High Quality Echelle Observations of T Tauri Stars

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ABSTRACT. This is a very brief review of the high resolution line profile work that has been done on very young stars. The spectral anamolies peculiar to these stars are mentioned, with some discussion of what may give rise to them. The Hα line is discussed most extensively, as the most work has been done with it. While progress has been made in understanding the general nature of T Tauri spectra, there are very large gaps in our current understanding of the emission lines from these stars.

The T Tauri stars were noticed as a class because of their spectral peculiarities. While the primary identifying characteristic is the presence of Hα emission, as their spectra are studied in greater detail the number of puzzling features increases. We now understand them to be pre-main sequence stars which have recently emerged from their enveloping star-forming molecular cloud cores. Until recently it was rather difficult to study these stars with both high resolution and signal-to-noise, because the brightest of them is tenth magnitude and most are fainter than twelfth magnitude. The problem is particularly difficult in the blue, since most of them are K-M stars and the reddening is often substantial. I report on results obtained primarily at the MMT, the CASPEC at ESO, and the Hamilton spectrometer at the Lick Observatory. A number of very good reviews of T Tauri stars have appeared in the last few years; perhaps the most relevant to the topic at hand is that by Bertout (1984).

There are several peculiarities apparent in T Tauri spectra compared with their main sequence counterparts. The photospheric lines are sometimes "veiled", meaning their equivalent widths are reduced as though an extra source of continuum light were present. This effect generally increases at shorter wavelengths. A closer look also reveals that the reductions tend to be greater for lines which are stronger in standard stars of the same spectral type (note further that many diagnostics of spectral type itself can be disturbed in the T Tauri stars). The latter type of line weakening is called differential veiling. In the more extreme T Tauri stars the absorption line spectrum can be completely absent; the emission line spectrum becomes increasingly strong and includes the Balmer lines, Ca II lines, Fe I lines and other strong lines like Na D and Mg B and He I. The profiles of these lines become increasingly broad, and exhibit asymmetries diagnostic of mass flows. In some lines, sharp or broad high velocity absorption components

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are seen (usually blueshifted). The widths of the lines can acheive several hundred km/s. Finally, there can be great variability of both the line profiles and line strengths, on time scales from hours to years. None of the above effects can be properly studied without high quality spectra (meaning velocity resolution of at least 10000 and S/N of at least 30:1).

A few atlases of line profiles have been published. Mundt and Giampapa (1982) address the question of profile variability, Hartmann (1982) produced a catalog of line profiles relevant to the envelope, Mundt (1984) also studies primarily the absorption line components arising from outflowing shells in Hα and Na D but with higher quality, Ulrich and Knapp (1985) display the appearence of several diagnostic lines from a number of stars, and Appenzeller, Jankovics, and Jetter (1986) published the entire spectrum of two extreme T Tauri stars including many line identifications. It is now possible to have spectra which contain essentially all the information available in the optical bandpass obtained at the same time. These are simultaneously useful for a number of fruitful lines of investigation, and provide a large increase in the observational contstraints under which any theoretical understanding must proceed.

Closest examination of complete spectra has been made by Finkenzeller and Basri (1987) who study 7 moderate T Tauri stars, provide absolute calibration of the spectra, and make comparisons with spectral standards. This data can be used for a direct confrontation between physical models and observations throughout the entire region of spectral formation Their analysis of the absorption line spectrum makes it clear that the phenomenon of "differential veiling" is the predicted effect of a deep chromosphere on the line source functions. The stronger line cores are formed closest to the temperature minimum and lower chromosphere where the temperatures are higher than for an inactive main sequence star of the same spectral type. In fact, division of a T Tauri spectrum by an appropriate standard is the software equivalent of a solar eclipse and yields a rather similar psuedo-emission spectrum. In conjunction with observations of X-ray flaring and dark spots on T Tauri stars, it is clear that the stars themselves have fairly normal deep photospheres overlain with strong stellar magnetic activity.

Of particular interest is the study of the breadth of the Ca II K line compared with Hα . In all but one of the stars in their sample, the K line was narrow and symmetric as should be expected from a low-lying stellar chromosphere, while even when the Hα line was weak it still had much greater breadth. In one case, a broader asymmetric component was evident in the wings of the K line (and also in the infrared triplet lines of Ca II), but the chromospheric central component was also still in evidence (BP Tau is another example of this). This suggests that the Hα line is primarily a feature of what I have referred to as the "envelope" (meaning simply that it is not from the stellar surface), and that as the envelope becomes a stronger emitter it starts to cover over the surface line profiles for lines of increasingly smaller optical depths. In the most inactive T Tauri stars, even the Hα line eventually comes to resemble the Hα lines of the RS CVn stars: active post-main sequence subgiants which are thought to be primarily chromospheric. In the more active T Tauri stars the envelope increasingly becomes the primary source of the emission lines, making them broader, stronger, and less symmetric.

