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X-ray observations of 4 Draconis: symbiotic binary or cataclysmic triple?

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ABSTRACT

We present the first X-ray observations of the 4 Draconis system, consisting of an M3 III giant with a hot ultraviolet companion. It has been claimed that the companion is itself an AM Her-type binary system, an identification that places strong constraints on the evolution of cataclysmic variables. We find that the X-ray properties of 4 Draconis are consistent with the presence of an accreting white dwarf, but not consistent with the presence of an AM Her system. We conclude that 4 Draconis is therefore most likely a symbiotic binary containing a white dwarf accreting material from the wind of the red giant.

The X-ray spectrum of 4 Draconis is sometimes dominated by partially ionized photoelectric absorption, presumably due to the wind of the red giant. We note that X-ray monitoring of such systems would provide a powerful probe of the wind and mass-loss rate of the giant, and would allow a detailed test of wind accretion models.

Key words: accretion, accretion discs – binaries: close – stars: individual: 4 Draconis – novae, cataclysmic variables – white dwarfs – X-rays: stars.

1 INTRODUCTION

Reimers (1985) reports the discovery of an ultraviolet companion to the M3 III giant 4 Draconis. *International Ultraviolet Explorer* (*IUE*) observations show that its spectrum is similar to that of high accretion rate cataclysmic variables, with a slowly decreasing continuum in the range 3000–1500 Å which then rises steeply to shorter wavelengths. There are strong and broad high-excitation emission lines (also typical of cataclysmic variables) and some narrow low-excitation emission lines which Reimers attributes to the ionized wind of the giant.

More detailed ultraviolet and optical-radial-velocity measurements are presented by Reimers, Griffin & Brown (1988). They determine the orbit of the giant and claim that the ultraviolet flux is modulated at a period of 4 h. Based largely on this period, they conclude that the ultraviolet companion is most likely an AM Her-type cataclysmic variable.

Eggleton, Tout & Bailyn (1989) point out that the orbit of the wide pair in 4 Draconis ($P_{\rm orb} = 1703$ d) severely limits the size of the progenitor of a cataclysmic variable and places unique constraints on its evolution. Without constraints on even the inclinations of the two binary orbits, they argue that any cataclysmic variable must have evolved from a progenitor with initial $P_{\rm orb} \leqslant 100$ d. However, Eggleton et al. also point out that the identification as an AM Her system is uncertain, and that an isolated white dwarf may explain the observations equally well. In this picture the white dwarf would be accreting from the wind of the giant and the 4-h period would be its spin period. This requires a magnetic field on the white dwarf sufficient to funnel the accretion flow on to its poles.

In this paper we present the first X-ray observations of 4 Draconis, and discuss the nature of the system.

2 OBSERVATIONS

4 Draconis was observed four times with *ROSAT* (Trümper 1983): once during the *ROSAT* All-Sky Survey (RASS) with the Position Sensitive Proportional Counter (PSPC: Pfeffermann et al. 1987); twice during the pointed phase of the mission with the PSPC, once as the target and once serendipitously; and once with the High-Resolution Imager (HRI: Zombeck et al. 1995). In Table 1 we present a log of the pointed observations. 4 Draconis was detected in all four observations (see Section 3.1) and light curves and spectra were extracted from circular regions of radius 1.3, 6.0 and 0.6 arcmin for the 1991, 1993 and 1996 pointed observations respectively. Background rates were estimated using large nearby regions free from obvious point sources. Raw count rates are presented in Table 2, as well as our best estimates of the equivalent on-axis PSPC count rate. The serendipitous off-axis observation has been corrected for vignetting and for source counts lost outside the selection radius (total factor of 1.91). The RASS count rate (Huensch et al. 1998) has been corrected using an intermediate factor (1.45). The HRI count rate has been corrected using a factor of 4.1 derived from PIMMS

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Table 1. Log of *ROSAT* pointed observations of 4 Draconis.

Obs. date	Instr.	Sequence no.	Off-axis[a]	Exp.[b]
1991 April 4–5	PSPC	300034	0	15.0
1993 June 5–6	PSPC	701225	51	5.7
1996 October 8–20	HRI	300492	0	41.8

[a]Off-axis angle (arcmin); [b]exposure (ks).

