Astron. Astrophys. 342, L45–L48 (1999)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Evidence for a brown dwarf in the TOAD V592 Herculis*

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Received 15 December 1998 / Accepted 12 January 1999

Abstract. We present optical R and I photometry of V592 Her obtained one year before its 1998 outburst. We identify V592 Her with a faint blue star, showing variability in R with a standard deviation of ~ 0.07 mag. With mean quiescent magnitudes of $R = 21.5$ and $I = 21.4$, its outburst amplitude is ~ 10 mag, which is at the very upper end of the range observed for Tremendous-Outburst-Amplitude Dwarf novae. A main sequence secondary would imply a distance > 1500 pc, which is inconsistent with the absolute magnitudes in outburst and quiescence expected for a dwarf nova. We conclude that the secondary is a brown dwarf. The quiescent flux is almost completely from the white dwarf, which gives a white dwarf temperature of $10\,000$ K and a distance of ~ 700 pc. The non-detection in a ROSAT PSPC observation implies an upper limit to the X-ray luminosity of $\lesssim 4 \times 10^{30}$ erg s^{-1} and to the accretion rate onto the white dwarf of $\lesssim 10^{-12}\,\mathrm{M}_{\odot}\mathrm{yr}^{-1}$.

Key words: accretion, accretion disks – stars: individual: V592 Her – stars: low-mass, brown dwarfs – stars: novae, cataclysmic variables – X-rays: stars

1. Introduction

V592 Her (Nova Herculis 1968, S 10376) was discovered by Richter (1968) on Sonneberg plates showing the object in outburst reaching 12.3 mag. Duerbeck (1987) tentatively classified V592 Her as a dwarf nova or, based on the similarity to V616 Mon (A0620-00), as an X-ray nova. Two more outbursts of V592 Her have been recorded: one in 1986 (Richter 1986a) and one very recently (Waagen 1998). Richter (1986b) reports that no outburst was recorded on 397 sky patrol plates taken between 1929 and 1966. A recurrence time of ~ 15 yr and an outburst amplitude of $\gtrsim 9$ mag are not unusual for a recurrent nova, but the reported decay time of $t_3 = 27$ days and the blue color at maximum are most consistent with a dwarf nova (Duerbeck 1987). Howell et al. (1995) list V592 Her as a member of the "tremendous outburst amplitude dwarf novae" (TOADs), a group of dwarf novae which show outburst amplitudes of 6–10 mag and interoutburst times of months to decades. The presence of superhumps with a period of ~ 1.5 hr during the 1998 outburst (Duerbeck & Mennickent 1998) rules out the recurrent nova hypothesis, and makes V592 Her a TOAD with one of the largest outburst amplitudes.

Duerbeck (1987) proposed two candidate identifications for the postnova. Unfortunately, the labels on his finder chart are inconsistent with the given positions. Howell et al. (1991) obtained photometry of the field of V592 Her and claimed that only Duerbeck's candidate star #1 showed significant variability, with large-amplitude flickering of ~ 0.5 mag over a 1.7 hr time interval. The position of V592 Her measured from a recent outburst image (Masi 1998) corresponds almost exactly to the coordinates of Duerbeck's star #1. In this *Letter*, we re-address the identification of the quiescent object and present R and I-band photometry of V592 Her obtained almost exactly one year before its 1998 outburst and serendipitous ROSAT X-ray observations obtained in 1992.

2. Optical observations

On August 1–5, 1997, we obtained R and I CCD photometry with the IGI focal reducer at the 2.1m telescope at McDonald Observatory. Using a f/1.96 135 mm camera lens and a 1026×1024 TK4 CCD with 24μ pixels, the measured scale was $\sim 0.31''$/pixel and the field of view almost $6' \times 6'$. Conditions ranged from photometric to very poor, with a seeing of $1.2 - 1.8''$. We obtained 41 R images and 40 I images, most of them with exposures of 6 min and most of the images taken in the first 3 nights when conditions were best. Relative fluxes of all stars near the nova position were obtained by measuring intensities within $1.5''$ circular apertures centered on the star. Typical errors in the derived differential magnitudes were 0.05 mag in R and 0.1 mag in I for a 21 mag star. Magnitudes in the Johnson-Kron-Cousins photometric system were estimated by comparison with images of Landolt fields (Landolt 1992) taken during the photometric night.

