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RX J1313.2−3259, a missing link in CV evolution? *

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Abstract. We present low-state IUE spectroscopy of the ROSAT-discovered polar RX J1313.2−3259. The SWP spectrum displays a broad Lyα absorption profile, which can be fitted with a two-temperature model of a white dwarf of $T_{\rm wd} = 15\,000$ K with a hot spot of $T_{\rm spot} = 34\,000$ K which covers $f \sim 0.01$ of the white dwarf surface. The white dwarf temperature is atypically low for the long orbital period (4.18 h) of RX J1313.2−3259. This low temperature implies either that the system is a young CV in the process of switching on mass transfer or that it is an older CV found in a prolonged state of low accretion rate, much below that predicted by standard evolution theory. In the first case, we can put a lower limit on the life time as pre-CV of 10^8 yrs. In the second case, the good agreement of the white dwarf temperature with that expected from compressional heating suggests that the system has experienced the current low accretion rate for an extended period $> 10^4$ yrs. A possible explanation for the low accretion rate is that RX J1313−32 is a hibernating post nova and observational tests are suggested.

Key words: accretion – binaries: close – stars, individual: RX J1313.2−3259 – X-rays: stars

1. Introduction

Most fundamental physical stellar parameters of field white dwarfs, such as effective temperature, surface gravity, and magnetic field strength can directly be measured with high precision from spectroscopic observations. Assuming a mass-radius relation, both mass and radius may be inferred independently of the distance. Determining these properties also for the accreting white dwarfs in cataclysmic variables (CVs) is a relatively new research field, essential not only for testing stellar (binary) evolution theory, but for understanding the physics of accretion in this whole class of binaries.

The last years saw a rapid growth of identified polars, CVs containing a synchronously rotating magnetic white dwarf. Despite the large number of know systems ($\gtrsim 60$) rather little is known about the temperatures of the accreting white dwarfs in these systems. The main reasons for this scarcity are twofold. (a) In the easily accessible optical wavelength band, the white dwarf photospheric emission is often diluted by cyclotron radiation from the accretion column below the stand-off shock, by emission from the secondary star, and by light from the accretion stream. Even when the accretion switches off almost totally and the white dwarf becomes a significant source of the optical flux (e.g. Schwope et al. 1993), the complex structure of the Zeeman–splitted Balmer lines and remnant cyclotron emission complicate a reliable temperature determination. (b) At ultraviolet wavelengths the white dwarf entirely dominates the emission of the system during the low state and may be a significant source even during the high state. However, the faintness of most polars requires time-consuming space based observations (e.g. Stockman et al. 1994).

2. Observations

IUE observations of RX J1313.2−3259 (henceforth RX J1313) were carried out in March, 1996. One SWP (1150−1980 Å) and one LWP (1950−3200 Å) low resolution spectrum were obtained on March 2 and March 6, respectively (Table 1). The LWP image was taken prior to the failure of Gyro #5, read-out of the image had to await that control over the spacecraft was re-established. Both observations were taken through the large aperture, resulting in a spectral resolution of ≈ 6 Å. Because of the faintness of RX J1313, the exposure time of the SWP spectrum was chosen roughly equal to the orbital period. The spectra have been processed through the IUE NEWSIPS pipeline, yielding flux and wavelength calibrated spectra.

The SWP spectrum is shown in Fig 1. It is a blue continuum with a flux decline below ≈ 1400 Å. Due to the long exposure time, the spectrum is strongly affected by cosmic ray hits. Some emission of C IV λ 1550 and He II λ 1640 may be present in the spectrum of RX J1313, but from the present data no secure detection of line emission can be claimed.

3. Analysis and Results

The absence/weakness of emission lines strongly indicates that the IUE observations were taken during a period of very low

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* Based on observations made with the International Ultraviolet Explorer