Table 2. Count rates and results of centroid fitting for the *ROSAT* observations of 4 Draconis. $\Delta\theta$ is the angular separation between the position of 4 Draconis and the fitted centroid of the spatial count distribution. HWHM is the half-width at half-maximum of the count distribution, also expressed as an angle.

				Count rate (s^{-1})	
Obs. date	Instr.	$\Delta\theta^a$	HWHM[a]	Raw	Corrected[b]
1990 Nov.	RASS	–	–	0.033 ± 0.008	0.048
1991 Apr.	PSPC	0.26	0.35	0.011 ± 0.001	0.011
1993 Jun.	PSPC	0.6	3.1	0.371 ± 0.008	0.707
1996 Oct.	HRI	0.15	0.14	0.059 ± 0.001	0.172

[a](arcmin); [b]corrected to PSPC on-axis response.

(Mukai 1993) and assuming our best-fitting spectrum to the 1993 *ROSAT* spectrum of 4 Draconis (see Section 4.1).

3 RESULTS

3.1 X-ray detection

An X-ray source is detected at the position of 4 Draconis in all three *ROSAT* observations. Table 2 shows the results of fitting for the centroid of the spatial count distribution. In each case the difference in position between the count centroid and 4 Draconis is less than or equal to the half-width at half-maximum (HWHM) of the distribution. The probability of chance alignment is small. For example, the probability of a single source lying so precisely at the centre of the HRI detector is $\sim 6 \times 10^{-5}$. There are only about 10 sources detected in the image, so we are confident that the probability of chance alignment is $<10^{-3}$ and that the detected source is 4 Draconis. The count rates presented in Table 2 show that it is highly variable.

3.2 X-ray spectroscopy

Fig. 1 shows the spectra of 4 Draconis extracted from the two PSPC pointed observations. They have been fitted with an optically thin thermal plasma model (Mewe, Gronenschild & Van denOord 1985; Kaastra & Mewe 1993). The off-axis 1993 observation is well fitted with this model, with a temperature of $4.4\pm^{2.6}_{0.8}$ keV and absorbing column density of $(1.5 \pm 0.2) \times 10^{19}$ cm^{-2} (reduced $\chi^2 = 1.05$ with 26 degrees of freedom). Fig. 2 shows the constraints on these parameters. In contrast, the 1991 observation is very poorly fitted with this model (reduced $\chi^2 = 6.7$ with 4 d.o.f.).

The unabsorbed 0.1–2 keV flux for the fit to the 1993 spectrum is 9×10^{-12} erg s^{-1} cm^{-2}. Including a bolometric correction factor of 2.4, this corresponds to a luminosity of 6×10^{31} erg s^{-1} at the *Hipparcos* distance of 4 Draconis (178 pc: Perryman et al. 1997).

