derived from three He II emission lines, those of the cool star from the calcium K absorption line.

The new observations are clearly compatible with the TNR theory which predicts the accreting star to be near the Chandrasekhar limit. Nevertheless, the peculiar emission line spectrum of the "hot component", formed in the accretion disk around the white dwarf, is poorly understood. Does it indicate that the accreted matter is helium-rich, or is it only the effect of high temperature? Is the secondary a normal main-sequence star of spectral type F, as indicated by its mass, its feeble impression on the total spectrum, and by the orbital elements? Can a sufficiently detailed TNR model be found which matches all the observed properties, or does one have to go back to other models, e.g. accretion disk instabilities? These questions have to be answered, and for this, additional observations are highly desirable.

It appears that theory and observation of recurrent novae are coming of age. We wonder what the state of knowledge will be after another 130 years have elapsed and VLT time will have been granted for nova research!

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Rotation of T Tauri Stars from Multi-Site Photometric Monitoring

J. BOUVIER, Laboratoire d'Astrophysique, Observatoire de Grenoble, France

1. Introduction

The present-day Sun has a very low rotational velocity: ≈ kms^{-1} at the equator. In this respect, the Sun is representative of all low-mass main-sequence stars, whose rotational velocities usually amount to less than 5 kms^{-1}. These stars have not always been such slow rotators, however. In the mid-80's, CORAVEL measurements of the rotational velocities of pre-main sequence solar-type stars, the so-called T Tauri stars with an age between 1 and 10 million years, were performed at the 1.5-m Danish telescope on La Silla and showed that their average rotation rate is about 15 kms^{-1}, i.e., nearly 10 times larger than the billion-year-old Sun. Long before the rotation rates of young stars were measured, Schatzman (1962) hypothesized that low-mass stars are braked on the main sequence, loosing angular momentum to their magnetic stellar winds. As a result, all low-mass dwarfs that have evolved onto the main sequence have lost the memory of their initial rotation rate and exhibit uniformely slow rotation by the age of the Sun.

Clues to the initial velocity distribution of solar-type stars can therefore only be obtained from the measurement of the rotation rates of very young stars, such as T Tauri stars. In turn, the rotational properties of these newly-formed stars provide constraints on the star-formation process and on the very early stellar evolution. A point of particular interest is to investigate how accretion of material from a circumstellar disk affects the rotational evolution of young stars. Approximately half of the TTS, the so-called "classical" T Tauri stars, exhibit strong mass-loss and are believed to simultaneously accrete material from a circumstellar disk at a high rate. The other half, designated as "weak-line" T Tauri stars because of their relatively weak emission-line spectrum, do not possess an accretion disk and have much weaker stellar winds (see the review on T Tauri stars by Bertout 1989). Comparison between the rotation rates of classical and weak-line T Tauri stars thus provides a way to study the impact of disk accretion and mass-loss onto their rotational evolution.

2. The "COYOTES" Campaign

Extensive measurements of spectroscopic velocities, $v\sin i$, of T Tauri stars using CORAVEL and other spectrographs have proved very powerful to derive the *statistical* rotational properties of young stars (see a review by Bouvier 1991). However, a major uncertainty arises from the unknown value of the geometric factor sin*i* included in the spectroscopic velocity. A more direct, but much more demanding, measurement of rotation consists in monitoring the photometric variations of young stars. T Tauri stars exhibit brightness inhomogeneities at their surface ("spots") which modulate the stellar flux as the star rotates. As a result, the light curve includes a quasi-sinusoidal component whose period is a direct measure of the star's rotational period. Rotational periods thus derived are not affected by projection effects and are usually measured with an accuracy of better than 10%.