The importance of detailed profile studies is illustrated by the remarkable behavior of SU Aur (G2IV). Its Hα line is relatively weak and appears in the Hartmann (1982) atlas as rather anamolous, with a suggestion of emission cut by several absorption components. In Fig. 1a are shown the profiles from Oct. 1986 and April 1987, which are rather different from it, but like each other. The abscissa is a relative velocity scale in km/s. Here we see a simple flat-topped profile interrupted by a single central absorption component. Such a profile would traditionally indicate spherical optically thin constant velocity outflow under a cool stationary shell. Less than a month later, the profiles in Fig. 1b were obtained. Now the central absorption has become an emission feature flanked on either side by small absorption features, and a major absorption feature is seen at the blue edge of the emission on one night, but disappears the next night. In Fig. 1c (Dec. 1986) something similar to the original 1982 profile has appeared. The flanking absorption components have moved out and deepened, and the central emission is being eaten away by a newly emerging absoption component. There appears to be reasonable evidence for a cycling of the profile components, which might serve as the key to unlocking a rather complex structure.

SU Aur is a rather atypical case, but now that repeated high quality observations are becoming available, it is clear that probably most stars show some interesting variability in their Hα profiles. Two other examples are given in Fig. 2. CO Ori is another G star, with the almost triangular shape also seen in GW Ori. At least that was true in Oct. 1986; by Dec. 1986 the triangular wings had noticeably weakened and a low, broad very blueshifted emission component had appeared. The strong X-ray emitter ROX-29 shows significant changes in both the blue and red wings on two successive nights. My impression is that the weaker Hα profiles show more rapid variations, but this remains to be confirmed by a much more extensive set of observations. A very strong and broad Hα line (as in DF Tau or RW Aur) seems to retain its basic structure over time, although variations in the absorption components and the peaks are certainly seen.

I believe that interpretation of these profiles in terms of the usual P Cygni explanation is dangerous at best. Firstly, one wouldn't expect the rapid variability of the emission wings if they really arose from a large region around the whole star. Secondly the general appearence of the lines has been successfully interpreted by a variety of models (Bertout 1984) so the P Cygni paradigm is not required. Thirdly, it has been shown that a variety of possibly relevant radiative transfer effects which are not accounted for in the simple picture can markedly change the expected appearence of the line. The great width of the line is something of a puzzle, since velocities at the edges of the emission line are not usually seen in absorption components. The simultaneous presence of red and blueshifted components is also an indication that a simple picture is not sufficient.

As an example of an alternative interpretation which must be considered, it has lately become increasingly apparent that many (and perhaps all but the "naked") T Tauri stars are still surrounded by disks of gas and dust. The evidence is accumulating (Bertout, Basri, and Bouvier 1988) that a number of these are still active accretion disks, with an active boundary layer where the accreting material meets the slowly rotating star. While very little is known about the details of the boundary layer structure, there is evidence that the Balmer continuum emission and perhaps most of the line emission could arise in such a layer.

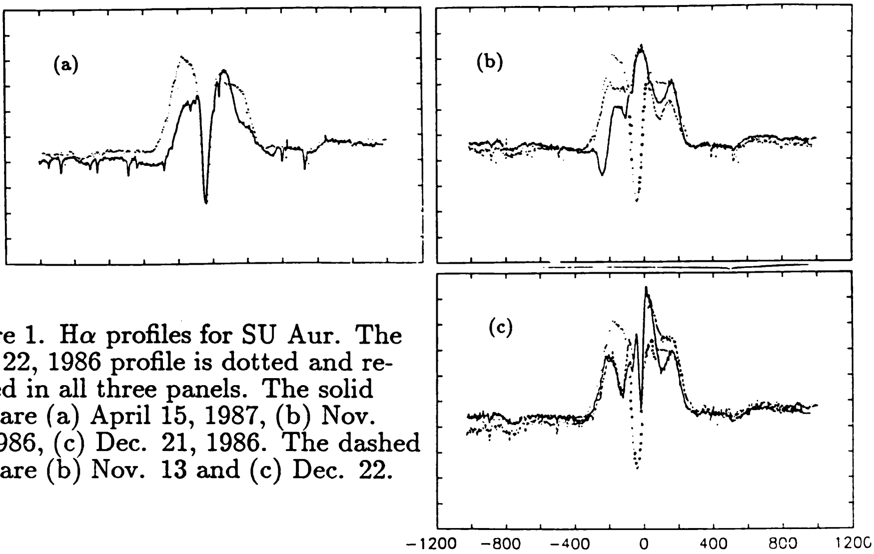

Figure 1. Hα profiles for SU Aur. The Oct. 22, 1986 profile is dotted and repeated in all three panels. The solid lines are (a) April 15, 1987, (b) Nov. 11, 1986, (c) Dec. 21, 1986. The dashed lines are (b) Nov. 13 and (c) Dec. 22.