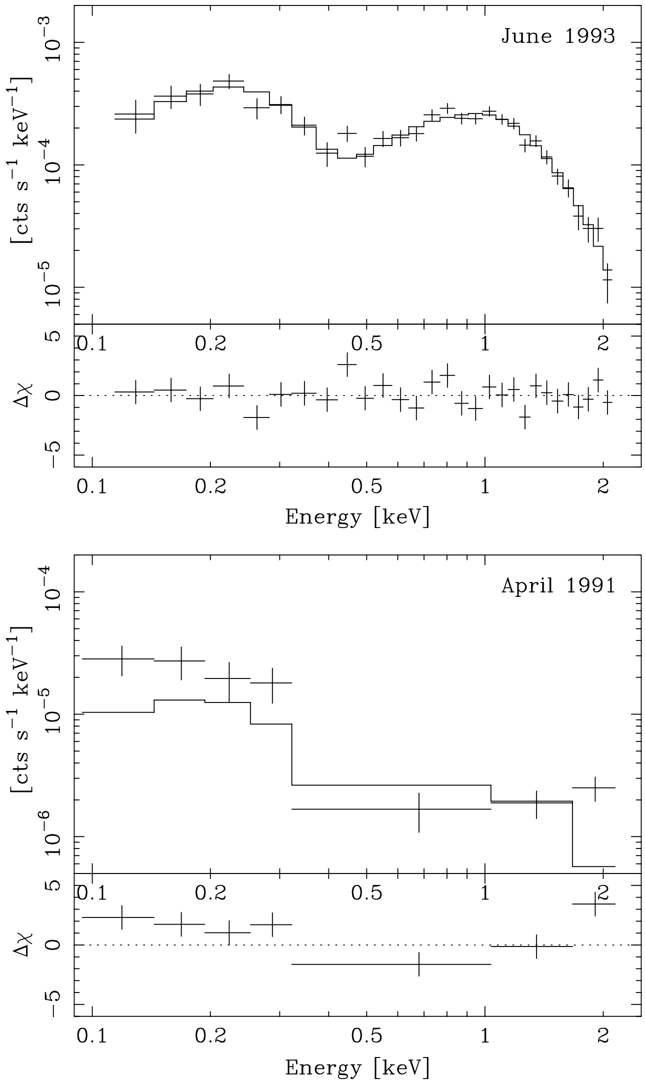

Figure 1. *ROSAT* PSPC spectra of 4 Draconis. Both spectra have been fitted with an optically thin thermal plasma model. The lower panel in each case shows the fit residuals scaled by the error on each data point.

The fit residuals for the 1991 spectrum show a minimum around 1 keV (Fig. 1) which corresponds to the maximum of the effective area of the PSPC and so must represent a true minimum in the X-ray flux. No physically plausible pure-emission model can reproduce this minimum, but a partially ionized absorber does so naturally. Photoelectric absorption by cold cosmic-abundance material increases to low energies, but soft photons can leak through if low-energy edges have been removed through ionization. We find that such a model readily reproduces the observed 1991 spectrum, and we plot a typical fit in Fig. 3 (with hydrogen column density of 4×10^{23} cm^{-2} and ionization parameter $\xi = 5.8$). Unfortunately the combination of low spectral resolution and low signal-to-noise ratio prevents a unique fit to an ionized absorption model, and we cannot well constrain the properties of the absorbing medium. However, the wind of the red giant star is an obvious candidate absorber and the X-ray source itself may supply the photoionizing flux. The difference between the 1991 and 1993 observations may be explained in part or entirely by a changing column density and/or ionization fraction along our line of sight through the wind.

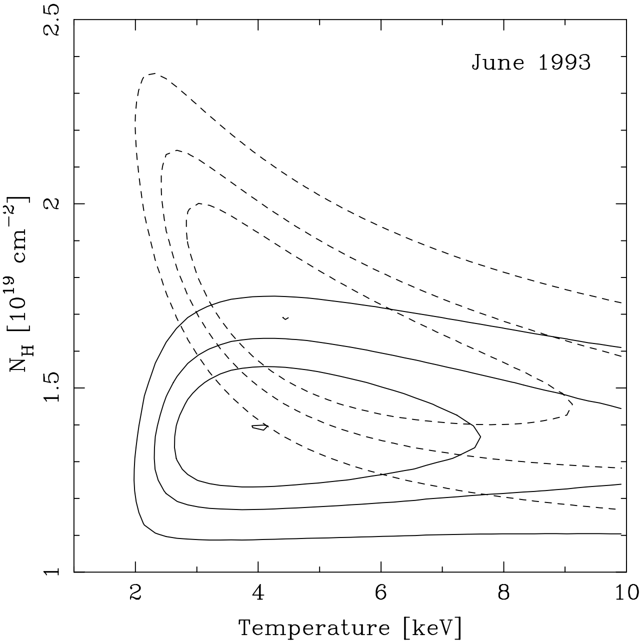

Figure 2. Contour plots of allowed parameter values for our fits to the 1993 PSPC spectrum of 4 Draconis. Solid contours show the constraints on a bremsstrahlung model. Dashed contours show the constraints on the MEKAL plasma model. Contours represent 68, 90 and 99 per cent confidence for two interesting parameters ($\Delta\chi^2 = 2.3$, 4.61 and 9.21 respectively).