3. Astrometry

In order to measure the position and proper motion of V592 Her, we obtained scanned images of three archival plates from the

* Based on observations collected at McDonald Observatory, Texas

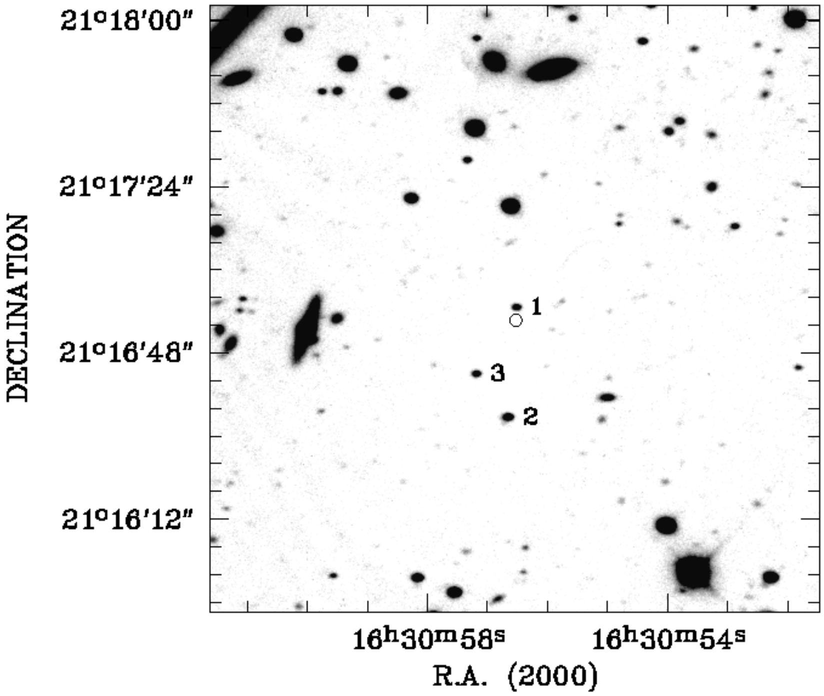

Fig. 1. Mean R image of V592 Her. Stars 1 and 2 correspond to Duerbeck's candidates 1 and 2. Star 3 is very red and may not have been visible on Duerbeck's CCD frame. The circle shows the position of Nova Herculis 1968 obtained from Sonneberg plates. The galaxies belong to the cluster 1629.1+2140 or the cluster 1626.2+2045. The streak in the upper left-hand corner is a diffraction spike of β Her

Sonneberg Plate Stacks taken during and after the 1968 eruption. The plates were taken with the GC-Astrograph (400 mm aperture, f/4) on 1968 June 30, 31 and July 29. The astrometric analysis was performed using both our own routines and the MIDAS `ASTROMET` package using 30 stars from the HST Guide Star Catalogue.

The image of V592 Her from 1968 June 30 was too saturated to provide an accurate position, but the other two plates both provided a position of $\alpha_{2000} = 16^h30^m56.35^s \pm 0.4''$ and $\delta_{2000} = +21°16'54.8'' \pm 1.5''$. This position corresponds almost exactly to that of Duerbeck's candidate #1 (though not to his finder chart) and is only $\sim 3''$ away from a very faint star on our McDonald R-band images.

