The Recurrent Nova U Sco – a Touchstone of Nova Theories

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Almost 130 years ago, on May 21, 1863, N. Pogson entered the following lines in his notebook: "[A variable star] discovered by me in a hazy sky at Madras. Observed last night and again this night with a steel micrometer. Showed this – my fourteenth variable star – to Lizzy about 10 pm before observing it: also later to C. Ragoonatha Chary [the night assistant] to enable him to make pretty sure of it on the meridian." The star was at that time of magnitude 9, and fading rapidly. The entry for May 27 reads "Shown to Sir W. Denison and party. His Excellency could just discern it, but not so Lady Denison" (see Pogson 1908).

The star sank into oblivion, until Thomas (1940) found two more rises in brightness on Harvard plates taken in 1906 and 1936. Its large amplitude and long outburst intervals indicated that U Sco belonged to the small, but very interesting group of recurrent novae. Webbink (1978) analysed Ragoonatha Chary's 1863 positional measurements and was able to identify the nova in its minimum state as a star of 19th magnitude. Only two years later, another outburst was observed and followed closely by optical and UV spectroscopy (Barlow et al. 1981, Williams et al. 1981). First models for the outburst of recurrent novae were calculated. Quite unexpectedly, U Sco erupted again in 1987.

A nova outburst is successfully modelled as a thermonuclear runaway (TNR) in hydrogen-rich matter on the surface of a white dwarf of fairly high mass. The white dwarf is composed of carbon and oxygen, or oxygen, magnesium and neon, the hydrogen-rich matter is accreted from a close binary companion via an accretion disk, deposited on the surface of the white dwarf, and compressed to high densities. Depending on the mass of the white dwarf, the temperature in its upper layers, and the amount of mixing of heavy elements from the interior of the white dwarf into the hydrogen-rich layer, nuclear reactions set in sooner or later. Since the accreted layers are degenerate, the rise of temperature caused by the reactions at first does not lead to expansion and cooling. Only after the temperature has risen to many million degrees, degeneracy is lifted, and the outer layers of the object expand violently: the object undergoes a nova outburst.

To start this TNR, the density of the accreted matter in the lowermost layer must reach a critical value. If too little matter is accreted, it takes a long time, perhaps millions of years, before an outburst occurs. For explosions of recurrent novae which occur with timescales of as little as ten years, a high mass transfer rate must be invoked. There is, however, a problem: If too much mass is accreted in too short a time, it cannot cool efficiently and does not become sufficiently degenerate, the nuclear reactions set in very mildly, and no nova explosion occurs. It has been shown in the theory of nova explosions that short intervals between outbursts are only possible for white dwarfs with high masses (about 1.38 $M_\odot$), close to the Chandrasekhar limit. Such white dwarfs have small radii, the accreted matter is highly compressed, and the explosion can take place after a short time of mass transfer from the secondary, when only some 10^{-8} $M_\odot$ have been accreted (Starrfield et al. 1985, Livio 1988, Kato 1990).

Are the theoretical concepts concerning recurrent novae correct? We can test them by measuring the mass of the white dwarf. Most recurrent novae, however, have giant companions, and the light of the white dwarf and the accretion disk are difficult to trace; furthermore, orbital periods are of the order of several hundred days. T Pyx, a recurrent nova with a dwarf companion, is seen at very low inclination angle, so that its orbital period, while short, cannot be measured with sufficient accuracy.

In 1988, Bradley Schaefer found that U Sco and V394 CrA also have short periods of P = 1.2344 and P = 0.7577 days, respectively. U Sco shows deep eclipses, indicating that the orbital inclination is close to 90°. If it is possible to measure the radial velocity curves of both, the white dwarf and the cool mass transferring component, the masses of the two components can be measured, and our theoretical concepts of the TNR can be checked.

After Schaefer had published his results in 1990, we immediately applied for observing time to test the TNR theory of recurrent novae by observing U Sco. Time for spectroscopic observations was granted in 1992 and observations were carried out with EFOSC1 at the ESO 3.6-m telescope on July 1 and 3. The nights were chosen in such a way that most phases of the radial velocity curve could be covered by observa-

