ROSAT observations of V471 Tauri, showing that stellar activity is determined by rotation, not age.

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ABSTRACT
I present pointed ROSAT PSPC observations of the pre-cataclysmic binary V471 Tauri. The hard X-ray emission (>0.4 keV) is not eclipsed by the K star, demonstrating conclusively that this component cannot be emitted by the white dwarf. Instead I show that its spectrum and luminosity are consistent with coronal emission from the tidally spun-up K star. The star is more active than other K stars in the Hyades, but equally active as K stars in the Pleiades with the same rotation periods, demonstrating that rotation—and not age—is the key parameter in determining the level of stellar activity.

The soft X-ray emission (<0.4 keV) is emitted predominately by the white dwarf and is modulated on its spin period. I find that the pulse-profile is stable on timescales of hours and years, supporting the idea that it is caused by opacity of accreted material. The profile itself shows that the magnetic field configuration of the white dwarf is dipolar and that the magnetic axis passes through the centre of the star.

There is an absorption feature in the lightcurve of the white dwarf, which occurs at a time when our line-of-sight passes within a stellar radius of the K star. The column density and duration of this feature imply a volume and mass for the absorber which are similar to those of coronal mass ejections of the Sun.

Finally I suggest that the spin-orbit beat period detected in the optical by Clemens et al. may be the result of the interaction of the K-star wind with the magnetic field of the white dwarf.

Key words: accretion, accretion discs – binaries: close – stars: activity – stars: individual: V471 Tauri – novae, cataclysmic variables – white dwarfs – X-rays: stars.

1 INTRODUCTION
The eclipsing close binary V471 Tauri is a member of the Hyades open cluster, and contains a white dwarf and K2V star in a 12.5 h orbit (Nelson & Young, 1970; Young & Nelson, 1972). The white dwarf is hot, $T = 3 \times 10^4$ K, and is a strong source of ultraviolet and soft-X-ray emission (Guinan & Sion, 1984). Observations with EXOSAT by Jensen et al. (1986) revealed a double-peaked modulation of the soft X-rays at a period of 555 s. They suggested this could be caused by either the changing viewing angle of bright and dark regions on the white dwarf, the 555 s period being the rotation period of the white dwarf, or radiatively-driven g-mode pulsations. Bright or dark regions could be formed by magnetic accretion of the K-star wind onto polar regions of the white dwarf: bright regions due to heating or dark regions due to opacity of accreted material. The detection of the same period in the optical (Robinson, Clemens & Hine, 1988; Clemens et al., 1992), but in anti-phase with the X-rays (Barstow et al., 1992), proved that the modulation could not be due to pulsations. It also showed that the polar regions of the white dwarf are probably dark in X-rays and bright in the optical.

Barstow et al. (1992) presented ROSAT all-sky-survey observations of V471 Tau. They detected the white-dwarf spectrum but also some X-ray emission at energies higher than could be attributed to the white dwarf (>0.3 keV). Together with the observation that a fraction of the X-ray flux is not eclipsed (Jensen et al., 1986), this suggests that the K star is a significant source of X-rays.

In this paper I present observations of V471 Tau made with the ROSAT position-sensitive proportional counter (PSPC) during the pointed phase of the mission. These confirm that the K star is a significant X-ray source, and show that its emission is consistent with that expected from a rapidly-rotating K star. The pointed ROSAT observations are the first with sufficient sensitivity and spectral resolution to separate the X-ray emission of the white dwarf and K star.
2 OBSERVATIONS

V471 Tau has been observed twice with the ROSAT PSPC (Trümper, 1983; Pfeffermann et al., 1986) during the pointed phase of the mission: once in February 1991 with 4 ks exposure, and once in August 1991 with 28 ks exposure. The first observation was performed on-axis, and so the lightcurves are modulated by occultations of the source by the PSPC window support wires. The second was made with the standard 40 arcmin offset, and is thus free from this contamination. In this paper I concentrate on the second observation. It spans 24 h, or roughly two orbital periods of V471 Tau, with a mean count rate $2.97 \pm 0.01$ s$^{-1}$ (after corrections for vignetting and occultation by PSPC window support wires). Spectra and lightcurves were extracted from a region of 5.75 arcmin radius around the source, and the background was estimated from a large region in another PSPC off-axis segment (chosen to be free of sources). Lightcurves were extracted in two energy bands, soft: pha 8–39, 0.1-0.4 keV; and hard: pha 40-120, 0.4-1.2 keV.

