Do T Tauri Stars Have Extensive Coronae?

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Introduction

T Tauri stars are low-mass ($\lesssim 3\ M_\odot$ pre-main-sequence stars. They have been recognized the first time as an individual group of stars in 1945 by Alfred Joy. They show irregular photometric variability and are located without exception in, or very close to, dark clouds. In 1958 another pioneer of variable-star research, George Herbig, proposed a number of spectroscopic criteria:

(1) The hydrogen lines and the H and K line of Ca II are in emission.

(2) The fluorescent Fe I emission lines λλ 4063, 4132 are present.

(3) Forbidden lines are often present.

(4) In those stars which show an absorption spectrum (from late F to M) Li I λ 6707 is present as a strong absorption line. Later, more characteristics have been found for T Tauri stars, e.g. IR excess, "veiling", complex emission line profiles and a lot more. The strength of the emission lines varies strongly from star to star. In the following we want to discuss some emission-line properties and the place of their origin.

Already Joy mentioned that the spectrum of T Tauri stars resembles the chromospheric spectrum of the sun, the so-called "flash" spectrum. In this spectrum, which originates in the solar chromosphere, all the Fraunhofer lines of the photospheric absorption spectrum are seen in emission. But the chromospheric spectrum is in no way a simple reversion of the photospheric spectrum, since the strength of lines of ionized atoms and of highly excited atoms is enhanced compared to the absorption line strength. The strongest lines in the flash spectrum are the Ca II H and K lines, the hydrogen lines of the Balmer series and the He I λλ 4471, 5876 lines. Since the Balmer lines and the Ca II H and K lines are normally the strongest emission lines in the spectrum of a T Tauri star (see Herbig's criterium (1) and He I is often present in emission, one immediately recognizes the similarity. Herbig suggested in 1970 that the same mechanism producing the solar chromosphere is also operating actively in T Tauri stars.

UV and X-ray Observations of T Tauri Stars

Observations of T Tauri stars in the satellite UV spectral range with the International Ultraviolet Explorer (IUE) provided us with new information on the emission line chromospheric region. As an example Figure 1 shows the UV spectra (1200 Å ≤ λ ≤ 3200 Å) of the T Tauri stars DR Tau, CoD – 35° 10525 and AS 205 observed by Appenzeller et al. (*Astronomy and Astrophysics,* **90**, 184, 1980). Common to all spectrograms is the occurrence in emission of certain strong resonance multiplet and ground-state intercombination lines such as Mg II, Si II, Si III, Si IV, C I, C III, C IV, etc. Also a number of emission lines of singly ionized metals are present. As shown by the figure, the relative strength of the emission lines and the line emission strength relative to the continuum varies from star to star. (One should note, however, that in Figure 1 the wavelength positions of various expected spectral lines or blends are indicated. Therefore, not all indicated features are regarded by the authors as real.)

These emission lines reveal the presence of very hot regions around the stars. The ion of highest ionization stage observed is the N V λ 1238 resonance doublet. This line, present in DR Tau and in CoD –35° 10525 (and in RU Lup), requires some 200,000 K to be formed. Hence the emitting regions around T Tauri stars cover a large range in temperature – from about 7,000 K to at least 200,000 K! (For further interpretation of the UV spectra we refer the reader to the review article by G. Gahm in "The Universe in Ultraviolet Wavelengths: The First Two Years of IUE", ed. R. D. Chapman, NASA publication).

A quantitative analysis of the emission line spectrum can be done by calculating volume emission line measures Vn_e^2. This quantity is a characteristic measure of the emissivity of an envelope. The volume emission line measures that can be derived from emission lines formed at different temperatures can be 10^4 to 10^6 larger than the corresponding solar values (Cram et al., *Astrophysical Journal,* **238**, 905, 1980; Gahm in the above cited review article). For a given star this scaling factor is approximately the same for lines found at different temperatures. In other words: Chromospheres of T Tauri stars are ten thousand to one million times more "powerful" than the solar chromosphere!

