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Zeeman lines and a single cyclotron line in the low-accretion rate polar 1RXS J012851.9–233931 (RBS0206)*

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Abstract. We present a low-resolution discovery spectrum and CCD-photometry of the bright X-ray source 1RXS J012851.9–233931 found in the ROSAT All-Sky Survey. These first observations suggest that the source is an AM Herculis star (polar) accreting at a low rate. The optical spectrum is dominated by Zeeman absorption features from the white dwarf, indicating a mean photospheric magnetic field of 36 ± 1 MG. Only weak Balmer line emission was observed. In the near infra-red, a single intense cyclotron hump was observed. The inferred magnetic field strength in the accretion plama is 45 ± 1 MG, the temperature in the plasma is below 2 keV. Likely orbital periods are $\sim$90 min or $\sim$146 min, the latter inside the cataclysmic variable period gap. The system is an ideal target for further detailed investigations of the field structure on a magnetic white dwarf by phase-resolved spectropolarimetry.

Key words: accretion, accretion disks – stars: novae, cataclysmic variables – stars: individual: 1RXS J012851.9–233931 – stars: magnetic fields

1. Introduction

Several dozen new AM Herculis binaries (polars) were identified in recent years as optical counterparts of bright soft X-ray/EUV emitters, most of them in the systematic identification program of bright, soft, high-galactic latitude X-ray sources found in the RASS (ROSAT All-Sky Survey) by Thomas et al. (1998). Other main sources of new systems are the ROSAT/WFC survey (Pye et al. 1995) and serendipitous ASCA/ROSAT/EUVE discoveries. Thus, a total of about 60 polars are known meanwhile, more than three times the number of sources from the pre-ROSAT era. New interesting individual systems, e.g. bright eclipsing systems, have emerged and systematic studies became possible concerning e.g. the period or magnetic field distribution.

We are running an identification program of all bright, high-galactic latitude sources found in the RASS, primarily in order to establish complete X-ray selected samples of extragalactic X-ray emitters. Selection criteria are a RASS count rate above $0.2\,\mathrm{s}^{-1}$ and galactic latitude $|b| > 30°$. This program, termed the ROSAT Bright Survey RBS (Fischer et al. 1998), has impact also on galactic work. Among other fields, we mention the quest for isolated neutron stars (Schwope et al. 1999, Neuhäuser & Trümper 1999). By expanding the selection criteria applied by Thomas et al. including fainter and harder sources we also find new cataclysmic variables. The first one emerging from this program, RBS1735 (=EUVE J2115–58.6), turned out to belong to the rare class of only 4 polars with a slightly asynchronously rotating white dwarf (Schwope et al. 1997). This system had, contrary to the large majority of the newly discovered polars a rather hard X-ray spectrum. Here we report on the discovery of a new polar with a soft X-ray spectrum. The new system shows two features of magnetic activity, photospheric Zeeman absorption features and a cyclotron emission spectrum. Hence, it is a prime candidate for a detailed investigation establishing a map of the magnetic field on the surface of the white dwarf. The present database is too small to achieve this and further observations (photometry, spectroscopy, spectro-polarimetry) at optical, infra-red and X-ray wavelength are highly demanded.

2. Observations

2.1. X-ray observations

1RXS J012851.9–233931 was detected during the RASS as a variable soft X-ray source at a mean countrate of $0.34\,\mathrm{s}^{-1}$. The source was scanned 23 times during the RASS and had a total exposure of 452 sec. It displayed flux variations by 100% with minimum countrate of zero and peak countrate of $0.93\,\mathrm{s}^{-1}$. A variability analysis revealed no obvious periodicity. It has a soft spectrum with X-ray hardness ratio HR1 = -0.84 ± 0.04, where HR1 is defined in the usual way, HR1 $= (H - S)/(H + S)$ with H and S being the counts in the soft (0.1–0.4 keV) and hard (0.5–2.0 keV) bands, respectively. The X-ray source appeared as object 206 in the target list of the RBS (Schwope et al. 1999, in preparation), we refer to it as RBS0206 in the following.

It was not detected in the all-sky surveys performed in the softer spectral regimes with the EUVE satellite (Bowyer et al. 1996, Lampton et al. 1997) and with the WFC onboard ROSAT (Pye et al. 1995).

