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HS 1023+3900 – a magnetic CV in the period gap with a distinct cyclotron emission line spectrum*

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Abstract. We report on the discovery by the Hamburg Quasar Survey of a magnetic CV with a pure cyclotron emission line spectrum. With a photometric and spectroscopic period of 167.6 min it is located in the CV period gap. From 91 spectra taken over 1.2 orbital periods we identify the n = 2 and 3 cyclotron harmonics of the main accretion pole with 60 MG as well as the n = 2 and 3 modes of the secondary pole with 68 MG. HS 1023+3900 has not been seen as an X-ray source by ROSAT. The estimated accretion rate is with $\dot{M} < 3 \cdot 10^{-13} M_{\odot} yr^{-1}$ at least two orders of magnitude lower than normally observed in polars. The observations of a pure cyclotron spectrum together with a low specific accretion rate ($< 10^{-3}\, g\, cm^{-2} s^{-1}$) are consistent with theoretical computations of cyclotron spectra of magnetic white dwarfs based on the so called "bombardment solution" by Rousseau et al. (1996) which predict just such behaviour. The location in the period gap is also consistent with an extremely low accretion rate according to standard scenarios for the evolution of CVs.

Key words: stars: individual: HS 1023+3900 – stars: novae, cataclysmic variables – stars: magnetic fields – stars: white dwarfs – stars: binaries: general

1. Introduction

Cyclotron line emission has been observed in a number of AM Her systems. The cyclotron lines originate in accretion shocks in small spots, and resolvable cyclotron harmonics (n≈ 3 to 8) are seen in the optical spectra of higher field AM Her stars. A common feature seems to be also two-pole accretion, where the main accretion spot is at the lower field pole, e.g. in VV Pup (Wickramasinghe et al. 1989), UZ For (Schwope et al. 1990), or DP Leo (Cropper et al. 1990). Field strengths in the main spot are always below $\sim$ 60 MG (except AR UMa with a probable field strength of 230 MG, Schmidt et al. 1996). For reviews on the topic see Schwope (1990, 1995), Chanmugam (1992), Beuermann et al. (1995), Beuermann (1997). Most of the presently known $\sim$ 50 AM Her systems are X-ray selected which favours the detection of objects with high accretion rates. On the other hand, cyclotron line emission is predicted to be dominant for low specific accretion rates (see Rousseau et al. 1996). Selection effects have therefore apparently worked against the discovery of magnetic CVs with specific low accretion rates and spectra dominated by well separated strong cyclotron harmonics. In this letter we report on the discovery of such a star in the course of the Hamburg Quasar Survey where the object had been selected on deep objective prism plates as a high-redshift QSO candidate

2. Observations

2.1. Discovery

HS 1023+3900 was discovered in the course of the Hamburg Quasar Survey (HQS), a wide-angle survey for bright QSOs based on objective-prism plates taken with the 80 cm Calar Alto Schmidt telescope (the former Hamburg Schmidt). The plates are digitized and automatically searched for QSO candidates which are subsequently observed spectroscopically with larger telescopes (Hagen et al. 1995). According to its blue flat spectrum which extended bluewards to the atmospheric limit and an apparent emission line at the longest wavelengths ($\lambda >$ 5000 to 5400 Å), HS 1023+3900 was suspected to be a z ≈ 3.2 QSO. Coordinates are α = 10 26 27.5 δ = 38 45 01 (2000), the B magnitude is roughly 18 according to the objective prism spectrum.

2.2. Optical spectroscopy

The object was observed during a regular QSO candidate follow-up observing run using the Calar Alto 2.2m telescope equipped with CAFOS. The discovery spectrum, Fig. 1, shows a featureless blue continuum blueward of $\sim$ 5500 Å , an extremely strong and broad (FWZI ≈ 800 Å) emission line at $\sim$ 5950 Å and an M dwarf spectrum longward of 6200 Å . The extreme width and strength of the line as well as its wavelength, which resisted an obvious identification with a strong atomic transition, led us immediately to the suspicion that the line could be a cyclotron transition in strong magnetic fields of an AM Her type object.

