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CSS091109:035759+102943 – a candidate polar

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We report optical time-resolved photometry of the CRTS transient CSS091109:035759+102943. Pronounced orbital variability with a 114 min period, large X-ray variability and the IR to X-ray spectral energy distribution suggest a classification as a magnetic cataclysmic binary, a likely AM Herculis star or polar.

1 Introduction

Polars are magnetic cataclysmic variables (CVs) harboring a strongly magnetic white dwarf which accretes matter from a late-type main-sequence star (for a comprehensive overview see Warner 1995). Accretion in the strongly magnetic environment happens initially via free-falling streams which are later threadened by the magnetic field so that a quasi-radial accretion column in the vicinity of the magnetic pole(s) arises. These accretion regions are sources of hard and soft X-rays from the thermal plasma and the heated polar cap(s). Consequently, many of the ∼100 now known polars were identified as optical counterparts of soft X-ray sources detected in the ROSAT all-sky survey (RASS, e.g. Beuermann & Schwope 1994). More recently, numerous CVs have been identified spectroscopically in the SDSS (Szkody et al. 2011, and references therein). Despite the large collecting area of XMM-Newton and Chandra, only a few objects have been discovered with these observatories due to the low surface density of the objects.

An alternative route to discover CVs involves comprehensive photometric surveys performed with a high cadence like the Catalina Real-time Transient Survey (CRTS; Drake et al. 2009). The CRTS variable CSS091109:035759+102943 was suggested to be a magnetic cataclysmic variable in an eMail notification by the variable star network VSNET. This preliminary identification rested on significant intra-night variability and transitions from low to high optical states observed in the CRTS and the association with a cataloged X-ray source (2XMM J035758.6+102938; Watson et al. 2009).

Here we describe time-resolved follow-up photometry of CSS091109:035759+102943 (henceforth CSS091109) which, combined with archival multiwavelength data, led to the (almost) unique identification of the new variable.

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2 Observations and analysis

2.1 Time-resolved photometry

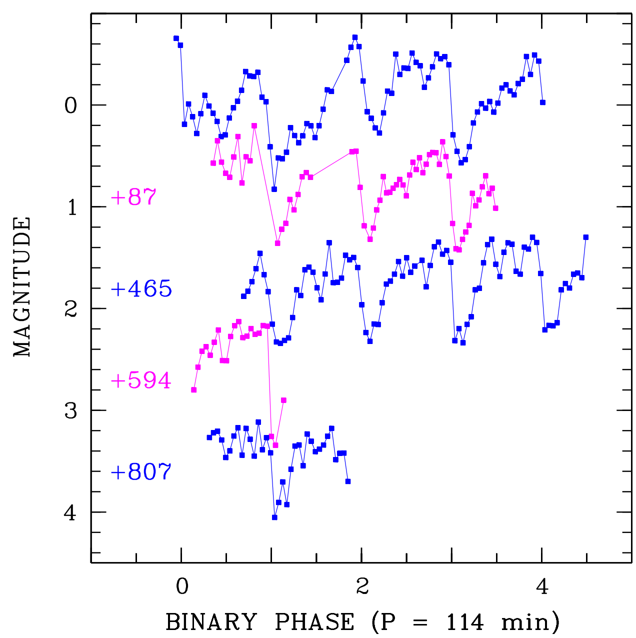

Fig. 1 White-light time-resolved photometry of CSS091109 obtained at Inastars observatory with a time resolution of 5 min. Shown are data from five nights, each vertically shifted by 0.9 magnitudes. Data appear in original time sequence, but transformed to orbital phase using Eq. 1. The phase offset per night is indicated in the figure.

Time-resolved white-light photometry of the field of the CRTS-variable was obtained during 6 nights between Nov. 19, 2009 and Jan. 22, 2010, from Potsdam-Bornim using a robotically controlled Celestron C14 equipped with an ST8XME CCD-camera. The observations were made

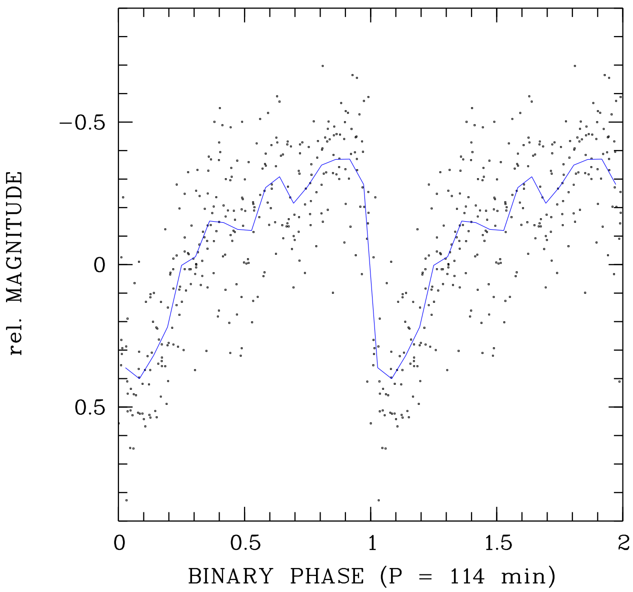

Fig. 2 Phase-folded light curve of CSS091109. The mean brightness per night was subtracted from the individual data points obtained during that night. The blue line gives the mean brightness after binning into 18 phase bins. Phases were computed according to Eq. 1.