The position of our candidate star was obtained by adding 20 secondary standards measured from the Digital Sky Survey image to the 5 GSC stars in the field: $\alpha_{2000} = 16^h30^m56.32^s \pm 0.5''$ and $\delta_{2000} = +21°16'57.9'' \pm 0.6''$, in agreement with the position measured during the recent outburst by Masi (1998). Thus, this faint star is clearly V592 Her in quiescence. From our photometry we derive mean magnitudes for V592 Her of $R = 21.49 \pm 0.03$ and $R-I = 0.11 \pm 0.04$. Given an outburst brightness of $V = 12.0$ (Waagen 1998), the amplitude of the 1998 outburst was ~ 10 mag. We note that there is no evidence for a nova shell down to a magnitude of ~ 25, which would be expected if the outbursts of V592 Her are the result of thermonuclear runaways.

Our mean R-band image is shown in Fig. 1, along with the mean Sonneberg position. The slight difference between the 1968 and 1998 positions corresponds to a proper motion of $3 - 12''$/century, or a velocity perpendicular to the line-of-sight of $70 - 280$ km/s at a distance of 500 pc - a reasonable velocity for an old disk or halo cataclysmic variable (CV).

4. Optical variability

In Fig. 2 we show the R and I light curves obtained in the first 3 nights, together with those of stars #2 and #3. The latter two do not show any sign of variability, with 3σ upper limits to random peak-to-peak variability of $\Delta R < 0.08$ mag and $\Delta I < 0.10$ mag for star 3, and $\Delta R < 0.08$ mag and $\Delta I < 0.07$ mag for star 2. V592 Her on the other hand, shows 98.9% significant variability in R with a standard deviation of ~ 0.07 mag (3σ upper limit to random peak-to-peak variability of $\Delta R < 0.15$ mag). There is no sign of any systematic variability such as an orbital modulation, and the variability in R looks more like random flickering. Because V592 Her is much fainter in I we can only put a 3σ upper limit of $\Delta I < 0.23$ mag.

Howell et al. (1991) report much larger-amplitude flickering (~ 0.5 mag in wide R) from Duerbeck's star #1 (assuming that their identification refers to the publeshed coordinates).

5. Distance

With galactic coordinates $l = 39°, b = 40°$, the reddening to V592 Her is probably not very large. Using the stellar reddening data for this direction from Guarinos (1992), the estimated visual extinction is $A_v \approx 0.07$, which gives $E_{R-I} \lesssim 0.03$. $R-I = 0.1$ then corresponds to a late-A spectral type.

We can obtain crude estimates of the distance via statistical comparisons with other dwarf novae. With the orbital period $P_{\rm orb} \approx 1.5$ hr estimated by Duerbeck & Mennickent (1998) from the superhump period, the correlation between $M_{\rm V}$(min), $P_{\rm orb}$, and the outburst recurrence time (Warner 1987) suggests $M_{\rm V}(\min) \sim 13$, which yields $d \sim 500$ pc. The correlation between $M_{\rm V}$(max) and $P_{\rm orb}$ suggests (for a superoutburst) $M_{\rm V}(\max) \approx 3.8 - 5.3$ (Warner 1995), which, when combined with the recent maximum brightness of 12.0, yields a distance of $d \sim 220 - 440$ pc. A similar distance estimate can be obtained by using Eq. (11) of Warner (1987), which gives the visual magnitude of an optically thick disk with a mean surface brightness depending on $(B-V)_0$ and a size depending on $P_{\rm orb}$ and the white dwarf mass. With an assumed very blue disk with $(B-V)_0 \sim -0.3$, we find $M_{\rm V}(\max) \sim 4 - 6$, in agreement with the estimate above. It is possible that TOADs do not fit very well in the above correlations, in particular because the mass in the thermally critical pre-outburst disk may be significantly larger than in a typical dwarf nova, in which case the outburst disk could be brighter by 1–2 mag. In any case, however, the distance of V592 Her is certainly less than 1 kpc.

6. The nature of the secondary

The properties of the secondary star are constrained by the distance derived above and the quiescent photometric magnitudes and color. A blue main-sequence star dominating the observed flux is clearly ruled out because this would imply a huge distance of $\gtrsim 60$ kpc. An orbital period of ~ 1.5 hr corresponds either to a main-sequence M5V donor of $\sim 0.13 M_\odot$ with absolute magnitudes $M_{\rm R} = 12.99$ and $M_{\rm I} = 11.36$ (Baraffe et al. 1998), or to a much fainter brown dwarf donor of $\sim 0.03 - 0.04 M_\odot$ with $M_{\rm R} > 19$ and $M_{\rm I} > 17$ (Allard et al. 1996).

