

The short-period supersoft source in M31

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ABSTRACT

We show that the recently discovered short period supersoft source in M31 is probably a progenitor of a magnetic cataclysmic variable (CV). The white dwarf spins asynchronously because of the current high accretion rate. However its fieldstrength is typical of an AM Herculis system, which is what it will ultimately become. We discuss the relevance of this system to CV evolution, and its relation to some particular CVs with special characteristics.

Key words: accretion, accretion discs – stars: variables: other – galaxies: individual: M31 – X-rays: individual: XMMU J004319.4+411758 (M31PSS) – X-rays: stars.

1 INTRODUCTION

A recent *XMM-Newton* observation of the central region of M31 (Osborne et al. 2001) has revealed a supersoft X-ray source XMMU J004319.4+411758, hereafter M31PSS (=M31 periodic supersoft) with a coherent period of $P = 865.5$ s. Periodicities in supersoft sources have all hitherto been straightforwardly interpretable as orbital. However the 865.5-s period of M31PSS is so much shorter than the others ($P \geq 80$ min; Greiner 2000) that this interpretation is questionable. We examine in turn the ideas that the period is orbital, or instead reflects the white dwarf spin.

2 M31PSS AS AN ULTRASHORT-PERIOD BINARY

If the periodicity seen in M31PSS is orbital, the binary is too tight to contain a main-sequence star, and must thus have a degenerate companion. In this case the companion mass $M_2 = m_2 M_\odot$ is given by

$$m_2 \approx 1.5 \times 10^{-2} (1 + X)^{5/2} P_h^{-1} \quad (1)$$

and the mass-transfer rate driven by gravitational radiation follows from

$$-\dot{M}_2 \approx 1.3 \times 10^{-3} (1 + X)^{-20/3} m_2^{14/3} M_\odot \text{ yr}^{-1} \quad (2)$$

(e.g. King 1988). Here X is the fractional hydrogen content by mass, and P_h is the binary period in hours. A period of 865.5 s is below the minimum value for a hydrogen-rich secondary (e.g. King 1988), so the companion must be helium-rich ($X \approx 0$). For M31PSS ($P_h = 0.24$) we obtain $m_2 \approx 0.0625$, $-\dot{M}_2 \approx 3 \times 10^{-9} M_\odot \text{ yr}^{-1}$. There appear to be four possible ways of attempting to explain M31PSS as an ultrashort-period binary.

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2.1 M31PSS as a double-degenerate supersoft binary

van Teeseling et al. (1999) suggested that RX J0439.8–6809 (the orbital period of which is unknown) might be a double-white dwarf supersoft binary, on the basis of a very high X-ray to optical flux ratio. Clearly this interpretation cannot work for M31PSS if it is a member of M31, as accretion of helium-rich matter does not produce a significant nuclear burning luminosity.

2.2 M31PSS as a double-degenerate low-mass X-ray binary

Since the nuclear luminosity of helium-rich accretion is too low to power M31PSS if it is a member of M31, the only remaining way of giving an ultrashort-period system the luminosity required for this is to assume that the accretor is a neutron star or black hole. 4U1820–30 (with a period of 11 min) is probably a system of this type (Stella, White & Priedhorsky 1987). However it is then difficult to understand the observed supersoft spectrum. While this is natural for a white dwarf accretor, where the characteristic effective temperature T_{eff} is always close to 10^5 K, neutron stars and black holes have $T_{\text{eff}} \sim 10^7$ K, giving emission peaking near 1 keV rather than 10 eV as in supersoft sources. In line with this, the observed spectrum of 4U1820–30 is a 2.2 keV black body plus a power law (Haberl et al. 1987), and thus completely unlike the supersoft spectrum observed for M31PSS.

The next three possible explanations thus abandon the idea that M31PSS is a member of M31, and assume instead that it is a foreground Galactic source, and thus intrinsically much fainter.

2.3 M31PSS as an AM CVn system

The AM CVn systems are cataclysmic variables with He-rich secondary stars and orbital periods of 17–46 min, and so M31PSS could be a member of this class if it is a foreground object.