2.3. CCD-photometry

In order to determine the period of the suspected AM Her type star we obtained a total of 243 R band CCD images in 4 nights

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* Based on observations at the German-Spanish Astronomical Center, Calar Alto, Spain and at the Wendelstein Observatory

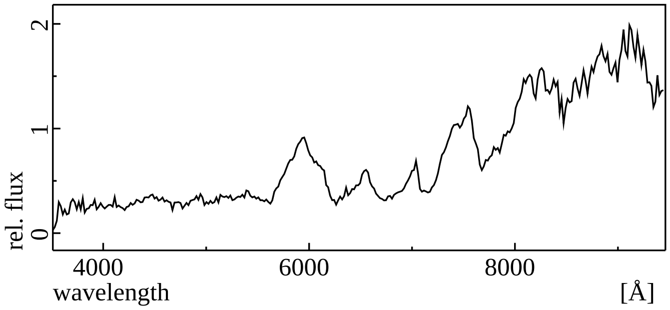

Fig. 1. Discovery spectrum of HS1023+3900 taken with CAFOS at the Calar Alto 2.2 m telescope. The spectral resolution is 5 Å FWHM. Notice the extremely broad emission line at 5950 Å and the M dwarf spectrum in the red.

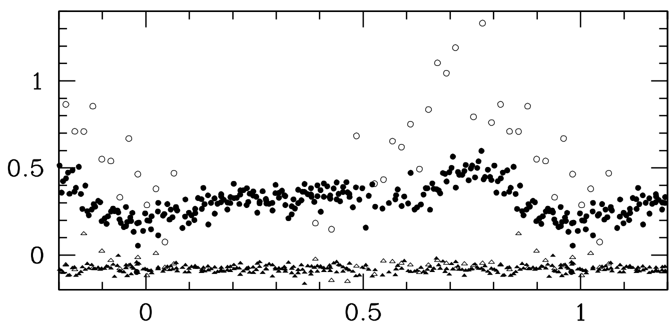

Fig. 2. Relative R light curve taken with the Wendelstein 0.8 m telescope. Symbols: • Observations Jan. 30 to Feb. 2, 1998. ○ Feb. 10, 1998. Filled and unfilled triangles show the faintest reference star respectively. A period of 0.11638 days has been used. T_0 = Jan. 30. 90833 ± 0.0042 (UT).

with the 0.8 m telescope of the Wendelstein observatory. The individual exposure times were about 60 sec and we obtained continuous monitoring in these 4 nights for several hours with a typical sampling of 3 to 5 minutes. After we applied the usual CCD corrections to all frames, HS1023+3900 as well as 6 neighbouring stars of similar flux have been measured with the MIDAS standard package for aperture photometry. The scatter of the differences of the instrumental magnitudes of these comparison stars is always less than 0.05 mag.

In the relative lightcurves, where we plotted the magnitude difference of HS1023+3900 minus the mean of the comparison stars versus time, some shallow and broad minima are visible. The lightcurve of the first night already indicates a possible period slightly less than three hours. The times of the minima were estimated and used to calculate a more precise value of P = 0.11638 days (see Table 1). All data were put together to a common lightcurve with relative magnitude versus phase (Fig. 2). The data from Jan. 30, 1998 to Feb. 1, 1998 show a small total amplitude and fit pretty well the same average lightcurve.

There exists a scatter of about slightly less than 0.1 mag against that average lightcurve and the data of the individual nights indicate that flickering might be present in this system. The data of Feb. 10, 1998 show an enhanced amplitude and seem to indicate an increase in activity around orbital phase 0.75.

Table 1. Minima timings for HS 1023+3900 from differential R band CCD photometry. Times are given in UT.

date	time m	time d	time h	number of frames
1998	01	30	21.8	96
	01	31	0.8	
	02	01	1.8	91
	02	01	23.9	24
	02	10	2.5	32

