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OPTICAL AND X-RAY OBSERVATIONS OF T TAURI STARS

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1. DEFINING CHARACTERISTICS AND GENERAL PROPERTIES

Herbig (1962) set up the defining criteria for T Tauri stars in terms of their optical spectroscopic features as follows: emission lines of hydrogen (strong Hα), CaII H, K, FeII, fluorescent FeI λ4063, 4132 and occasionally HeI and [OI], [SII]. The underlying absorption spectra are in the range G to early M and the recent survey by Cohen and Kuhi (1979) showed that most T Tauri stars are of late K spectral type. There is a large range in the strength of the line emission with most stars showing an almost normal photospheric spectrum upon which are superimposed modest Hα and CaII H, K emission. As the "T Tauri nature" increases the emission lines grow stronger and many more lines appear in emission. Finally in the most extreme cases the emission lines completely dominate the spectrum so that no underlying photospheric spectrum is even visible. These extreme stars constitute perhaps 10% of the T Tauri population but are most often thought of as the typical T Tauri star. However, as Cohen and Kuhi have shown, the typical T Tauri star is probably of spectral type K7 with modest Hα and CaII emission. At the time of their discovery Joy (1945) remarked that the extreme examples of T Tauri stars resembled very closely the spectrum of the solar chromosphere as observed at solar eclipse. Their possible connection with flare stars has been discussed at length by Haro (1954, 1955, 1956).

Two peculiarities also appear in the underlying photospheric spectrum. The lithium doublet LiI λ6708 is present in unusual strength compared to main sequence stars of the same spectral type. The behavior of this feature as a function of age was investigated by numerous people for normal stars and summarized by Skumanich (1972) who found that the lithium line strength decreased as the inverse square root of the age. Since then a strong lithium line absorption has been taken as an indicator of stellar youth. The abundance of lithium in T Tauri stars was comparable to that of the chondritic meteorites and presumably represents the primeval lithium abundance. As the stars age, convection to hotter regions destroys the lithium by nuclear burning. The second peculiarity is that many absorption lines appear broad or washed out as if overlain by some continuous emission or broadened by rapid rotation. Four stars were actually measured for rotational velocity by Herbig (1957): these were in the range of 25 to 75 km/sec, which is indeed very high for G and K type stars and led to the generalization that T Tauri stars were rapid rotators.

The continuous energy distributions are also peculiar compared to those of normal stars. Many T Tauri stars are unusually bright in the U-filter band, perhaps 0.5 to 1.0 mag brighter than normal G and K stars of the same spectral type. This has become known as the ultraviolet excess

(Haro and Herbig 1955). At higher resolution it is still present and a likely explanation is that the source is bound-free and free-free emission of hydrogen, the Balmer continuum in particular. Infrared excesses were discovered by Mendoza (1966) and studied more extensively by others (Strom et al. 1972, Cohen 1973, Cohen and Schwartz 1976, Rydgren et al. 1976). They show up in the form of extra emission in the infrared from wavelengths of ~ 1 μ to 20 μ. In many cases the excess is due to thermal re-emission from dust; in others to free-free emission from ionized hydrogen.

T Tauri stars are found in regions of nebulosity both bright (e.g. Orion) and dark (e.g. Taurus-Auriga) in groups called "T associations." They are a common constituent of many dark clouds with regions of active star formation. They are typically 12th mag and fainter which makes high dispersion spectroscopy difficult. The stars are also irregularly variable in light: broadband measurements in UBV can change by a few tenths of a magnitude in a few days or by much larger amounts in months or years. A few have shown dramatic increases in brightness, the so-called "FU Orionis" phenomenon (Herbig 1977). A good example is V1057 Cyg (Grasdalen 1973) which brightened by ~ 6 mag in ~ 200 days and changed its spectral type from a strong emission line T Tauri star to a B star and now has decreased somewhat in brightness and has a spectral type of early F. Short timescale variations have also been looked for but nothing periodic has been found. The closest is a pseudo-periodicity of ~ 4 to 6 days found by Hoffmeister (1958) for a few stars which was interpreted as the rotational modulation produced by spots on the surface. There are no known eclipsing systems, although a few spectroscopic binaries have recently been discovered. The problem is mainly an observational one.