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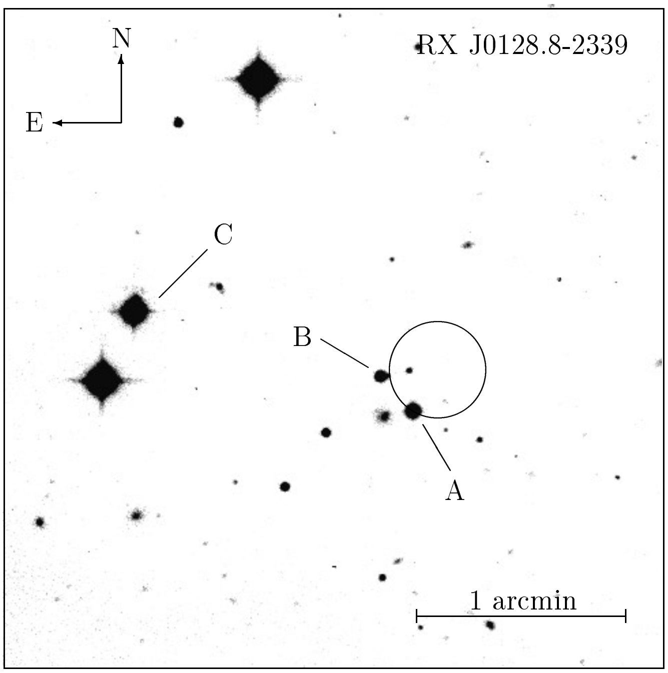

Fig. 1. Finding chart for RBS0206, the image is the average of all Gunn i CCD frames of Jan. 24. The image size is 3 by 3 arcminutes. The X-ray source, an AM Herculis star, is object 'A'. The optical coordinates are $\alpha_{2000} = 01^h28^m52\overset{s}{.}3, \delta_{2000} = -23°39'44''$

2.2. Low-resolution spectroscopy

The X-ray positional uncertainty of RBS0206 as given in the 1RXS-catalogue (Voges et al. 1996) is 9 arcsec. The digitized sky survey DSS shows several possible counterparts at or just within the 90% confidence X-ray error circle. The object nearest to the RASS X-ray position at a distance of $7.6''$ is the faintest (Gunn $i = 19\overset{m}{.}9$), it appears just above the plate limit and was not observed optically by us. The others labeled 'A' and 'B' on the finding chart reproduced in Fig. 1 are at distances of $13.2''$ and $15.9''$, respectively.

Low-resolution spectra of objects 'A' and 'B' were taken with the ESO Faint Object Spectrograph and Camera EFOSC mounted to the ESO 3.6m telescope in the night November 14, 1998. Both objects were put on the spectrograph slit, the integration time was 1200 sec, the exposure started at 4.2872 UT. A grism with 236 grooves/mm was used as dispersive device (grism #13), providing a wavelength coverage of more than 5000 Å at a resolution of about 12 Å FWHM. Spectrophotometric standard stars were observed twice in the night. Due to transparency changes of the atmosphere these observations gave inconsistent photometric results. The observations of the standard stars were nevertheless useful in order to establish the overall spectral response. An absolute calibration of the stars in the field was possible with the CCD-photometry of Jan. 1999 (see next section). We estimate the finally achieved photometric accuracy of our spectra to be better than ~15 %, where this estimate is based on the photometric accuracy of our Jan. 1999 imaging observations. Object 'B' turned out to be a faint K-star ($V = 19\overset{m}{.}1$) and is not the counterpart of the RASS X-ray source. The spectrum of object 'A' is reproduced in Fig. 2. With $V = 18\overset{m}{.}9$ this star was slightly brighter than 'B'. It has a blue continuum with deep absorption lines and an intense broad hump centred on ~8000 Å. Hα was observed to be weak in emission. The object was identified as a likely AM Herculis star in a low state of accretion.