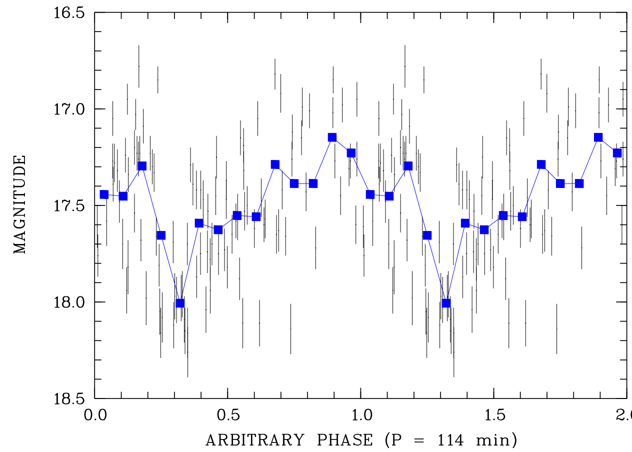

Fig. 3 High-state phase-folded light curve of CSS091109 based on CRTS data. Shown are the original data with their error bars and phase-averaged data binned into 14 phase bins.

through a CLS-filter from Astronomik with full transmission between 450 nm and 540 nm and longward of 635 nm thus suppressing Hg- and Na-lines from street lamps.

Differential photometric measurements were made with respect to the 14.5 mag comparison star USNO B1.0 1005-0036054, while USNO B1.0 1005-0036059 (14.5 mag) and USNO B1.0 1005-0036004 (14.7 mag) served as reference stars. In sum, 331 individual measurements were made with a median uncertainty of 0.08 mag after five minutes of integration. Individual zero points displayed nightly variability of about 0.04 mag; both uncertainties do not affect the result of our study.

We found the object displaying pronounced variability with a peak-to-peak amplitude of about 0.8 mag. A period search was performed using the TSA-package within MIDAS. It revealed just one pronounced peak in a Lomb-Scargle periodogram at 114 min that could already be spotted in the nightly raw light curves.

The most pronounced feature in the light curve is a steep decrease of the brightness from a maximum value into a dip-like minimum. We measured the times of dip ingress at half light between maximum pre-dip and average dip-brightness via graphic cursor in our data (13 epochs with measurement uncertainty of about 90 s). A linear regression combining the 13 epochs of this feature revealed an ephemeris

$$\mathrm{BJD}(T_0) = 2455155.3658(4) + E \times 0.079181(1) \quad (1)$$

where the numbers in parenthesis indicate the uncertainties in the last digits. This ephemeris was used to create the final versions of the light curve plots, both in original time sequence and after phase-binning involving all individual measurements (Figs. 1 and 2). The mean light curve displays a saw-tooth shape. The dip feature lasts about 0.2 phase units. After the dip the brightness increases more gradually until the steep decrease into the dip phase begins. The 114 min periodicity is interpreted as being due to the orbital motion of a binary star and the apparent brightness of the star, orbital variability $16.8 - 18.0$, indicates that it was observed in a high accretion state.

2.2 Archival CRTS photometry

We retrieved the currently available CRTS data obtained between Sep. 11, 2007, and Mar. 16, 2011, from the CRTS archive (211 individual measurements)[1]. The data can be grouped into low (orbital variability only below 18.3 mag), intermediate (orbital variability between $17.3 - 19.4$) and high accretion states (orbital variability between $16.8 - 18.2$). An independent period-search within the high-state data revealed weak evidence for the same 114 min periodicity but could not be used to improve the accuracy of the ephemeris. A phase-binned representation of the CRTS high-state data using the period given in Eq. 1 is reproduced in Fig. 3. The light curve has similar shape and amplitude of variability as obtained from our dedicated follow-up. It thus appears that the shape of the light curve displays a rather stable pattern, at least in the high accretion state.

2.3 The spectral energy distribution

The VIZIER online tool was used to search for additional observational data from wide-field imaging surveys. Data are available from WISE, GALEX, ROSAT-HRI and XMM-Newton. The object has no entry in the 2MASS point source catalog. We therefore retrieved catalogs from

[1] available at http://nesssi.cacr.caltech.edu/catalina/20091109/911091090214133107.html

2MASS in that field and determined an upper limit magnitude for JHK from 50% completeness. Those data are indicated with arrows in the $(\nu, \nu f_\nu)$ diagram of Fig. 4. GALEX revealed a detection in the FUV band only with a relatively large error (3σ detection) but not in the NUV band.

The photometric data from the Catalina survey are shown in Fig. 4 with blue lines. The length of the line indicates the amount of orbital variability in the high and the low accretion states, respectively.