The emission line profiles observed for Hα fall into several categories: symmetrical profiles essentially Gaussian in appearance; double-peaked profiles with the longward peak stronger than the blue and an "absorption" component displaced by 50 to a few 100 km/sec to shorter wavelengths; P Cygni profiles with a shortward absorption component displaced 100 to 300 km/sec to the blue. No inverse P Cygni profile has been observed at Hα. Other emission lines fall into the same categories but in a number of stars (especially those with an ultraviolet excess) inverse P Cygni profiles have been observed in the higher Balmer lines (such stars are known as YY Orionis stars (Walker 1972)). The peak intensity at Hα can be many times that of the adjacent continuum, as much as 30 in extreme cases. The interpretation of the profiles has been in terms of some kind of mass outflow (or infall in the case of the inverse P Cygni profiles) with mass loss of 10^{-7} to 10^{-9} $M_\odot$/yr with a mean of ~ 3 x 10^{-8} $M_\odot$/yr (Kuhi 1964). These estimates were based on observations of several bright T Tauri stars and show the danger of assuming that the brightest stars are typical of the class. More recent observations (Ulrich and Knapp 1979) show that the interpretation of the line profiles is considerably more complicated and that the prototype star, T Tauri, is not very typical of the T Tauri population. Nevertheless the mass flow rates (whether infall or outflow) are still of the order of ~ 10^{-8} $M_\odot$/yr regardless of the details of the model. Basically one is counting up the emitting atoms in an extended envelope and the number needed to produce a given hydrogen line flux is about the same for most spherically symmetric models.

The emission and absorption line spectra can also vary on a variety of timescales. For example, in XZ Tau one can see an increase of FeII emission line strength in one month but even more striking is the weakening of the TiO molecular absorption bands. This may be due to a change in the continuum intensity or may reflect an increase in temperature of the TiO absorbing region. An extreme emission star, RW Aur, shows changes in emission line strength over a period of two hours, e.g. the NaI D line decreased by a factor of two as well as changes over one night during which the general emission line strength has decreased quite substantially (easily a factor 2 to 3 in most lines) and NaI D has gone from emission to absorption. Recently the spectrum of RW Aur has been observed in a very weak emission line phase in which some features of a late K-type photospheric spectrum were visible (Aiad et al. 1983). Similar changes occur in most T Tauri stars that have been monitored but on different time scales. Some stars, however, have shown no changes of any kind, others seem to be different each time that they are observed. No patterns of regularity have yet been discovered in this variability although the observations are perhaps insufficient to warrant such a conclusion. The stars also change in broad-band measurements but again no general patterns have been discovered, there being any combination of behavior in different filters that one could expect to find (Cohen and Schwarz 1976). We will discuss line profile variations later.

2. LOCATION ON THE HR DIAGRAM

Early UBV measurements of young clusters like NGC 2264 (1956) by Walker indicated that the T Tauri stars lay above and to the right of the zero-age-main-sequence on the color magnitude diagram. Ambartsumian even earlier (1947) had suggested that they were pre-Main Sequence objects. Recently Martin Cohen and I (1979) made a major survey of some 500 T Tauri stars which had as one of its goals the more precise location of the stars on the HR diagram. Scanner spectra of 7 Å resolution of both program stars and spectral standards were obtained with the scanner at Lick Observatory. Spectral types were determined from comparison with a sequence of standard star spectra and translated to effective temperature assuming that a unique relation between T_{eff} and spectral type exists for these peculiar stars. Since most T Tauri stars are not very different from late K stars this assumption is not likely to cause us grief until the more extreme T Tauri stars are reached. In these, the only normal stretch of the spectrum lies between λ5000 and 7000 Å, the region used for classification. In the most extreme cases no classification could be made because of the lack of photospheric features. In addition it was assumed that the intrinsic color over this spectral region was uniquely defined by the spectral type. In this way a reddening correction could be determined (using a standard reddening law) and applied to the optical and infrared flux measurements. Integration over the corrected fluxes (usually from ~ 0.4 to 3.5 μ) then gives the luminosity of the object. For the extreme T Tauri stars (~ 5-10%) no corrections were possible and only a lower limit could be determined. The errors in spectral classifications are likely to be quite small so one expects little change along the T_{eff}-axis. An error in the reddening correction would usually act to move the star up in luminosity. A typical result is represented by the HR diagram for the Taurus-Auriga dark cloud. Most of the stars are of spectral type late K with luminosities between 0.5 and 5 $L_\odot$. Evolutionary tracks for comparison purposes were modified from those of Iben (1965) but are convective-radiative tracks which seem to fit the observations best. A representative mass would be 0.7 $M_\odot$ with an age of ~ 10^6 yr if one believes the tracks for much younger objects. These tracks were chosen over more complex dynamical ones because they represent the only complete set of tracks for a wide range of masses and most dynamical tracks do not fit the observations. For example, Larson's (1972) track for a 1 $M_\odot$ star passes through the region in which the stars are observed to be but not as a visible object. The radiative portion is not in doubt but final conclusions concerning the convective portion will have to await better dynamical collapse models. I should again mention that extreme members of the T Tauri population cannot be located on such diagrams.