2.3. Optical photometry

Optical photometry of RBS0206 was obtained on January 24 and 26, 1999, with the Danish 1.5m telescope at ESO La Silla. The source was exposed for a total of 2 and 2.3 hours, respectively, with integration times of individual exposures of 60 sec. Main aim of these observations was the determination of the orbital period of the binary. The feature with expected highest photometric variability in the spectrum of RBS0206 (Fig. 2) is the hump at 8000 Å. The photometric observations were therefore performed with a Gunn i filter with central wavelength at 7978 Å and width of 1430 Å. Differential magnitudes of objects 'A' and 'B' with respect to star 'C' were derived using the profile fitting algorithm of DOPHOT (Mateo & Schechter 1989). The accuracy of a single observation is 0.05 mag. Subsequent observations of Landolt (1992) standards allowed the absolute calibration of our photometric and spectroscopic reference stars, $i = 13\overset{m}{.}92$ for star 'C' and $i = 17\overset{m}{.}38$ for star 'B'. The resulting light curves of the two occasions are shown in Fig. 3. RBS0206 displayed brightness variations by 0.5 mag on a timescale of less than one hour with short-term fluctuations of 30% superimposed. The mean brightness level of $i \sim 16\overset{m}{.}3$ indicates a brightening of the source with respect to the spectroscopic observations by about 1.3 mag.

3. Analysis and discussion

3.1. Spectroscopic identification of RBS0206

The spectrum of RBS0206 shows the signs of a polar in a low state of accretion. The emission lines of Hydrogen and Helium, which are so prominent in the high accretion states of these systems, have almost vanished. Only Hα and Hβ are weakly detectable in emission. The absence of all radiation components dominating the optical spectra of polars in their high states (atomic emission lines, recombination continuum, quasi-continuous cyclotron emission) unveils the presence of the magnetic white dwarf in RBS0206. The continuum in the blue spectral range is dominated by the white dwarf, the pronounced absorption lines are Zeeman shifted Balmer lines of photospheric origin (Hα, Hβ and Hγ). Although in a low state, the spectrum has a broad intensity hump in the near-infrared at 8000 Å and width of about 1000 Å (FWHM) which can be nothing else than a cyclotron feature. Hence, accretion did not cease entirely. The spectrum does not show any obvious feature from the mass-donating secondary star. We will discuss the various spectral features subsequently, but try to determine the binary period beforehand.

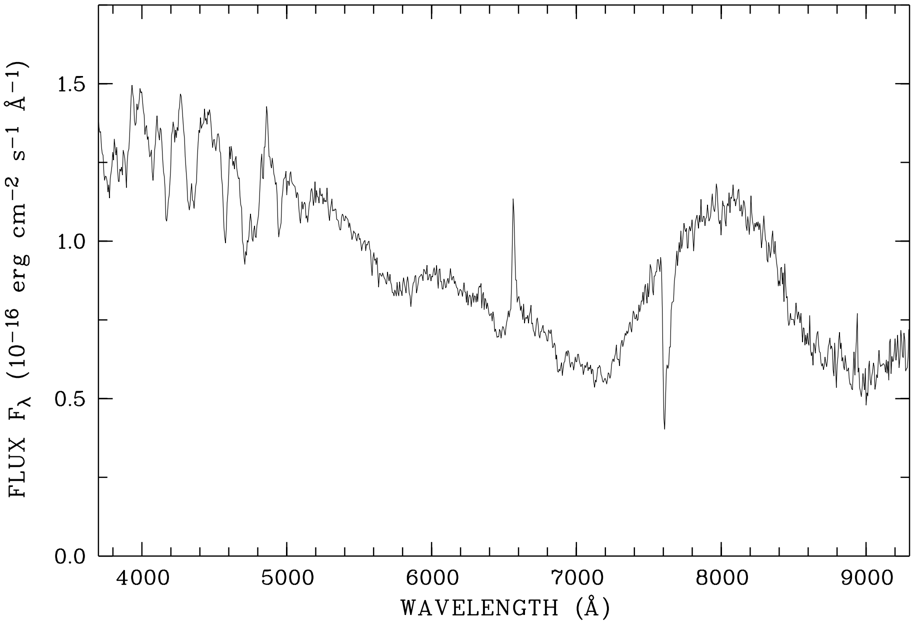

Fig. 2. Low-resolution discovery spectrum of 1RXS J012851.9–233931 (=RBS0206) taken with the ESO 3.6m telescope and EFOSC2 on November 14, 1998