In order to tackle the issues outlined in the Introduction, we organized an international photometric monitoring campaign on T Tauri stars (TTS) which took place between November 1990 and February 1991. This campaign was dubbed COYOTES, which stands for Coordinated Observations of Young ObjecTs from Earthbound Sites. The COYOTES campaign lasted three months. During this time the night-to-night variability of 23 TTS from the Taurus-Auriga stellar formation region was monitored in UBVRI photometry using eight telescopes in seven sites: ESO (S.Cabrit, Grenoble), Calar Alto (M. Fernandez, Madrid), La Palma (E. Martin, Canarias), Las Campanas and CTIO (J. Matthews, UBC), Catania (E. Covino, Catania), and Cananea (L. Terranegra, Mexico). Due to bad weather, no data could be collected at the last two sites. The resulting light curves span a time interval from typically 60 days, with unfortunate gaps due to non-photometric weather and/or instrumental problems, and up to 90 nights for 3 objects of the sample.

Periodic light variations were searched for in the light curves of the 23 stars using Fourier techniques. Quite

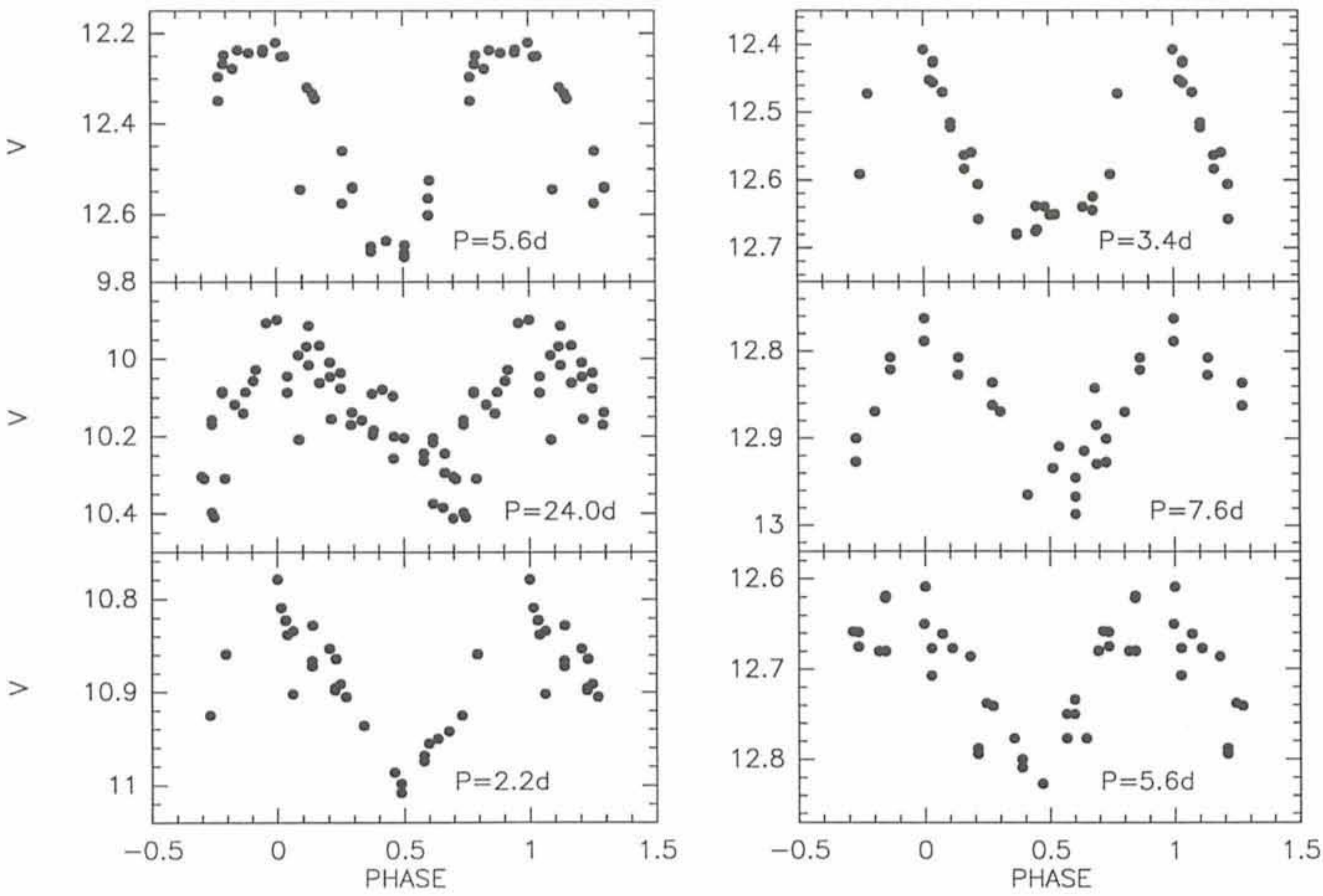

Figure 1: *Phased light curves of 6 stars from the COYOTES sample in the V-band. The photometric period is indicated in each panel. From bottom left to top right: LkCa-19, RY Tau, LkCa-7, IW Tau, DE Tau, LkCa-4.*

surprisingly, we found that *all* the 23 stars exhibit periodic light variations with periods between 1.2 and 24 days. Previous monitoring studies, spanning a time period of typically two weeks, had a detection rate of about 30%. Our much higher success rate mainly results from the much longer time period (3 months versus 2 weeks) over which we monitored the light curves of the programme stars. The phased light curves of 6 of the COYOTES stars are shown in Figure 1.

3. Cool and Hot Spots on T Tauri Stars

In 20 of the 23 programme stars, the photometric period results from the modulation of the stellar luminosity by surface spots, which directly yields the star's rotational period. The periodic light variations of the 3 remaining stars probably result from orbital motion in a binary system. The temperature and size of the spots responsible for the modulation of the stellar flux can be estimated from a model that reproduces the variation of the amplitude of modulation with wavelength from the U to I-band. Application of the spot model to the light curves of the programme stars indicates