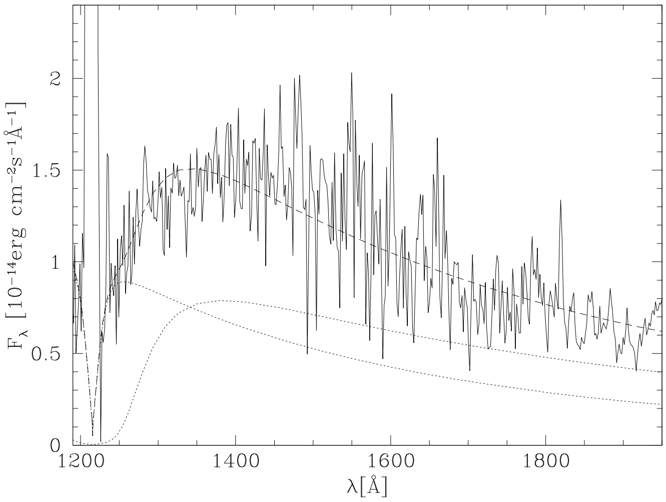

Fig. 1. IUE SWP low state spectrum of RX J1313. Plotted as a dashed line is the best-fit two temperature model of a white dwarf of $T_{\rm wd} = 15\,000$ K with a hot spot of $T_{\rm wd} = 34\,000$ K covering $f \sim 0.01$ of the white dwarf surface. The dotted curves show the individual contributions of the two components.

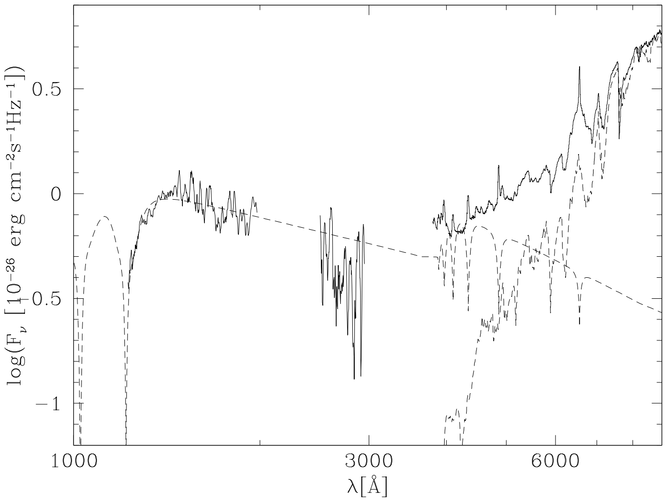

Fig. 2. Non-simultaneous IUE SWP / LWP and optical low state spectra of RX J1313. Plotted as a dashed line is the best-fit two temperature model from Fig. 1 and an observed M3 dwarf. Note that only the SWP data were used for the fit.

Table 1. IUE observations of RX J1313−32. Listed are the IUE frame numbers, the observation dates, and the exposure times.

Image No.	Exp. start (UT)	Exp. time (sec)
SWP56879L	02 Mar 1996 08:01:49	13800
LWP32069L	06 Mar 1996 18:20:31	2100

accretion activity. The broad flux turnover below ≈ 1400 Å is reminiscent of the photospheric Lyα absorption observed during low states, e.g. in AM Her (Szkody et al., 1982; Gänsicke et al., 1995) or DP Leo (Stockman et al., 1994). Our first approach was, thus, to fit the SWP data with non-magnetic pure hydrogen white dwarf model spectra (Gänsicke et al., 1995). However, none of the models could satisfyingly describe the observed spectrum. While the continuum requires a rather low temperature, $\approx 15\,000$ K, the steep slope in the narrow core of the Lyα absorption (1220 − 1300 Å) is in disagreement with the very broad Lyα line of such low-temperature models.

The analysis of low-state ultraviolet spectroscopy of other polars taught us that the white dwarfs often have a non-uniform temperature distribution over their surface (Gänsicke, 1998; Stockman et al., 1994), possibly due to heating by low-level accretion (Gänsicke et al., 1995). We, therefore, fitted the IUE data of RX J1313 with a two-temperature model, using again our non-magnetic pure hydrogen model spectra and leaving four free parameters; the temperatures and scaling factors of both components. The best fit is achieved by a white dwarf with a "base" temperature of $T_{\rm wd} = 15\,000$ K and a "spot" temperature of $T_{\rm spot} = 34\,000$ K (Fig. 1). For a distance $d = 200$ pc, as derived by Thomas et al. (1999), the white dwarf radius resulting from the scaling factors is $R_{\rm wd} = 1.1 \times 10^9$ cm. Assuming the Hamada-Salpeter (1961) mass-radius relation for a carbon core, the corresponding mass is $\sim 0.4\,M_\odot$, which is consistent with the mass derived by Thomas et al. (1999).

Because the IUE/SWP observation represents the orbital mean of the ultraviolet emission of RX J1313, the spot size cannot be directly estimated. Assuming that the ultraviolet-bright spot shows a similar variation as the X-ray spot observed with ROSAT (Thomas et al., 1999), we estimate a fractional area $f \sim 0.01$. For a somewhat larger spot, the temperature would be correspondingly lower.

