and temperature distribution. It is worth noting that if this perturbation is small, one could in principle use the observed spectral variations as a probe of the physical conditions in the outer stellar atmospheres.

Circumstellar Dust

Variability of a peculiar star may also be caused by other physical processes, such as extinction by circumstellar dust regions with variable thickness. The typical case is represented by the galactic superluminous star η Car. This is presently a sixth magnitude star, but 150 years ago it was one of the brightest stars in the sky (Fig. 4). Since 1856 the stellar magnitude gradually decreased, and this suggested the (uncorrect) classification of η Car as a very slow nova. The star is presently a very bright infrared source. Andriesse et al. (1978) found that the bolometric magnitude derived from the infrared energy distribution is close to the estimated bolometric magnitude during the bright phase of last century. This suggests that the large fading after 1856 is due to the start of the dust-condensation process. The optical and ultraviolet radiation of the central star is more and more absorbed by the expanding envelope, and reemitted in the infrared. Presently, the star is in fact surrounded by a small dusty nebula whose total mass is a few solar masses, formed by matter ejected during the past 150 years.

Circumstellar dust is not exceptional among the most luminous emission-line stars. For instance, recent infrared surveys of the Magellanic Clouds have disclosed several stars with IR excess attributed to thermal emission from dust heated by the stellar radiation (Stahl et al. 1984, 1985, Glass 1984). The question is still open whether this dust is protostellar, or formed from the stellar wind in the present or in a previous evolutionary stage of the star. Anyhow, we cannot exclude that in the extreme conditions which cloud be present in the atmospheres of the S Dor and Hupple-Sandage variables, dust grains could be formed and/or accreted in their stellar winds, causing a considerable attenuation of the stellar light. Subsequent changes in the physical conditions of the stellar atmosphere might destroy the grains, or dissipate the dust envelope, resulting in an apparent brightening of the star. It is therefore attractive to conclude that these processes could be at least partly at the origin of the large brightness variations observed in the Hubble-Sandage variables, and that *these variations occur at probably constant bolometric luminosity,* as in the case of η Car.

It is clear from the above arguments that the study of the (variable) structure of the envelopes of luminous emission-line stars is crucial to understand their nature. The problem of the *circumstellar dust* is a particularly interesting one and should deserve more investigation in the future. However, although the most luminous stars have been the subject of a large number of studies in the last years, it is far from clear what is their role in the evolution of massive stars, and, in particular, which are their basic physical parameters, such as temperature, luminosity, chemical abundance, mass and mass-loss rate. More systematic studies are required of a number of representative individual objects in our Galaxy, as well as in the MCs and in external galaxies, in order to provide a more *complete* and *homogeneous* set of observational data which could be useful for making appropriate theoretical models.

I am very grateful to Aldo Altamore, Roberto Gilmozzi, Gerard Muratorio and Corinne Rossi for their collaboration in this investigation, and for providing me with unpublished data, and to Michael Friedjung for discussions and comments on the manuscript.

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Rotation and Activity of T Tauri Stars

J. Bouvier and C. Bertout, Institut d'Astrophysique de Paris

T Tauri stars are late-type, pre-main-sequence stars that, although at present quite active, will evolve in time into stars resembling the Sun. They are emission-line variables with strong ultraviolet and infrared excesses. They display flare-like X-ray emission, and a few can be detected in the radio range as well. Mass-loss rates estimated for these objects reach about $10^{-8} M_{\odot}$ /yr, and some T Tauri winds drive anisotropic, often bipolar, high velocity molecular outflows. A question which naturally arises when studying T Tauri stars is therefore what makes these objects so different from the main-sequence stars they are likely to become. In other words, is the T Tauri phenomenon due to a specific and as yet undetermined physical process, or is it only an exaggerated form of solar-type activity?

Stellar evolution theory might have been able to offer an answer to this question, at least in a first approximation, since pre-main-sequence evolution in spherical symmetry has been computed by various groups. But the T Tauri phase corresponds to the transition between the protostellar and main-sequence stages, and little understood magnetic and convective phenomena are expected to influence the evolution and spectral appearance of the star during this phase. Since the