The general conclusions from this work are as follows: most Hα stars are still fully convective and range in age from ~ 10^4 to 6 x 10^6 yrs, in mass from 0.2 to 3 $M_\odot$ and in radius from 1 to 5 $R_\odot$. In a statistical sense the youngest stars show the richest emission line spectra, are still associated with nebulosity (as indicated by the forbidden lines), show the largest ratio of infrared to optical luminosity and give the impression that emission activity decreases with increasing age. However, from the data for any individual star one cannot draw any such conclusion about its evolutionary behavior. There is simply too much spread in the characteristics of individual stars. Similar results were found for other clusters and associations and leave little doubt that we are dealing with very young stars.

3. ROTATION

Since the T Tauri stars are very young stars one might expect that they still have considerable angular momentum and hence should rotate rapidly. Indeed the measurements of 4 stars by Herbig (1957) suggested that this was the case. The work of Kraft (1967) indicated that the rotational velocity decreased with increasing age for G and K stars on and slightly evolved off the main sequence. Also, those stars in the field showing CaII H and K emission (and hence younger than those that don't) had larger velocities than those that had no CaII emission. Skumanich (1972) later showed that the rotational velocity, CaII K emission and the LiI strength all decayed inversely with the square root of the age. In addition, for main sequence stars a dramatic break in rotational velocity occurs around 1.2 $M_\odot$ (spectral type F6) with stars of lower mass having very small rotation rates. Extrapolating these results back in time would suggest that T Tauri stars, being very young, should be rapid rotators. The CaII K line is certainly very strong in T Tauri stars but it is not yet clear whether it follows the Skumanich relation.

Stuart Vogel and I (1981) attempted to measure vsin i for a large number of pre-main-sequence stars in Taurus-Auriga and NGC 2264. The method of attack was to use a Fourier transform technique which essentially compared power spectra of several 100 Å of spectrum close to the MgI b band of program stars with standard stars of known vsin i and similar spectral type. The wavelength region was chosen to have a large number of absorption lines of moderate strength so that the signal-to-noise could be improved over that of a single absorption line. We had to be careful to remove those lines known to go into emission in T Tauri stars (e.g. Hβ, MgI, FeII) because, without knowledge of the velocity field of the emitting region it would not be possible to use emission lines in measuring vsin i. We also noticed a peculiar effect in the absorption lines, namely, that stars of the same spectral type would show certain lines as being filled in. These would look broadened at first glance but really are the filling-in effects of a chromospheric contribution. The effect is most pronounced for stronger lines (where the line goes clearly into emission) which are formed in the upper layers of the photosphere and hence are most likely to be affected by a chromospheric contribution in their cores. Rotational broadening, on the other hand, would affect all lines equally. The power spectra clearly distinguish these two effects but one has to be extremely careful in selecting the right set of lines for rotation measurements. The method itself has a sensitivity of ~ 10 km/sec for the dispersion used but the image tube degraded the actual limit to ~ 25 km/sec for all but the brightest stars. Thus we seem to have direct evidence for chromospheric effects which implies that the so-called "veiling" is not really a smooth overlying continuum (although some such contribution may still be present) but rather a selective filling-in of the cores of lines of large optical depth.