Fig. 2 shows the IUE SWP and LWP spectra along with an average optical low state spectrum, as well as the two-component model. The flux of the LWP spectrum is somewhat lower than predicted by the model, which could be due either to heavy underexposure (Table 1) or to the fact that the LWP spectrum covers only ≈ 0.14 of the orbital period, possibly resulting in a lower spot-contribution than in the orbital-averaged SWP spectrum, or both. The agreement of the model spectra with observed optical flux is reasonably good, especially when considering that only the 1225–1900 Å range was used for the fit and that the ultraviolet and optical spectra were taken at different epochs. The summed spectrum of the white dwarf model and a red dwarf matching the red end of the RX J1313 spectrum has $V = 16.4$, which is in agreement with the observed low-state magnitude of the system (Thomas et al., 1999). During the low state, the optical and ultraviolet emission of RX J1313 is, hence, dominated by its two stellar components.

For completeness, we mention that an additional possible source of Lyα absorption is the interstellar gas. We computed the interstellar Lyα profile for the absorption column derived from the X-ray data, $N_{\rm H} = 9 \times 10^{19}{\rm cm}^{-20}$ (Thomas et al., 1999). The width of this line is smaller than the geocoronal emission in the SWP spectrum. Thus, interstellar absorption cannot explain the narrow "core" observed in the IUE spectrum.

4. A note on the use of non-magnetic model spectra

A major uncertainty in the computation of realistic hydrogen line profiles in magnetic atmospheres is the treatment of the Stark broadening in the presence of a magnetic field. The Stark broadening of the individual Zeeman components is smaller than that of the entire transition in the non-magnetic case, but no detailed calculations are available. This uncertainty can be taken into account by treating the amount of the Stark broadening as a free parameter in the model atmosphere calculation and calibrating it with observations (Jordan, 1992). For Lyα, this approach is, however, difficult. On one hand, there are only few single magnetic white dwarfs for which good ultraviolet spectroscopy has been obtained. On the other hand, the three Zeeman components of Lyα become visible as individual absorption features only for fields $B \gtrsim 100$ MG. For lower field strengths the Lyα profile is still dominated by the Stark effect and the Zeeman shifts introduce only an additional broadening which is, again, difficult to quantify.

An additional problem in the computation of synthetic Lyα profiles arises for low-temperature atmospheres ($T_{\rm eff} \lesssim 20\,000$ K). In ultraviolet observations of non-magnetic white dwarfs in this temperature range, quasi-molecular absorption of H_2^+ and H_2 produces strong absorption features at ≈ 1400 Å and ≈ 1600 Å, respectively, which are overlayed on the red wing of Lyα (Koester et al., 1985). Calculations of these transitions in the presence of a strong magnetic field have not yet been approached. We have retrieved the IUE spectra available for all magnetic white dwarfs listed by Jordan (1996), and find that in at best two of them the H_2^+ feature can be identified (BPM 25114, $B \approx 36$ MG and KUV 23162−1230, $B \approx 56$ MG). Also, none of the accreting magnetic white dwarfs in polars with $T_{\rm eff} \lesssim 20\,000$ K observed in the ultraviolet display noticeable H_2^+ absorption (Gänsicke, 1997). From Fig. 1 it is apparent that also the spectrum of RX J1313 is devoid of noticeable absorption at 1400 Å and 1600 Å. In summary, observations indicate that the H_2^+ and H_2 quasi-molecular absorption lines may be weaker in a strongly magnetic atmosphere than in a non-magnetic one.

Assuming a magnetic field strength of $B = 56$ MG for RX J1313, as derived by Thomas et al. (1999) from the cyclotron emission, the expected shift of the σ^+, σ^- components is ± 34 Å, causing the centre of the σ^+ component to coincide with the steepest slope of the Lyα profile. While the Zeeman effect may broaden the observed Lyα profile, the reduced Stark broadening will cause an opposite effect. We estimate that the use of non-magnetic model spectra in the analysis of the Lyα profile may cause a temperature error of a about ± 1000 K.

We conclude that the theoretical uncertainties in the Stark broadening do presently not warrant the use of magnetic model spectra. The narrow core in the broad Lyα absorption observed in RX J1313 cannot be produced by magnetic effects supporting our interpretation of a rather cool white dwarf with a localized hot region.