2.4. Phase resolved optical spectroscopy

HS 1023+3900 was monitored spectroscopically with CAFOS at the MPIA 2.2m telescope on Calar Alto, Spain, on Feb. 19, 1998. Spectral resolution is 40 Å. Wavelength and flux calibration followed standard procedures. We have taken 91 exposures of 100 sec every 134 s covering slightly more than one photometric period. While conditions at the beginning were excellent, the weather conditions (seeing and transparency) declined markedly during the ∼ last hour of the monitoring run. In order to achieve a reliable relative calibration of the CV contribution, we corrected for the varying atmospheric transparency by adjusting the M dwarf spectra in the red, in particular at the band heads, to the same level. Already during the observing run it became clear that the cyclotron line picture is correct. While the strong 5950 Å feature varied with the photometric period between strong and completely absent, a second line at ∼ 5220 Å showed up, roughly in antiphase to the 5950 Å line. (Fig. 3). Apparently we watch the appearance and disappearance of two high magnetic field spots on a degenerate star during one orbital (= rotational?) period. But how about further cyclotron modes, typically seen in AM Her stars with optical cyclotron spectra. Since shortward of 5000 Å , where the blue continuum is only slightly contaminated by the M type companion, there is no evidence for further emission, we subtracted the M star from the combined spectrum in order to look for the possible presence of lower cyclotron modes longward of 7000 Å . Since the spectral type of the M dwarf and its spectral energy distribution are not sufficiently well known, the best method to subtract the M dwarf spectrum in the red is to use the continuum energy distribution of the binary itself. For that purpose we have subtracted a mean spectrum of the short phases where both magnetic poles are invisible (φ = 0.47 to 0.55) from each individual spectrum. The result is shown in Fig. 3, where the 91 spectra are displayed in a time sequence (bottom to top). Two additional broad cyclotron features become visible, which appear to be lower modes for the λ 5950 Å and 5220 Å features respectively. While the described method to remove the M dwarf in red is optimal for showing the pure cyclotron spectrum, it has the disadvantage that the blue continuum, due to the magnetic WD in the system, is removed as well. In order to recover the blue star spectrum, we subtracted an appropriately normalized spectrum of the d M 4.5 e star G3–33 (Beuermann et al., 1988) which turned out to give an excellent fit to the secondary in our system. In addition,

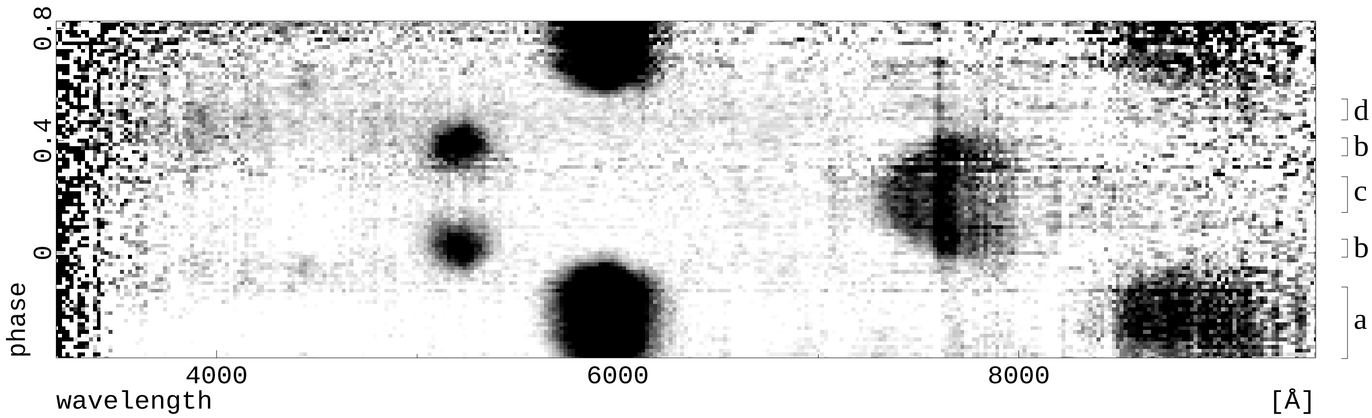

Fig. 3. Phase resolved cyclotron spectra of HS1023+3900 after subtraction of the M dwarf plus white dwarf spectrum. The 91 spectra assembled here together have been taken every 134 sec with 100 sec exposure time each. They cover roughly 1.2 periods. Marked are the spectra shown in Fig. 4a–d. Notice the degrading atmospheric conditions at phases 0.5 to 0.8.

we obtain thus a distance of HS 1023+3900 of 140 $\pm$ 50 pc with the G3–33 parameters as given by Beuermann et al. (1988).

Individual spectra of four relevant phases with the M star removed are shown in Fig. 4a–d. Fig. 4d, in particular, shows the spectrum of the magnetic WD. Longward of 6500 Å, its spectrum is highly uncertain due to the subtraction of the brighter M star.