that cool spots, i.e., spots that are cooler than the stellar photosphere by about 1000K, are responsible for the variability of weak-line TTS. These cool spots are stellar analogues of sunspots, albeit on a much larger scale since they cover typically 15% of the stellar surface compared to 0.01% for sunspots. The detection of such extended cool spots provides one of the strongest indirect evidences for the existence of kilogauss magnetic fields at the surface of T Tauri stars.

While only cool spots seem to be present at the surface of weak-line TTS, both cool and hot ($T_{spot} - T_{eff} \simeq 1000$K) spots are responsible for the flux modulation of classical TTS. The modelling of the light curves indicates that hot spots usually cover a much smaller fraction of the stellar surface than cool spots, typically a few per cent. That hot spots are exclusively found at the surface of stars which are surrounded by an accretion disk suggests that they trace the accretion shock at the stellar surface. The detection of rotational modulation by small hot spots then implies that the accretion flow is not uniformly distributed along the stellar equator, as could be expected from an axisymmetric accretion disk, but is strongly asymmetric. A possible explanation is that the accretion flow is channelled along the lines of the strong stellar magnetic field close to the stellar surface, thus resulting in localized hot accretion spots at the stellar surface.

4. The Rotational Properties of T Tauri Stars

Another clue for the interaction between the accretion disk and the star's magnetic field comes from the comparison between the rotational periods of weak-line (WTTS) and classical (CTTS) T Tauri stars. Histograms of the rotational periods of WTTS and CTTS are shown in Figure 2. These histograms include the rotational periods of 14 K7-M1 TTS from the COYOTES campaign as well as those published for 12 other K7-M1 TTS of the Taurus-Auriga cloud. Only stars with a spectral type between K7 and M1 are shown in order to deal with a homogeneous sample of 0.8-1.0 $M_\odot$ stars. The histograms show a statistically very significant difference between the rotational period distributions of WTTS and CTTS: 9 out of 11 WTTS have periods ranging from 1.2 to 6 days, while 13 out of 15 CTTS have periods between 6 and 12 days. The mean rotational period is 4.1 ± 1.7 d for WTTS, and 7.6 ± 2.1 d for CTTS. Hence, WTTS rotate faster than CTTS by nearly a factor of 2 on average.