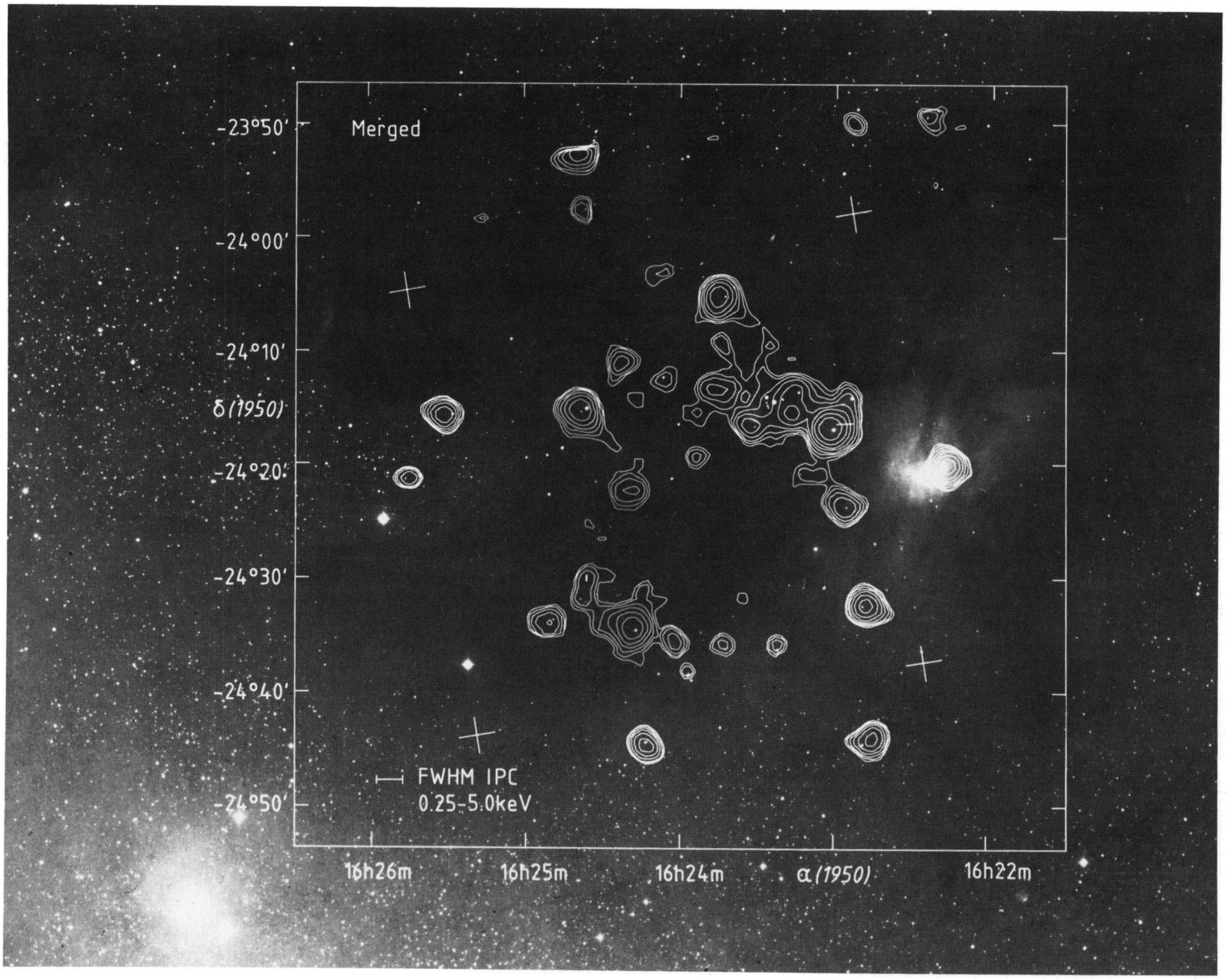

Fig. 1: *X-ray map of the ϱ Ophiuchi dark cloud from Montmerle et al. (1983,* Ap. J., ***269,*** *182). The contour levels show the detected X-ray sources, most of which are pre-main-sequence stars.*

physics of these phenomena cannot be taken into account in evolutionary codes, several empirical models have been proposed which shed light on particular properties of T Tauri stars; but to date none has been able to account for enough aspects of the T Tauri phenomenon to have gained widespread acceptance. Theory's inability to answer our question leads us to try an observational study of the similarities between T Tauri stars and other late-type stars.

Magnetic fields drive the surface activity of late-type dwarfs via dynamo processes resulting from the interaction between rotation and the deep convective zones present in these stars. While details of stellar dynamos are still in question, strong support to the dynamo hypothesis is given by the observed relationship (also predicted by dynamo models) between the stellar rotation rate and indicators of atmospheric activity, such as the X-ray flux and the flux in the Ca II H and K line emission cores. Recent progress in these matters has been reviewed by Pallavicini in *The Messenger* No. **35,** p. 5. By studying rotation in T Tauri stars, we might thus find out if dynamo processes are at work in these stars. We might also discriminate between those properties of T Tauri stars which are the result of magnetic activity and those which result from other physical processes. Identifying these unknown processes will indeed be easier when the role of magnetism in T Tauri activity will be clearly defined. All these reasons have led us to study the relationships between rotation and various activity criteria in T Tauri stars.