The rotation results themselves are also most interesting and unexpected. Three of the four stars measured by Herbig were also measured by us and his velocities were confirmed. But for all other low mass stars we found only upper limits except for V410 Tau which has a vsin i = 76 km/sec. The histogram of the measured vsin i's shows a most peculiar distribution: most stars have vsin i < 25 km/sec but one or two stars are found in each velocity bin up to 200 km/sec. When the velocities are plotted on the HR diagram for NGC 2264 one notices immediately that most low mass stars ($M < 1.5\ M_{\odot}$) have vsin i < 25 km/sec as do most Hα emission stars. Except for one case (which may be a binary) only stars with $M > 1.5\ M_{\odot}$ have large vsin i's. In addition, with the exception of one star, all convective track stars show no measurable velocity within our limit. This leads to a striking conclusion: the angular momentum problem has been basically solved <u>before</u> the stars become visible and show a photospheric absorption spectrum. This refers to the orders of magnitude of angular momentum loss that need to take place and not the additional factors of 2 to 5 required to get agreement with the Pleiades low mass stars. In addition, the break between low and high mass stars is already present when they first become visible.

We note that the Skumanich relation as originally stated for vsin i obviously fails in view of these null results. However, if one uses the angular momentum rather than surface velocity as the crucial parameter and corrects for the changes in internal structure of the star as it evolves from convective to radiative tracks (the star becomes more centrally condensed) then our results are consistent with the reformulated Skumanich relation. In particular the reformulated relation predicts velocities of ~ 20 km/sec which do fall within our limit of ~ 25 km/sec. However I note that Smith (1982) has measured vsin i for G stars in Orion and has found values in the range of 5 to 10 km/sec. If these results hold up then there is a major discrepancy with the Skumanich relation in that these stars would be rotating too slowly; e.g. much more slowly than comparable stars in the Pleiades which are already on the main sequence and have vsin i ~ 25 to 35 km/sec. This is obviously a most fruitful area for future research.

4. EMISSION LINE PROFILES

Until the recent advent of sensitive detectors, high resolution line profiles existed only for a few of the brightest T Tauri stars which have turned out not to be very typical of the T Tauri population as a whole. Mundt and Giampapa (1982) have obtained excellent high resolution profiles of Hα for a number of T Tauri stars. Most Hα profiles are either of the symmetrical type (e.g. BP Tau) or the double-peaked structure with a shortward displaced absorption feature (if it really is absorption) at velocities from 40 to 250 km/sec (e.g. RY Tau, S Cr A and RW Aur). In the case of BM And the absorption feature clearly goes below the continuum hence confirming that it really is produced by absorption and not simply by the absence of emission as had been suggested by Ulrich (1976) for the other double-peaked profiles. It should be noted that S Cr A is the star showing clear cut inverse P Cygni profiles in the higher Balmer lines (Wolf et al. 1977) but there is no evidence of such behavior at Hα.

There are a few stars that show very strong P Cygni type profiles at Hα, i.e., strong shortward displaced absorption going almost to zero intensity (e.g. AS 205, LKHα120 and AS353A) and give incontrovertible evidence for mass outflow. For AS353A the strong absorption component in Hα, β, γ and higher Balmer lines is striking but one should note that it is not present in the adjacent FeII 4352 line which presumably arises from the chromosphere. This suggests that the bulk of the high velocity hydrogen absorbing material lies farther out from the star. The behavior of the CaII H and K lines demonstrates this point even more dramatically: the K line is very strong in emission but the H line is completely absorbed by the overlying shortward displaced component of Hε. This striking behavior is not common; it is usually seen only for those stars having very strong P Cygni profiles in the hydrogen lines. Finally, a most unusual profile for Hα has been shown by DR Tau (Mundt and Giampapa 1982): a very strong broad emission with two shortward displaced absorption components. Such multiple components are known to occur in other lines such as NaI D (see below) but very rarely in Hα.

The hydrogen line profiles in individual stars can be quite variable on time scales from a few hours to days to weeks or even longer. An example is AA Tau (Boesgaard and Herbig 1981) which shows inverse P Cygni profiles for the hydrogen lines (but CaII K does not show such a component) yet one day earlier the profiles were quite symmetrical. This type of variability occurs quite often for that 5 to 10% of the T Tauri population known as the YY Orionis stars (Walker 1972). Their defining characteristic is the presence of inverse P Cygni profiles in the hydrogen lines. The longward displaced absorption components are best seen in Hγ, Hδ, Hε and H8-12 after which they seem to peter out. However, Hα has not yet been observed to show an inverse P Cygni profile. Occasionally redward-displaced components are also displayed by the NaI D lines.

