HIGH S/N SPECTROSCOPY OF PRE-MAIN SEQUENCE STARS I

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ABSTRACT. The spectra of PMS stars usually are superpositions of contributions from a relatively normal photosphere, an often strongly enhanced chromosphere, and of circumstellar matter related to stellar winds, accreation flows, jets, and cool circumstellar disks. Only high S/N data allows a reliable separation of these different contributions. Because of the high optical depths of PMS chromospheres, the PMS photospheres often can be observed in the very weak spectral lines only, which are undectable on low S/N spectrograms. Finally, magnetic fields are assumed to play a particularly important role for the appearance and evolution of PMS objects. Their spectroscopic measurement requires very high S/N data.

1. INTRODUCTION

PMS stars are very young stars where significant nuclear burning has not yet started. The low mass PMS stars are classified as T Tauri or Post-T Tauri stars, and their basic properties have been reviewed recently e.g. by Kuhi (1983), Bertout (1984), and Appenzeller (1985). The higher mass PMS stars are called Herbig-Ae-Be stars and have been described e.g. by Herbig (1960) and Finkenzeller and Mundt (1984).

Most known PMS stars have been identified by their characteristic emission lines using very low S/N objective prism spectrograms. Most qualitative properties of these objects were derived from low S/N photographic or image tube spectrograms. On the other hand, for a detailed quantitative derivation of the physical structure of PMS objects high S/N is perhaps more important than for any other class of stars. There are three effects, which make high S/N a prerequisite of success in quantitative investigations of PMS stars: Firstly, PMS stars generally show "composite" spectra containing contributions of a hydrostatic photosphere,

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 87–93.

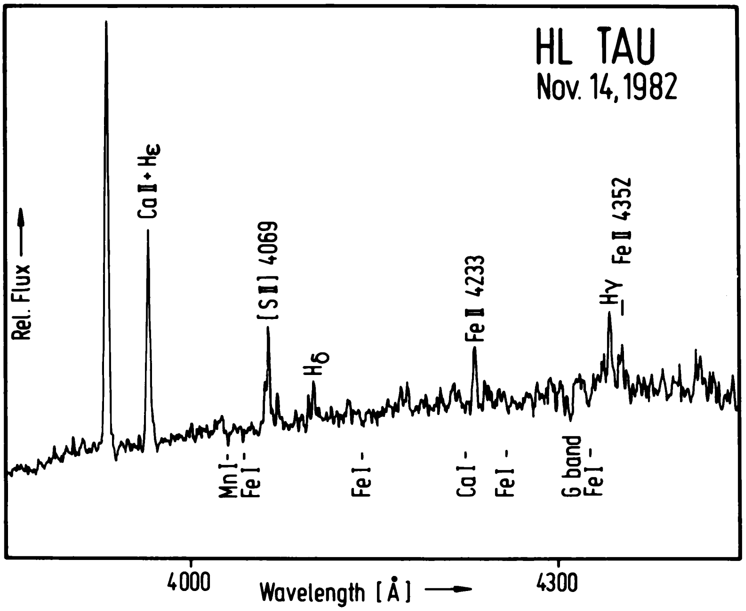

Fig. 1. The spectrum of the young PMS star HL Tau, showing contributions of a late type photosphere (Fe I absorption lines, G-band), a dense chromosphere (producing e.g. the Ca II and He I emission), and of circumstellar gas ([SII], Balmer lines, broad metallic lines).

contributions by an (often strongly enhanced) chromosphere, and contributions of circumstellar matter related to stellar winds, accretion flows, jets, and cool dusty circumstellar disks (cf. Fig. 1). Quantitative studies of PMS stars require a reliable separation and subtraction of the different contributions, which is possible only with high S/N linear spectrograms. Secondly, the PMS stars (and in particular the T Tauri stars) often show chromospheres of exceptionally high optical depths. Hence, in these stars the "strong" (i.e. high optical depth)lines are formed near the temperature minimum or in the chromosphere. As a result the normally strong photospheric lines tend to become very weak or occur in emission (cf. e.g. Cram 1979, Finkenzeller and Basri 1987). In the particularly interesting "extreme" T Tauri stars only the very weak spectral lines can be detected as photospheric absorption features (Appenzeller et al. 1986). Finally, as pointed out in the reviews listed above, we have indirect but reliable evidence for the presence of