The AM CVn systems are very faint X-ray sources, having luminosities $L_x < 10^{31} \text{ erg s}^{-1}$ (van Teeseling & Verbunt 1994;

Ulla 1995; Verbunt et al. 1997). However, they do not have supersoft X-ray spectra. We have fitted archival ASCA data of the brightest AM CVn, GP Com, and find that it is well described by optically thin emission at $kT \sim 4$ keV, typical of non-magnetic CVs in general. Ulla (1995) also does not find a supersoft X-ray spectrum from AM CVn itself. The supersoft X-ray spectrum of M31PSS strongly distinguishes it from the AM CVns.

2.4 M31PSS as a double-degenerate AM Her system

Cropper et al. (1998) suggested that RX J1914.4 + 2456 might be a double-degenerate AM Herculis system. Interpreting M31PSS as a foreground object in this way would differ from the AM CVn idea above in that accretion would occur along magnetic fieldlines to a restricted region of the white dwarf.

In this picture the white dwarf rotation is phase locked to the orbit, so the modulation arises from occultation of the small bright accretion spot by the body of the white dwarf as it rotates. The X-ray light curve of RX J1914.4+2456 is indeed consistent with this explanation, the X-ray flux going to zero as the small spot rotates over the white dwarf limb. However the soft X-ray light curve of M31PSS (Osborne et al. 2001) does not support this idea. Its simple sinusoidal shape, with non-vanishing flux at all phases, is quite unlike that of any of the known AM Her systems, with the conceivable exception of RX J0453.4–4213 (Burwitz et al. 1996) which was observed at fairly low signal-to-noise ratio. Thus, to retain this explanation we would require either that the accretion spot is unusually large, and/or that we view the system from a very special orientation. Given that we already require the source to be positioned quite by chance in front of M31 it is clear that this is not a promising explanation.

2.5 M31PSS as a foreground soft intermediate polar

We conclude, in agreement with Osborne et al. (2001), that a more plausible interpretation is that the period P of M31PSS is the white dwarf spin. This star must then possess a magnetic field strong enough to channel the accretion flow, but too weak to lock the spin and orbital rotations. There are two possibilities here: we examine below the alternative possibility that M31PSS is intrinsically much brighter, and actually a member of M31. If instead M31PSS has the typical accretion-powered luminosity of known intermediate polars, it cannot be a member of M31 but must again be a foreground object.

Intermediate polars with strong soft components are rare, but do exist (Haberl & Motch 1995): currently three are known out of a total of more than 20 intermediate polars. A problem for this interpretation is the failure to detect an optical counterpart of M31PSS down to a limiting magnitude of $B = 19$ in the 2000 December *XMM-Newton* Optical Monitor observation in which M31PSS was faint in X-rays (Osborne et al. 2001). Even assuming that the optical luminosity of M31PSS was dominated by the companion star, with no accretion contribution, the galactic latitude of M31 implies an implausibly large system distance z from the Galactic plane; we find $z \gtrsim 350$ pc for an intermediate polar with orbital period $\gtrsim 5$ h. Such a distance is also required if M31PSS is not to be considerably fainter in soft X-rays than the other intermediate polars with soft components. Given that we are again requiring chance positioning in front of M31, it is clear that this type of explanation is rather unlikely.

3 M31PSS AS A SUPERSOFT INTERMEDIATE POLAR IN M31

Given our conclusion above that the period P of M31PSS is the white dwarf spin, we are now left only with the possibility that the object is a genuine member of M31, and is therefore intrinsically bright, i.e. is indeed the supersoft source it appears to be. M31PSS is thus the first known intermediate polar among supersoft X-ray binaries. The latter systems consist of a white dwarf of mass M_1 accreting from a hydrogen-rich companion but differ from CVs in that $M_2 \gtrsim M_1$. This leads (van den Heuvel et al. 1992) to mass transfer on the thermal time-scale of the companion.

Thermal time-scale mass transfer rates are much higher than those in CVs, which are usually driven by angular momentum loss. They lead to the possibility of steady nuclear burning of the accreted matter on the white dwarf surface. Assuming that M31PSS is a member of M31, the X-ray luminosity implies that it has a typical supersoft X-ray binary mass-transfer rate $-\dot{M}_2 \sim 3-10 \times 10^{-8} M_\odot \text{ yr}^{-1} \approx 2 \times 10^{18} \text{ g s}^{-1}$.