The large outburst amplitude and blue color suggest that the quiescent light, even in the R- and I-bands, is mostly from the white dwarf. If the secondary is a quasi-main-sequence star, however, it may also contribute some flux, in particular in the I-band. The ($\sim 3\sigma$) upper limit on the intrinsic color, $(R-I)_0 < 0.2$, gives a lower limit on the white dwarf temperature: with an M5V secondary (using Baraffe et al. 1998) we find $T_{\rm wd} > 20\,000$ K ($> 65\,000$ K) for a $0.4 M_\odot$ ($1.4 M_\odot$) white dwarf. With $R = 21.5$, this in turn gives a lower limit on the distance of $d > 1500$ pc (almost independent of the white dwarf mass). Since this is clearly inconsistent with the much lower distance estimated above from the outburst magnitude and the quiescent brightness–recurrence time correlation, this strongly suggests that the secondary star in V592 Her is not a normal hydrogen burning star, but a brown dwarf.

If the secondary is indeed a brown dwarf, the R flux must be almost completely from the white dwarf. Scaling the pure-hydrogen white dwarf models of Bergeron et al. (1995) to the Nauenberg (1972) mass-radius relation (for $0.4 - 1.0\,{\rm M}_\odot$ roughly given by $R_1 \approx 8.4 \times 10^8\, m_{0.6}^{-0.73}$ cm with $m_{0.6}$ the white dwarf mass in units of $0.6{\rm M}_\odot$), and taking $R_0 = 21.44 \pm 0.04$, and $(R-I)_0 = 0.09 \pm 0.04$, we derive a white dwarf temperature of $(10\,000 \pm 800)$ K and a nominal distance $d \approx (710 \pm 70)\, m_{0.6}^{-0.73}$ pc (400–1000 pc for typical masses between 1.0 and 0.4 ${\rm M}_\odot$). Given the uncertainties, this is quite consistent with the distance derived in the previous section.

The presence of small-scale variability suggests that some quiescent accretion was occuring a year before the 1998 outburst. At such low mass-accretion rates, however, the color of the disk contribution is likely to be very red (Paschen continuum emission), minimizing the disk contribution in R. If the disk flux does contribute in I, the inferred distance and white dwarf temperature are both somewhat higher, but our conclusions about the nature of the secondary are unchanged.

