPROXIMATE MODEL FOR XUV IONIZATION

In this section, we will follow the treatment applied to dMe stars (Giampapa *et al.* 1978) for estimating the relationship between L_X and the flux in He I 5876. Although this treatment is very approximate, it is justified in the present case, since we are only looking for an order-of-magnitude effect.

Let us assume that the most important mechanism for determining the He ionization equilibrium is ionization by a source of XUV radiation. Let us further assume that the density is low enough that all transitions between excited states are optically thin, so that electrons in excited states after recombination cascade down without producing further absorptions. This is the situation found in nebulae, so that the number of ionizing photons N_{IO} can be written as (Osterbrock 1974)

$$N_{IO} = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu}\, d\nu \sim \frac{4\pi}{3} R_*^3\, \alpha_\beta(\mathrm{He})\, N_{He}\, N_e \quad , \qquad (1)$$

where α_β(He) is the total He I recombination coefficient. Here, R_* is the stellar radius, and N_{He} and N_e the helium and electron densities respectively. On the other hand,

$$4\pi R_*^2 F_{5876} \sim \frac{4\pi}{3} R_*^3\, \alpha^{ef}_{5876}\, N_{He}\, N_e\, h\,\nu_{5876} \quad , \qquad (2)$$

where F_{5876} is the flux in He I 5876 and α^{ef}_{5876} is the effective recombination coefficient for this transition (Osterbrock 1974). Therefore,

$$N_{IO} = \frac{4\pi R_*^2}{h\,\nu_{5876}}\, \frac{\alpha_\beta(\mathrm{He})}{\alpha^{ef}_{5876}}\, F_{5876}$$

$$= \frac{1}{h\,\nu_{5876}}\, \frac{\alpha_\beta(\mathrm{He})}{\alpha^{ef}_{5876}}\, L_{5876} \quad , \qquad (3)$$

where L_{5876} is the luminosity in He I 5876, assuming that the emission comes from an homogeneous, spherically symmetric region. The values of α(He) and α^{ef}_{5876} have been given by Brocklehurst (1972).

The number of X-ray photons N_X for bremsstrahlung is given by (Haisch *et al.* 1977):

$$N_X \sim 2.65 \times 10^{27}\, T^{-1/2} \int N_e^2\, dV$$

$$\times \int_{1A}^{504A} \frac{1}{hc\lambda}\, e^{-hc/\lambda kT}\, d\lambda \quad , \qquad (4)$$

The total X-ray luminosity can be estimated from the total radiative loss in X-ray bands calculated by Raymond, Cox, and Smith (1976)

$$L_X \sim \left(\frac{\Lambda}{N_e^2}\right) \int N_e^2\, dV \quad , \qquad (5)$$

where Λ is the power radiated per cm^3.

In order to relate the number of ionizing photons to the number of X-ray photons, we have to estimate the relative importance of all the radiative factors that can produce He I ionization in TTS. As determined by model atmosphere calculations, the structure of the chromosphere in TTS is similar in temperature and density to that of solar flares (Calvet 1983*b*). Canfield *et al.* (1980) have measured the radiative energy output of the 5 September 1973 flare from below 1 A to above 1 m within a period of several days around flare maximum. The observations of Canfield *et al.*, averaged over time, indicate that the total power radiated in soft X-rays, between 1 and 20 A, is ~ 1.6 times higher than that in the He II lines with $\lambda \leq 304$ A, and ~ 1.2 times higher than that in the brightest coronal XUV lines, between 171 and 345 A, of Ca XVII, Ca XVIII, Fe XIII, Fe XIV, Fe XV, Fe XVI, Ni XVII, and Ni XVIII. Using these values as representative of the situation in T Tauri atmospheres, the ratio N_X/N_{IO} can be obtained, and from it using equations (5), (4), and (3), the relationship between L_X and L_{5876} for a given temperature.

Figure 1 shows the result of the calculations for temperatures of the X-ray producing region between 5×10^5 and 1×10^8 K. The emission in He I 5876 increases with temperature for a given flux of ionizing X-ray radiation. However, this emission reaches a maximum value for $T \sim 2 \times 10^7$ K and then decreases, as N_X begins to decrease with temperature for a given L_X in equation (4).

Figure 1 also shows observed values of L_{5876} and L_X. The X-ray luminosity is taken from Gahm (1980), Feigelson and De Campli (1981) and Walter and Kuhi (1981). Upper limits for L_X are also marked in the figure. Values for the surface fluxes of He I 5876 have been estimated from the data in Cohen and Kuhi (1979), and luminosities in the line have been obtained using stellar data also from this compilation. The stellar data for the continuum stars has been taken from Calvet and Albarrán (1984). The optical and X-ray observations are uncorrelated in time. There is a difference of approximately two orders of magnitude between the observed He I 5876 luminosities and those predicted by the XUV photoionization model. The implications of this difference will be discussed in the next section.