The first result from Fig. 3 is that the spectra confirm the photometric period of 2.79 h. Folding the sequence of spectra shown in Fig. 3 with the Johnson R-filter which has its maximum transmission at $\sim$ 6000 Å, allows us to understand the origin of the light curve (Fig. 2) and to check subsequently period and phase. The light curve is indeed reproduced. The maximum at phase 0.75 originates in the maximum of the n = 3 cyclotron harmonic at 5950 Å which is covered twice by our spectra. The flare-like brightening on Feb. 10 is thus due to an enhanced (factor $\sim$ 2) n = 3 cyclotron harmonic of the main spot. We also confirm period and phase of the light curve as found by CCD photometry. Flickering ($\pm$ 0,1 mag) of the light curve must be caused by flickering of the cyclotron emission lines.

2.5. X-ray observations

HS 1023+3900 has got an exposure time of 408 sec in the ROSAT All Sky Survey, where it has not been detected (Voges, priv. comm.). In addition it was by chance in a deep pointed ROSAT PSPC observation (WG 900 529) with an exposure time of 7867 sec, again with no source detected which yields an upper limit of roughly 10^{-3} cts. s^{-1}. We are forced to conclude that with respect to X-ray emission HS 1023+3900 is distinctly different from all other known magnetic CVs which are typically strong soft and highly variable X-ray sources. With an estimated distance of $\sim$ 140 pc of the system, HS 1023+3900 is at least a factor of 10^3 fainter in X-rays than QS Tel, the other known AM Her system in the period gap (Schwope et al. 1995). HS 1023+3900 has also not been seen in the ROSAT WFC and the EUVE Surveys (Pye et al. 1995, Bowyer et al. 1996).

3. Analysis and preliminary interpretation

3.1. The cyclotron line spectrum

As is evident from the displayed spectra, HS 1023+3900 possesses the most prominent cyclotron spectrum among all known magnetic CVs. We can distinguish two accreting poles, the more luminous one with a strong line at 5950 Å and a further harmonic at $\sim$ 8900 Å which can be interpreted as n = 3, n = 2 cyclotron harmonics at B = 60 MG (see Chanmugam, 1992). The secondary, less luminous pole with features at 5220 Å and 7700 Å yields n = 3 and 2 at B = 68 MG. We notice that such high field strengths, in particular for the primary pole are close to the upper limit of what is known among magnetic CVs (see Beuermann 1997). The only exception is AR UMa with probably 230 MG (Schmidt et al. 1996) and unidentified features in the optical. The allover variations, in particular the variations in antiphase of the primary and secondary cyclotron modes can be understood from rotation of a decentered dipole with the two accretion columns being occulted by the degenerate star itself due to rotation. The decentering can be estimated roughly from the phase resolved spectra (Fig. 3): Notice that there is a short phase (φ = 0) where both bright spots are visible while half a period later both spots are invisible. According to this observation the decentering must be of the order of 10°. In addition, as in all known cases with different field strengths at two poles, the main accretion spot is at the lower field pole (see Beuermann et al. 1995).

We have no explanation for the secondary minimum seen in the n = 3 secondary pole cyclotron line light curve around phase 0.21. The secondary minimum cannot simply be due to an eclipse since it is barely visible in n = 2 at 7700 Å. Further spectra at higher S/N taken with a larger telescope are needed. If confirmed, a possible explanation is that at these particular phases the lines of sight are roughly parallel to the magnetic field lines, while cyclotron emission has its maximum perpendicular to the field lines. The observation that this effect is seen only in some of the modes hints at optical depth effects and can probably by explained only by detailed radiative transfer