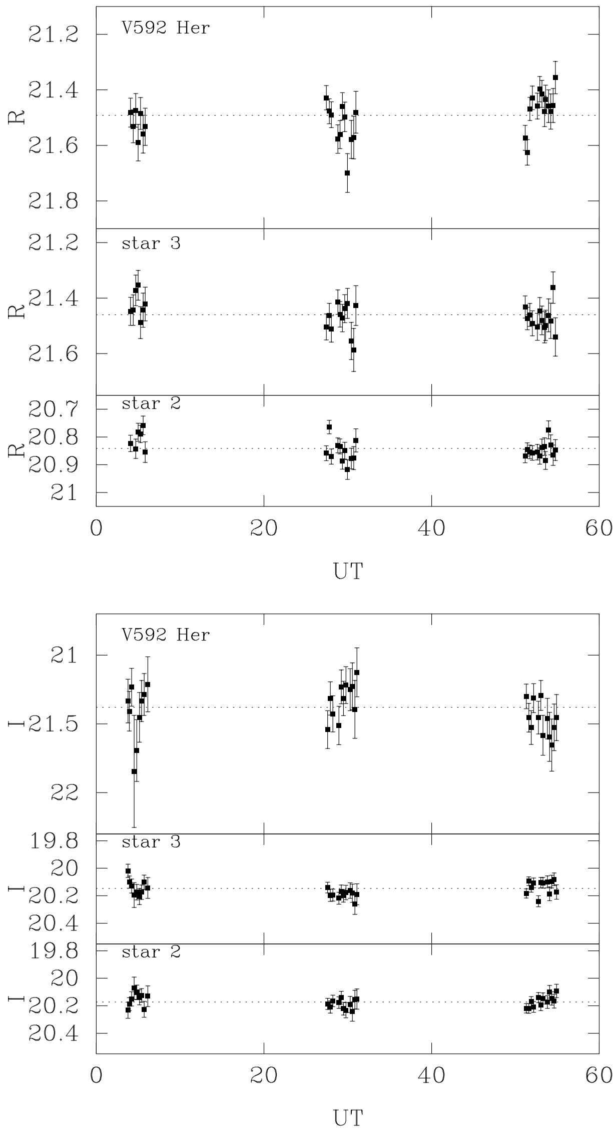

Fig. 2. R and I light curves of V592 Her and the neighbouring comparison stars 2 and 3. UT time is measured in hours from JD 2450 662.5

The known temperatures of white dwarfs in non-magnetic CVs range from 12 000 to 50 000 K (Gänsicke 1999). Certainly, cooler white dwarfs are more difficult to measure and the known temperatures are biased towards higher values because of selection effects. However, the estimated temperature of $\sim 10\,000$ K for the white dwarf in V592 Her is on the low side, and is likely the result of a low long-term mean mass-accretion rate.

7. Quiescent X-ray luminosity and accretion rate

V592 Her is in the pointed ROSAT PSPC observation of β Her (obs. id. 201228p), obtained on 1-4 September 1992, but was not detected in this 5563 s observation, with a 3σ upper limit to the count rate in channels 11–240 of < 0.0038 cts s^{-1}. For a moderately absorbed ($n_{\rm H} < 3\times10^{20}$ cm^{-2}) 1–10 keV bremsstrahlung spectrum (typical for a non-magnetic CV; Van Teeseling & Verbunt 1994), this corresponds to an unabsorbed 0.1–2.4 keV flux of $< 6 \times 10^{-14}$erg cm^{-2}s^{-1} and a 3σ upper limit for the 0.1–2.4 keV luminosity of $< 4 \times 10^{30}\ m_{0.6}^{-1.46}$ erg s^{-1}. With an estimated ultraviolet+optical flux of $\sim 10^{-13}$erg cm^{-2}s^{-1}, we note that the upper limit for the X-ray flux gives a ratio of 'bolometric' X-ray to ultraviolet+optical flux of $\lesssim 1$, consistent with a dwarf nova in quiescence (Van Teeseling et al. 1996). Assuming that roughly half of the total accretion energy is released in observable X-rays (which is only true for very low accretion rates and also depends on the orbital inclination) the corresponding mass-accretion rate onto the white dwarf is

$$\dot{M}_{\rm x} \approx \frac{2\,R_1\,L_X}{GM_1} \lesssim 1 \times 10^{-12}\, m_{0.6}^{-3.2}\,{\rm M}_\odot{\rm yr}^{-1} \quad (1)$$

We can crudely estimate the disk luminosity and the mass-transfer rate by assuming that the optical flickering is due to a classical "bright spot" radiating at the canonical temperature of $\sim 10\,000 - 15\,000$ K: if the bright-spot R-band flux is $4 - 10\%$ of $F_{\rm R}$ ($\Delta R \sim 0.07$ mag), then the bright-spot luminosity is $L_{\rm spot} \approx 0.2 - 1 \times 10^{30}\ m_{0.6}^{-1.46}$ erg s^{-1}. This bright-spot luminosity is produced by the gravitational potential drop between the L$_1$-point and the outer disk radius, the latter roughly equal to the 3:1 resonance radius $R_{3:1} \approx 1.9 \times 10^{10}\ m_{0.6}^{1/3}$ cm needed to produce the observed superhump phenomena (Warner 1995, p. 207, with $P_{\rm orb} = 1.5$ hr). We then derive an estimated mass-transfer rate (Warner 1995, p. 83)

$$\dot{M}_{\rm spot} \approx \frac{8\,R_{3:1}\,L_{\rm spot}}{GM_1} \approx 0.6 - 3 \times 10^{-11}\, m_{0.6}^{-2.13}\,{\rm M}_\odot{\rm yr}^{-1} \quad (2)$$

Given the fact that the accretion disk is not in a steady-state, that the inclination and white dwarf mass are not known, that Eq. (2) is based on very crude approximations, and that the inner disk may also contribute to the flickering, this is not in contradiction with Eq. (1).