At the base of a steady white dwarf burning shell the pressure takes values up to $10^{17} \text{ dyn cm}^{-2}$ – less than the ignition pressure, but still much too large for magnetic confinement. Once initiated, burning will rapidly propagate and consume any hydrogen-rich material anywhere on the white dwarf surface. However in a supersoft system with a significant magnetic field, as we have inferred for M31PSS, H-rich fuel steadily arrives at the magnetic poles. Since the nuclear burning rate is strongly dependent on the fractional H content, most burning will occur near the poles – the H content of the newly arriving matter will drop severely as it flows away from these sites, through the combined effects of burning and geometrical dilution. The accretion rate needed to maintain steady burning in this case is probably somewhat lower than in the non-magnetic case, where the accreting matter is rather more spread out in the disc boundary layer.

These considerations also allow us to rule out an alternative to the steady nuclear burning identification – a late stage of a nova outburst. Any asymmetry in the nuclear burning shell on a spinning WD could provide the observed period of 865.5 s until the nova fades in X-rays. However, our discussion of the previous paragraph shows that in a nova, where no significant amount of new H-rich fuel arrives after ignition, nuclear burning will quickly become spherically symmetric; the slowly accumulated fuel has had ample time to diffuse over the entire white dwarf surface. Godon & Shaviv (1995) show that initial perturbations (e.g. local ignition at the poles) become global on a dynamical time-scale. Novae will therefore have spherically symmetric nuclear burning and show *no* obvious azimuthal inhomogeneity, and thus no periodicity. We conclude that the most likely interpretation of M31PSS is as a supersoft intermediate polar.

4 THE MAGNETIC FIELD OF M31PSS

Thermal time-scale mass transfer of the type inferred for M31PSS is possible without extreme assumptions only for orbital periods $P_{\text{orb}} \gtrsim 5$ h (King et al. 2001), and most observed periods are $\gtrsim 10$ h (Greiner 2000). This implies $P/P_{\text{orb}} < 0.05$ for M31PSS, suggesting that the system accretes from a fully developed Keplerian disc rather than directly from an accretion stream, or a magnetically influenced non-Keplerian disc (cf. King & Wynn 1999). In the Keplerian disc-fed case the specific angular momentum j_{acc} accreted by the white dwarf is significantly less than that of matter leaving the companion through the inner Lagrange

point (j_{L1}), leading to an equilibrium with $P/P_{\text{orb}} \lesssim 0.04$, whereas one gets $P/P_{\text{orb}} \approx 0.04$ in the stream-fed case with $j_{\text{acc}} = j_{L1}$ (King & Lasota 1991; King 1993), and a whole series of equilibria with $0.04 \lesssim P/P_{\text{orb}} \lesssim 0.7$ in the non-Keplerian case.

This identification of M31PSS constrains the magnetic moment $\mu = BR_1^3$ of the white dwarf (B = surface field, R_1 = radius). Assuming this accretes from a Keplerian disc, rough equality of magnetic and material stresses shows that the accretion flow will be channelled by the field within a radius

$$R_M \approx 1.4 \times 10^{10} \dot{M}_{18}^{-2/7} m_1^{-1/7} \mu_{34}^{4/7} \text{ cm} \quad (3)$$

with $\dot{M}_{18} = -\dot{M}_2/(10^{18} \text{ g s}^{-1})$, $m_1 = M_1/M_\odot$ and $\mu_{34} = \mu/(10^{34} \text{ G cm}^3)$ (see e.g. Frank, King & Raine 1992, equation 6.10). The minimum requirement for channelling, i.e. $R_M > R_1 \sim 10^9 \text{ cm}$, is satisfied for $\mu \gtrsim 10^{32} \text{ G cm}^3$, or a surface field $\gtrsim 10^5 \text{ G}$.

A more stringent constraint comes from the assumption that the white dwarf spin rate is close to the equilibrium value at which spin-up via accretion is balanced by centrifugal repulsion and other torques. Magnetic accretors are likely to reach this equilibrium on a time-scale $\sim 10^5 \text{ yr}$, i.e. much shorter than their evolution time $M_2/(-\dot{M}_2) \sim 10^7 \text{ yr}$. Variations in accretion rate on time-scales either \ll or $\gg 10^5 \text{ yr}$ will still leave the spin close to its current equilibrium value. The equilibrium assumption therefore gives a reasonable estimate of the fieldstrength.