The variability of the profiles of hydrogen in S Cr A is has been dramatically shown by the work of Bertout et al. (1982) in which they obtained an 11 day sequence of spectral and photometric data. The relative intensities of the blue and red peaks changes by a factor of two on timescales of a day for Hβ and for Hγ and δ the redward peak occasionally disappears completely, as if swallowed up in a strong absorption feature. The CaII H and K emission lines show a redward displaced absorption component at most times but the most striking thing is a strong sharp shortward shifted component at -105 km/sec in both H and K which maintains a constant velocity over the 11 days. The velocity of the blue component is too high for it to be an interstellar feature so one is forced to acknowledge the presence of high velocity outflow (presumably at a great distance from the star) from an object which so clearly shows infalling material in the hydrogen lines at various times. Thus one may be forced to conclude that the behavior of the hydrogen lines is produced locally (e.g. by large scale prominence activity) but that the dominant flow is outwards, i.e. a stellar wind which takes over at large distances. In other words, close to the star one may be dealing with a very nonspherically symmetric situation. It doesn't take too much imagination to extrapolate from the solar case of coronal loops and holes to the S Cr A situation. Also Cohen is now convinced that the flow for many young T Tauri stars must be bipolar. The final resolution must await more detailed observations and modelling.

The NaI D lines have been observed by Ulrich and Knapp (1979) and Mundt (1982). They are very sensitive to local conditions, being so easily ionized, and should be very useful in setting constraints on the models. However they show a bewildering complexity of behavior: absorption components are seen most clearly in AS205, DG Tau and S Cr A. Curiously, the velocity of this component for S Cr A seems to be the same as that of the sharp CaII H and K component but at NaI D it is much broader indicating formation closer to the star and the presence again of outflowing material, in a star whose hydrogen lines often show infalling material. Some years ago I also noted variability in the NaI D lines, especially in BP Tau (Kuhi 1975) which could show absorption to the red and the blue at different times. Some kind of close-to-surface variable activity is again indicated.

Multiple components are also seen (Mundt 1982): T Tauri is a good example with two currently at -71 and -99 km/sec. These two components have been observed over the past 40 years and have shown a decrease in velocity with time amounting to ~ 2 km/sec/year, indicating a decelerating flow. These components are relatively sharp and must be formed at some distance from the star. S Cr A is another star showing this deceleration in a distant component, the CaII K component being first observed at -120 km/sec but is now at -102 km/sec. The star with a record number of components is V1057 Cyg: the NaI D lines show at least four with velocities from -90 to -180 km/sec. The largest velocity component seems to be broader than the lowest which would again indicate a decelerating flow, but with ejection in the form of shells, the -180 km/sec component being the most recent.

The other emission lines (FeII, HeI, etc.) are most often symmetrical in profile (but not always of the same width) with no absorption components. In the most extreme T Tauri stars the strongest FeII lines will occasionally show absorption components either on the blue or the red sides in step with the hydrogen lines. The forbidden lines, when present, are almost always sharp, indicating a small velocity dispersion and are likely to be formed at very great distances from the star. In fact it is not clear where the T Tauri star's envelope leaves off and the

Herbig-Haro object begins. We've already heard a great deal about these objects and their connection to T Tauri stars at this conference so I need say nothing more.

5. X-RAY OBSERVATIONS

The Einstein satellite X-ray telescope was first used with the imaging proportional counter to detect X-ray sources in the Trapezium region of Orion by Ku and Chanan (1979). Many discrete sources were found at flux levels of ~ 10^{30} ergs/sec whose positions coincided with some 25 known nebular variables. Half of these were T Tauri stars and the other half were flare stars. The distinction between these two groups has become increasingly blurred and may only be one of mass and relative evolutionary age with the cooler T Tauri stars merging with the warmer flare stars. Gahm (1981) followed up with observations of several T Tauri stars and detected only one of them at $L_X = 6 \times 10^{30}$ ergs/sec. Surprisingly two extreme optical emission objects, RW Aur and RU Lup were not detected. He proposed that an X-ray emitting corona still existed but that its X-ray emission was absorbed by overlying cooler material in the circumstellar envelope. Feigelson and DeCampli (1981) then observed a further 20 T Tauri stars and detected 8 of them with $L_X \sim 10^{30}$ to 10^{31} ergs/sec. The ratio of X-ray to bolometric luminosity was typically 10^{-3}. No convincing correlations with optical characteristics were found although Gahm postulated that those stars of light curve classes I and II (i.e. stars which are most often bright) were most likely to be detected as X-ray sources when the star flared. This was based on Feigeleson and DeCampli's detection of an X-ray flare from DG Tau which is a strong emission line star. The flux increased by a factor of 10 in 35 min from a bare detection to a solid 5σ observation. The actual rise time was ~ 200 sec but the observations were not long enough to show an appreciable decay. Walter and I (1981) then observed a further two dozen T Tauri stars in Taurus and again detected 8 sources with $L_X \sim 10^{30}$ to 10^{31} ergs/sec. DG Tau was not detected although observed for a long time in the hopes of catching another flare. In fact, no flaring activity was detected in any of the 23 stars observed.