We can also estimate the mean long-term transfer rate from the outburst energy and recurrence time: With $V({\rm max}) = 12$, $BC \approx -2$ (as appropriate for a blue outburst disk; Paczyński & Schwarzenberg-Czerny 1980), and $t_3 \sim 27$ d, we obtain a mean outburst luminosity of $L_{\rm outb} \sim 10{\rm L}_\odot$ and, for a recurrence time $t_{\rm rec} \sim 15$ yr, a transfer rate

$$\dot{M}_{\rm outb} \approx \frac{2\,L_{\rm outb}\,t_3\,R_1}{t_{\rm rec}\,GM_1} \approx 6 \times 10^{-11} m_{0.6}^{-3.19}\,{\rm M}_\odot{\rm yr}^{-1}. \quad (3)$$

The mean mass transfer rate inferred for short-period CVs is $\sim 4 \times 10^{-11}\ {\rm M}_\odot{\rm yr}^{-1}$ (Patterson 1984), but this is dominated by systems with hydrogen burning secondaries. With a degenerate brown dwarf secondary the mass-transfer rate driven by gravitational radiation at $P_{\rm orb} = 1.5$ hr and for $M_2/M_1 \ll 1$ is

$$\dot{M}_{\rm GR} \approx 3 \times 10^{-12}\, m_{0.6}^{2/3}\,{\rm M}_\odot{\rm yr}^{-1}. \quad (4)$$

With a relatively massive white dwarf $\dot{M}_{\rm x}$, $\dot{M}_{\rm spot}$, $\dot{M}_{\rm outb}$, and $\dot{M}_{\rm GR}$ are all consistent at $< 10^{-11}\ {\rm M}_\odot{\rm yr}^{-1}$.

8. Conclusions

We have presented optical and X-ray photometry of V592 Her in quiescence obtained one year before the 1998 outburst. The R-band brightness of $R = 21.5$, flickering amplitude of $\Delta R < 0.15$ mag, the large outburst amplitude of 10 mag, and the blue $R-I$ color of $R-I = 0.1$ are consistent with a nearly bare white dwarf with a low temperature of $\sim 10\,000$ K and a distance of $400 - 1000$ pc. Combining the empirical $M_{\rm V}({\rm max})$–$P_{\rm orb}$ relation for dwarf novae with the observed $V({\rm max}) = 12$, and the correlation between $M_{\rm V}({\rm min})$ and the outburst recurrence time with the observed $R({\rm min}) = 21.5$, we have shown that the distance is likely to be significantly less than 1 kpc.

Given an orbital period of 1.5 hr, the presence of a main sequence secondary is unlikely, because the implied distance of > 1500 pc is very difficult to reconcile with the observed outburst and quiescent magnitudes. This suggests that V592 Her contains a degenerate brown dwarf secondary and has passed through the period minimum of CVs, as has been speculated lately to be the case for TOADs in general (e.g. Politano et al. 1998). The low mass-transfer rate expected for a brown dwarf secondary is consistent with the non-detection in X-rays, the low bright-spot luminosity inferred from the small-amplitude flickering, the long inter-outburst timescale, and the low white dwarf temperature.

Acknowledgements. We would like to thank G.A. Richter and P. Kroll for providing scanned images of the Sonneberg plates. This research was supported by the DARA and the Deutsche Forschungsgemeinschaft under grants 50 OR 96 09 8 and He 2296/11-1&11-2.

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