Assuming accretion from a Keplerian disc as before, equilibrium requires R_M to be close to the disc radius where the local Kepler period is the observed spin period $P = 865.5 \text{ s}$, i.e.

$$R_M = 1.5 \times 10^8 P^{2/3} m_1^{1/3} = 1.4 \times 10^{10} m_1^{1/3} \text{ cm}. \quad (4)$$

Combining (3) and (4), with $\dot{M}_{18} = 2$, we see that

$\mu \approx 1 \times 10^{34} \text{ G cm}^3$, or a surface field $\approx 1 \times 10^7 \text{ G}$. These values are typical of the AM Herculis class of strongly magnetic CVs. The equilibrium condition (3) also implies a fractional accreting polecap area

$$f \approx \frac{R_1}{2R_M} \approx 0.04 \quad (5)$$

(cf. Frank et al. 1992, equation 6.14). This relatively large value means that the linear dimensions of the accretion region are a significant fraction of the white dwarf radius, as is strongly suggested by the approximately sinusoidal shape of the observed X-ray light curve.

Given an estimate of μ we can check the condition that the white dwarf spin should not be locked to the binary orbit. As shown by Hameury et al. (1987) this is equivalent to the requirement

$$2R_M \lesssim a, \quad (6)$$

where $a = 3.53 \times 10^{10} P_{\text{orb,h}}^{2/3} m_1^{1/3} \text{ cm}$ is the binary separation, with $P_{\text{orb,h}}$ the binary period measured in hours. This leads to

$$\dot{M}_{18} \gtrsim 0.01 \mu_{34}^2 m_1^{-5/3} P_5^{-7/3} \text{ g s}^{-1} \quad (7)$$

where P_5 is the orbital period measured in units of 5 h. Since we have $P_5 \gtrsim 1$ (see above) this condition is easily satisfied. We conclude that the identification of M31PSS as a supersoft intermediate polar is self-consistent.

5 THE FUTURE EVOLUTION OF M31PSS

The thermal time-scale mass transfer driving the evolution of M31PSS to its current state has increased the white dwarf spin to the observed value. Once the mass ratio has reduced so that

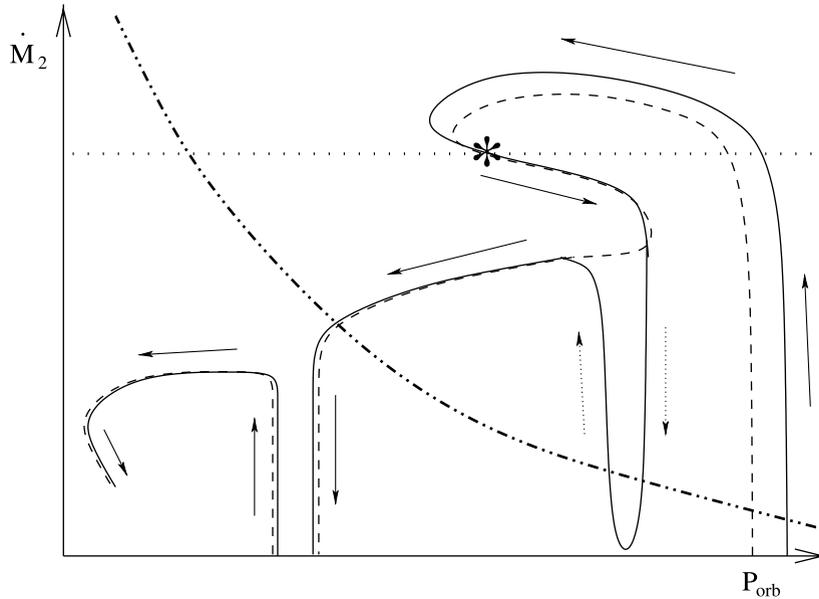


Figure 1. Two possible scenarios for the future evolution of M31PSS, assuming its current state (marked *) is a magnetic thermal time-scale system with steady nuclear burning on the white dwarf surface. Arrows indicate the direction of evolution; the dotted line is the current mass transfer rate in M31PSS, and the dash-dotted curve is the AM Her condition given by (7). The full curve shows a schematic evolution for very strong thermal time-scale mass transfer. The dip in $-\dot{M}_2$ after the period maximum marks the end of relaxation from the thermal time-scale phase. Relaxation began at the local period minimum, typically around 6–10 h. For a slightly weaker thermal–timescale phase, the broken curve shows an evolution without such a drop. Both curves cross the AM Her line at short orbital periods (3–4 h), but the first one also has a brief AM Her phase around the period maximum (similar to V1309 Ori), typically 8–12 h. Both types of system spend the remainder of the evolution above the CV period gap as strongly magnetic, asynchronous white dwarfs (i.e. possibly SW Sex systems) rather than normal IPs.