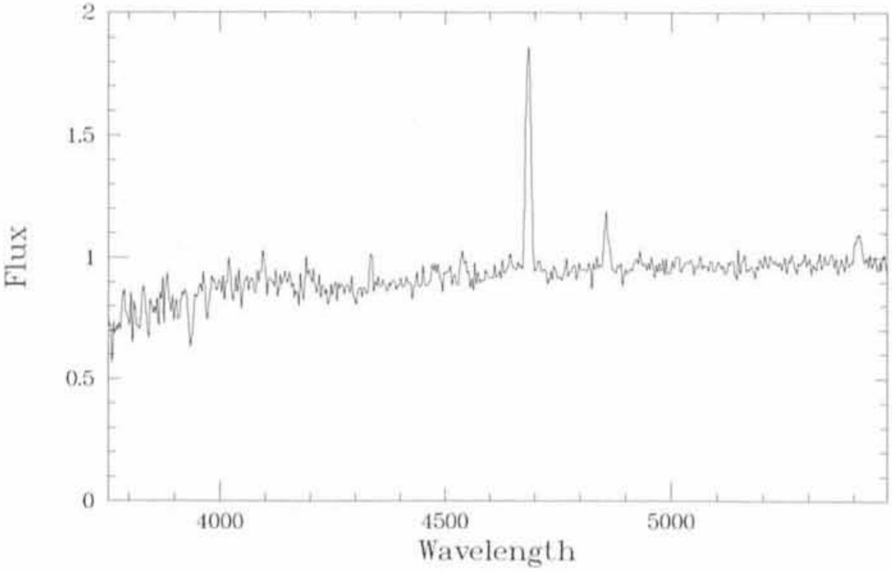

Figure 1: *Averaged spectrum of U Sco. The emission lines, formed in the disk surrounding the white dwarf, are due to ionized helium. Hydrogen lines are probably absent. The Ca II H and K lines and a few additional weak features of the cool secondary component are also seen.*

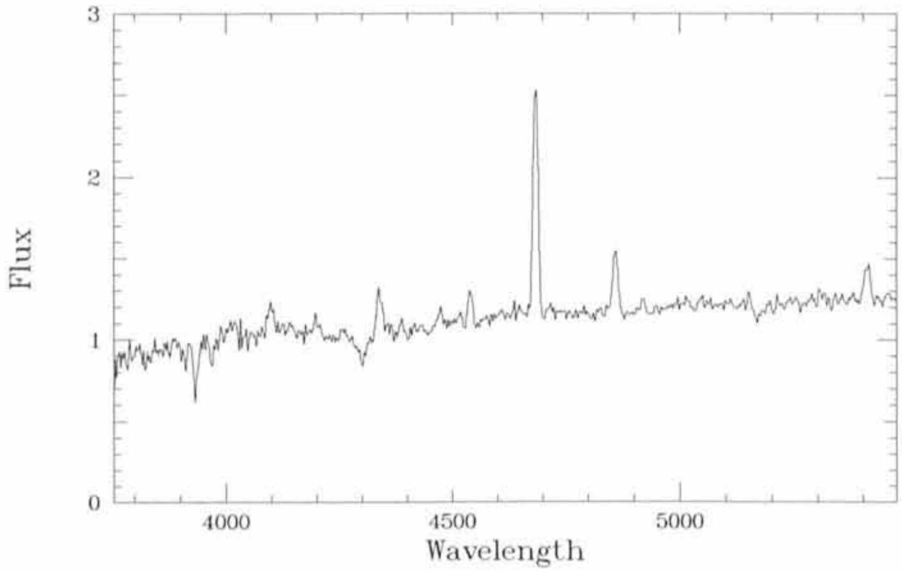

Figure 2: *Averaged spectrum of V394 CrA. The emission lines match those of U Sco quite well, the absorption lines are somewhat stronger.*

tions. Despite the poor winter skies, the first night was perfect and the second one acceptable, yielding at least a few spectra taken through gaps in the clouds. The mean spectrum of U Sco is shown in Figure 1. Most of the lines are due to He II. The strongest one is He II 468.6 nm, the others belong to the Pickering series which is shown to high series members, hydrogen is hardly visible. Features from the secondary star include the H and K lines of Ca II and a few weaker absorption lines.

It should be mentioned that the recurrent nova V394 CrA was also monitored in the two nights of July 1992. Its minimum spectrum, an almost identical twin of the U Sco spectrum, is shown in Figure 2. Only the secondary star appears slightly cooler, perhaps of type G, as indicated by its comparatively strong absorption features. The radial velocities appear to be very erratic.

While our observations were made, a preprint arrived at La Silla showing that U Sco had been observed with the Mt. Palomar 5-m telescope immediately after Schaefer's findings in 1990 and 1991. The authors, Johnston and Kulkarni (1992), found deviating properties of the system: Schaefer's period did not fit the radial velocity variations sufficiently well, so that they assumed a somewhat different period (actually, they suggested two alternative periods). Even so the hot (= white dwarf) and cool (= red dwarf) components showed radial velocity curves with considerable phase shift. The amplitudes were poorly determined ($K_{WD} = 35\pm17$ km/s, $K_{RD} = 156\pm19$ km/s) and the mass of the white dwarf, with a 3σ upper limit of 0.9 solar masses, turned out to be small. Was this the Waterloo of the TNR theory for recurrent novae?