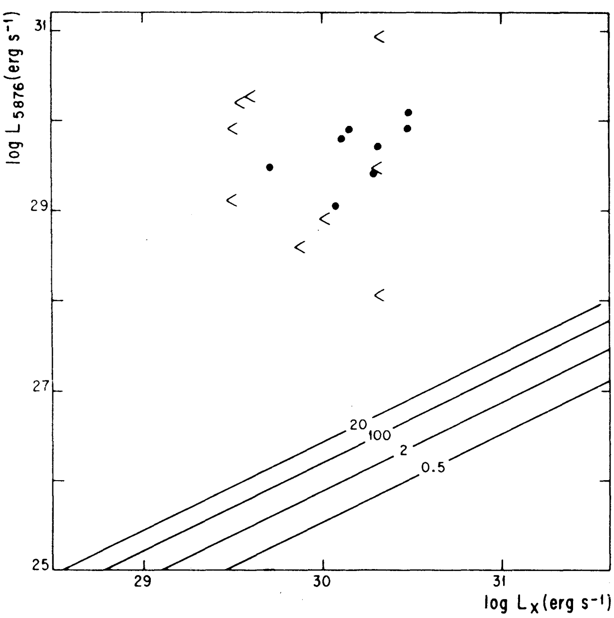

Fig. 1. Luminosity in He I 5876 versus X-ray luminosity. Continuous lines represent predicted fluxes for the case of XUV ionization. Curves are labeled by the value of the temperature of the X-ray emitting region, in units of 10^6 K. Solid points represent observations for stars with detected X-rays. Stars with upper limits for L_X and observed L_{5876} are also indicated in the figure.

IV. DISCUSSION AND CONCLUSIONS

The large difference between observed and predicted luminosities for the case of XUV photoionization has interesting implications. The data shown in Figure 1 seem to indicate that there is no way for radiation from hotter atmospheric regions to be dominating the population equilibrium in He I in the atmospheres of TTS. Excitation and ionization by collision is then indicated. In the solar case, collisional processes cannot explain the observed facts, because they require high density material at high temperatures, which would contradict other spectral diagnostics (Zirin 1975). The situation is different in the atmospheres of TTS, since chromospheric models constructed to reproduce observations of a set of spectral diagnostics characteristic of several atmospheric regions, indicate higher densities throughout the chromosphere than in the solar case (Calvet 1981; Calvet, Basri, and Kuhi 1983). Collisional processes in He I are then expected to be more important in TTS than in the sun, as they are for dMe stars (Giampapa *et al.* 1978). Milkey, Heasley, and Beebe (1973) calculated the He I spectrum in the sun, using the Vernazza, Avrett and Loeser (1973) model. They included in their calculation the effect of ionization by radiation coming from hot atmospheric layers, although they omitted the flux below ~ 200 Å. Still, Milkey *et al.* found that triplet levels are populated by radiative recombination only for regions with $T \leq 10\,000$ K. These were the only regions sensitive to excess ionizing radiation. In the Vernazza *et al.* model, chromospheric regions with $T \leq 10\,000$ K have electron densities of $\sim 10^{11}$ cm^{-3}. In contrast, in TTS, the regions with $T \leq 10\,000$ K have electron densities an order of magnitude higher than this value (Calvet, Basri, and Kuhi 1983), suggesting again that collisional excitation and ionization of He I dominate throughout the atmosphere.

The high densities found in T Tauri atmospheres may be sufficient to produce the observed fluxes in He I 5876. Alternatively, a mechanism of ionization by penetration of hot electrons, similar to that proposed by Jordan (1975) in the solar case, may be required. Detailed calculations using appropriate model chromospheres are necessary to decide between these two alternative hypotheses.

The data plotted in Figure 1 show that there is no systematic difference in L_{5876} between stars with and without X-ray detection. This fact argues in favor of a similar mechanism for the formation of He I 5876 in both types of stars. Moreover, it seems to imply that the high chromospheric densities required for He I 5876 to be formed by collisional processes in stars with X-rays must also be present in stars without X-ray detection. It is suggested then that TTS have similar structure in atmospheric regions with $T \leqslant 50\,000$ K, since the high excitation potential of the levels forming He I 5876 requires T to be between 40 000 and 50 000 K and $N_e \sim 10^{11}$ cm^{-3} in order for collisional ionization to be the dominant mechanism (Athay and Johnson 1960). This range of conditions puts restrictions on models for mechanical energy input in the atmospheres of TTS. For instance, models assuming deposition of Alfvén wave energy and momentum in the upper atmospheric layers, with wave dissipation length of ~ 1 R_*, predict that temperatures of order 50 000 K can be reached at a density of $\sim 10^9$ cm^{-3} (Hartmann, Edwards, and Avrett 1982), a value too low compared to that required for He I 5876 formation.

The following conclusions can be derived from this work:

1) Collisional excitation and ionization appear as the most likely mechanisms determining the behavior conditions of the He atom in the atmospheres of T Tauri stars.

2) Since collisional processes seem to be the dominating mechanisms determining the He excitation and ionization, the absence of He II 1640 in stars undetected in X-rays cannot be used as an argument in favor of the absence of coronae in these stars.

3) The similarity in He I 5876 luminosities between stars with and without X-ray detection argues for a similar chromosphere-lower transition region structure in T Tauri stars. According to this argument, stars with He I 5876 in emission must have regions in their atmosphere with $T \leqslant 50\,000$ K and $N_e \gtrsim 10^{10}$ cm^{-3}, even if they have strong winds.

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