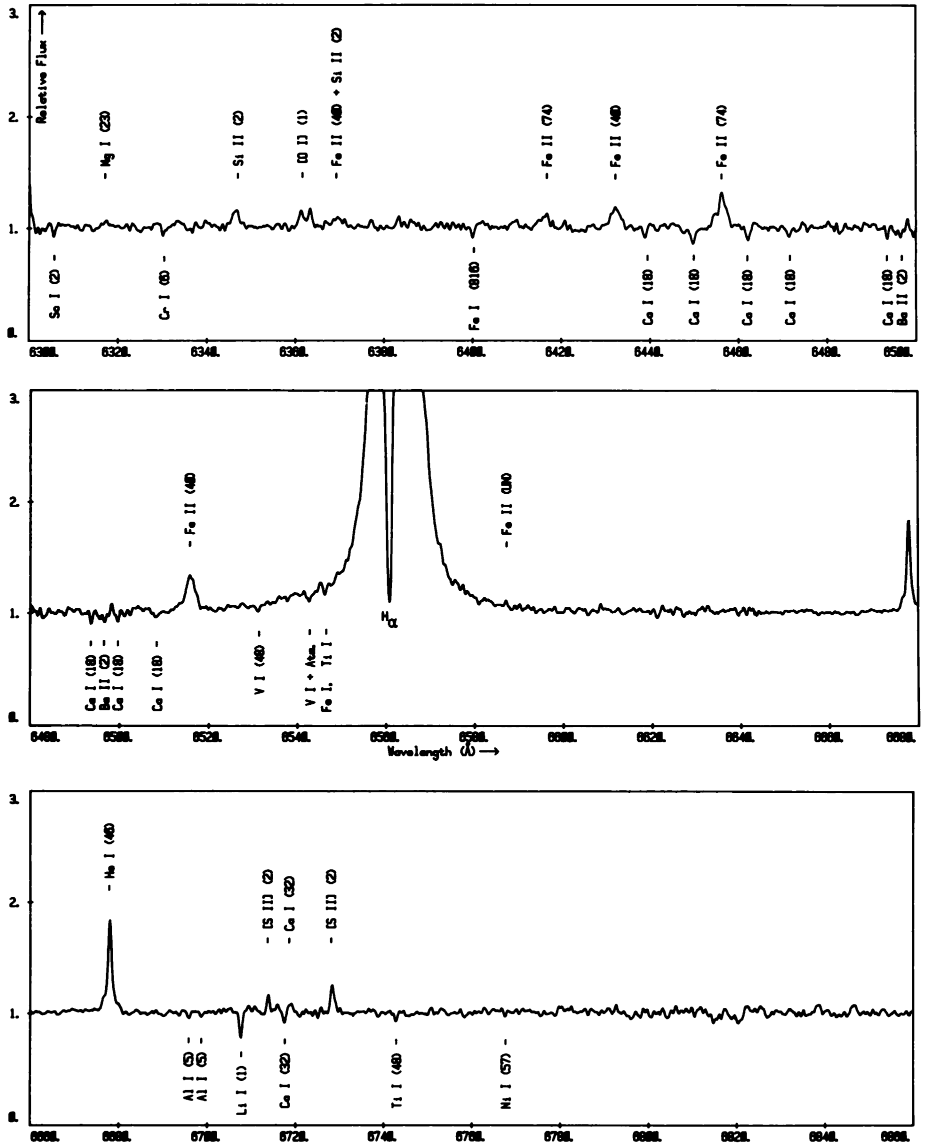

Fig. 2. Section of a high S/N spectrogram of the extreme T Tauri star S CrA.

extended magnetic fields on the surface of PMS stars. Since the evolution of contracting stars depends on their surface properties, these fields probably have a profound influence on the structure and evolutionary time scale of these stars (Appenzeller 1985). Thus, measurements of these fields are