The XMM-Newton count rates from the 2XMM-catalog were transformed to fluxes using the standard energy conversion factors which assume an AGN-type power law spectrum as emission model. CSS091109 was discovered in all five standard energy bands between 0.2 and 10 keV with. XMM-Newton revealed 53 photons during an observation that lasted 15977 s, i.e. which covered 2.3 orbital cycles of the 114 m binary. There is a ROSAT discovery as well made with the High Resolution Imager (HRI). The HRI has no energy resolution, and the count rate of $5.3 \times 10^{-4}\,\mathrm{s}^{-1}$ was transformed to flux assuming a thermal bremsstrahlung model. The flux observed with ROSAT was found to be a factor ∼10 higher than the flux from the XMM-Newton observation indicating changes in the mass accretion rate perhaps of that order. The XMM-Newton data do not show an obvious indication of a soft component,

WISE detections are reported in the windows W1-W3 at 3.4, 4.2, and 12 μm, respectively but not in W4, the longest wavelength band at 22 μm. The color W1-W2 = 0.61 is slightly redder than expected for any main-sequence star and in particular redder by about 0.3 mag than a main-sequence star filling the Roche lobe of a 114 min binary (Kirkpatrick et al. 2011). The observed color W2-W3 = 2.56 is even redder than any known brown dwarf. This kind of IR excess might be due to cyclotron radiation but much more likely due to a circumbinary disk (see Brinkworth et al. 2007; Hoard et al. 2007, for similar cases and a more comprehensive discussion). If we assume that the mass-donating (secondary) star follows the spectral sequence described by Knigge (2007) it should have spectral type dM4.8 which corresponds to $T_{\rm eff} \simeq 3200$ K. Such a template spectrum is shown in Fig. 4, scaled to make it consistent with the CRTS photometry, the non-detection in the 2MASS point source catalog, and to reflect the observed WISE flux in the W1 and W2 bands, respectively.

The non-detection of CSS091109 in 2MASS, $K_{\rm lim} \geq 15.9$, suggests a distance larger than 350 pc if we assume a secondary star with that brightness following Knigges's donor star sequence, $K = 8.08$ at $P_{\rm orb} = 114$ min.

3 Discussion and conclusion

We interpret the periodicity of 114 min detected in time-resolved photometry of CSS091109 and covering more than 800 cycles as the orbital period of a cataclysmic binary. The stable pronounced variability, the change between high

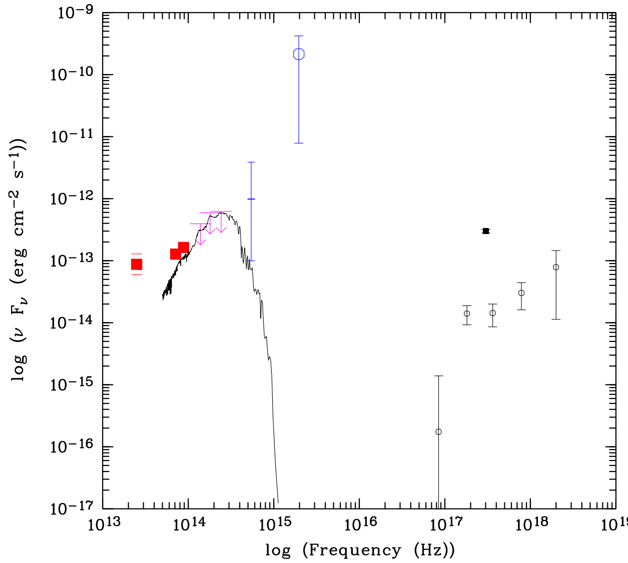

Fig. 4 Infrared to X-ray spectral energy distribution of the CSS091109. Included are data (from low to high frequencies) from the WISE satellite, 2MASS upper limits, the CRTS, GALEX, ROSAT, and XMM-Newton. The black curve adapted to the optical/infrared spectral range is a $T_{\rm eff}$ =3200 K model spectrum used as template for an assumed M5 donor star.

and low brightness states in the optical and at X-ray wavelengths, and the overall shape of the SED are strongly suggestive of a magnetic binary, a so-called polar or AM Herculis star. Final confirmation though could be derived from time-resolved optical spectroscopy or polarimetry.

The object is apparently non-eclipsing which restricts the inclination to something less than 73°. The light curve with its pronounced dip is likely shaped by absorption in an accretion stream, irradiation of the stream and the secondary star, projection effects of the stream and the accretion region on the white dwarf, and cyclotron beaming.

X-ray surveys with eROSITA will discover several 10^4 new compact binaries (Predehl et al. 2010; Schwope 2012). Massive spectroscopic surveys with e.g. 4MOST (de Jong et al. 2012) will reveal identification spectra and Gaia the distances for most of the CVs. Comprehensive photometric follow-up will be needed to uniquely identify the type of a cataclysmic binary and eventually to uncover the period distribution of the class, an opportunity for amateur involvement on a larger scale.

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