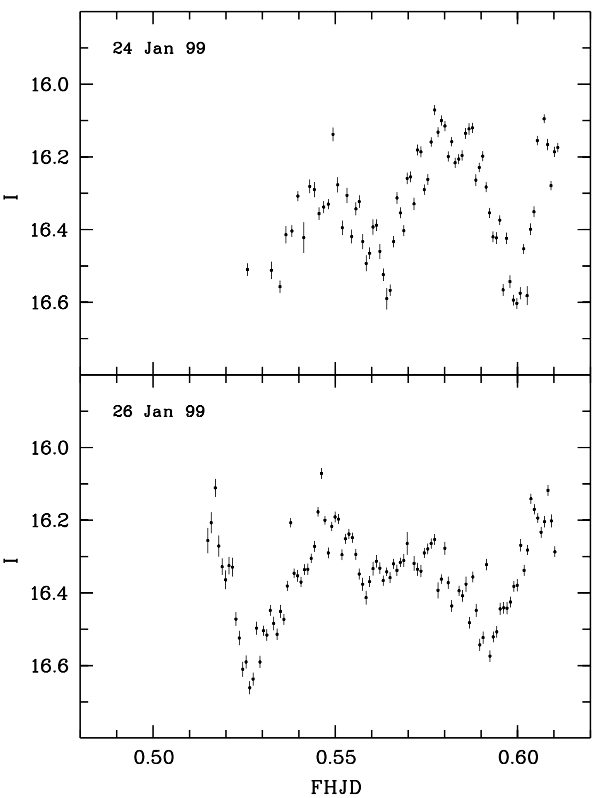

Fig. 3. Time-resolved optical photometry of RBS0206 through Gunn i filter. The abscissa gives fractional heliocentric Julian days with corresponding integer parts 2451202 and 2451204, respectively

3.2. Optical variability

The lightcurves shown in Fig. 3 display pronounced minima which are in principle useful for a period determination. With the small database at hand, however, our results are not unique. It is in particular not clear, whether the two minima in the lightcurve of Jan. 26, 1999, represent the same feature in two successive cycles or not. A periodogram computed with the *analysis-of-variance (AOV)* algorithm (Fig. 4; Schwarzenberg-Czerny 1989) reveals possible periods around 90 min (0.0625 days) and around 146 min (0.1 days). The former solution would imply that the two observed minima on Jan. 26 represent the same feature, the latter that they are different. Folded light curves using the three trial periods indicated in Fig. 4 are shown in Fig. 5. Each folded light curve has intervals with a very large scatter of data points at given phase probably caused by cycle-to-cycle variations of the brightness. The folded light curves for periods around 90 min resemble those of MR Ser or QQ Vul, which both have their main accreting pole continously in view. The optical light curves of these two systems are modulated by strong cyclotron beaming. Primary minima occur in these systems when we are looking almost pole-on, secondary minima in the centre of the bright hump, when the main pole vanishes partly behind the limb of the white dwarf. The folded light curve using the trial period of 146.4 min shows a rather short bright phase (centred on phase zero) which is disrupted by an eclipse-like minimum. Such a feature may be caused by absorption in the intermittent accretion stream crossing the line of sight to the accretion spot. We regard a period around 90 min as likely but cannot exclude longer periods, significantly shorter periods are certainly excluded. Clearly, observations with a longer time base are needed to clarify the situation. With this period, the likely accretion geometry is such, that the accretion spot is continously in view. This view is supported by the RASS X-ray light curve which has non-vanishing X-ray flux for all but one scans.

3.3. Spectral analysis

The absence of any obvious M-star feature in our spectrum can be used to derive a distance estimate to the system. We assume