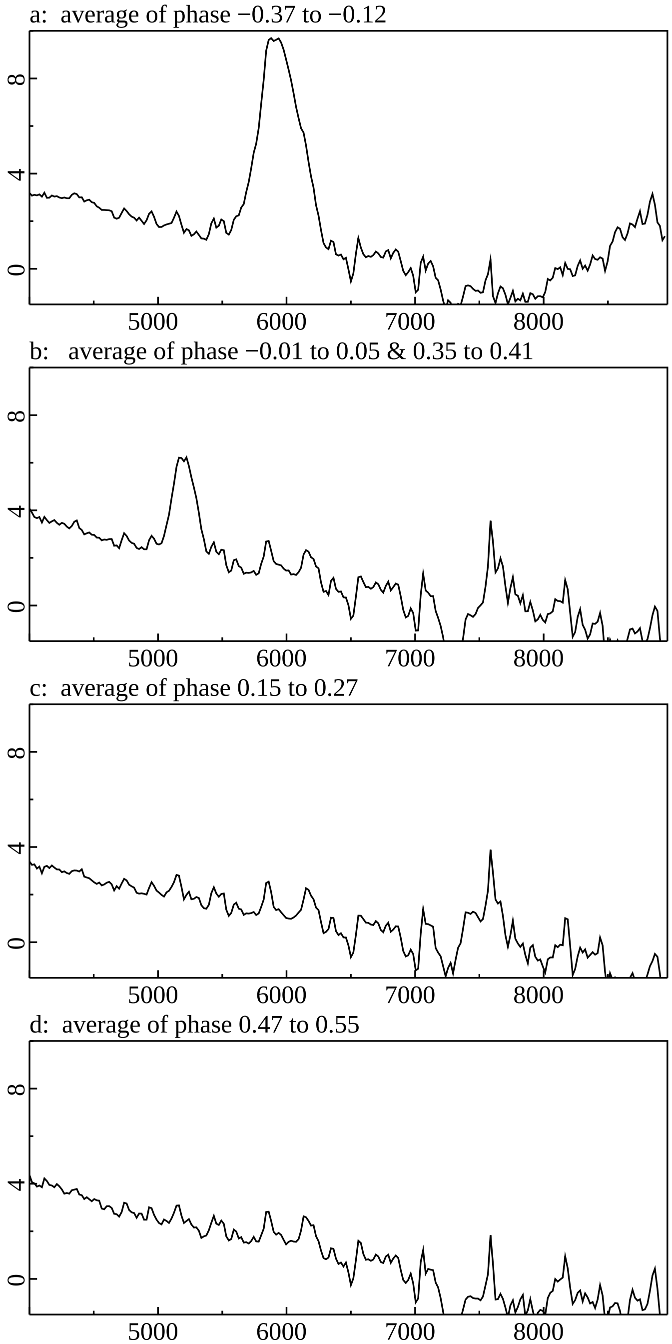

Fig. 4a–d. Relative flux spectra in of HS 1023+3900 after subtraction of a normalized spectrum of G3-33 (M 4.5e) at four representative phases (marked in Fig. 3).

calculations which are far beyond the scope of this discovery paper. A further complication should be mentioned: The secondary minimum seen at 5220 Å is seen in the corresponding n=2 mode only at the longer wavelengths around 7830 Å, while at shorter wavelengths (< 7500 Å) this effect is not visible. This observation would argue for a secondary spot with rather inhomogeneous magnetic fields where different parts of the spot show distinctly different cyclotron emission. Together with the

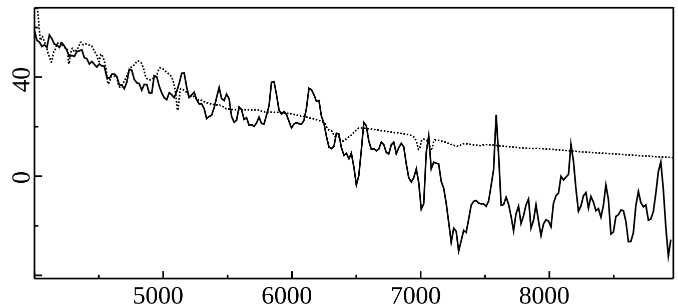

Fig. 5. Comparison of a scaled “pure” white dwarf spectrum (Fig. 4d) with a theoretical flux spectrum calculated for T_e = 13000, log g = 8.0 and a dipole field of 60 MG (Jordan, priv. comm.). The observed spectrum for $\lambda > 6500$ Å is unreliable due to subtraction of the much brighter M dwarf.

relative narrowness of the cyclotron lines this argues for a low plasma temperature, consistent with the absence of X-ray emission (Schwope 1995).

A further unsolved question is why the strong n=3 harmonic at 5950 Å is not accompanied by higher cyclotron harmonics, at least by the n=4 harmonic at 4460 Å. While this observation could cast doubts on our whole interpretation, the calculations by Rousseau et al. (1996) predict an extremely strong cyclotron line decrement at low specific accretion rates. In the end phase-resolved spectropolarimetry might help to answer this question.

We also notice that phase dependent shifts of the maxima of the harmonics seen in other magnetic CVs (Schwope, 1995), are not observed in HS 1023+3900 (see Fig. 3).