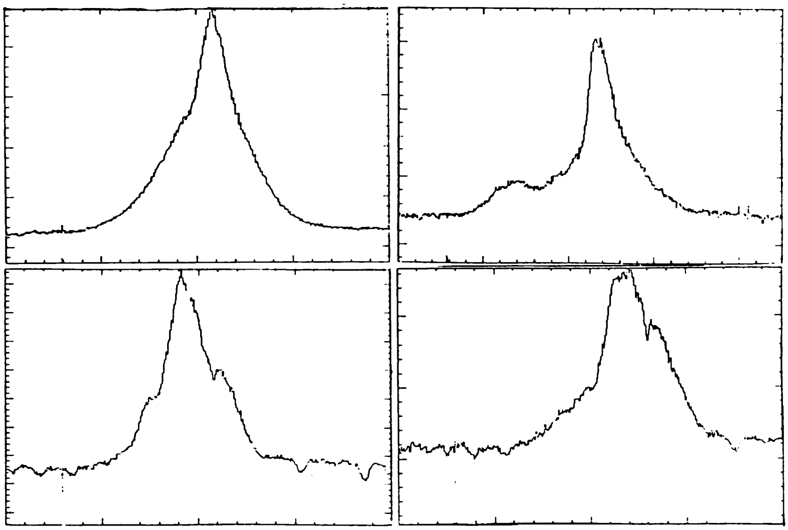

Figure 2. Hα profiles for CO Ori (upper panels) on Oct. 22, and Dec. 21, 1986; and for ROX-29 (lower panels) on June 9 and 10, 1987.

This might be expected to yield a symmetric component of emission with about the observed breadths. Bipolar outflows could give rise to absorption components, whose appearance would depend somewhat on the viewing angle of the system. The geometry would therefore have at best axial symmetry, and shadowing by the disk becomes an important ingredient. This would have the virtue of explaining why the redward emission from Hα is usually seen, while it is never seen in the forbidden line emission which arises over hundreds of AU from the star. Redward absorption components could arise from material flowing from the disk to the star. One would expect cyclical variations if the system has a non-axial component. The weaker, flatter profiles might be from stars which have largely lost their disks and are winding down from the strong mass loss phase.

At the moment, the above is almost completely speculative. Clearly there needs to be much more detailed observational and theoretical work before an understanding of line emission from T Tauri stars is acheived. Our underlying physical conception of what we are looking at must be solidified before a detailed quantitative analysis will be really useful.The most crucial observations will be from repeated high quality echelle spectra, which provide full velocity information from many lines of different optical depths and formation conditions at the same times. A new threshold in research on young stars has been opened up by the modern capability for high resolution and signal-to-noise stellar spectroscopy of faint objects.

References:

Appenzeller, I., Jancovics, I., Jetter, R., 1986, Astron. Ap. Supp.**64**, 65.
Bertout, C., 1984, Rep. Prog. Phys. **47**, 111.
Bertout, C., Basri, G., Bouvier, J., 1988, Ap. J. (submitted)
Edwards, S., Cabrit, S., Strom, S.E., Strom, K.M., 1987, Ap. J. (in press)
Finkenzeller, U. and Basri. G., 1987, Ap. J. **318**, 823.
Hartmann, L., 1982, Ap. J. Supp.**48**, 109.
Mundt, R., 1984, Ap. J. **280**, 749.
Mundt, R. and Giampapa, M.S., 1982, Ap. J. **256**, 156.
Rydgren, A.E., Strom, S.E., Strom, K.M., 1976, Ap. J. Supp. **30**, 307.
Ulrich, R. and Knapp, G., 1985, preprint.

DISCUSSION

GRAY One might look for different rotation rates in chromospheric and photospheric lines.

BASRI I think that the low chromospheric diagnostics, (narrow symmetric emission or filling in) are not formed significantly above the photosphere, and so will have the same v sin i. The broader components are probably formed farther out, so they may well have a different rotation.

APPENZELLER How good are homogeneous chromosphere models in view of the spotty structure of T Tauri photospheres indicated by the rotational variations?

BASRI They are even worse than homogeneous chromospheric models for active main sequence stars. There really isn't spatial information in the observed narrow symmetric lines. The best hope is through studies of rotational modulation as mentioned by Dr. Bouvier.

HENRICHS How would you identify the characteristic timescales of the spectral variations you observe ? Are they comparable to flow timescales or rotational timescales?

BASRI There are all timescales observed, from hours to months or years. These should not be thought of as arising from a common mechanism ; some are rotational, some due to changes in the flow, some due to changes in activity or in the geometry of regions, etc.

PRADERIE When you speak of a deep chromosphere, how deep means deep? Don't you have to take curvature effects in the computation of your non-LTE line spectrum?

BASRI The "deep chromosphere" means the part directly above the photosphere and so a plane parallel approximation is sufficient for this. It is at mass column density of $\simeq 1$ g/cm^2. The filled in absorption lines and narrow symmetric emission lines should be formed there. Any broader or asymmetric components are likely formed farther out where geometry should be accounted for.

LINSKY Please comment on the spectral resolution needed to study the emission lines and the narrow circumstellar absorption features?

BASRI It depends somewhat on what you want to learn. The work done with Finkezeller had $R = 15000$ which is sufficient for studying the broad components and for separating chromospheric and envelope contributions. To study narrow circumstellar features one prefers $R > 30000$. To look at magnetic fields requires $R > 100000$.