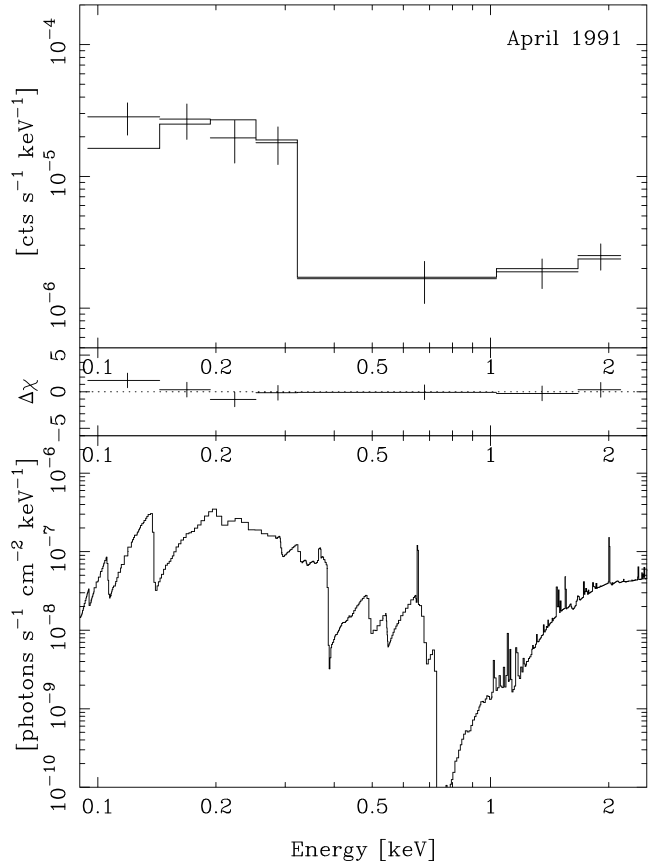

Figure 3. The 1991 *ROSAT* PSPC spectrum of 4 Draconis fitted with an ionized absorber model. The top panel shows the observed spectrum, the middle panel shows the fit residuals and the bottom panel shows the model spectrum.

3.3 X-ray time-series analysis

The light curves from all three *ROSAT* observations reveal variability on short time-scales. The light curve from the 42-ks HRI observation is presented in Fig. 4. It shows strong variability on time-scales between minutes and days, but there is no evidence for the 4-h periodic modulation claimed by Reimers et al. (1988) from *IUE* observations. Fig. 5 shows the power spectrum of the HRI light curve, in which no obvious periodic signal is apparent. There is excess power close to the *ROSAT* orbital period (96 min), with the strongest peak at a slightly shorter period (86 min), and there is another suggestive peak at 37.5 min, but neither is sufficiently strong to represent a conclusive detection of periodic modulation.

4 DISCUSSION

4.1 The nature of 4 Draconis

Previous *ROSAT* observations have shown that red giants are not substantial X-ray emitters. Only one late-type giant was detected in the RASS (Haisch, Schmitt & Rosso 1991; Haisch, Schmitt & Fabian 1992; Huensch et al. 1996), and pointed observations placed an extremely tight upper limit of 3×10^{25} erg s^{-1} on the X-ray flux of the K1 III red giant Arcturus (Ayers, Fleming & Schmitt 1991). Thus we can be confident that the X-ray emission from 4 Draconis reported in this paper originates on the ultraviolet companion, 4 Dra B.

Our *ROSAT* observations are consistent with this secondary containing an accreting white dwarf. The ∼5-keV temperature of the optically thin X-ray spectrum is characteristic of non-magnetic cataclysmic variables (e.g. Wheatley et al. 1996) and of the 'bombardment solution' for radial accretion on to a white dwarf (e.g. Woelk & Beuermann 1995). The bombardment solution applies when the mass accretion rate per unit area is too low for a stand-off shock to form ($\dot{m} < 10^{-1}$ g s^{-1} cm^{-2}). Our measured luminosity of 6×10^{31} erg s^{-1} implies an accretion rate of 0.24–1.8×10^{15} g s^{-1} for white dwarf masses in the range 0.3–1.0 $M_\odot$. For the bombardment solution to apply, this accretion rate must be spread over an area of at least 0.24–1.8×10^{16} cm^2, although this is a small fraction of the surface area of even a massive white dwarf.