This is a surprising result on several grounds. First, extensive measurements of the spectroscopic rotational velocities, *v*sin*i*, of many T Tauri stars performed in the 80's failed to reveal any significant difference between the rotation rates of WTTS and CTTS. Presumably, both measurement uncertainties and the unknown value of sin*i* conspired to hide the relatively subtle difference revealed by the COYOTES campaign. Second, while photometric monitoring demonstrates that CTTS rotate more slowly than WTTS, one would naively expect the opposite on theoretical grounds since CTTS accrete material from their rapidly rotating circumstellar disk, which ought to spin the star up, while WTTS do not possess accretion disks.

A possible explanation for the faster rotation rates of WTTS compared to CTTS is that the former are slightly older than the latter, though the two stellar groups are commonly believed to have similar ages. This belief mainly rests on their similar location in the H-R diagram and their similar lithium abundances. Still, these arguments are more suggestive than conclusive. On the one hand, it is not easy to locate classical T Tauri stars in the HR diagram due to the strong non-photospheric UV and IR excesses they exhibit. On the other hand, interpretation of lithium abundances of pre-main-sequence stars is somewhat uncertain due to the poor knowledge we have of the lithium depletion timescale at this stage of stellar evolution. Both WTTS and CTTS are contracting onto their pre-main-sequence evolutionary tracks toward the ZAMS. Therefore, if we assume that WTTS are slightly older than CTTS, their faster rotation rate would naturally result from their smaller radii (assuming no angular momentum loss). The observed difference of a factor of 2 between the rotation of WTTS and CTTS would then imply an age difference of a few 10^6 yrs, much smaller than the contraction timescale to the main sequence (a few 10^7 yrs). This hypothesis, however, is unlikely. If correct, it would imply that pre-main-sequence stars are continuously accelerated as they contract towards the main sequence, thus reaching the ZAMS with a rotational velocity in the range from about 40 to 150 km s^{-1}. While approximately half of ZAMS solar-mass stars do have velocities in this range (Stauffer 1991 and references therein), the other half have velocities less than 10-20 km s^{-1}, which cannot be explained in the framework of this hypothesis. Therefore,

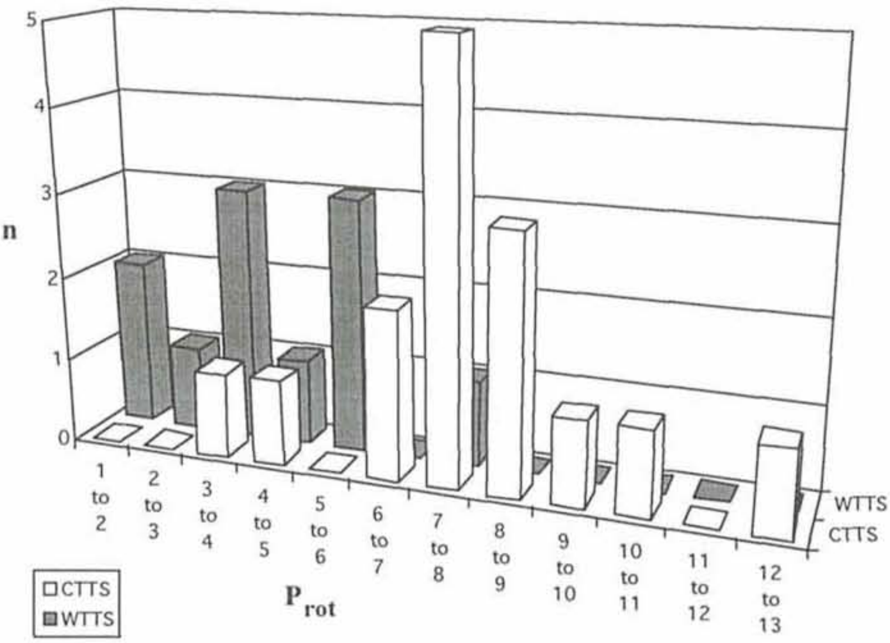

Figure 2: *Histograms of the rotational periods of weak-line (grey) and classical (white) T Tauri stars. A Kolmogorov-Smirnov test shows that the 2 distributions are different at the 99.9 % level, indicating that WTTS rotate faster than CTTS.*

the results of the COYOTES campaign provide independent support to the coevality of CTTS and WTTS.