3 RESULTS

3.1 The eclipse and orbital-timescale variability

The soft and hard eclipse ROSAT lightcurves of the August 1991 observation are plotted in Fig. 1. They have been binned at the white-dwarf spin period (554.635 s, Barstow et al., 1992), and plotted against orbital phase, where zero is the optical eclipse centre according to the ephemeris of Clemens et al. (1992). The observations span two orbital periods, and one eclipse is covered partially.

Figure 2 shows the first data section binned at 50 s. The hard X-rays are not eclipsed, demonstrating conclusively that they are not emitted by the white dwarf. This effect was noted in the ROSAT all-sky survey data by Barstow et al. (1992), but at only marginal significance, due to the low exposure of individual survey scans. The K star is the obvious candidate source of the hard X-ray component (see Sect. 3.4).

Outside eclipse, both lightcurves remain significantly variable. I find a reduced $\chi^2$ of 1.6 with 56 degrees of freedom (d.o.f.) for the soft lightcurve when compared with its weighted mean count rate of 2.63 s$^{-1}$. And a $\chi^2$(d.o.f.) of 1.9(61) for the hard lightcurve compared with its mean value of 0.31 s$^{-1}$. The variability of the soft lightcurve is dominated by a single bin in the second data slot. Removing this dip (see Sect. 3.3 and Fig. 5) the variability is barely significant, with reduced $\chi^2$ of 1.2(58). The RMS amplitude (excluding the eclipse and dip) is 0.13 s$^{-1}$ (5%) for the soft and 0.06 s$^{-1}$ (19%) for the hard lightcurve. Assuming the K star accounts for the variability in both bands, these amplitudes suggest it may emit up to a quarter of the soft-band flux.

The single narrow dip is the only sign of the deep orbital dips seen in a subset of EXOSAT observations (Jensen et al., 1986), and an EUVE observation (Cully et al., 1996).

3.2 White-dwarf spin modulation

The white-dwarf spin modulation, discovered by Jensen et al. (1986) with EXOSAT, is apparent in the soft X-ray lightcurve of Fig. 1. In Fig. 3 I show the power spectra of the full soft X-ray lightcurves of both ROSAT PSPC observations. These were calculated using the Lomb-Scargle algorithm (Scargle, 1982), as implemented by Press et al. (1992). Clearly the August 1991 spectrum is less heavily aliased than that of the short February 1991 observation, but the results are consistent. The two peaks marked “W” are introduced by the 400 s ROSAT wobble, which is performed in order to blur the shadows of the PSPC window support wires. A periodic signal is detected with a period of 555 s and an amplitude of 8% (presumably the spin period), which has a strong first harmonic with 12% amplitude, showing that the pulse profile is double peaked. These results are identical to those found with EXOSAT by Jensen.
Figure 3. Power spectra of the soft X-ray ROSAT lightcurves of V471 Tau. The white-dwarf spin and its first harmonic stand out clearly. There is no sign of the sideband modulation found at optical wavelengths. The peaks labeled “W” in the lower panel are instrumental effects introduced by the “wobble” of the ROSAT spacecraft.

et al. (1986). No periodic signal is found in the hard X-ray lightcurve.

Clemens et al. (1992) present optical observations of V471 Tau which are modulated at the same periods, but also at the lower orbital sideband of the 555 s period: 562 s. This peak is not apparent in our X-ray power spectra, and I find a 95%-confidence upper limit to the amplitude of such a pulse of 4% (by fitting a sine function to the folded August 1991 lightcurve). In Sect. 4.2 I suggest this modulation may be a result of the interaction of the wind of the K star and the magnetic field of the white dwarf.