At this point arises of course our title-question: Do T Tauri stars also have such powerful 10^6 K coronae with scaling factors up to 10^6 compared to the solar corona? Indeed, recently such coronae with temperatures between one and two

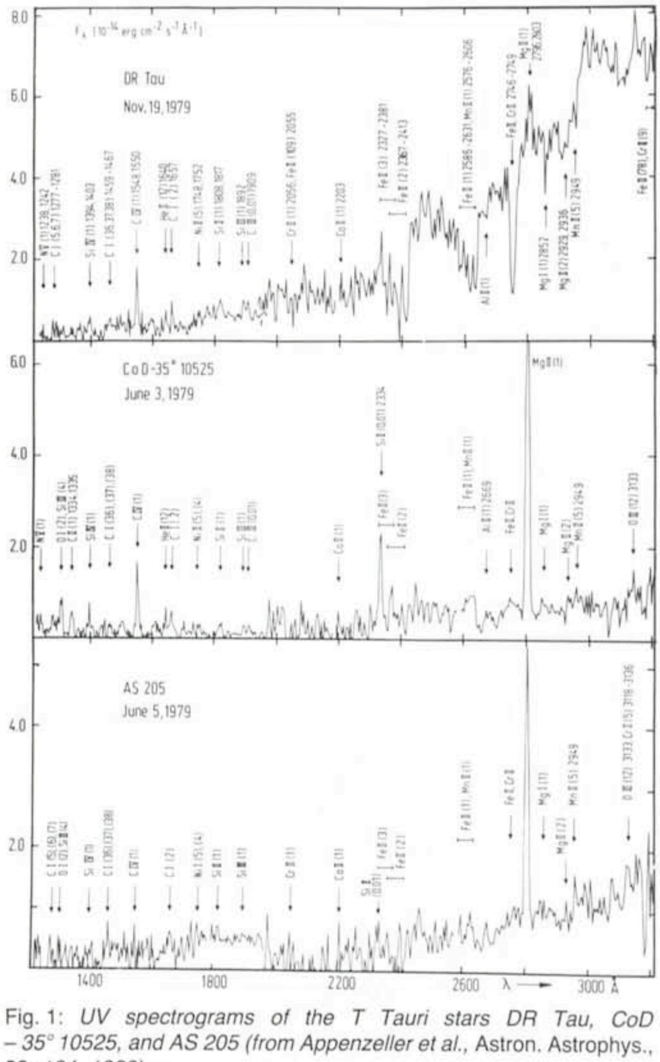

Fig. 1: *UV spectrograms of the T Tauri stars DR Tau, CoD – 35° 10525, and AS 205 (from Appenzeller et al.,* Astron. Astrophys., **90**, *184, 1980).*

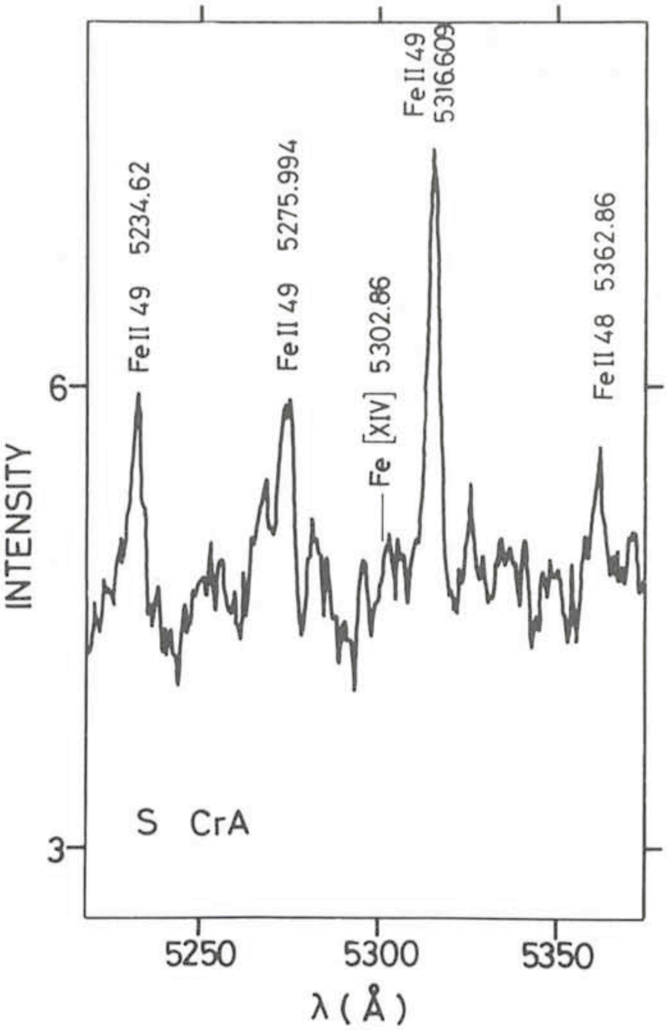

Fig. 2: *Spectral region around the [Fe XIV] λ 5303 line in S CrA.*

million Kelvin have been proposed in theoretical models by various authors. These models predict strong X-ray radiation from such 10^6 K coronae.