What is then the origin of the different rotation rates between WTTS and CTTS? A paradoxical possibility is that accretion of circumstellar material leads to the braking of the central star rather than to its acceleration. Rotational braking due to accretion of circumstellar material is not a new idea. It was originally proposed by Ghosh and Lamb in 1979 to explain why some strongly magnetized, compact objects spin down while accreting material from a nearby companion. The deceleration of the accreting object is described as resulting from the interaction of the accretion flow with the strong star's magnetic field, which leads to a transfer of angular momentum from the star to the accretion disk. TTS are not pulsars; their magnetic field is much weaker than that of white dwarfs and neutron stars. Still, kilogauss fields appear to be sufficient to disrupt the inner regions of their accretion disk up to a distance of several radii from the star, thus channelling the accretion flow along the field lines and, incidentally, producing the hot accretion spots revealed by photometric monitoring. Models analogous to the Ghosh and Lamb model for compact objects have started to be developed for T Tauri stars (e.g., Königl 1991) and show that the disk may indeed be disrupted up to a large enough distance from the star (beyond the disk's corotation radius) so that angular momentum flows from the star to the disk, thus effectively braking the central star. By demonstrating that CTTS do rotate more slowly than WTTS, the results of the COYOTES campaign provide one of the strongest evidences for the interaction of the accretion flow with the stellar magnetic field and lend support to the recently developed models that describe the magnetospheric coupling between the central star and the disk.

5. Towards an Understanding of the Rotational Evolution of Young Stars

The hypothesis that young stars are braked by their accretion disks opens new perspectives to understand their subsequent rotational evolution to the zero-age main sequence (ZAMS). The observation that approximately half of the solar-type ZAMS stars have rotational velocities less than 20 km s^{-1} while the other half have velocities in the range from 40 to 150 km s^{-1} has remained a challenge to theoretical models for the last few years. The major difficulty was to understand how the relatively small dispersion of rotation rates observed among solar-mass T Tauri stars (from ≃ 5 to 30 km s^{-1}) could result in such a wide range of velocities at the ZAMS (from ≃ 5 to 150 km s^{-1}), 3 10^7 yrs later. The proposed interpretation of the COYOTES results may considerably alleviate this difficulty. In the framework of our hypothesis, WTTS do not possess accretion disks and are therefore continuously accelerated as they contract towards the main sequence. According to pre-main sequence evolution models, they will then end up onto the ZAMS with rotational velocities between 40 and 150 km s^{-1}, as observed for half of ZAMS, solar-type stars. CTTS, in contrast, are braked down to low velocities up to the point where they disperse their disk. The disk survival time is estimated to be of the order of 10^7 yr at most, i.e., the star is still some 2 10^7 yr away from the ZAMS. From thereon, having lost its disk, the star will spin up as would a WTTS. However, if the star was braked down to a velocity of a few km s^{-1} at the end of the accretion phase, it will still reach the ZAMS with a velocity of less than 20 km s^{-1}, thus accounting for the other half of ZAMS stars observed to have small velocities.

Admittedly, the above description of how CTTS evolve into slowly rotating ZAMS stars while WTTS are the progenitors of rapidly rotating ZAMS dwarfs may be a little over-optimistic. Many issues have to be addressed more quantitatively. For instance, are CTTS really braked by their disks down to small enough velocities, i.e., a few km s^{-1} at most, so that they reach the ZAMS with a *v*sin*i* of less than 20 km s^{-1}? The answer to this and other pending questions awaits further observational and theoretical work. Other campaigns such as COYOTES I will have to determine the rotational periods of stars with an age intermediate between T Tauri stars and ZAMS dwarfs, which will allow one to trace observationally the evolution of angular momentum of solar-type stars prior to the main sequence. Observations will also have to provide better estimates of both the strength and surface coverage of magnetic fields in T Tauri stars and bring clues to the field structure (dipole vs. multipole?). Helped by these new constraints, theoreticians will have to develop more realistic models of the interaction between the accretion flow and the star's magnetic field, thus enabling more accurate predictions as to the impact of disk accretion onto the angular momentum evolution of young stars.