3.2. The continuum

While the cyclotron lines vary strongly with phase, there is no evidence for any variation of the underlying continuum. The pure CV continuum (Fig. 4d) has been extracted from phases around $\varphi \sim 0.5$ where both accreting poles are invisible (Fig. 3). The absence of any detectable variations in our spectra, in particular between phases with visible poles and phases without visible poles, shows that the contribution from the accreting poles to the continuum must be small, and the blue continuum is exclusively from the WD. In order to estimate the temperature of the WD, we compared the spectral energy distribution (Fig. 4d) with a grid of WD model atmosphere spectra between 10000 K and 15000 K, log g = 8, and a dipole field of 60 MG, kindly provided by S. Jordan. An optimal fit is obtained for T_e = 13000 K $\pm$ 1000 K (Fig. 5). The Balmer lines are only marginally detected (if at all), and spectra with higher S/N and spectral resolution should be taken in order to determine the photospheric magnetic field strengths. The log g = 8, T_e = 13000 K model represents a WD with M = 0.61 $M_\odot$, R = 0.013 $R_\odot$ and M_v = 11.57 (Wood, 1994). With a distance of d = 140 pc and V = 18.1 (according to Fig. 4d) we would obtain M_v = 12.35, i.e. a smaller WD radius $R_{WD} \sim 0.009$ $R_\odot$. This would imply a WD mass of roughly 0.9 $M_\odot$ according to the mass-radius relation (e.g. Koester & Reimers, 1996).

3.3. The explanation: a low accretion rate in the period gap

Several distinct observational facts make HS1023+3900 a unique member of the magnetic CV class

- with P = 2.79 h = 167.6 min it is in the (magnetic) CV period gap, in particular in a period regime close to the upper boundary which is up to now empty (see Beuermann (1997), Table 1 and Fig. 5). The closest neighbours in the period distribution of magnetic CVs are AM Her (182m) above the gap, and QS Tel (140m); the latter is an X-ray selected magnetic CV (Schwope et al. 1995)
- HS 1023+3900 appears to show a pure cyclotron line emission spectrum without a detectable continuum
- with 60 MG for the main pole and 68 MG for the secondary pole it possesses field strengths at the upper end of what is common among magnetic CVs (Beuermann, 1997).
- contrary to all other known magnetic CVs it is not an X-ray source

In the following we make plausible that the observations might fit well into the standard evolutionary model of CVs and that the spectral properties (pure cyclotron spectrum, no X-rays) are due to an extremely low accretion rate. Theoretical cyclotron spectra of magnetic accretion columns have been calculated by Woelk & Beuermann (1992, 1996) and Rousseau et al. (1996). In particular the model computations by Rousseau et al. (1996) show that the cyclotron harmonics detectable at optical wavelengths are formed in stars like UZ For in areas with the lowest specific accretion rates $\dot{m}$. For $\dot{m}$ values $5 \cdot 10^{-4}$ g cm$^{-2}s^{-1}$ and below, cyclotron line spectra similar to those observed in HS 1023+3900 are produced (Fig. 3, Rousseau et al. 1996).

The specific accretion rate in our case can be estimated roughly: The sum of the observed flux maxima of the two poles is $f \simeq 5 \cdot 10^{-13}\, erg\, cm^{-2}\, s^{-1}$ (for n = 2,3). The omission of n = 1 probably causes no great errors since the line fluxes increase strongly with n, up to n = 3. Since cyclotron emission is highly angular dependent, the combination of the observed maxima with the assumption of spherically symmetric emission probably overestimates the accretion luminosity L_{acc} considerably. This yields $L_{acc} \leq 1 \cdot 10^{30} (d/140\, pc)^2$. With $\dot{M} = L_{acc} \cdot R/G \cdot M$ we obtain an accretion rate $\dot{M} \leq 3 \cdot 10^{-13} (R/R_{WD})(M/M_{WD})^{-1} (d/140\, pc)^2 M_\odot\, yr^{-1}$ with $M_{WD} = 0.6 M_\odot, R_{WD} = 0.012 R_\odot$. This is at least two orders of magnitude lower than normally observed in polars (log $\dot{M} \simeq -10 \pm 1$). With an estimate for the size of the accreting spots $d \leq 0.12 R_{WD}$ or area $A \leq 10^{16}\, cm^2$ (e.g. Piirola, 1995) we find a specific accretion rate of $< 10^{-3}\, g\, cm^{-2}\, s^{-1}$. The real value could easily be a factor of 10 or more lower.