5. Discussion

It is well established that the white dwarfs in CVs tend to be hotter than single white dwarfs. This observational result suggests that accretional heating takes place in addition to the secular core cooling of the white dwarfs in CVs (e.g. Sion 1991,1999). Furthermore, the white dwarfs in CVs below the period gap are on average cooler than those in CVs above the gap (Gänsicke 1997,1998; Sion 1991,1999). A combination of two effects is thought to be responsible for this difference: (i) the average age of the short-period CVs below the period gap is about an order of magnitude larger than that of CVs above the gap (Kolb & Stehle, 1996) and core cooling of their white dwarfs has progressed correspondingly; (ii) the average accretion rate in short-period CVs is about an order of magnitude lower than in long-period CVs (King, 1988), resulting in reduced accretional heating. Warner (1995) shows – admittedly only for a small sample of CVs – that the expected correlation between accretion rate and white dwarf temperature does, in fact, exist.

RX J1313 is the polar with the fourth-longest period. It is, therefore, expected to be rather young, to experience a comparatively high time-averaged accretion rate, and to have a correspondingly hot white dwarf. Contrary to these expectations, however, it harbours the coldest white dwarf of all the CVs above the period gap. In fact, the temperature of the white dwarf in RX J1313 is comparable to the average white dwarf temperature in short-period CVs. We suggest two possible scenarii which can explain the atypically low white dwarf temperature.

(a) RX J1313 has only recently developed from a detached pre-cataclysmic binary into the semi-detached state. Mass transfer is in the process of turning on and substantial heating of the white dwarf has not yet taken place. In this case, the observed effective temperature of the white dwarf allows to estimate a lower limit on the cooling age and, thereby, on the time elapsed since the system emerged from the common envelope. The time scale for the turn-on of the mass transfer is $\sim 10^4$ yrs, which is short compared to the $\sim 10^8$ yrs that a CV spends above the gap (Ritter, 1988). The probability of finding a CV in this stage of its evolution is rather small, but non-zero.

(b) RX J1313 is a "normal" long-period CV, but has more recently experienced a low accretion rate for a sufficiently long time interval ($> 10^4$ yrs) which allowed its white dwarf to cool down to its current temperature. Long-term ($\tau \gtrsim 10^4$ yrs) fluctuations of the accretion rate about the secular mean predicted from angular momentum loss by magnetic braking (King, 1988) are consistent with the large range of observed accretion rates at a given orbital period (Patterson, 1984; Warner, 1987). Two possible explanation for these fluctuations have been suggested. (b1) A limit-cycle in the secondary's radius driven by irradiation from the hot primary (King et al. 1995,1996) which causes a corresponding variation in the mass transfer rate. (b2)

CVs possibly enter a prolonged phase of low (or zero) $\dot{M}$ following a classical nova eruption, referred to as hibernation (Shara et al., 1986). RX J1313 may be such a hibernating CV. However, the low temperature of the white dwarf in RX J1313 argues against a very recent nova explosion. In V1500 Cyg, the white dwarf cooled from the nuclear burning regime, i.e. several 10^5 K in 1975 to $\sim 95\,000$ K in 1992 (Schmidt et al., 1995). On the theoretical side, Prialnik (1986) shows in a simulation of a $1.25\,M_{\odot}$ classical nova that the white dwarf reaches its minimum temperature ~ 8000 yrs after the nova explosion.

Two observational tests could help to decide whether RX J1313 is a rather "fresh" post-nova with its secondary only marginally filling its Roche-lobe: (1) A nova eruption may break synchronization, as observed in V1500 Cyg (Stockman et al., 1988; Schmidt & Stockman, 1991), causing the orbit to widen and the secondary to retreat from its Roche lobe. The resynchronization of the white dwarf spin with the orbital period occurs in V1500 Cyg apparently on a time scale of a few hundred years (Schmidt et al., 1995). More accurate ephemerides of RX J1313 than presently available (Thomas et al. 1999) are necessary to test for a small remnant asynchronism of the white dwarf spin. (2) The nova eruption may contaminate the binary system with material processed in the thermonuclear event, resulting in deviations from the typical population I abundances found in most CVs (Marks & Sarna, 1998). Anomalous ultraviolet emission line ratios similar to those observed in post-novae have been found in the asynchronous polar BY Cam (Bonnet-Bidaud & Mouchet, 1987). The white dwarf in BY Cam has $T_{\rm wd} = 20\,000$ K (Gänsicke, 1997), which is in rough in agreement with the temperature expected a few 1000 years after a nova explosion. BY Cam contains also a slightly asynchronously rotating white dwarf, which leaves the question of the expected time scale for resynchronization somewhat unsettled. High-state ultraviolet observations of the CNO lines in RX J1313 do not exist so far and will serve to test the post-nova hypothesis. If no evidence for a nova event should be found, RX J1313 is either very young as a CV or experiences a prolonged low state in some kind of mass transfer cycle.