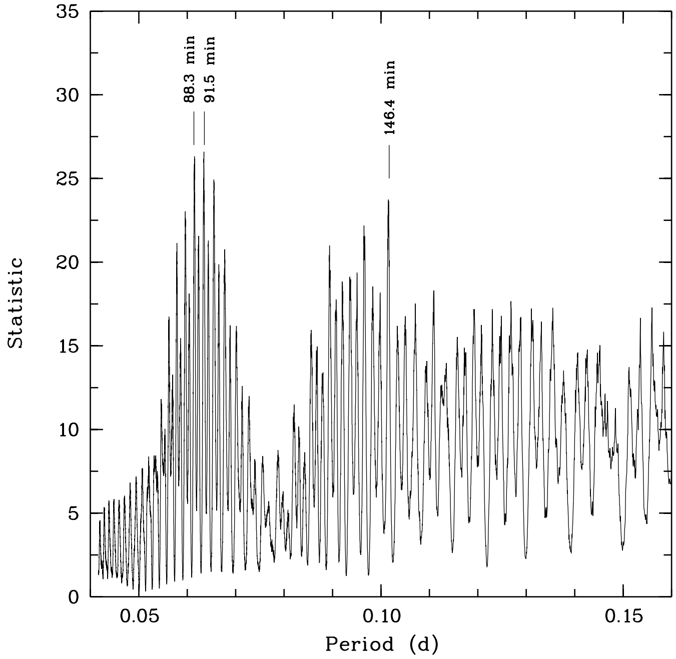

Fig. 4. Periodogram (AOV-statistic) of the time-resolved data shown in Fig. 3

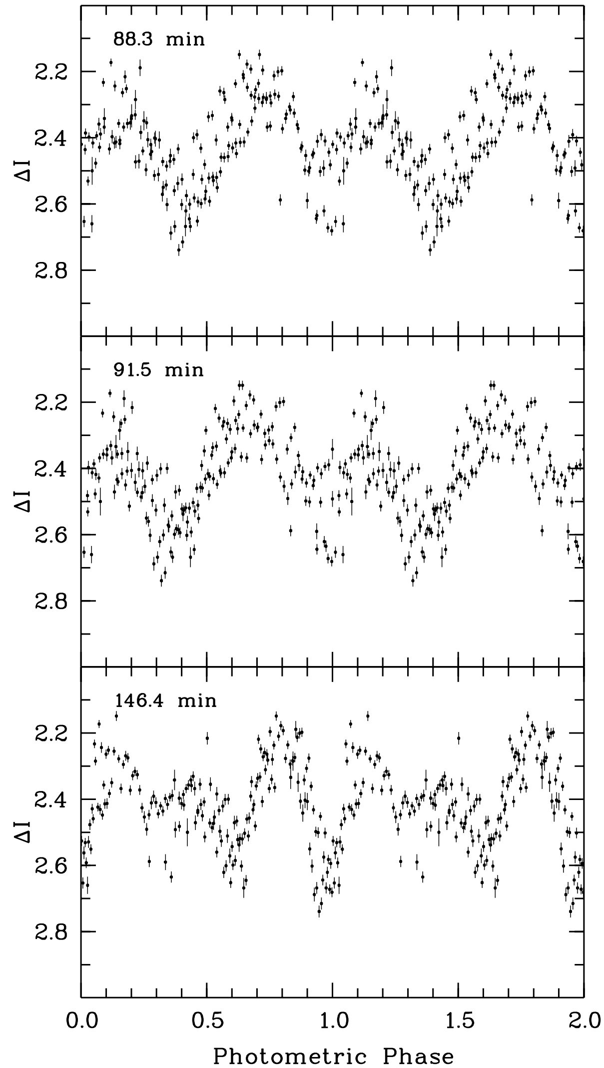

Fig. 5. Folded light curves using trial periods indicated in Fig. 4

that the maximum contribution of the M-star at 9000 Å is 80% and use as template spectrum for the secondary in RBS0206 the M6 dwarf Gl406 with $M_K = 9\overset{\text{m}}{.}19, V - K = 7\overset{\text{m}}{.}37$. This type of M-star would be appropriate for a cataclysmic binary with $P_{\text{orb}} \sim 90$ min. The scaled V- and K-band brightnesses of Gl406 are $V_{\text{sc}} = 23\overset{\text{m}}{.}5$ and $K_{\text{sc}} = 16\overset{\text{m}}{.}1$. We assume a Roche-lobe filling secondary star at a period of 90 min which has a spherical equivalent Roche radius of $\log(R_2/R_\odot) = -0.86$. Using Bailey's (1981) method combined with the improved calibration of the surface brightness of late-type stars by Beuermann & Weichhold (1999, in prep.) which predicts a surface brightness $S_K = 4.9$ for a star like Gl406, the distance to RBS0206 is > 240 pc.

