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Discovery of a Dwarf Nova Breaking the Standard Sequence of Compact Binary Evolution

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Abstract

We revealed that the dwarf nova 1RXS J232953.9+062814 is an SU UMa-type system with a superhump period of 66.774 ± 0.010 min. The short period strongly indicates that the orbital period of this object is below the period minimum of cataclysmic variables. The superhump period is $4.04 \pm 0.02\%$ longer than the photometric period during quiescence (64.184 ± 0.003 min), which is probably associated with the orbital period. Although the standard evolutionary scenario of cataclysmic variables predicts lower mass-transfer rates in systems with shorter orbital periods, we found firm evidence of a relatively high mass-transfer rate from its large proper motion and bright apparent magnitude. Its proximity indicates that we have overlooked a number of objects in this new class. With the analogous system of V485 Cen, these objects establish the first subpopulation in hydrogen-rich cataclysmic variables below the period minimum.

Key words: accretion, accretion disks — stars: binaries: close — stars: individual (1RXS J232953.9 + 062814)

1. Introduction

Cataclysmic variables (CVs) are compact binary systems in which the surface gas of a secondary star overflows and is accreted by a more massive white dwarf (Warner 1995). The long-lived mass-transfer is maintained by the continuous removal of their orbital angular momentum. In systems with short ($\lesssim 2$ hr) orbital periods, it is believed that the mass-transfer rate is governed by the angular-momentum loss caused by gravitational radiation (Taam et al. 1980). Losing angular momentum, systems evolve into those with shorter orbital periods, smaller secondaries, and hence lower mass-transfer rates. When the secondary star becomes degenerate, a decrease of mass leads to an expansion of the secondary, and then, an increase of the orbital period. The above scenario has been applied to explain the observed "period minimum" of about 80 min, and has been widely accepted as the standard evolution model of compact binary systems (Paczynski 1981; King 1988).

1RXS J232953.9+062814 was discovered as an X-ray source with the Röntgen Satellite (ROSAT) X-ray telescope (Voges et al. 1996). The object is identified with an optical source whose V-magnitude is 15.7 (Hu et al. 1998). Optical spectroscopy revealed two distinct states of this object (Hu et al. 1998). One is a faint state in which the optical spectrum is dominated by hydrogen emission lines, indicating that this object is a hydrogen-rich CV. Noteworthy features during this state are the relatively strong He I emission and TiO absorption bands, the latter being typical for M-type stars. The other state is a bright one in which the hydrogen lines appear in absorption. Based on these observations, this object has been classified as a dwarf nova (DN), a sub-group of CVs which experience repetitive outbursts with typical amplitudes of 2–5 mag (Warner 1987). DN outbursts are considered to be a suddenly enhanced release of gravitational energy induced by the thermal instability of an accretion disc (Osaki 1996).

Here, we report on the first detailed photometric observations of this object, including an outburst detected in 2001 November 3, in which we reveal that this object is an ultrashort period system with a relatively high mass-transfer rate. Our detailed results concerning superhump evolution in this system will be reported in a forthcoming paper.

2. Observation

Our CCD photometric observations were performed with 30-cm class telescopes from 2001 November 4 to December 4 at Kyoto (26 nights), Auburn (9), Wako (3), Bisei (1), Okayama (5), Tsukuba (5), Idstein (3), Landen (3), Clovis (10), Nyrola (2), and Potenza (1). The exposure time was 30–120 s. After dark subtraction and flat fielding on the images, we performed aperture photometry and obtained differential magnitudes of the object using a comparison star, GSC 591.1689. The constancy of the comparison star was checked by GSC 584.366. The magnitude scales of each observatory were adjusted to that of the Kyoto system. We could obtain magnitudes almost equal to the R_{c} system from observations at Kyoto in which we used an unfiltered ST-7E CCD camera, since the sensitivity peak of the camera is near that of the R_{c} system and the color of the object is $B - V \sim 0$. Heliocentric corrections to the observed times were applied before the following analysis.