An excellent way to check this prediction are X-ray surveys with the Einstein observatory. Several surveys have been carried out by Gahm (*Astrophys. J.,* **242**, L163, 1980), Feigelson and de Campli (*Astrophys. J.,* **243**, L89, 1980), and Walter and Kuhi (preprint). But for most T Tauri stars no X-ray flux could be detected. Furthermore, with one exception, all T Tauri stars detected with Einstein show only very weak emission lines in the visual spectral range. The X-ray luminosities of these stars are up to 10^5 times larger than the corresponding solar values. For most stars with strong emission lines like RU Lup, RW Aur, and S CrA no X-rays were detected at all. When comparing with the X-ray flux from the sun in the same energy band, the corresponding scaling factor is less than 1,000.

One explanation for this behaviour is that T Tauri stars have coronae which are 10^4 to 10^6 times as strong as the solar corona, but most X-rays are absorbed in circumstellar gas which does not contribute to the visual extinction towards the star. Some stars, especially those with weak emission lines, have only little circumstellar gas and appear as strong X-ray sources.

But there is another possible explanation: Those T Tauri stars which were not detected at X-ray energies do not have powerful 10^6 K coronae. The X-ray activity observed could be explained by some flare-like activity. This assumption is strengthened by the extremely rapid variations which have been found in the X-ray flux of DG Tau, the T Tauri star with the strongest emission lines in the visual spectral range.

Coronal Line Emission of T Tauri Stars

We have seen that X-ray observations cannot unambiguously clarify our title question. But fortunately observations in the visual spectral range can help us. From spectroscopic observations of the solar corona we know that there are two strong coronal emission lines in the visual spectral range, namely the "green" coronal line of forbidden [Fe XIV] λ 5303 and the "red" coronal line of forbidden [Fe X] λ 6375. These lines are formed at temperatures of about 10^6 K.

The idea is now: If we find such a coronal emission line in the spectrum of a T Tauri star we can compare the absolute flux of this line with the flux of the corresponding solar line. By doing so we again obtain a scaling factor for the corona of the T Tauri star compared to that of the sun. If we do not find coronal lines in the spectra of T Tauri stars we can at least give an upper limit for the line flux and hence for the scaling factor. A first attempt was made by Gahm et al. *Monthly Notices of the Royal Astronomical Society,* **195**, 59 p, 1981) who found for RU Lup from the [Fe X] λ 6375 line an upper limit for the scaling factor of 6,000.

In our programme, red spectrograms of a sample of 14 T Tauri stars were carefully searched by us for coronal line emission. The spectrograms of 11 stars were obtained with the Boller and Chivens spectrograph at the Cassegrain focus of the ESO 1.5 m telescope. The spectrograms were recorded on IIa-O plates behind a 2-stage Carnegie image tube. Calibration plates were taken with the spot sensitometer. The spectrograms of the remaining 3 T Tauri stars were obtained with the B&C spectrograph in the Nasmyth focus of the 1.23 m telescope of the Calar Alto observatory, Spain. For these observations an electrostatically focused single stage ITT F4078 intensifier and 103a-D plates were used.

The result of our search was that none of our spectra showed any of the coronal lines in emission. As an example Figure 2 shows the spectral region around the [Fe XIV] λ 5303 line of the T Tauri star S CrA. Identifications for the most prominent emission lines are given. The position of the [Fe XIV] line is indicated by a dash. Due to the total absence of any coronal emission line we could determine only upper limits for the fluxes of the lines.

This procedure shall be described in short: At first we set an upper limit for the equivalent width of the coronal line. For that we determined the noise level and assumed a maximum line width of the coronal line. Since in a number of T Tauri stars the width of the emission lines decreases with increasing degree of ionization we expect possible coronal lines to be relatively narrow.

With this upper limit of the equivalent width, the continuum flux at the corresponding wavelength, the distance of the star, and the interstellar absorption, we could calculate upper limits for the absolute fluxes of the coronal lines.

In reality there have been some difficulties: Since simultaneous photometric observations existed only for two stars, average photometric values had to be used for most of our stars. In addition, the interstellar absorption is not known for many stars; we have adopted an $A_V = 1\overset{m}{.}5$, a value relatively high for a T Tauri star. There are also uncertainties in the distances of the stars. But since these uncertainties can affect our results in both directions we think that we got good average values.

By comparison with the absolute fluxes of the solar coronal lines which were measured when the sun was in a quiescent state we got the result that for 10 stars the upper limit of the scaling factors are between 2,000 and 8,000. We have got higher values for the other 4 stars because we have spectroscopic data only for the λ 6375 line, the intensity of which in the sun is smaller by a factor of 4.5 compared to the λ 5303 line. Since these results are for the quiet sun, we would get even lower values if we took the absolute solar line fluxes for a more active sun.