At such low specific accretion rates, which are normally observed only in the outer regions of the accretion spots of systems like UZ For in its low state, the peak temperatures may well be below 1 keV (Rousseau et al. 1996) which would explain the absence of X-ray emission in HS 1023+3900. Such extremely low accretion rates are also in accordance with the position of our system in the period gap. The standard explanation for the CV period gap is that as the CVs develop from longer to shorter periods, the secondary at the point when it becomes fully convective can switch off the mass-transfer temporarily (Spruit & Ritter, 1983), the system becomes detached and is no longer seen as CV. In case of a magnetic WD, the primary with its strong field interacts with the secondary and is apparently still able to draw small amounts of matter from the secondary down to its poles. Observational selection effects have worked against detecting magnetic CVs similar to HS 1023+3900. (1) Most magnetic CVs (80%) known today are X-ray selected (Beuermann, 1997). (2) Objects in the period gap have such low accretion rates that CV activity is normally spectroscopically inspicious, and the amplitudes of optical variability are small (see Fig. 1). (3) A distinct cyclotron spectrum like that of HS 1023+3900 is shifted to optical wavelengths only for high field strengths. Notice that HS 1023+3900 had been discovered on an objective prism plate as a z = 3.2 QSO candidate only because of the strong single emission line at 5200 Å , the n = 3 cyclotron transition at B = 68 MG.

There are alternatives to the standard evolutionary scenario of magnetic CVs. The extreme assumption would be that magnetic CVs synchronize almost instantly when they emerge from the common envelope phase, that the secondary is filling its Roche lobe, and that gravitational radiation (GR) is the only sink of angular momentum. Wickramasinghe & Wu (1994) give an estimate of the mass-transfer for this case. Using their formula, we find an accretion rate to the primary of $\dot{M}_2 \approx -10^{-10} M_\odot/yr$, much higher than observed in case of HS1023+3900. However, the assumptions used by Wickramasinghe & Wu (1994) in deriving $\dot{M}_2$ (no mass and angular momentum loss from the system) may be not valid.

It might also be the case that HS1023+3900 has a high state like other magnetic CVs like AM, and that the deduced mass-transfer rate is underestimated. However, the typical behaviour of AM Her itself is that the star is mostly (roughly 90% of the time) in a high state (see Fig. 70 in Hoffmeister et al. 1984), and that the low state is only 2 mag fainter. Assuming the rather improbable case we observed HS 1023+3900 in its low state only, a high state 2 mag brighter would still yield a mass-transfer rate far below the pure GR value.

A further argument against the evolution under the sole action of gravitational radiation is the thus predicted nonexistence of a period gap in magnetic CVs. This is not supported by the observations. The most recent compilation of the period distribution of 55 polars is given by Beuermann (1997) which clearly shows the existence of a period gap. According to Beuermann (1997), the only possible difference to nonmagnetic CVs seems to be an enhanced number of magnetic CVs at the lower end of the gap (P = 120 to 140 min).

An alternative is the so called reduced magnetic braking model proposed by Wickramasinghe & Wu (1989) and Li et al. (1994, 1995) where in a synchronized system the magnetic field lines of the secondary and the white dwarf connect and produce dead zones, where the secondary wind is trapped, which leads to a reduction of the magnetic braking efficiency.

Li et al. (1994) come to the conclusion that GR could be the dominant mechanism for the loss of angular momentum in the synchronously rotating magnetic binaries. Li et al. (1995) show that for high WD magnetic fields like in HS 1023+3900 the braking rate may drop to values below the value expected for GR. The GR mechanism of loss of angular momentum grossly overestimates the observed accretion rate (see above). A realistic alternative appears to be that the secondary underfills its Roche surface by several (many) pressure scale heights leading to a grossly reduced mass transfer rate.

Epilogue: This is a pure discovery paper on an up to now unique object. The simplicity of its spectrum should invite both thorough theoretical modelling as well as more observations, e.g. of the expected high polarization of the cyclotron harmonics and of the long term behaviour of the system. HS 1023+3900 offers, in particular, the opportunity to study the WD photospheric magnetic fields (from Zeeman absorption lines) and the magnetic fields at the accreting poles (cyclotron lines) simultaneously as a function of phase yielding a full surface map of the magnetic fields.

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