We chose to concentrate on the ϱ Ophiuchi region because it has been well studied in X-rays (cf. Fig. 1) and because it is easily observed from La Silla. But deriving accurate rotation velocities for T Tauri stars, which are rather faint objects, typically of the twelfth magnitude and higher, is not an easy task. We first describe below the different ways of doing this, and then summarize in the last part of this article our first results.

Measuring Rotational Velocities in Faint Stars

The spectral lines of a fast-rotating star appear broader than those of a slow-rotating one. In the ideal case where the axis of rotation is perpendicular to the line of sight, this broadening is a measure of the star's equatorial velocity. In reality, however, the rotation axes are randomly orientated relative to the line of sight so that the broadening is a measure of the projected rotational velocity, v.sini, where i is the angle between the rotation axis and the line of sight. V.sini is thus a lower limit of the true equatorial velocity, and spectroscopic determinations of stellar rotation have only a statistical meaning.

An example of rotational broadening appears in Fig. 2, which shows a selected spectral region of two T Tauri stars,

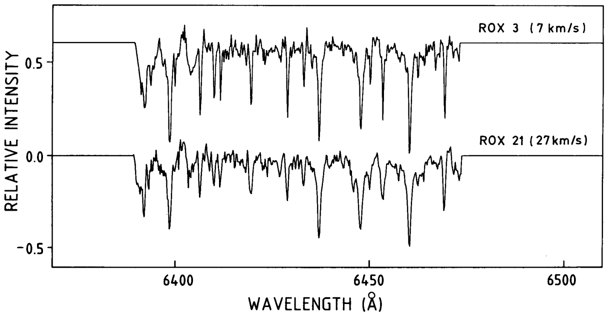

Fig. 2: *A selected spectral region for two T Tauri stars of the ϱ Ophiuchi cloud. Both stars are of spectral type M 1. Broader absorption lines in the spectra of ROX 21 are due to higher rotational velocity.*

both of spectral type M 1 and located in the ϱ Ophiuchi dark cloud. The spectrograms were obtained at the ESO 3.6 m telescope with CASPEC at a resolution of 20,000 in February 1984. Although these two objects are quite faint (V = 13.2 and 13.4), a good signal-to-noise ratio was reached in one hour of exposure time. Comparison of the broader photospheric absorption lines of the lower spectrum (v.sini = 27 km/s) to the upper one (v.sini = 7 km/s) illustrates the effect of rotation.

Recent progress in instrumental techniques and in the sensitivity of detectors now allows the use of powerful methods to measure v.sini that take into account the changes caused by rotation both in line width and in line profile shape. Behind these methods lies the principle that a rotationally broadened spectral line can be described as the convolution of the rotationally unbroadened line with a given rotation function. Under certain assumptions which remain valid for moderate rotators (v.sini <50 km/s, typically), this rotation function is easily calculated and only depends upon rotation rate and wavelength. Fourier analysis then becomes a powerful means to study rotational broadening, since convolution converts to ordinary product in Fourier space. Some results obtained by this method are shown in Fig. 3. In Fig. 3a, the Fourier transform of a CASPEC spectrogram of the T Tauri star LH_α 332-20 is shown as a solid line. The reference star, HR 1136, is a main-sequence star of the same spectral type and rotating at 2.2 km/s. Its Fourier transform was multiplied by the Fourier transforms of rotation functions corresponding to rotational velocities of 30, 35 and 40 km/s, and the results are shown as squares. We then search for the best fit in the frequence region comprised between 0.15 and 0.8 $Å^{-1}$ since large-scale continuum variations affect the Fourier transform