These results lead us to the conclusion that the intensity of any 10^6 K corona is less than 8,000 times that of the sun, while lines forming in 10^4 to 10^5 K gas are 10^4 to 10^6 times stronger than those of the sun. From this one may conclude that T Tauri stars in general do not have an extensive corona.

Paschen and Balmer Lines in Active Galactic Nuclei

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1. Introduction

If there is substantial disagreement between an observational result and its expectation from established theory, astronomers tend to speak of a "problem". One of those problems which bothered optical and UV astronomers during the past years is the discrepancy of the observed ratio of the Lyα and Hβ line intensities with the value of this ratio predicted by simple recombination theory for a photoionized hydrogen gas.

In this process, ionization electrons are recaptured into higher levels and excited atoms formed this way decay to successively lower levels by radiative transitions, finally reaching the ground level. Thereby the various hydrogen recombination spectra are emitted. The lowest of them are the Lyman, Balmer and Paschen spectra (cf. Fig. 1). Now, the Lyα/Hβ ratio observed in quasars and active galactic nuclei are found to be by a factor of 3 to 10 times less than the theoretically predicted value (~ 30). There may be ways around the Lyα/Hβ problem by modifying the simple theory, but the solutions are unfortunately not unique. Some theorists believe that special radiative transport effects in the spectral lines and electron collisions during the line-formation process cause enhanced Balmer line strengths and thereby depress the Lyα/Hβ ratio. If the entire discrepancy is not to be explained by such processes alone, interstellar dust within and/or around the line-emitting regions (which are up to several light years across) may help to reconcile theory with observations (cf. e.g. Davidson, K. and Netzer, H., 1979, *Rev. Mod. Phys.*, Vol. **51**, No. 4, p. 715). To explain this, we have plotted in Fig. 2 the standard interstellar extinction curve as a function of wavelength known from our Galaxy. Along the curve we indicated the locations of the various hydrogen lines. It is obvious that the influence of dust extinction on these lines must be quite different due to its strong wavelength dependence. It is also recognized that Pα and Pβ are relatively unaffected by dust as a result of the decrease (approximately $\propto 1/\lambda$) of the extinction curve towards longer wavelengths. Moreover, because Pα and Hβ originate from the same upper atomic level, the Pα/Hβ ratio may be used as a sensitive indicator for the existence and importance of reddening by dust in addition to, or instead of, Balmer line enhancement due to optical depth effects. Therefore the measurement of the near infrared Pα and Pβ lines at 1.88 and 1.28 μm, respectively, may help to pin down an appropriate theoretical model for the hydrogen-emission-line region.

2. IR Spectrophotometry of Pα

As a result of strong efforts at various places (Caltech, ESO, La Jolla) on the technical side, the sensitivity and spectral resolution of infrared detectors has been substantially improv-

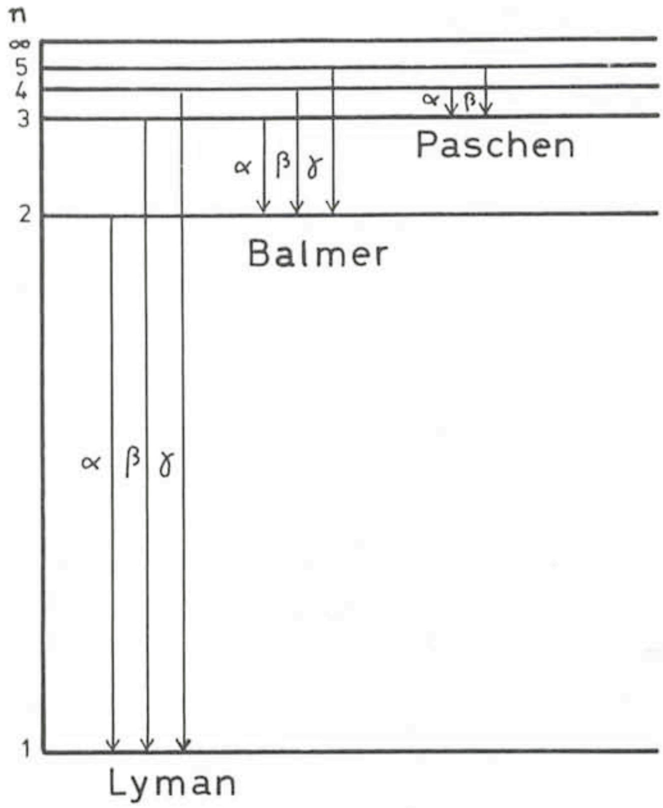

Fig. 1: *Energy-level diagram for the hydrogen atom showing the Lyman, Balmer and Paschen series. n is the principal quantum number.*