Although our observations are consistent with the presence of an accreting white dwarf, they do not support the presence of an AM Her system. First, the *ROSAT* spectra of AM Hers are typically dominated by intense optically thick soft emission, with characteristic temperatures of ∼20 eV. We can rule out the presence of such a component in the 1993 spectrum of 4 Dra B (Fig. 1). Secondly, it is clear from the HRI light curve (Fig. 4) that the X-ray emission is not strongly modulated at a period of 1–8 h, as it is for every known high-state AM Her system and most other magnetic cataclysmic variables.

AM Her systems have shown spectra much like that of 4 Draconis during low accretion rate states (e.g. Ramsay, Cropper & Mason 1995), but our measured luminosity is rather high for a low-state AM Her, and we believe the lack of an X-ray orbital periodicity alone is sufficient evidence to rule out the presence of an AM Her in the 4 Draconis system.

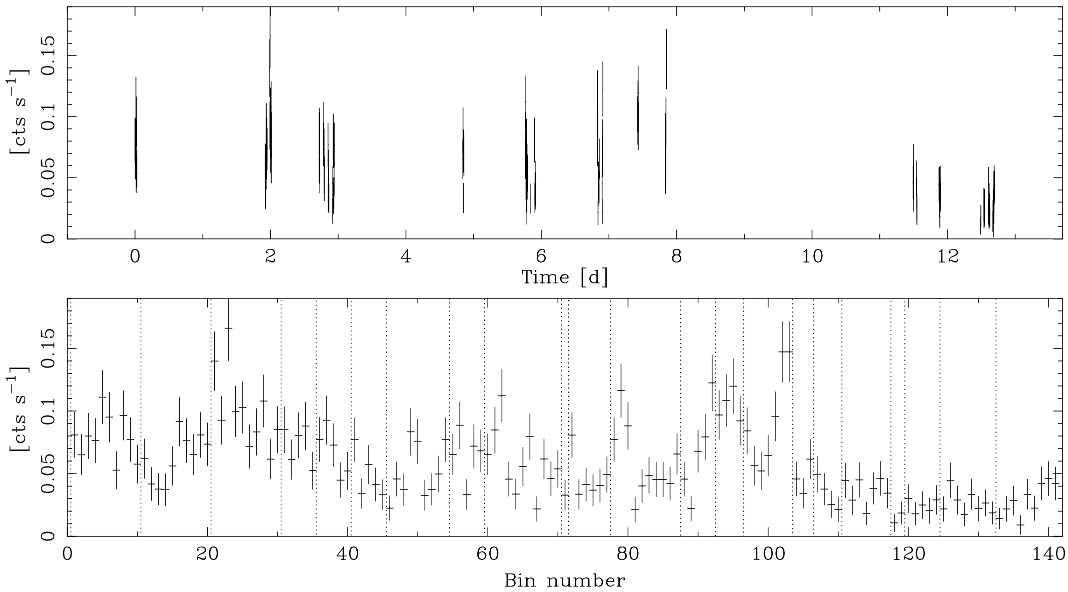

Figure 4. The 1996 *ROSAT* HRI light curve of 4 Draconis binned into 256-s bins. For clarity, data gaps have been omitted in the lower panel (dotted lines indicating breaks in the time axis). The top panel shows the full light curve.

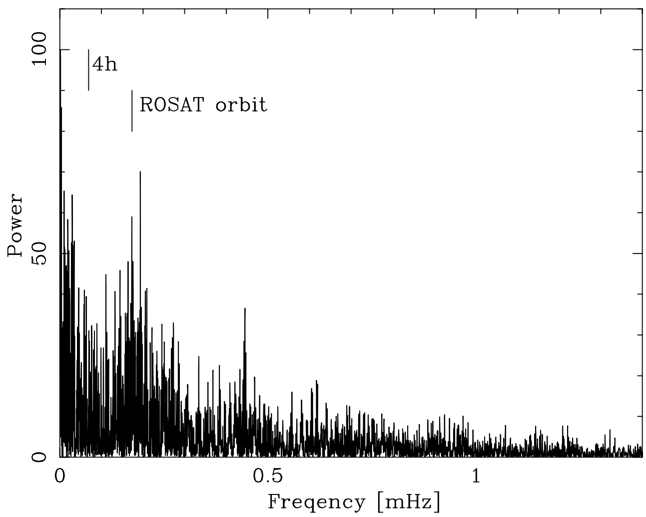

Figure 5. The power spectrum of the 1996 *ROSAT* HRI light curve of 4 Draconis.