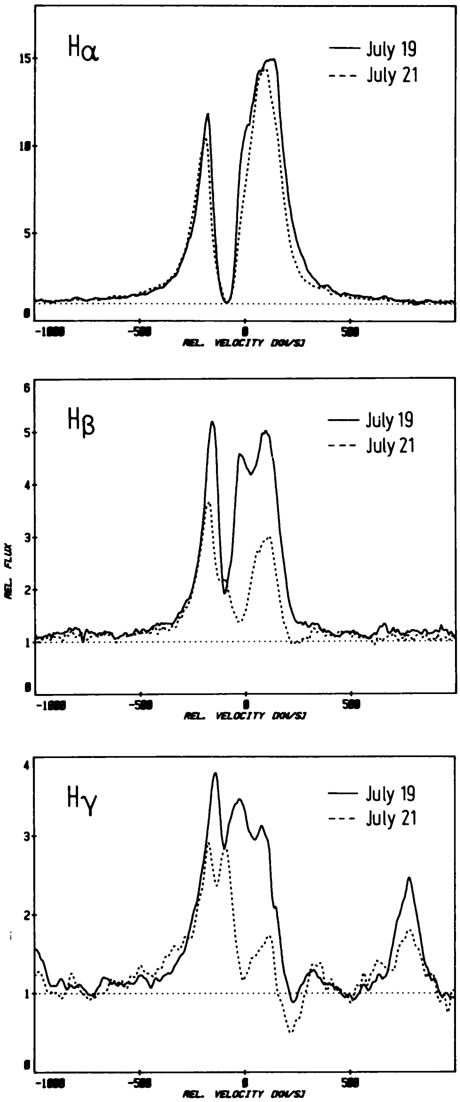

Fig. 3. Balmer line profile variations.

of great importance for a better understanding of PMS stellar evolution. As described by Saar, Marcy, Basri and others elsewhere in this volume, these measurements require very high S/N values. So far only upper limits or very marginal detections have been reported for PMS stars.

2. LIMITATIONS

In the case of massive stars the core hydrogen burning starts already during the IR or "protostellar" evolutionary phase. Hence all PMS stars are of relatively low mass and moderate to low luminosity. Furthermore, there are no star forming regions in the immediate solar vicinity. Therefore, PMS stars are generally rather faint objects. Typically the known PMS stars (as listed e.g. in the catalog of Cohen and Kuhi, 1979) have apparent visual magnitudes between 10^m and 20^m with a median of about 15^m. Following Matthews and Sandage (1963) the photon flux F_N of a star of visual magnitude m_v can be approximated by:

$$F_N = 10^{3-.4m_v} \text{ ph. } s^{-1} cm^{-2} A^{-1}.$$

Assuming that photon noise (of the signal) is the only source of noise, S/N = 100 requires 10^4 photons per resolution element. Using a 3.6-m telescope and assuming a total efficiency (atmosphere + telescope + spectrograph + detector) of .03 (which is not untypical for modern high resolution instruments with CCD detectors) the integration time for a PMS star of m_v = 15 becomes 1.8 hours for a spectral resolution of R = $\lambda/\Delta\lambda$ = 10^4 and 18 hours for R = 10^5. Obviously, high S/N spectroscopy of PMS stars is time-consuming and feasible only for the

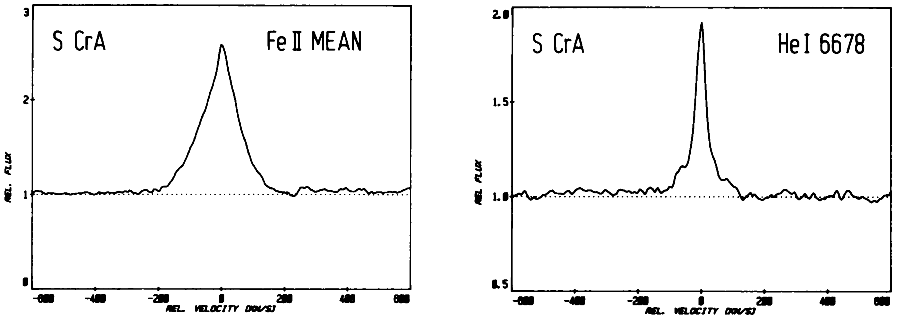

Fig. 4. Mean Fe II (average of four unblended lines) and He I emission line profiles of S CrA.

brighter members of this class of objects.