Figure 4 shows the soft-band August 1991 lightcurve folded at the white-dwarf spin period. The top panel shows the individual data points, and the bottom shows them binned into twenty phase bins. The RMS amplitude of the double-peaked pulse profile is 10%. I have adopted the ephemeris of Barstow et al. (1992), for which the accumulated phase error is 0.2. Within this error, the deep minimum is at the same phase as the minimum found by Barstow et al. (1992) in the ROSAT WFC and PSPC all-sky survey data. This confirms their result that the X-ray and optical modulations are in anti-phase. Barstow et al. found only a single minimum in their lightcurve, and suggested that the profile may have changed between the EXOSAT and ROSAT all-sky survey observations. The pointed ROSAT lightcurves, however, measured just 6 months and 12 months after the survey, have identical profiles to the EXOSAT observations. Given the poor phase coverage of the survey observations, and their poor statistical quality, it seems most likely that the profile has remained constant throughout the period of EXOSAT and ROSAT observations. Recent EUVE observations also show the same profile (Dupuis et al., 1997).

3.3 The dip: coronal mass ejection?

Figure 5 shows the first three sections of the August 1991 PSPC lightcurve, in which there are two obvious deviations from the folded pulse profile of Fig. 4 (which is overlayed in Fig. 5). The first is the eclipse, which is discussed in Sect. 3.1, and the second is the dip feature in the second slot. The third slot is typical of all the other slots (not plotted).

The dip is narrower than the dramatic orbital dips seen in the first EXOSAT observation of V471 Tau (Jensen et al., 1986). But it does occur close to eclipse, as did the EXOSAT dips and a similar dip observed with EUVE (Cully et al., 1996). Of course at these times our line of sight passes close to the limb of the K star, and absorption by its wind and any magnetically supported structures may be expected to be most apparent. The dip occurs at orbital phase of 0.07,
while the duration of the eclipse is just 0.08. Thus the dip occurs when our line of sight passes within one stellar radius of the stellar surface. The observations do not cover the dip phase a second time, so I can place no limits on its lifetime. As may be expected, the dip is not apparent in the hard-band lightcurve, which probably represents emission from the K star itself.

At mid dip the count rate falls to 0.9 s\(^{-1}\), from a mean of 2.63 s\(^{-1}\). From the eclipse light curve (Fig. 2) I estimate the soft-band K star count rate is 0.4 s\(^{-1}\). Thus the white-dwarf count rate falls by a factor 4.5. The column density of neutral material required to produce this drop, in this energy range, and with the best fitting spectrum of Sect. 3.4 is \(N_\text{H} = 9 \times 10^{19} \text{ cm}^{-2}\), with the usual assumptions of solar abundance and absorption cross sections given by Morrison & McCammon (1983). The true column may be substantially greater than this because the absorber must be at least partially ionised. Indeed Cully et al. find their dip is not apparent at long wavelengths suggesting that the absorbing material must be highly ionised. Both the EUVE and EXOSAT bandpasses extend to longer wavelengths than the ROSAT PSPC, so the greater widths of dips seen with those instruments may be due to their sensitivity to smaller column densities.

One can estimate the size of the absorbing region from the duration of the dip, \(\sim 230\) s. The relative velocity of the two stars in V471 Tau is \(\sim 300\) km s\(^{-1}\), so, assuming the absorber is close to and moves with the K star, it must have a width of \(\sim 4 \times 10^5\) cm. Assuming it has approximately the same depth along our line-of-sight as it has width perpendicular to it, I find the absorber has a number density of hydrogen atoms of \(10^{10} \text{ cm}^{-3}\). Assuming further that it is spherical, the total mass of the absorbing medium must be of order \(10^{16}\) g. These estimates of density and mass are similar to those measured for solar coronal mass ejections (e.g. Wagner, 1984; Kahler, 1992). So I suggest that the X-ray absorption dips seen in V471 Tau are caused by material ejected from the K star in a similar manner.

### 3.4 The K star spectrum

The ROSAT observations presented here are the first X-ray observations of V471 Tau in which the K2V star spectrum can be separated from that of the white dwarf. I make no attempt to investigate the spectrum of the white dwarf, since this has been done using more appropriate data by Barstow et al. (1997), Dupuis et al. (1997) and Werner & Rauch (1997). Instead I take the white-dwarf spectrum into account using the homogeneous hydrogen and helium model of Koester (1991), and parameters derived from ORFEUS and IUE data by Barstow et al. (1997). I allowed only the normalisation and helium abundance to vary. The K star spectrum was modelled with one and two-temperature optically-thin thermal plasma models (Mewe, Gronenschild & Van den Oord, 1985; Kaastra & Mewe, 1993), as the spectral response of the ROSAT PSPC does not merit a full differential emission measure treatment.