We do not know what happened in 1990 and 1991. Maybe the nova was in a somewhat more cooperative state in July 1992. In any case, our short time base makes small uncertainties in the period unimportant, while a global solution of all radial velocity data indicates that Schaefer's period is not so bad after all: it can be used with only a small correction, to describe all existing spectroscopic observations, except two measurements discussed below. The improved period is P = 1.234518 days. The reason why the Palomar astronomers chose another period is due to two radial velocities (out of 17) which deviate to a large degree from the radial velocity curve when Schaefer's period is used. Since these values were derived from the poorest spectra of their sample, we found it acceptable to exclude them from our period analysis. Schaefer's period, slightly changed, then describes all remaining radial velocity observations including the new ones, very well. No satisfactory result can be obtained with the periods suggested by Johnston and Kulkarni.

The quality of our measurements is not better than those made at Palomar – both sets of data are quite poor, but one must keep in mind that we try to determine radial velocities of a 19th-magnitude object. The radial velocity curve derived from our measurements is shown in Figure 3. The sine fit of our data has a scatter of 74 km/s. The amplitudes are $K_{WD} = 164\pm33$ km/s, $K_{RD} = 116\pm35$ km/s. The derived masses are 1.16 ± 0.69 $M_\odot$ for the hot and 1.64 ± 0.83 $M_\odot$ for the cool component. The velocities of the white dwarf are

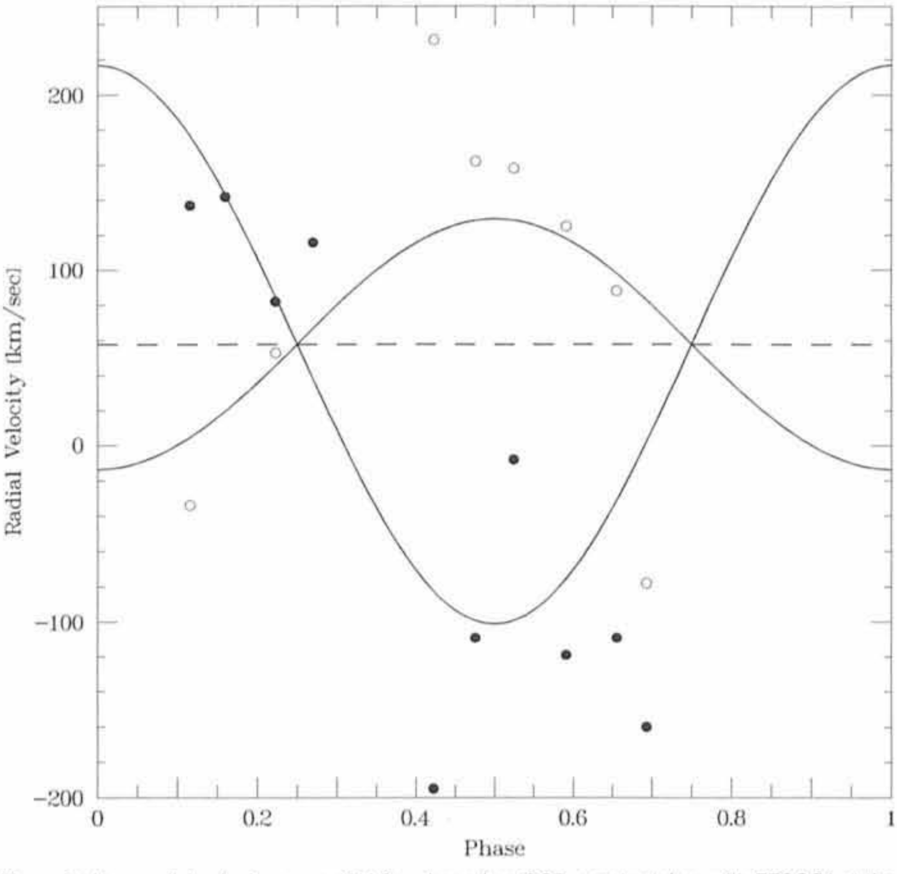

Figure 3: *New radial velocity curve of U Sco, based on CCD spectra taken with EFOSC1 at the 3.6-m telescope. Grism B150 was used, the exposure time of a single spectrum was 30 minutes.*

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

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1. Introduction

The present-day Sun has a very low rotational velocity: $\simeq$ 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