We also looked for correlations of X-ray detection with optical properties after limiting the sample to those stars bright enough to be detected. There seemed to be a limiting visual magnitude in Taurus-Auriga below which no stars were detected. This implies a roughly constant ratio of X-ray to visual luminosity and suggested $m_V \approx 13$ as the cutoff magnitude. We then combined all the observations of Taurus-Auriga stars and found only one suggestion of a correlation, namely that the stronger the Hα flux the less likely the X-ray detection. For example, no stars with Hα E.W. > 100 Å were detected; one of three stars with 50 < E.W. < 100 Å was detected; for E.W. = 50 Å more than 2/3 were detected and for E.W. < 50 Å all stars were detected. Our proposed explanation was that the Hα is clearly a measure of the overlying, cool gas column density and that the coronal X-rays, which are produced fairly close to the star, are simply absorbed by this cooler region. A crucial test would be to detect the change in the X-ray spectrum as the absorption (i.e. Hα strength) increases, the opacity being strongly frequency dependent. To this end we observed three stars with Hα E.W. of 37, 71 and 155 Å, the latter two with very long integration times (10^4 sec for E.W. = 155 Å). As expected, the strongest Hα star was detected (barely) with an intensity about half that of the middle star. However, the weakest Hα star which had been a very strong X-ray source before was detected at 1/10 of its previous flux level. Almost simultaneous ground-based data showed that the hydrogen line strengths had increased by a factor of 3 over their previous levels. Qualitatively this seems to go in the right sense, i.e. the Hα E.W. increased drastically and the X-ray luminosity decreased accordingly. To confuse the situation further, one of the other stars may have undergone a modest flare. The data are not good enough for clean spectral information concerning the X-ray absorption and consequently we cannot make a clearcut decision as to the validity of the "smothered corona" model.

Another explanation could be that the highest temperatures reached above the transition region are simply not hot enough to produce X-rays. As has been suggested by Linsky and Haisch (1979) for normal G and K dwarfs and giants, the energy that would have gone into heating up the corona may have gone into accelerating a cool stellar wind instead, as indicated by CaII H, K absorption components. The stars that have been detected in X-rays do not show these lines but do show ultraviolet emission lines corresponding to a hot transition region and of course the X-rays indicate the presence of a corona. The division into two groups is no longer so clean; Reimers (1982) has found X-rays from stars with both CaII H, K absorption components and hot transition region lines. The same possibility exists for T Tauri stars but the supporting observations are even less clear. Almost any combination of lower and upper chromosphere, cooler and hotter transition lines and X-ray detection can be found. Somewhat better coordinated data have been obtained recently by Imhoff (1983), who claims that those stars with the strongest CIV emission are X-ray sources whereas those with weak or no CIV emission are not. Given the intrinsic variability of these stars and the non-simultaneity of the different observations it is premature to try to answer this question.

Finally one should note that the model in which X-rays are detected usually only during flares is not ruled out either. In fact the very exciting recent results of Montmerle et al. (1983) for pre-main sequence stars in the ρ Ophiuchi region would strongly suggest that such a situation is most likely to be correct. They detected some 50 sources in the dark cloud region, most of which are highly variable by as much as one magnitude in a day. The overall distribution of the normalized amplitude variations follows a power-law and leads to the interpretation of strong flaring activity. The X-ray luminosity most likely still has a quiescent level which is simply overwhelmed by the flares. They also do not confirm the correlation found by Walter and Kuhi (1981) for all sources in the ρ Ophiuchi group but some trend remains for stars having Hα emission greater than 20 Å in equivalent width. Some evidence for a "smothered corona" may therefore remain but the situation is obviously very complex and not resolved at present. Montmerle has already presented the details of these observations in his X-ray movie which we have seen earlier at this conference. We can only hope that EXOSAT can provide the crucial observations to enable us to understand the structure of the T Tauri coronae and winds.