I applied these models to two spectra simultaneously. One extracted from eclipse, in which only the K star spectrum is visible (0.4 ks), and one extracted from most of the remainder of the August 1991 observation (26 ks). All parameters were forced to be the same for the two data sets, except the normalisation of the white-dwarf atmosphere model which was set to zero for the eclipse spectrum. I also allowed the normalisation of the K star spectrum to be different for the two data sets, but the relative importance of the two temperatures was forced to be the same.

Figure 6 shows the spectra and best-fitting model. The first bin in the out-of-eclipse spectrum shows strong positive residuals in all my fits. This is probably due to the “after pulse” effect, introduced by contamination of the PSPC gas supply (e.g. Snowden et al., 1994). I take the simplest approach to remove this effect by excluding this point from my fits. The second panel of Fig. 6 shows the residuals of my single-temperature fit to the K star spectrum. This is an unacceptable fit with a reduced \(\chi^2\) (d.o.f.) value of 8.7(32). The fit to the two-temperature model (residuals in the third panel) is much better and marginally statistically acceptable with a reduced \(\chi^2\) of 1.45(30). The strongest residuals occur below 0.4 keV in the out-of-eclipse spectrum, and have the signature of the well-known temporal gain variation problem of the PSPC (e.g. Prieto, Hasinger & Snowden, 1996). I remove this effect by adding a somewhat arbitrary 10% systematic error to the pha channels 8–40. This results in an acceptable fit with reduced \(\chi^2\) of 1.11(30) (panel four of Fig. 6). I am satisfied that this is justified especially because the out-of-eclipse spectrum in this range is dominated by the spectrum of the white dwarf—of which we are not concerned here. The two temperatures selected by this fit to the K star spectrum are 1.6 ± 0.2 keV and 0.36 ± 0.05 keV (68%-

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confident that the total X-ray luminosity will be about 35% larger than that in the range 0.1–2.5 keV.

3.4.1 Comparison with other active dK stars

My results show that the un eclipsed X-ray emission of V471 Tau is somewhat different to that of other K stars in the Hyades. Stern et al. (1994) present one deep ROSAT pointing of part of the Hyades, and fit the spectra of a number of active K stars. They find, as I do, that single-temperature models do not adequately describe the spectra, but that two-temperature models can. Their fitted temperatures, however, are lower than those I find for V471 Tau. From their fits one would expect a K star to have fitted temperatures around 0.1–0.2 keV and 0.5–1.0 keV (rather than 0.4 and 1.6 keV as I find).

Pye et al. (1994) present ROSAT data from a number of pointings of the Hyades. They do not attempt to fit spectra, but derive luminosity functions for dK and dM Hyads based on count rates. They estimate an X-ray luminosity for each source by assuming a common distance (45 pc) and assuming that 1 cts s\(^{-1}\) in the PSPC corresponds to an X-ray flux of 6 × 10\(^{-12}\) erg cm\(^{-2}\) s\(^{-1}\). This method yields an estimate of 1 × 10\(^{30}\) erg s\(^{-1}\) for the luminosity of the un eclipsed source in V471 Tau (consistent with my measured value). They detect thirteen of the seventeen K Hyads in their ROSAT fields, with X-ray luminosities in the range 1.3–30 × 10\(^{28}\) erg s\(^{-1}\). Thus the most luminous K star Pye et al. find in the Hyades has a luminosity a factor three less than I find is emitted by the K star in V471 Tau.