Using the observed slope and flux level of the white dwarf in the blue spectral regime the questions of white dwarf radius, temperature and distance to the system can be addressed, too. For that exercise we use the model spectra for non-magnetic white dwarf atmospheres by Gänsicke et al. (1995) kindly provided by B. Gänsicke. We assume a normal 0.6 $M_\odot$ white dwarf with $R_{wd} = 8 \times 10^8$ cm. The observed spectrum is reasonably well reflected with a 10000 K white dwarf at a distance of only 130 pc, although the model predicts a steeper spectral slope than observed. A white dwarf at a distance of 240 pc as estimated above must have a considerably higher temperature of about 20000 K in order to match the observed flux level at 6000 Å. At this high temperature the continuum slope is much steeper than observed and the fit in general is clearly worse than that for 10000 K. In order to resolve the discrepancy between the different distance estimates one definitely needs phase-resolved data. These would allow in the first place to determine the orbital period. Should our period estimate for some reason be wrong and the orbital period shorter than 90 min, one can hide an even fainter secondary star with later spectral type in the spectrum which would be less distant than the derived 240 pc for a period of 90 min. Phase-resolved spectroscopic data in the blue spectral regime would allow to disentangle between radiation from the undisturbed photosphere and a warm accretion spot.

The purity of the Zeeman spectrum shortward of Hα allows a direct measurement of the mean magnetic field strength. We fitted a second order polynomial to interactively defined continuum points and divided the observed spectrum by this curve. The result is shown in Fig. 6 together with a simple Zeeman model plotted below the observed spectrum. The model is based on the detailed computations of the wavelengths and oscillator strengths of the individual non-degenerate Zeeman transitions of H-Balmer lines by Forster et al. (1984) and Rösner et al. (1984). For the present purpose we use the transitions of Hα, Hβ and Hγ, which lie in the spectral range covered by our spectrum. Our model just sums the oscillator strengths of all Balmer transitions mentioned weighted according to an assumed mag-

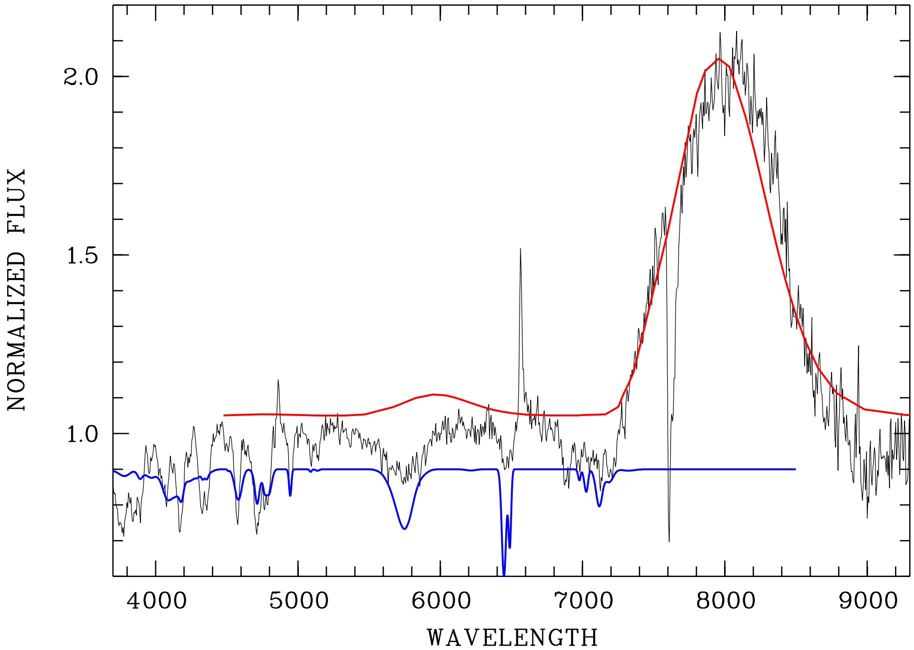

Fig. 6. Normalized spectrum of the white dwarf in RBS0206 together with simple Zeeman and cyclotron models used for the determination of the mean magnetic field and the field in the accretion spot