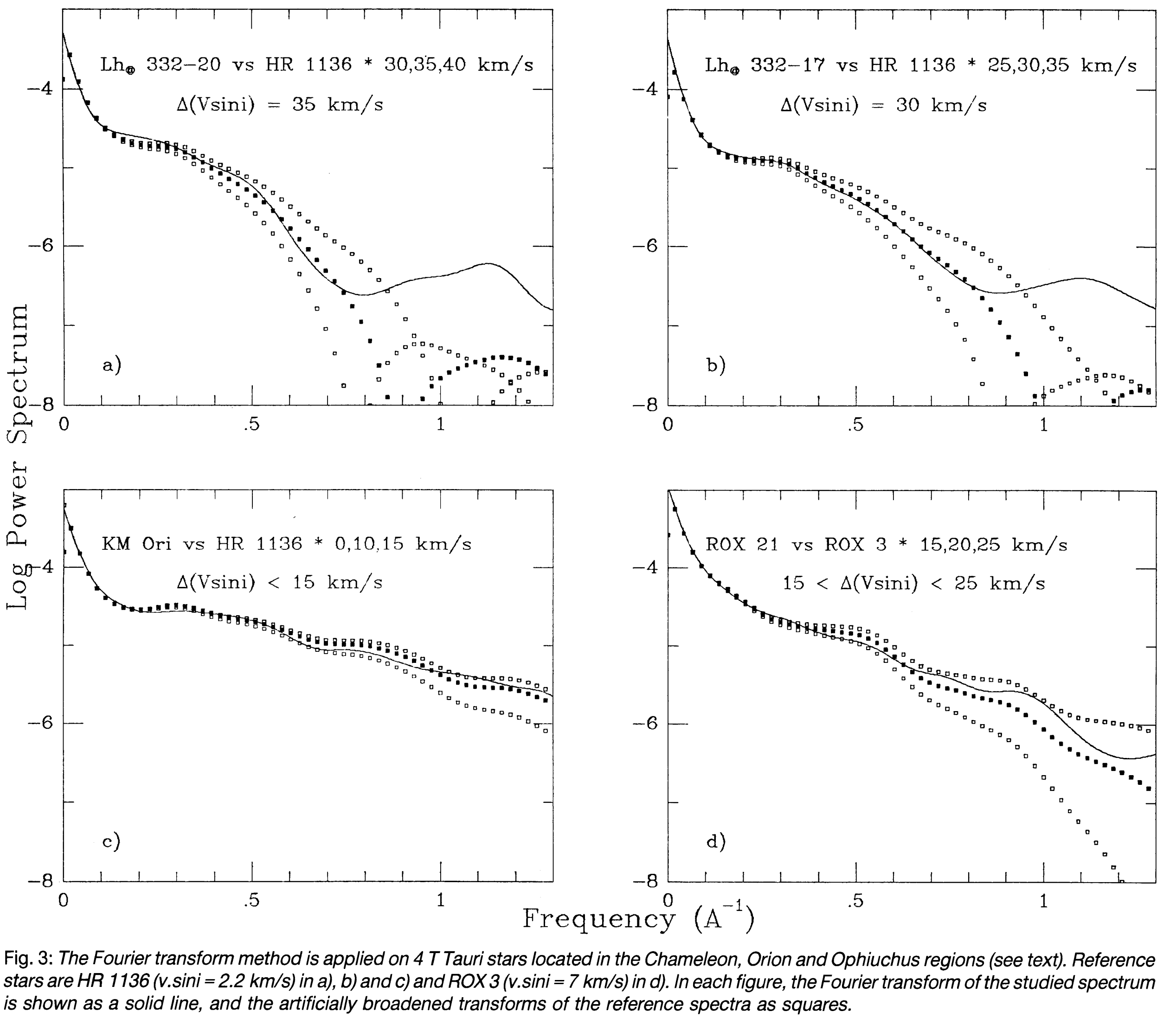

Fig. 3: *The Fourier transform method is applied on 4 T Tauri stars located in the Chameleon, Orion and Ophiuchus regions (see text). Reference stars are HR 1136 (v.sini = 2.2 km/s) in a), b) and c) and ROX 3 (v.sini = 7 km/s) in d). In each figure, the Fourier transform of the studied spectrum is shown as a solid line, and the artificially broadened transforms of the reference spectra as squares.*

below 0.15 Å^{-1} and noise dominates the transform above 0.8 Å^{-1}. As seen in Fig. 3a, the best fit arises for v.sini (LH$_\alpha$332-20) – v.sini (HR 1136) = 35 km/s, giving a rotational velocity of 37 km/s for LH$_\alpha$332-20. Figs. 3b to 3d show similar analyses for 3 other T Tauri stars.