The most likely cause of the higher temperatures and excess X-ray luminosity is the high rotation rate imposed on the K star tidally by the white dwarf (P\(_{rot}\) = 12.5 h). The correlation of magnetic activity and rotation rate for late-type stars is well documented (e.g. Hartmann & Noyes, 1987). I can test this assertion by comparing my results with ROSAT observations of the Pleiades (Gagné, Caillault & Stauffer, 1995), since the Pleiades is a younger open cluster than the Hyades and its members rotate more rapidly. Figure 5 shows very clearly that the rotation rate and X-ray luminosity of the K star in V471 Tau are indeed typical of K stars found in the Pleiades. This figure shows the X-ray luminosity as a fraction of bolometric luminosity (using the relation of Johnson, 1966) for K stars (0.8 < (B – V) < 1.5) in the Pleiades and Hyades as a function of their rotation period. Data are taken from Pye et al. (1994), Stern, Schmitt & Kahabka (1995), Gagné, Caillault & Stauffer (1995), Radick et al. (1987) and Prosser et al. (1995). Remarkably, the K Pleiads and Hyads seem to obey the same activity-rotation relation. To the best of my knowledge, this comparison has not been made before. The bolometric luminosity of the K star in V471 Tau is calculated from its spectral type K2V, rather than its B–V colour, since the B magnitude is contaminated by the white dwarf. Its presence among the Pleiades shows that the X-ray emission of late-type stars depends on rotation only, and not on their age. Finally, comparison with the spectral fits of Gagné, Caillault & Stauffer (1995) shows that my fitted X-ray temperatures are also typical of K Pleiads. I thus conclude that the un eclipsed X-ray emission of V471 Tau is indeed consistent with that expected for a rapidly rotating K star.
K stars—triangles; Pleiades K stars—circles; and my measur-
ment, plotted as a function of rotation period for a sample of H yades
rather than its age (Fig. 7). This demonstrates that rotation
most-likely emitted by the K star.

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find that the spectrum and luminosity of this component is
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show conclusively, for the first time, that the hard X-ray
4.1 The K star
I show conclusively, for the first time, that the hard X-ray component of V471 Tau is not eclipsed by the K star. I
find that the spectrum and luminosity of this component is
typical of rapidly-rotating K stars, and conclude that it is
most-likely emitted by the K star.

I note that this X-ray flux is normal for its rotation rate
rather than its age (Fig. 7). This demonstrates that rotation
is the key parameter in determining stellar activity, and not
age. In most studies, age and rotation rate are too closely
related to be separable.

I also observe an absorption dip in the X-ray emission
of the white dwarf, absent in the K-star flux, which implies a
column density and length-scale for the absorber similar
to coronal mass ejection events seen on the Sun. I conclude
that similar processes are probably at work on the K star in
V471 Tau, and may account for the more dramatic orbital
dips seen with EXOSAT and EUVE (because both these in-
struments are sensitive to a smaller absorbing column density).

4.2 The white dwarf
I detect the 555 s X-ray modulation discovered by Jensen
et al. (1986). The pulse-profile is identical to that measured
with EXOSAT and EUVE, and is also stable throughout the
ROSAT observations. This is consistent with the idea that
the modulation is caused by opacity of material accreted
at the magnetic poles of the white dwarf (since this opacity
cannot vary on timescales shorter than the diffusion of
metals in the atmosphere of the white dwarf).

The profile itself is double-peaked, and the two peaks
are separated in phase by precisely 180°. If the modulation
is indeed caused by the opacity of accreted material, then
the magnetic field of the white dwarf must direct the accre-
tion flow onto two regions directly opposing each other. This
shows that the magnetic field configuration must be dipolar,
and that the magnetic axis must pass though the centre of
the white dwarf.

I do not detect the beat pulse discovered in the optical
by Clemens et al. (1992) and place a 95% upper limit
to its X-ray amplitude of 4%. Clemens et al. interpret this
pulse as reprocessing of ionising radiation on the face of the
K star. However the beat pulse is single peaked while the
X-ray pulse is double peaked, and Clemens et al. can only reconcile these facts by assuming the X-ray emission
does not trace the bulk of the ionising radiation. Instead I
suggest that the beat pulse may reflect a modulation in ac-
cretion rate caused by the interaction of the wind of the K
star with the magnetic field of the white dwarf. Beat peri-
ods arise naturally in systems where the accretion flow has
memory of orbital phase (e.g. Warner, 1986). However the
same problem arises with this interpretation because in a
high-inclination system, such as V471 Tau, where we see
both magnetic poles, one would expect to see modulation at
the frequency (2f spin − f orbit) rather than that detected by
Clemens et al. (f spin − f orbit) (Wynn & King, 1992). Still, as
the geometry of magnetic wind accretion is poorly known,
there may be scope to explain the single peaked beat pulse.

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