Before we discuss the temperature of the white dwarf photosphere, $T_{\rm eff} = 15\,000$ K, we comment on the "warm" ultraviolet-bright spot with $T_{\rm eff} \simeq 34\,000$ K. RX J1313 is yet another polar in which the white dwarf appears to have a non-uniform temperature distribution. Other examples are AM Her (Gänsicke et al., 1995), DP Leo (Stockman et al., 1994), or QS Tel (de Martino et al., 1998). These hot spots are best explained by the localized irradiation of the photosphere with cyclotron and X-ray photons from the accretion funnel which is continuously fed at a low rate. In the case of RX J1313, we estimate the luminosity of the ultraviolet-bright spot to be $L_{\rm spot} \simeq 10^{31}$ ergs s^{-1}, corresponding to an accretion rate of $\dot{M} > 3 \times 10^{-12}\,M_{\odot}\,{\rm yr}^{-1}$, which is consistent with the low-state accretion rate, $\dot{M} \simeq 6 \times 10^{-12}\,M_{\odot}\,{\rm yr}^{-1}$, derived by Thomas et al. (1999).

We now discuss accretion heating of the white dwarf in RX J1313. As shown by Giannone & Weigert (1967) and by Sion (1995) this is an inherently time-dependent process. Accretion compresses the outer non-degenerate layers of the white dwarf which heat up approximately adiabatically if the accretion rate is high. The core suffers some compression, too, which heats primarily the non-degenerate ions. For intermittent accretion, the thermal inertia of the deep heating produces a time delay which causes an enhanced luninosity long after accretion stopped. For very low accretion rates, $\dot{M} \sim 10^{-11}\,M_{\odot}\,{\rm yr}^{-1}$, on the other hand, prolonged accretion may lead to a quasi-stationary state in which the energy loss balances compressional heating (Giannone & Weigert, 1967) and the temperature profile of the envelope remains stationary.

The simplest way to view compressional heating is to consider the energy released when the accreted mass is added. Since the envelope mass is small and represents a practically constant fraction of the white dwarf mass, $\dot{M}$ increases the mass of the degenerate core of mass $M_{\rm c} \simeq M_{\rm wd}$, radius $R_{\rm c}$, and temperature $T_{\rm c}$. The energy released per unit time is $GM_{\rm wd}\dot{M}(1/R_{\rm c} - 1/R_{\rm wd})$ of which some fraction feeds the initial degeneracy of the electrons reaching $R_{\rm c}$. Apart from a factor of order unity, this energy equals the work performed by compression, $P\,{\rm d}(1/\rho)/{\rm d}t$ with P the pressure and ρ the density, integrated over the envelope. Note that this energy release is different from that freed at the surface, which equals $GM_{\rm wd}\dot{M}/R_{\rm wd}$ in an AM Her star, and represents the additional energy released by compression of the envelope of the white dwarf between radii $R_{\rm wd}$ and $R_{\rm c}$. If compression is adiabatic, the work performed is used to increase the internal energy of the gas, as prescribed by the first law of thermodynamics. In the isothermal case, the released energy would completely appear as radiative loss. We consider here the case of slow compression and assume that the energy released by accretion at a rate $\dot{M}$ equals the increment in luminosity

$$L_{\rm acc} = \eta\, GM_{\rm wd}\dot{M}\left(\frac{1}{R_{\rm c}} - \frac{1}{R_{\rm wd}}\right) \quad (1)$$

where G is the gravitational constant, and we estimate that η is between 0.5 and 1.0. Core heating is a minor effect and adds only $\sim 10\,\%$ to $L_{\rm acc}$. Hence, the compressional energy is primarily released in the envelope, at an approximately constant rate per radius interval.

In equilibrium, accretion at a rate $\dot{M}$ can maintain an effective temperature $T_{\rm eff}$ of the white dwarf defined by $L = 4\pi R_{\rm wd}{}^2\sigma T_{\rm eff}{}^4 = L_{\rm acc}$, even if the white dwarf had cooled to a substantially lower temperature before the onset of accretion.