Although this method is very powerful, accurate results can be obtained only from both very high signal-to-noise ratio (S/N = 300) and high resolution spectrograms. As a rule-of-thumb, the lowest rotational velocity which can be measured by this method is given by:

$$\text{v.sini (km/s)} = 1.0 \times \text{dispersion (Å/mm)}.$$

Since T Tauri are relatively faint objects it is difficult to fulfill both conditions except with large telescopes and state-of-the-art detectors. Indeed, Vogel and Kuhi, who used this method in 1981 (*Astrophysical Journal* **25,** 960) to determine the rotational velocity of pre-main-sequence stars could derive only upper limits of the rotational velocity for as much as 80 % of their sample. The most suitable instrument at La Silla for this method would be the CES on the CAT telescope owing to its very high resolution (R = 100,000). However, even with exposure times as long as 3 hours, a signal-to-noise of 300 cannot be reached for stars fainter than the sixth magnitude.

A less stringent method based on cross-corelation techniques can be used successfully for fainter stars. Cross-correlation works by shifting two spectrograms one relative to the other and calculating at each step a correlation coefficient which shows the degree of similarity between the two. For example, if both spectra are exactly the same, the correlation coefficient will be 1 when the spectrograms overlap and will decrease smoothly as the spectrograms are shifted. This will result in a correlation peak with a maximum value of 1. Fig. 4 shows the results obtained by applying this method to the two CASPEC spectrograms presented in Fig. 2. The spectrogram of ROX 21 was correlated with that of ROX 3 as reference, and the resulting correlation peak is shown as filled squares in Fig. 4. Then the spectrum of ROX 3 was artificially broadened by convolving it with rotation functions corresponding to different rotation values. The broadened spectra were correlated with the spectrum of ROX 3, and the resulting peaks are shown as broken and solid lines in Fig. 4. The full-widths at half-maximum of the latter and of the observed peak are then compared, with the best fit occurring for v.sini = 20 km/s.

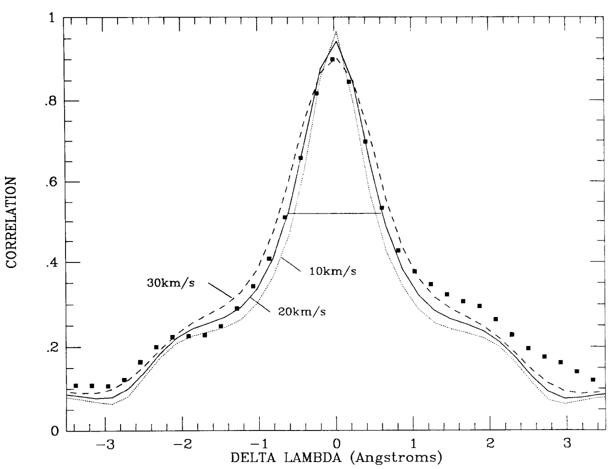

Fig. 4: *The observed correlation peak of the two spectrograms displayed in Fig. 2 is shown as filled squares and fitted by artificially broadened peaks for different values of the rotational velocity (see text). The best fit occurs for v.sini = 20 km/s. The large wings of the peak are caused by blends.*

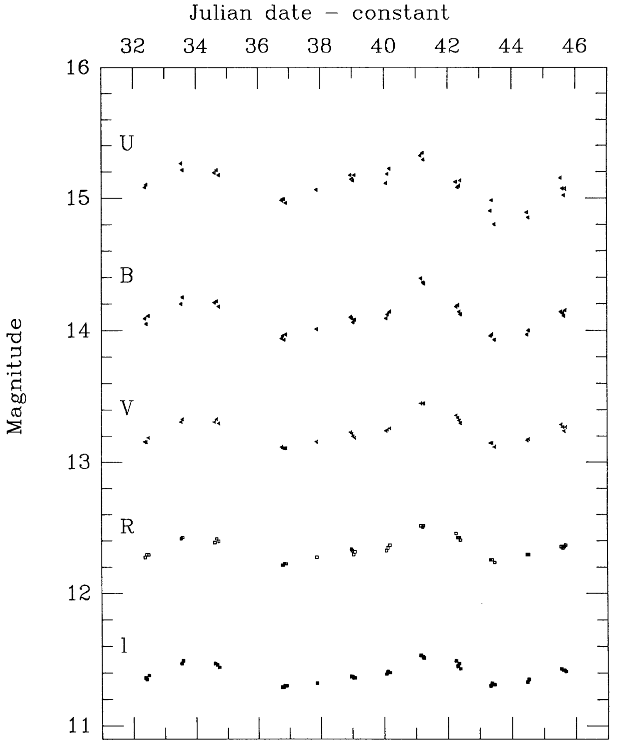

Fig. 5: *Light variations in five photometric bands of the T Tauri star SY Cha during 14 nights. The period of the variations is 6.12 days.*

Since ROX 3 is rotating at 7 km/s, we obtain 27 km/s for ROX 21. This is a more suitable method for studying T Tauri stars than are Fourier techniques since it can be used even in the case of relatively low signal-to-noise ratios (S/N = 50). However, high resolution is still necessary to measure slow rotators. For example, with CASPEC a signal-to-noise of 50 can be achieved on a 13th-magnitude star in one hour of exposure time, and its resolution of 20,000 allows one to determine rotational velocities as low as 10 km/s.