netic field distribution. For the model shown in Fig. 6 we assumed a Gaussian field distribution centred on $B = 36$ MG with a spread $\sigma_B = 2$ MG. The model, therefore, does not predict real spectral intensities but it predicts the wavelengths where spectral features are expected to occur. At the field strength realized in RBS0206 nearly all subcomponents of the Balmer lines appear as individual non-degenerate transitions due to the dominance of the quadratic over the linear Zeeman effect. Due to magnetic field smearing and to the limited spectral resolution these cannot be resolved in our spectrum, the Zeeman lines mainly appear as broad troughs. All features longward of 5300 Å belong to Hα, the features shortward of this wavelength belong to Hβ and Hγ and become partly intermixed. There are, however, some isolated features e.g. at 4580 Å and 4920 Å reacting sensitively on the adopted value of the centroid field strength. We estimate the uncertainty of the centroid field strength to be about 1 MG. We regard this field strength as mean photospheric field strength. If we want to infer the value of the field strength at the pole, we need to know (a) the inclination of the magnetic axis with respect to the line of sight at the time of the observation, (b) the true underlying distribution of the magnetic field, and (c) information about the temperature distribution over the white dwarf surface. All these quantities and distributions are unknown. However, if we assume a dipolar field structure, a homogeneous temperature distribution and a line of sight not directly towards the magnetic pole, then a typical value for the conversion between the mean magnetic field and the polar field strength is 1.6–1.7. Using these values a likely value of the magnetic field at the pole is 55–60 MG. A lower limit for the field strength at the magnetic pole is given by the high-field wings of the observed Zeeman lines, which indicate about 40 MG.

The occurence of a single cyclotron hump at 8000 Å is puzzling. All AM Herculis stars with individually resolved cyclotron harmonics show more than one harmonic in their optical or infrared spectra. One apparent exception is the recently discovered polar HS 1023+3900 (Reimers et al. 1999) observed at a very low accretion rate which shows at certain phases only one prominent cyclotron line at 6000 Å. Only the detailed analysis revealed a second cyclotron line as a faint addition to the bright spectrum of the secondary star in the near infrared at 9000 Å. In RBS0206 the cyclotron fundamental lies in the unobserved infrared, $\lambda_{\rm cyc} = 17850$–$26780$ Å for $B_{\rm pole} \simeq B_{\rm cyc} = 40$–$60$ MG. Our spectrum covers the corresponding harmonic numbers 2–5.3 or 3–8, respectively, hence we could expect to observe several higher cyclotron harmonics. The only way to hide these higher harmonics is to assume that the particular observed one is already almost optically thin, that the plasma temperature is very low (which gives a steep dependence of the absorption coefficient on the harmonic number) and that the plasma is rather dilute. As one example for such a model we show also in Fig. 6 a cyclotron model which fits these requirements. It is computed for a homogeneous, isothermal plasma with $kT = 2$ keV, magnetic field strength $B = 45$ MG, viewing angle $\Theta = 50°$ (angle between magnetic field and observer) and plasma density parameter $\log \Lambda = 2$ (see Barrett & Chanmugam 1985, Thompson & Cawthorne 1987). With these parameters the observed cyclotron hump is the $3^{\rm rd}$ harmonic, the $2^{\rm nd}$ is expected to lie in the infrared J-band (centred on 1.2 μm) and the cyclotron fundamental lies at 2.4 μm, at the edge of the K-band. The next higher harmonic, the fourth, is seen in the model as a small hump at 6000 Å. Such a feature can easily be overlooked in somewhat noisy data and can be hidden in a continuum which is strongly affected by Zeeman absorption. Our modeled hump at 8000 Å has the same width as the observed one. Since any inhomogeneity in the emitting plasma like a variation of the value of the magnetic field strength tend to smear a cyclotron line, the true plasma temperature is probably below 2 keV.

This is the lowest plasma temperature among all polars derived so far from optical cyclotron spectroscopy. It is in particular much lower than the shock temperature of a free-falling accretion stream on the white dwarf, by a factor of 10 for an assumed 0.6 $M_\odot$ white dwarf. This suggests an accretion scenario termed 'bombardement solution' (Kuijpers & Pringle 1982) where the accretion spot is heated by particle collisions. This scenario has been worked out in detail in a series of papers by Woelk & Beuermann (1992, 1993, 1996) and Beuermann & Woelk (1996). Interpreting the measured temperature as maximum electron temperature, Figs. 6, 8, and 9 of their 1996 paper suggest, that the specific mass accretion rate $\dot{m}$ is below 0.1 g cm^{-2} s^{-1}. Their modelling predicts furthermore that 100% of the accretion luminosity appears as cyclotron radiation. This is in apparent contradiction to the fact, that RBS0206 was discovered as X-ray source. However, AM Herculis binaries are known to have highly variable mass accretion rates on different time scales and we cannot exclude something like a high accretion state during the RASS and a low accretion state during our spectroscopic observations.