6. Conclusion

The unexpected results obtained from the COYOTES I campaign clearly illustrate how powerful coordinated observations of T Tauri stars are, even from such a site as La Silla where performing (relatively) accurate photometry of Taurus stars (Dec. ≃ +15°) with the bright moon not very far from the target stars is (almost) an art. At the time this contribution is being written, COYOTES II has been completed. It took place during the winter 1992–1993 and involved the same participants as COYOTES I plus a few more. The results are under analysis. A complete description and analysis of COYOTES I results are being published in two papers in A&A.

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TY CrA: a Pre-Main-Sequence Binary

A.M. LAGRANGE, J. BOUVIER, P. CORPORON, Observatoire de Grenoble, France

The southern young star TY CrA, embedded in the reflection nebulae NGC 6726/7, has a strong far-IR excess which is attributed to circumstellar cold grains, larger than the usual interstellar grains, cf. Cruz-Gonzales et al. [1984] and Bibo et al. [1992]. Photometric variability has been found by Kardopolov et al. [1981], and the photometric curve is known to be the one of an eclipsing binary system, with a 2.888777-day period.

Spectroscopic observations of this object have been performed in the period 1990–1992 with the CES and the 1.4-metre CAT at La Silla. Lines of CA II K, Ca II triplet, Mg II, Ti II, Hα, He I, O I and Na I were investigated (Lagrange et al. [1993] and we show in Figure 1 some of the spectra which were obtained.

The three main results are the following:

- Contrary to what is generally observed for Herbig stars, no strong emission is seen in any of the investigated lines. This had already been noticed by Finkenzeller and Mundt [1984] for the Hα line. However, it is still possible that this line, as well as the Ca II line, do have absorption that is partly filled by emission. Moreover, we detected for the first time transient, blue-shifted emission in the O I triplet lines.
- Narrow absorption lines are observed with FWHM ≤ 8 km s^{-1} in the CA II K, Ca II triplet, Ti II, Na I, O I, as well as cores in the Hα and He I lines. The Na I line additionally exhibits a broad absorption profile.
- The narrow absorption lines are periodically variable in velocity; this is shown in Figure 2, where a 2.888777d phase diagram has been constructed for the radial velocities of all the narrow lines. The radial velocity period is the same as the photometric period previously reported by Kardopolov et al. [1981].

Our data thus provide the first direct evidence that TY CrA is a spectroscopic binary. As the radial velocity variations of *all* the narrow lines can be phased together, we can conclude that all these lines have a common origin. In contrast, the broad components of the Na I lines exhibit radial velocity variations that are anti-correlated with those of the narrow component. This then argues for a different origin.

From Figure 2, we get a radial velocity semi-amplitude for the primary of ≃ 75 km s^{-1}. Assuming an eccentricity of 0 and sin*i* = 1 since it is an eclipsing system, and knowing the 2.888777-day period, we derive a semi-major axis of 4.56 $R_\odot$ for this component. For a mass ranging between 4 and 7$M_\odot$ for the B7 primary star, Kepler's third law implies a mass between 1.8 and 2.5 $M_\odot$ for the secondary, and a total semi-major axis between 15.4 and 18.1 $R_\odot$. This range of mass for the second component corresponds to spectral type A. Other observations will now be performed to further investigate the spectral types of both components.

The observations described above show that TY CrA is a spectroscopic binary. To our knowledge, this is the first spectroscopic binary observed among the Ae–Be Herbig stars. The origin of the narrow components, however, remains puzzling. If they are of photospheric origin, it would imply a spectral type B7 for the primary (somewhat earlier than B8-9 as previously reported) with $v \cdot sin(i) \leq$