While the method just described is to be used for previously recorded spectrograms, a similar correlation technique is used on-line in the CORAVEL instrument, described in some detail by W. Benz and M. Mayor (1981, *Astronomy & Astrophysics* **93,** 235). Typical integration time on a 13th-magnitude T Tauri star with CORAVEL is 30 minutes and the detection limit is 2 km/s.

As mentioned above, all these spectroscopic methods will lead to a determination of the projected rotational velocity. Direct determination of equatorial velocities is possible for some late-type stars which possess large dark spots on their surfaces (cf. Rydgren et al., 1984, *Astronomical Journal* **89,** 7). Since these surface spots are cooler than the surrounding photosphere and are rotating with the stellar surface, the star will appear successively brighter and fainter as it rotates, depending on whether the spot is located on the hidden or the visible part of the stellar surface. This rotational modulation results in quasi-sinusoidal variations in the light curve of the star. The period of these variations will then allow the derivation of the true stellar equatorial velocity if the radius of the star is known, whatever the orientation of the rotation axis. It is a method which can determine the rotational velocity of slow as well as fast rotators, provided one gets enough observing time to follow the light curve of the slow stars during at least 1.5 periods and as long as the sampling of the light curve is narrow enough for the fast stars. Moreover, this method can be applied to very faint objects since accurate photometry can be achieved at the 1 m telescope for stars as faint as m = 16.

Some T Tauri stars show periodic light curves that are interpreted in this manner. Among them is SY Cha, which was observed during 14 nights in February 1984 at the La Silla 1 m telescope equipped with the UBVRI photometer. Fig. 5 shows the light variations displayed in each photometric band during the observing run. Although the variations are not sinusoidal, meaning that the spot covers a non-negligible portion of the stellar photosphere, a periodicity of about 6 days can clearly be seen. Applying a period-finding algorithm developed on the VAX computer at La Silla by E. Zuiderwijk, we found a rotation period of 6.12 days which leads to a rotational velocity of 21 km/s if the radius equals 2.5 $R_\odot$. This method is only applicable to stars for which rotational modulation due to surface spots is not hidden by the apparently random photometric variations exhibited by most active T Tauri stars. Uncertainties about radii of T Tauri stars also remain a problem for this method's accuracy.

Rotation and X-ray Emission

Applying the different methods described above, we were able to derive rotational velocities for 12 T Tauri stars, 6 of them located in the ρ Ophiuchi region. In doing so, CORAVEL proved to be best for our purposes, and we wish to thank both M. Mayor for kindly proposing the use of this instrument for this programme and W. Benz for conducting the CORAVEL observations on the 1.5 m Danish telescope at La Silla in June 1984. The following discussion is based on rotation rates of 20 T Tauri stars, 8 of which were available in the literature.

In Fig. 6 we plot X-ray luminosity versus projected rotational velocity for late-type main-sequence stars (G to M), for T Tauri stars and for RS CVn systems. Late-type main-sequence stars are represented by empty symbols, RS CVn systems by star symbols and T Tauri stars by filled triangles. Vertical bars associated with T Tauri stars represent the observed range of variability in X-ray luminosity, and horizontal bars are the uncertainties on the projected rotational velocities.

RS Canis Venaticorum systems are active late-type spectroscopic binaries. Their large rotational velocities arise from the synchronization of their angular and orbital motions. That they are located higher in Fig. 6 than T Tauri stars is only the result of a selection effect since accurate rotational velocities are known only for the most active systems; X-ray surveys including T Tauri stars and RS CVn systems show that they display the same range of X-ray luminosities. A least-square fit performed on the data of Fig. 6 shows that the X-ray luminosity scales approximately as the square of the rotational velocity. Pallavicini found the same relationship for a sample of late-type main-sequence stars, and showed its consistency with predictions of stellar dynamo models.