In their discovery paper, Thomas et al. (1999) derive a mass of the white dwarf in RX J1313 of $M_{\rm wd} \simeq 0.40 M_{\odot}$ and a secondary mass of $M_2 \simeq 0.45 M_{\odot}$, with uncertainties of about $0.10 M_{\odot}$. There was some concern about the mass ratio which should be $M_2/M_{\rm wd} < 0.7$ for stable mass transfer. For definiteness, we assume here $M_{\rm wd} \simeq 0.5 M_{\odot}$. Thomas et al. (1999) also derived a mass accretion rate which is very low compared to other long period CVs. They observed the system over seven years and found that it hovers most of the time at low accretion luminosities corresponding to $\dot{M} \sim 10^{-11}\,M_{\odot}\,{\rm yr}^{-1}$.

Only twice was the system found in an intermediate state with an accretion rate of $\sim 10^{-10}\,M_{\odot}\,\mathrm{yr}^{-1}$, during the ROSAT All-Sky-Survey and in a subsequent optical follow-up observation in February 1993. It was never observed at an accretion rate of $\sim 10^{-9}\,M_{\odot}\,\mathrm{yr}^{-1}$, the typical value of CVs with P_{orb}= 4–5 h (Patterson, 1984). To be sure, the derived accretion rates depend (i) on the adopted white dwarf mass and (ii) on the soft X-ray temperature and the bolometric fluxes of the quasi-blackbody source, and the quoted rates are probably uncertain by a factor of ~ 2.

A white dwarf of $0.5\,M_{\odot}$ has a core radius $R_{\mathrm{c}}= 9.3\times10^{8}$ cm and a radius $R_{\mathrm{wd}}\simeq 1.05\times10^{9}$ cm at T_{eff}= 15 000 K. For these parameters, we find an equilibrium temperature from compressional heating alone of $T_{\mathrm{eff}} \simeq 16400\,(\eta\dot{M}_{-10})^{1/4}$ K, where $\dot{M}_{-10}$ K is the accretion rate in units of $10^{-10}\,M_{\odot}\,\mathrm{yr}^{-1}$. The observed temperature of 15 000 K can be maintained by an accretion rate of $7\times10^{-11}\,M_{\odot}\,\mathrm{yr}^{-1}$ for $\eta \simeq 1$, which is within the observed range of mass transfer rates. Since the internal energy source of the white dwarf will contribute to the observed luminosity, the actual accretion rate required to maintain the photosphere at 15 000 K may be somewhat lower. Alternatively, the efficiency η of converting the compressional energy release into the observed luminosity may be lower. Within the uncertainties, however, it is also possible that the present temperature is almost entirely due to compressional heating and that the white dwarf had cooled to a temperature substantially below 15 000 K prior to the onset of mass transfer. In any case, the cooling age of 1.3×10^{8} yrs to reach 15 000 K (Wood, 1995) is a lower limit to the actual pre-CV age of the white dwarf. Since the Kelvin-Helmholtz time scale of the envelope is roughly of the order of 10^{4} yrs, the low temperature of the white dwarf requires $\dot{M}$ to have been low for a comparable length of time.

If RX J1313 is a CV in the process of turning on mass transfer we would expect that the accretion rate in RX J1313 would ultimately reach $\sim 10^{-9}\,M_{\odot}\,\mathrm{yr}^{-1}$ at which time the white dwarf has been compressionally heated to $T_{\mathrm{wd}} \approx 30000$ K, the temperature typically observed in CVs with $P_{\mathrm{orb}}\simeq 4$ h (Sion, 1999).

6. Conclusion

We conclude that the low temperature of the white dwarf in RX J1313 is consistent with compressional heating by mass accretion at a rate substantially lower than the $\sim 10^{-9}\,M_{\odot}\,\mathrm{yr}^{-1}$ expected for a long period CV. The system has not passed through a phase of high accretion rate within at least the last 10^{4} yrs which is the approximate Kelvin-Helmholtz time scale for the envelope. There are three possible previous histories of RX J1313: (a) it is a young CV in the process of turning on the mass transfer; (b1) it is in a long-lasting phase of low accretion within an irradiation-driven limit cycle; (b2) it has passed through a nova outburst shutting off mass transfer for a prolonged period. We cannot presently distinguish between cases (a) and (b1), while observational tests of (b2) have been suggested above.

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