3. EXAMPLES

A few of the Herbig-Ae-Be stars are bright enough for high S/N observations, even with conventional Coude spectrographs. Using modern solid state detectors, for these bright objects S/N values of several 10^2 can be reached (cf. Catala elsewhere in this volume). For the fainter T Tauri stars high S/N spectroscopy became possible only with the introduction of sensitive photoelectric detectors. Spectroscopy with one-dimensional photon-counting detectors resulted in S/N values up to about 60 (see e.g. Mundt 1984). But high resolution observations of T Tauri stars of really high S/N (>100) became feasible only with CCD detectors at efficient Echelle spectrographs. Examples of these new instruments are the ESO CASPEC and the Lick HAMILTON spectrometers. Below, a few examples obtained with the CASPEC spectrograph are presented. Exciting results obtained more recently with the new HAMILTON spectrograph are given in the following paper by Dr. Basri.

Figure 2 shows (as an example of high S/N spectroscopy of an extreme T Tauri star) a section of the "spectral atlas" of S CrA (Appenzeller et al. 1986). Note that even in this extreme object a photospheric absorption spectrum is visible on high S/N spectrograms. However, in accordance with the theory, the photospheric spectrum is restricted to weak lines only. Also visible in Fig. 2 are the conspicuous differences in the profiles of emission lines formed in different volumes of the S CrA system.

Another important application of high S/N spectroscopy of T Tauri stars is illustrated by Fig. 3: Qualitatively the complex and rapidly variable structure of the Balmer emission lines of PMS stars has been known since years from lower S/N data. But only the new high S/N spectrograms allow a reliable identification of the many different components which form these profiles. Obviously the gas producing these lines is highly nonhomogeneous and follows a highly nonstationary flow pattern.

Examples of metallic and He I emission-line profiles are given in Fig. 4. These profiles are less variable than the Balmer lines. The narrow core of the He I line is only slightly broader than the photospheric absorption lines, confirming earlier suggestions that the (relatively high-excitation) He lines originate mainly in essentially static chromospheric layers. In contrast, from their width it seems clear that the Fe II lines must be formed in the moving gaseous envelope of the T Tauri star. The almost triangular shape of these lines obviously reflects the velocity field of the envelope. A simple curve of growth analysis of the Fe II lines of S CrA shows that these lines are optically thin, making a modelling of their profiles relatively easy. An exact match of the Fe II profile of Fig. 4 appears not possible with simple assumptions on the velocity field and line source function. However, a qualitative approximation of the observed profile is obtained with the assumption that the gas which produces the variable inverse P Cyg profiles at the higher (n>5) Balmer lines (cf. Fig. 3) is also responsible for the Fe II emission. In order to produce the inverse P Cyg profiles this gas must be falling inward towards the photosphere with a line-of-sight velocity component of about the free fall velocity. Assuming for simplicity a spherical and stationary free fall, we have for the velocity $v \sim r^{-1/2}$ and for the density $\rho \sim r^{-3/2}$, where r is the distance to the stellar center. Assuming furthermore that the line emissivity is proportional to ρ^2 we obtain for the line profile (as plotted in Fig. 4):

$$\frac{dI}{dv} = \frac{dI}{dr}\frac{dr}{dv} \sim r^2 \rho^2 r^{-3/2} \sim r^{1/2} \sim v^{-1} \qquad (2)$$

The resulting hyperbolic profile approximates the Fe II lines reasonably well, if we take into account that Fe II is expected to be the dominant Fe ion in a limited part of the envelope $r^{min} < r < r^{max}$ only.

In spite of the rough qualitative success of the simple spherical model for some details, a consistent description of the T Tauri spectra clearly requires more complex non-spherical configurations. Work on such improved models of PMS stars is in progress in various places. Thus, there is hope that the accurate observational data provided by modern high S/N spectroscopy of PMS stars will soon be matched by equally accurate theoretical model predictions.

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DISCUSSION

CAYREL DE STROBEL Has the G-band in T Tauri stars been studied also in very faint ($\simeq$ 19 mag) T Tauri objects ?

APPENZELLER It can be detected on low resolution spectrograms if the emission lines are weak.

DESHPANDE Do you observe any Doppler shift signatures on these lines ?

APPENZELLER The apparent velocities of the metallic lines vary with the ionization potential. The Balmer line components show complex time variations of their velocity shifts.

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