It thus appears likely that the mechanism responsible for X-

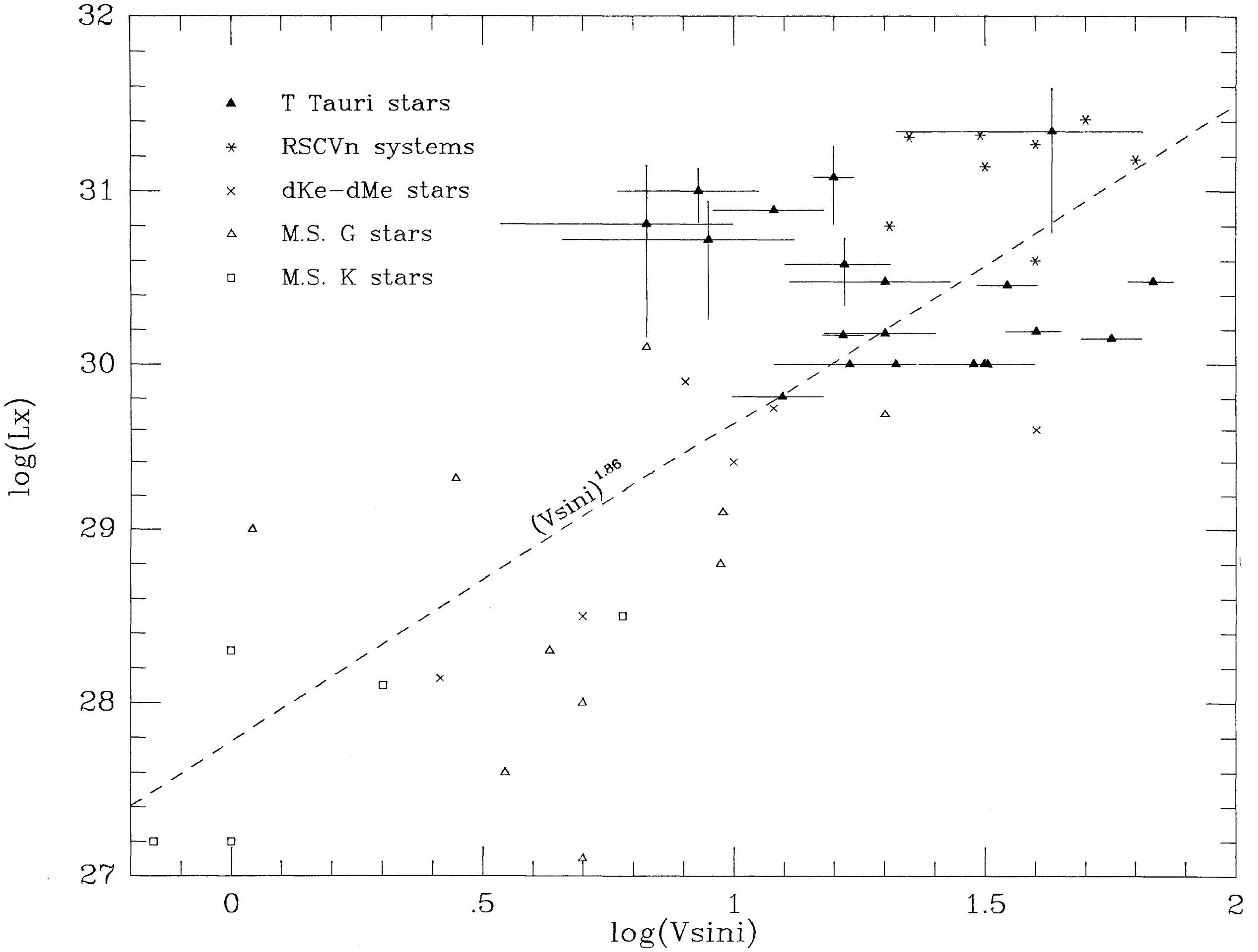

Fig. 6: *X-ray luminosity versus projected rotational velocity for late-type main-sequence stars, RS CVn systems and T Tauri stars (see text for details).*

ray emission is the same in late-type main-sequence stars, RS CVn systems and T Tauri stars. The enhanced X-ray emission displayed by T Tauri stars and RS CVn systems compared to main-sequence stars can be accounted for by their higher rotational velocities. Since X-rays originate from coronae in main-sequence late-type stars and RS CVn systems, this result suggests the presence around T Tauri stars of coronae responsible for a relatively low-level X-ray emission (of the order of 10^{30}erg/s) onto which strong flare-like eruptions are superimposed. The existence of coronae around T Tauri stars has been a topic of controversy in recent years, and this result may represent the best, albeit indirect, piece of evidence for coronae to date.