$M_2 \leq M_1$, mass transfer will start to decline to a much lower rate driven by angular momentum losses. Provided that this latter value is $\geq 10^{-10} M_{\odot} \text{yr}^{-1}$, equation (7) shows that the system will become a normal CV (note that $P_5 \geq 1$) with a strongly magnetic but asynchronous white dwarf. Such systems are expected to be very difficult to identify, as one can show (King & Lasota 1991, section IV) that both hard and soft X-ray emission will be strongly suppressed. However the discovery of periodically varying circular polarization in the SW Sex star LS Pegasi (Rodríguez-Gil et al. 2001) may offer a clue as to their observational appearance. As the binary period and mass-transfer rate decrease further, the system will eventually synchronize and become an AM Her system (typically at about 3 hr, or below the period gap at 2 hr). Signs of its interesting history would be a higher white dwarf mass than normal (the steady nuclear burning during the supersoft phase makes M_1 grow by a few tenths of a solar mass), and possibly some evidence of nuclear processing in its abundances when the former CNO-burning core becomes exposed. This evolution is shown as the broken curve in Fig. 1.

However for a sufficiently large initial mass ratio M_2/M_1 at the start of mass transfer, the evolutionary tracks can show a pronounced dip in mass-transfer rate at the very end of the thermal phase (see the full curve in Fig. 1). The same phenomenon is found by Podsiadlowski, Rappaport & Pfahl (2001) in their study of LMXB evolution, and is a result of relaxation back to thermal equilibrium. As \dot{M}_2 drops below $\sim 10^{-10} M_{\odot} \text{yr}^{-1}$, the WD is able to synchronize, and the system becomes an AM Her at an unusually long orbital period. The higher initial masses of the secondary star in this scenario makes nuclear evolution possible, and the system may show signs of CNO processing. A probable example of this case in our Galaxy is V1309 Ori ($P_{\text{orb}} = 8 \text{ hr}$), which indeed appears to have an overabundance of nitrogen (Schmidt & Stockman 2001) indicating an originally much more massive CNO-burning main-sequence star. Once the companion is fully thermally relaxed the mass-transfer rate is likely to recover to more usual values ($\geq 10^{-9} M_{\odot} \text{yr}^{-1}$) for the binary period. The white dwarf will be spun up and the system become asynchronous again. Eventually once the orbital period has shortened to $\sim 3\text{--}2 \text{ h}$ the white dwarf will synchronize once more, leading to the second and final AM Her stage of the system's evolution.

In both the evolutions described here, the system may become a propeller similar to AE Aqr (Wynn, King & Horne 1997) during spin-down phases, (e.g. when the white dwarf spin synchronizes) although the very short spin period (33 s) of AE Aqr itself requires a weaker magnetic field than in M31PSS. We note that AE Aqr shows the strongest evidence in any CV that nitrogen is enhanced at the expense of carbon (Jameson, King & Sherrington 1980). Curves like those in Fig. 1 can be matched to the parameters of AE Aqr (Schenker 2001; Schenker et al., in preparation).

In the December 2000 observation of M31, M31PSS had faded below detectability. Moreover the lack of an optical identification means that we have no information about masses or abundances. We are thus currently unable to say which of the evolutionary paths sketched above M31PSS will follow. Either way it is clear that it is probably a progenitor of a magnetic CV. Ironically we are largely prevented from observing such progenitors in our own Galaxy because their short lifetimes imply significant distances and thus

heavy absorption; conversely the distance to M31 means that CV descendants of systems like M31PSS will be very hard to discover. This has the unfortunate consequence that we cannot easily measure the relative numbers of CVs and supersoft progenitors in an unbiased way. However both considerations of the initial binary phase space, and the fact that we see at least two probable supersoft descendants (AE Aqr, V1309 Ori) in rather short-lived phases of their evolution as normal CVs, do suggest that CV descent from supersoft sources must be relatively common.

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