Non-magnetic cataclysmic variables (e.g. dwarf novae) usually have no optically thick component in the *ROSAT* bandpass (e.g. Wheatley et al. 1996), have characteristic X-ray temperatures lower than AM Hers, and do not exhibit strong orbital X-ray modulation. Therefore we cannot rule out the presence of a non-magnetic cataclysmic variable. However, the original case for the presence of a cataclysmic variable was based upon the claimed detection of a 4-h ultraviolet period (Reimers et al. 1988). Reviewing the light curve in fig. 3 of Reimers et al., we believe that the case for a periodic modulation is not strong. Also, more recent *HST* observations do not support the presence of a 4-h period (B. Gaensicke, private communication). Thus, in the face of evidence clearly supporting the presence of an accreting white dwarf, but none requiring the presence of a third star, we conclude that the companion to 4 Draconis is most likely a single white dwarf. The 4 Draconis system is then most likely a symbiotic binary.

4.2 X-ray spectra of symbiotic stars

We note that the absorbed 1991 X-ray spectrum of 4 Draconis is strikingly similar to that of the symbiotic star CH Cyg measured with *ASCA* (Ezuka, Ishida & Makino 1998). Muerset, Wolff & Jordan (1997) and Ezuka et al. (1998) interpret the X-ray spectrum of CH Cyg as a combination of accretion emission (hard X-rays) and the colliding winds of the two stars (soft X-rays). However, Wheatley (2001) and Wheatley (in preparation) reanalysed the *ASCA* spectrum and found that it could be interpreted instead as a single accretion-driven emission component viewed through a partially ionized absorber. Our discovery of the same behaviour in 4 Draconis shows that there is a distinct subclass of symbiotic stars in which the X-ray spectrum is dominated by complex absorption of a hard X-ray accretion-driven continuum. 4 Draconis and CH Cyg seem to be distinct from the other symbiotic stars studied by Muerset et al. (1997) which have much softer X-ray emission.

4.3 Absorption and orbital phase

Our results show a marked decrease in absorption between the 1991 and 1993 *ROSAT* observations of 4 Draconis. If the absorption is due to the wind of the red giant, then the change in absorption may be related to our changing line of sight through the wind to the X-ray source.

Reimers et al. (1988) studied the radial velocity variations of the red giant and measured its orbital elements. They find a mildly eccentric orbit, $e = 0.3$, with a 5-yr period. The orbital phases of the two *ROSAT* PSPC observations, relative to periastron, are 0.22 ± 0.03 in 1991 and 0.68 ± 0.03 in 1993. It can be seen that the high-absorption spectrum in 1991 was taken slightly closer to periastron, and the unabsorbed 1993 spectrum was taken slightly closer to apastron. Probably more importantly, the orbit is orientated such that the phase of the 1993 spectrum corresponds to a time when the X-ray source is in front of the red giant. This may explain the reduced absorption in this spectrum.

Fig. 6 shows the long term X-ray light curve of 4 Draconis using the estimated PSPC on-axis count rates for all four observations