Conclusions and Prospects

An important aspect of our results is that the RS CVn class can be used as a "stick" to measure magnetic surface activity in T Tauri stars. Since RS CVn stars are not fully understood yet, it is not a perfect measuring stick; but it is a definite help, since by comparing the different properties of T Tauri stars to those of RS CVn systems, we can, at least in principle, find out which are due to magnetic activity and which must be accounted for by other physical mechanisms.

To reach this goal, various activity indicators in both T Tauri and RS CVn stars must be observed systematically, and their relationship with rotation studied. For example, we plan to follow chromospheric indicators such as the Ca II H and K lines over at least one rotation period to find out the range of variation of their flux and to study possible correlations with phase. We already know that Hα emission strength is not correlated to rotation rate, which means that Hα emission is probably not directly related to magnetic activity, but a detailed study of Hα variability would be needed to confirm this result. Also, more data are needed on the rotation rates of T Tauri stars in order to improve statistics and to allow us to study correlations within the T Tauri class. But thanks to the friendliness of our Swiss colleagues and to CORAVEL's excellence, we know now that this is possible even for faint T Tauri stars.

Double Emission and Line Absorption Doubling in Mira Stars: A New Approach

D. Gillet and P. Bouchet, ESO
R. Ferlet, Institut d'Astrophysique de Paris
E. Maurice, Observatoire de Marseille

The spectra of Mira variables present a large number of emission and absorption lines which vary in strength and profile with phase. According to current models, these lines are the consequence of strong shock waves propagating through the stellar atmosphere. However, the dynamics of the shock propagation is so far not completely understood, and the interpretation of the emission and absorption line variability can only be made through semi-empirical models. Extensive studies during a whole variability period (Hinkle, Scharlach and Hall, 1984; Gillet, Maurice, Bouchet and Ferlet, 1985; hereafter: GMBF) can provide fundamental clues to the knowledge of the underlying physics. In the present note, through two examples, we show that it is possible to know the dynamical and physical conditions of the line emitting regions, using high resolution optical observations with modern detectors. All observations presented hereafter have been obtained with the Coudé Echelle Spectrometer (CES) of ESO equipped with a 1872-diode Reticon. The 1.4 m Coudé Auxiliary Telescope (CAT) or 3.6 m telescope were used to feed the CES. The resolving power was between 80,000 and 100,000. In the case of the 3.6 m telescope, the observations were obtained through a fiber optic link whose details are given in Lund and Ferlet (1984).

The Double Hα Emission Line: A Fundamental Geometric Effect

It is a classical result that the Balmer emission profiles in cool Mira stars present strong mutilations very likely due to absorptions by atoms and molecules of the upper atmosphere, i.e. above the shock wave (Joy, 1947). In o Ceti, these absorptions disappear before the luminosity minimum (phase ~0.36) when the shock reaches the low density part of the atmosphere (Gillet, Maurice, Baade, 1983; hereafter: GMB and Fig. 1 a). In S Car, the effective temperature is too high during the luminosity maximum, and the profile does not show any mutilations (GMBF and Fig. 1 b).

The wavelength scale in these two figures is given in the rest frame of the stars. It is obvious that there is a strong absorption centred at the laboratory wavelength. For o Ceti, it appears clearly around phase 0.4 when the redshifted emission component is fully developed, whereas it is already visible at the luminosity maximum for S Car.

We suggest that this large absorption is intrinsically different from the narrow absorptions observed in the blueshifted emission component of o Ceti around the luminosity maximum and discussed above. This absorption is only apparent and is the consequence of a geometrical effect. Indeed, if one assumes that the front velocity is high (70–80 km/s), the shock will reach already around phase 0.4 a layer far from the photosphere. The observer would then begin to receive the emission from the part of the shock propagating away from him, previously occulted by the stellar disk, and corresponding to the redshifted component. In this frame, the large absorption is not real, contrary to what was previously assumed in the literature.

This interpretation is consistent with the high shock front velocities deduced from the detailed Hα profile studies by GMB and GMBF, and with the jump velocities derived from the fluorescent lines by Willson (1976). Note that the presence of both emission components already at the luminosity maximum in the hot Mira star S Car is explained by the absence of a dense molecular atmosphere contrary to o Ceti (see GMBF).

The True Nature of the Absorption Line Doubling Phenomenon

It is another classical result that around the luminosity maximum many absorption lines in the near-infrared and infrared ranges are observed double. The current interpretation assumes the existence of two atmospheric regions with different velocities (two-component model), as a consequence of the propagation of the shock through the atmosphere (Wing, 1980).