3. Result

3.1. *Superoutburst in 2001 November*

Followig our detection of an outburst of this object on 2001 November 3 at 12.5 mag, we started CCD optical monitoring. Figure 1a shows the whole light curve during this outburst. The object gradually faded at a rate of $0.25\,\mathrm{mag\,d^{-1}}$ for the first 5 days. This decline rate is much slower than those observed in ordinary outbursts of DNe, and rather similar to those in superoutbursts of SU UMa stars. This plateau phase lasted for at least four days, and then the object rapidly faded. After the main outburst, we detected a short rebrightening starting on 2001 November 9, as can be seen in figure 1a. The brightness then gradually declined for about one week and returned to the quiescent level around 2001 November 18.

During the plateau phase, we discovered periodic modulations of brightness. The modulations appeared throughout the outburst, and even in the rebrightening and early quiescent phase. We show their typical light curves in figures 1b and c. The humps have a common profile of rapid-rise and gradual-decline, while their amplitudes decreased with time from about 0.25 to 0.10 mag. After we subtracted the linear fading trend from the light curve on November 4–7, we performed a period analysis on the humps during the plateau phase using the Phase Dispersion Minimization (PDM) method (Stellingwerf 1978). The best candidate of the period was then calculated to be 66.774 ± 0.010 min.

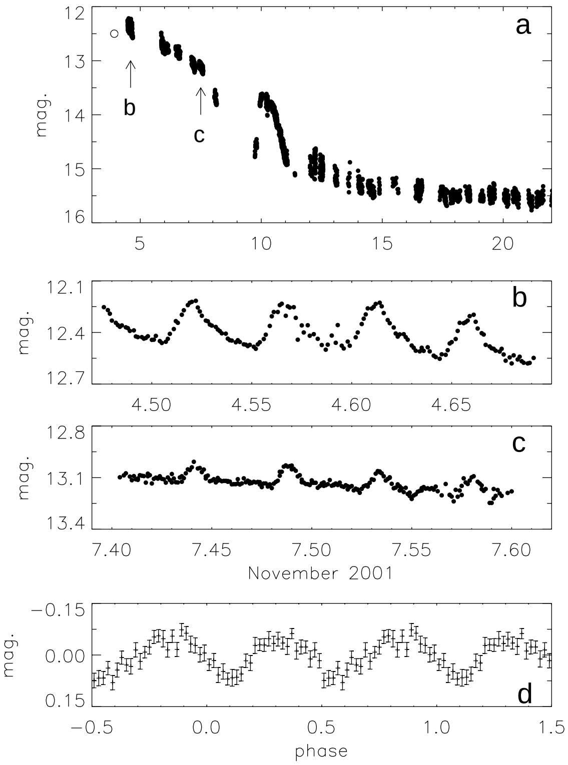

Fig. 1. Light curve of 1RXS J232953.9 + 062814 during the outburst in 2001 November. (a): The whole light curve of the outburst. The abscissa and ordinate denote the date and R_{c} magnitude, respectively. The open circle denotes the discovery of this outburst with the visual estimation performed by one of the authors (P.S.). (b) and (c): Light curves on November 4 and 7, respectively. The corresponding dates in these panels are marked in panel a. (d): Average light curve on November 19–December 4. We folded the light curves with the period of 64.184 min. The abscissa and ordinate denote the phase in this period and the relative magnitude, respectively. The epoch of the phase is arbitrary.

The characteristics of the humps are the same as those of superhumps, which are periodic modulations commonly appearing in SU UMa stars during their superoutbursts (O'Donoghue 2000). The period of superhumps is generally a few percent longer than the orbital period, which is now interpreted as a beat phenomenon between the orbital period and the period of slow apsidal motion of an elongated accretion disc caused by a tidal torque from the secondary star (Whitehurst 1988; Osaki 1989). Using the light curve in the quiescent phase (November 19–December 4), our PDM period analysis yielded a period of 64.210 ± 0.023 min. The period of the humps during the outburst was $4.036 \pm 0.015\%$ longer than this quiescent period. As shown in figure 1d, the profile of modulations during the quiescent phase was a double-peaked sinusoidal curve, which is completely different from those during the outburst, and hence, indicates their different natures. In conjunction with these two periodicities, we conclude that the periods during the outburst and quiescence can be identified by the superhump and orbital period, respectively. Using observations before this outburst, Zharikov and Tovmassian (2001)