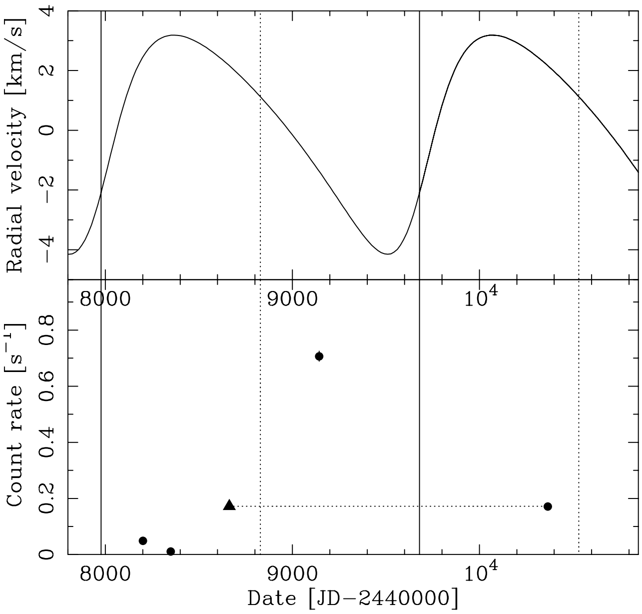

Figure 6. Long-term X-ray light curve of 4 Draconis (bottom panel) using estimated equivalent PSPC on-axis count rates for all four *ROSAT* observations (see Table 2 and Section 2). The 1996 HRI observation is plotted twice in order to show its relative orbital phase with respect to the other observations (triangle). The top panel shows the radial velocity of the giant star as determined by Reimers et al. (1988). The solid vertical lines represent periastron, and the dotted lines represent apastron. The orbital phase of the bright 1993 observation corresponds to a time when the X-ray source is in front of the giant.

(see Table 2 and Section 2). It can be seen that the four *ROSAT* observations are consistent with a smooth variation in count rate with orbital phase.

Further observations are required in order to test whether the X-ray absorption in the spectrum of 4 Dra B really varies smoothly with orbital phase. We note, however, that a set of X-ray observations covering all orbital phases would provide a powerful probe of the wind and mass-loss rate of the red giant star, and would allow a detailed test of wind accretion models.

4.4 Wind accretion

In order to test our conclusion that 4 Dra B is most likely a single white dwarf accreting from the wind of the giant, we estimate the expected wind accretion rate in such a system. For the purpose of this order-of-magnitude estimate we assume that the white dwarf is non-magnetic. A rotating magnetic field might act to reduce this accretion rate through the propeller effect.

The case of a white dwarf accreting from the wind of a red giant was treated by Livio & Warner (1984). Using their equation (3) we find a wind accretion luminosity of $L_{\rm acc} \sim 10^{34}$ erg s^{-1} using the values stellar separation $a \sim 4$au $= 6 \times 10^{13}$ cm (Reimers et al. 1988), wind velocity $v_{\rm w} \sim 10$ km s^{-1} (Reimers & Schroeder 1989), orbital velocity of the white dwarf $v_0 \sim 30$ km s^{-1}, and wind mass-loss rate $\dot{M}_{\rm w} \sim 10^{-8}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$.

This luminosity is larger than both our measured X-ray luminosity, 6×10^{31} erg s^{-1}, and the ultraviolet luminosity measured by Reimers (1985), 1×10^{33} erg s^{-1} (corrected to the *Hipparcos* distance, 178 pc). Many of the values used to estimate the wind accretion rate are uncertain, but it is clear that direct wind accretion *is* a viable energy source for the high-energy emission of 4 Dra B.

We note that the ratio of X-ray and ultraviolet luminosities is similar to that measured for the disc-accreting white dwarfs in dwarf novae (e.g. Wheatley et al. 1996).

The presence or otherwise of an accretion disc in a wind accretor depends sensitively on the relative velocity of the wind and accreting object (Livio & Warner 1984). Given the uncertainty in this quantity we cannot be sure whether or not an accretion disc is present around 4 Dra B. However, Reimers (1985) and Reimers et al. (1988) argue that the broad high-excitation emission lines of 4 Draconis are more like those of AM Her systems than disc-accreting white dwarfs. This may point to the absence of an accretion disc in 4 Draconis, with these broad high-excitation lines arising in the X-ray-illuminated, radial accretion flow: a geometry much like that found in AM Her systems.

5 CONCLUSIONS

We present the discovery of X-ray emission from the symbiotic system 4 Draconis. The X-ray flux is highly variable on time-scales from minutes to years. X-ray spectroscopy shows that the spectrum is sometimes dominated by strong absorption by partially ionized material, probably the wind of the red giant. When free from absorption the spectrum is consistent with bremsstrahlung emission at a temperature around 5 keV. We conclude that these data are consistent with the presence of an accreting white dwarf, but that the lack of periodic X-ray modulation rules out the previously proposed identification of the hot companion as an AM Her system (Reimers et al. 1988). Instead we conclude that the companion is most likely a single white dwarf accreting from the wind of the giant. Consequently the evolutionary constraints derived by Eggleton et al. (1989) need not apply. Finally, we show that wind accretion is a viable energy source in this system.

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