The very low value of the plasma parameter Λ supports the applicability of the bombardement solution and predicts an even lower specific mass accretion rate. The plasma parameter is given in terms of the magnetic field strength $B_{45} = B/45$ MG, the geometric path length through the plasma $s_6 = s/10^6$ cm and the electron density $n_{16} = n_e/10^{16}$ cm^{-3} as $\Lambda = 1.3 \times 10^6 s_6 n_{16} B_{45}^{-1}$. With the measured value of $\Lambda = 100$ this becomes $n_{16} \sim 10^{-4} s_6^{-1}$. The cooling length h of the plasma will not be smaller than 10^6 cm (Beuermann & Woelk 1996, Fig. 2), and by setting the cooling length h equal to the geometrical path length s the electron density in the cyclotron region must be extraordinarily low, $n_e \simeq 10^{12}$ cm^{-3}. For standard composition the post-shock density is $n_e = 3.8 \times 10^{17} (\dot{m}/10^2 \mathrm{g\,cm^{-2}s^{-1}})(M_\mathrm{wd}/M_\odot)^{-1/2}(R_\mathrm{wd}/10^9\mathrm{cm})$ cm^{-3}, suggesting $\dot{m} \simeq 10^{-3}$ for the case of RBS0206.

The predicted integrated cyclotron flux (integrated over all harmonics) is about 2×10^{-12} erg cm^{-2} s^{-1}. For a distance of 130 pc the cyclotron luminosity is $L_\mathrm{cyc} = \pi d^2 F_\mathrm{cyc} = 1 \times 10^{30} (d/130)^2$ erg s^{-1}. Assuming that 100% of the accretion luminosity is released as cyclotron radiation, as predicted by the Woelk & Beuermann models, the total mass accretion is $\dot{M} = L R_\mathrm{wd}/G M_\mathrm{wd} = 1 \times 10^{13} \mathrm{g/s} = 1.5 \times 10^{-13}\, M_\odot \mathrm{yr}^{-1}$. This value is $2-3$ orders of magnitude below the canonical value for a short-period polar, i.e. a system below the period gap, in a high accretion state.

The RASS X-ray data can be fitted with a soft blackbody and a (marginally detected) hard X-ray bremsstrahlung model. The integrated unabsorbed flux of the $kT_\mathrm{bb} = 20$ eV blackbody gives 5×10^{-11} erg cm^{-2} s^{-1}, which is a factor of 25 more than the derived cyclotron flux. These estimates suggest that the accretion rate has changed by a large amount between the RASS X-ray observations and the optical spectroscopy in November 1998.

4. Conclusions

We have presented first spectroscopic and photometric observations of the newly discovered AM Herculis star 1RXS J012851.9–233931 = RBS0206. Although not finally conclusive, our photometry suggests that it is a short-period system with $P_\mathrm{orb} \simeq 90$ min or that it is a system in the period gap with P_orb around 140 min. The probable accretion geometry is such, that the accreting pole is continuously in view. The discovery spectrum of RBS0206 was taken when the system was in an extreme low state of accretion. This derives from the absence of bright emission lines and photospheric absorption lines from the white dwarf. Even in the single discovery spectrum Zeeman and cyclotron lines could be detected. The inferred magnetic field strengths are 36 ± 1 MG for the mean photospheric field 45 ± 1 MG for the accretion spot. The plasma temperature in the cyclotron emission region is extremely low, $kT < 2$ keV, compared to the more usual 5–20 keV encountered in most AM Her systems. The derived integrated mass accretion rate is 2–3 orders of magnitude below the canonical value for short-period polars indicating a deep low accretion state of that system. RBS0206 seems to be an extraordinarily good target for a detailed study of the magnetic field structure over the white dwarf surface due to the presence of pronounced Zeeman lines and a cyclotron line in addition. The Zeeman lines are sensitive to the average surface field whereas the cyclotron line gives an extra constraint on the field in one particular spot. The system is also an excellent target for studies of cyclotron-line formation in the lowest harmonics by spectroscopy in the J and K bands, where pronounced optical depth effects are expected to occur (Woelk & Beuermann 1996).

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