6. SERENDIPITOUS X-RAY SOURCES

An extra bonus from the EINSTEIN observations was the discovery of serendipitous X-ray sources in Taurus-Auriga fields containing known T Tauri stars. Five of these have been examined spectroscopically and turn out to be late type stars with weak Hα emission (EW $\lesssim$ 6 Å) and strong CaII H, K emission. They would not have been picked up in the earlier Hα slitless surveys because their Hα flux is below the detection limit. They do not look very different from the weak-line T Tauri stars yet their X-ray flux is also ~ 10^{30} to 10^{31} ergs/sec. Mundt et al. (1982) have suggested that these stars may be the long sought after post T Tauri stars. This may be so, but at present there is very little evidence to distinguish them from any of the other weak line T Tauri stars, which of course may themselves represent the last vestiges of the T Tauri phenomenon. An exciting new photometric discovery may change this: Rydgren and Vrba (1983) have observed four of these stars along with V410 Tau (the only rapidly rotating low mass T Tauri star) with broadband filters and have detected beautifully periodic variations of $\lesssim$ 0.1 mag in V. They interpret this variation in terms of rotational modulation produced by a spotted stellar surface. In the case of V410 Tau the period agrees with our measured vsin i, thus indicating that the inclination of the rotation axis to the line-of-sight must be ~ 90°. The other stars would have v $\lesssim$ 20-25 km/sec for reasonable estimates of the radii. These results provide strong confirming evidence of our rotational measurements and, even more importantly, of the existence of large spots (and hence enhanced activity) on the surfaces of T Tauri-like stars. An ideal project for someone with access to large amounts of telescope time would be to monitor T Tauri stars (and serendipitous X-ray sources) with a narrow filter centered on the CaII K line; the variations should be very large.

In this connection one should mention the observations of the CaII infrared triplet by Herbig and Soderblom (1980). They measured the triplet line strengths (λλ 8498, 8542, 8662) for a large number of T Tauri stars and found that instead of the expected ratios (1:9:5 from the transition probabilities) the observed ratios were almost always close to 1:1:1, indicating that the lines are optically thick. However, the intensities of the triplet lines relative to the continuum varied considerably (by as much as a factor of five) from one star to the next even though the ratios stayed close to 1:1:1. Their interpretation is that the lines are formed in optically thick regions on the surface of the star or in the chromosphere (these lines presumably come from the chromosphere) which have different sizes in each star. This result again points strongly to spots and suggests that monitoring of the CaII K line would be most profitable.

7. SUMMARY AND CONCLUSIONS

We have seen that the T Tauri stars seem to be strongly concentrated along the convective tracks in the HR diagram provided that the method of deriving the effective temperature and luminosity is accepted. This lends strong evidence for the validity of convective tracks or at the very least provides observational constraints on the theoretical evolutionary tracks, be they dynamical or otherwise. In either case it is now well established that most T Tauri stars are not only in the pre-main sequence phase but are actually in the pre-radiative equilibrium phase as well. They are less than 10^6 years old and star formation on this timescale seems to be noncoeval. The bulk of the angular momentum problem seems to have been solved before the stars appear with well-developed photospheres.

The combined optical, IUE and X-ray data lead to an interpretation which is strongly tied to the solar analogy. A low-lying chromosphere can account for much of the emission spectrum that we see including the so-called veiling but some larger extended emitting region must be added to get the large observed Hα flux. Nuria Calvet will speak to this in a later paper. The observations also point to spotted surface: both the CaII triplet and the photometric data are best explained in this way. Future modellers will have to take this asymmetry into account. The spots are obviously indicators of very strong activity as are the X-ray observations of flaring. Presumably we are dealing with very energetic flares and we are easily led to think of coronal holes and closed loops. Material would be lost from flow through the holes but would return to the surface along the loops. Thus one could have both infall and outflow occurring in the same star, perhaps in the form of large scale prominences. But the dominant flow would be outflow as is clearly seen at larger distances from the star in the CaII K line. There could be a greater flow from the polar regions leading perhaps to a bipolar flow.