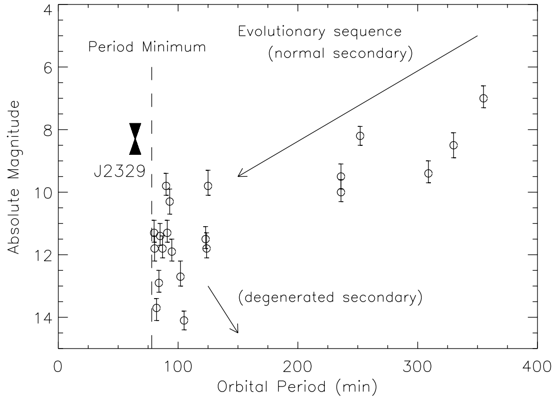

Fig. 2. Absolute magnitude of CVs as a function of their orbital period. We show the lower and upper limit of the quiescent brightness of 1RXS J232953.9 + 062814 as filled triangles and indicated by 'J2329.' The open circles denote DNe listed in Sproats et al. (1996). The arrows are schematic evolutionary sequences expected from theoretical models in which the orbital angular momentum is continuously removed from systems due to gravitational radiation. The upper and lower arrows correspond to that of CVs with a normal secondary star and a degenerated one, respectively. The vertical dotted line shows the observed period minimum (80 min).

reported a period of 64.2 ± 0.1 min, which is in complete agreement with our estimated one. This strongly supports the constancy of this period during quiescence, and that it is the orbital period. 1RXS J232953.9 + 062814 hence breaks the observed period minimum of about 80 min, which appears in hydrogen-rich CVs, as shown in figure 2.

3.2. *Estimation of the Distance and Absolute Magnitude*

The optical flux of a CV is dominated by emission from an accretion disc, particularly in short-period systems which have a very low-luminosity secondary. Since the emission from the disc is proportional to the mass-transfer rate, the absolute magnitudes (M_V) of CVs are good indicators of the mass-transfer rates (Sproats et al. 1996). To determine the absolute magnitude of an object, we need its distance. We applied two independent methods to set a limit on the distance of 1RXS J232953.9 + 062814, i.e., the transverse motion on the celestial plane and the famous empirical relation between the peak brightness and the orbital period ($P_{\rm orb}$) (Warner 1995).

Using our images taken on 2001 November, we measured the position of the object to be R.A. = $23^{\rm h}29^{\rm m}54\overset{\rm s}{.}23$ and Dec. = $+06^\circ 28' 12\overset{''}{.}4$ using template stars in the USNO-A2.0 catalogue (Monet et al. 1998). On the other hand, we obtained the position in 1951.6 using the USNO-A2.0 catalogue, in which it is reported to be R.A. = $23^{\rm h}29^{\rm m}54\overset{\rm s}{.}357$ and Dec. = $+06^\circ 28' 10\overset{''}{.}35$. From these positions, we obtained significant proper motions of ΔR.A. = 38 mas yr^{-1} and ΔDec. = 41 mas yr^{-1}. To calculate a secure upper-limit of the distance, we neglected the radial velocity and considered the transverse velocity of this object to be 100 km s^{-1}, which corresponds to the maximum expected velocity dispersion of CVs (Harrison et al. 2000). With the above proper motion, it yields a distance of < 380 pc.

With the framework of the disc-instability model for DN outbursts, the peak luminosities strongly depend on the amount of mass stored in the disc, namely the size of the disc and the binary system (Osaki 1996). The well-known empirical law $M_V(\text{peak}) = 5.74 - 0.259\,P_{\rm orb}(\text{hr})$ can be interpreted with this theoretical prediction (Warner 1995). The peak magnitude in this equation is not those in superoutbursts which are accompanied by superhumps, but in normal ones whose peak magnitudes are generally fainter than those of superoutbursts. We can thus obtain a lower limit of the distance from our observations of the superoutburst of 1RXS J232953.9 + 062814. The above equation indicates that the 64.2-min orbital period yields a peak absolute magnitude of 5.46 mag. With the observed apparent magnitude of 12.41 mag, we calculated the lower-limit of the distance to be ~ 245 pc, while neglecting intersteller extinction and a term concerning the inclination of the disc.