In the matter of infall and outflow my own personal belief is that the T Tauri stars are past the dominantly infall phase associated with dynamical collapse and represent instead a transition phase to the normal photosphere, chromosphere, corona and stellar wind stage. All of the activity we see takes place close to the surface of the star (i.e. $< 1\ R_*$) and presumably is a result of various instabilities associated with that transition. The physical details of the responsible mechanisms have yet to be investigated; obviously this is a very fruitful field for the budding theoretician. The single most important need observationally is for high resolution coordinated observations, otherwise the variability remains as an inhibiting factor to our final understanding of the T Tauri stars. Finally, the recent discovery of an infrared companion to T Tauri (Dyck et al. 1982) adds yet another complication whose significance is not at all clear.

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DISCUSSION

S. Strom: It appears that the Cohen/Kuhi (L,T) diagrams for NGC 2264 and the Taurus Cloud T Tau stars are very different: the age spread in NGC 2264 appears to be $\sim 2\times10^7$ yrs with star formation almost continuous; in the Taurus clouds the main spread in time is much smaller. Would you comment? Also, the agreement between the locations of stars in the HR diagram and the PMS tracks is surprisingly good. Do you think the tracks are that good?

Kuhi: 1) Obviously star formation is non-coeval on time scales of $\lesssim 10^7$ years. The Taurus-Auriga association is much younger and perhaps will continue to form low mass stars for some time. NGC 2264 has many OB stars whereas Taurus does not; perhaps the appearance of such stars in Taurus will occur in $\sim 10^7$ years and cut off any further star formation. 2) No, I do not think the tracks are that good. The main conclusion may simply be that the T Tauri stars are in the pre-radiative equilibrium phase. This happens to be the convective region for Hayashi tracks but may be something completely different for dynamical tracks.

Montmerle: (*Comment*) If the flare interpretation of this strong X-ray variability we find in the Rho Oph cloud is correct, it does not in fact preclude the existence of a corona, possibly smothered by an expanding envelope ($\propto r^{-2}$), strong flares (= large flares) are not expected to be absorbed, but smaller ones may remain smeared and absorbed. We may have evidence of "quick star" activity in the source Rox-20, possibly of a coronal origin.

Walter: (*Comment*) The picture of large flares being due to large volumes of flaring material is correlated by observations of large X-ray fluxes in DG Tau (Feigelson and DeCampli 1981) and AS 205 (Walter and Kuhi 1983), both continuum stars which have never been detected as quiescent X-ray sources, and which have upper limits in L_x of $\sim 3\times10^{29}$ erg s^{-1}. Here the circumstellar material may be sufficient to smother whatever quiescent emission exists, yet be overwhelmed by an extremely large flaring event.

Kuhi: Yes, I can only agree.

Schmelz: (*Comment*) S. Strom asked the evidence for any results concerning differences in old and young T Tauri stars. The results of my Master Thesis seem to indicate that the variability (chromospheric depth, dust shell depth, photospheric spectral type) seems to decrease with increasing age of the T Tauri star. These results were presented in the poster session.

Franco: Assuming that the evolutionary tracks are not far from correct ones, you derived the mass spectrum and (at least for Orion and Taurus-Auriga) the formation rates. Have you made any attempt to derive correlations between molecular densities and the SFR and efficiencies?

Kuhi: No, we have not attempted to do this. The efficiencies we estimated have a very large uncertainty because of the corrections involved. Even so, it might be worthwhile doing.

Giampapa: (*Comment*) I certainly agree with you that the filling in of T Tauri photospheric lines is related to deep chromospheric heating. I think that it is significant to note in this regard that the onset of this so-called "blue veiling" is correlated with enhanced mass outflow. This indicates that the mechanism that is responsible for chromospheric heating is also responsible for the initial acceleration of massive winds originating near the stellar surface. As a second comment, the Sun serves as a useful guide in this area of research. The high speed streams of the solar wind emanate from coronal holes, which are open magnetic field regions *and* which are X-ray *quiet*. Intense coronal/chromospheric emission arises from the closed field regions with little or no mass outflow. Hence the degree of mass outflow and atmospheric (i.e., chromospheric/coronal) heating will depend on the magnetic field configuration present on the surface at the time of observation. The situation for the T Tauri stars must be analogous.

Kuhi: I can only agree with you.

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