The above two estimations of the distance are consistent with each other and yield a quiescent absolute magnitude of $+7.8 < M_V < +8.8$ using a quiescent V-magnitude of 15.7. The estimated quiescent brightness is surprisingly high. DNe at quiescence are generally much fainter than this object around the orbital period just above the period minimum ($M_V = 10$–14, see figure 2) (Sproats et al. 1996). We can estimate the absolute magnitude of the secondary star to be fainter than 12.7 mag under the condition of a secondary star filling the Roche lobe of a system with $P_{\rm orb}$ = 64.2 min and having the effective temperature of an M-type main-sequence (Hu et al. 1998; Wei et al. 2001). This faint secondary star cannot explain the observed absolute magnitude. We thus consider that the optical flux is dominated by the accretion-disc emission in 1RXS J232953.9 + 062814, as in other short-period systems. This is also supported by the quiescent optical spectrum, since it shows the continuum much bluer than that in a single M-type star (Hu et al. 1998). We therefore conclude that it has an intrinsically high mass-transfer rate, which completely contradicts the standard evolutionary scenario, as depicted in figure 2.

4. Discussion and Summary

CVs which have a secondary star of a helium white dwarf are known to have orbital periods shorter than 1RXS J232953.9 + 062814 and relatively high mass-transfer rates (Ulla 1994). These systems with hydrogen-deficient secondary stars have been proposed to have evolutionary tracks distinct from those of ordinary systems with hydrogen-rich stars (Sarna et al. 1996). On the other hand, the strong hydrogen emission lines seen in the quiescent optical spectrum indicate that this object does not belong to this class.

Besides the high mass-transfer rate, another notable feature is the large superhump excess of 4.04%. Both theoretically and empirically, systems with a smaller mass ratio ($q = M_2/M_1$) are generally expected to have smaller superhump excesses (Patterson 2001). We can understand this by the weak tidal effect from quite low-mass secondary stars in short-period systems. This superhump excess is one of the largests in SU UMa stars, and thus indicates the unexpectedly large mass ratio of this system. The empirical relation yields $q = 0.19 \pm 0.02$ (Patterson 2001). On the other hand, although the quiescent optical spectrum indicates the presence of a secondary star with an effective temperature similar to that of M-type stars, it is certainly too large for the secondary star of this ultrashort period object (Hu et al. 1998; Wei et al. 2001). These arguments imply the presence of a relatively massive secondary. In conjunction with the ultrashort orbital period, it may partly cause the high mass-transfer rate driven by the gravitational radiation. In this case, the secondary star probably evolves off the main-sequence, which means a distinct evolutionary sequence compared with the ordinary hydrogen-rich CVs. It is possible that a quite low-mass white dwarf causes the small mass-ratio and a secondary when a moderate mass star is heated by the UV–X-ray flux from the accretion disc. In this case, we expect a temperature inversion in the atmosphere of the secondary star and the formation of emission lines. The quiescent spectrum, however, shows no evidence for such lines (Hu et al. 1998; Wei et al. 2001).

In known hydrogen-rich CVs, we can find one analogous object, that is, the DN V485 Cen, whose quiescent apparent magnitude is $V = 18.4$ and orbital period is 59 min (Augusteijn et al. 1996, 1993). V485 Cen and 1RXS J232953.9 + 062814 have some noteworthy common features, that is, a short duration of outbursts, a rebrightening phenomenon, and relatively strong He I emission (Olech 1997). We thus propose that these two objects establish a new sub-class below the period minimum. The short distance of 1RXS J232953.9 + 062814 strongly indicates that we have overlooked a number of objects which belong to this class.

We revealed that 1RXS J232953.9 + 062814 is an SU UMa-type DN below the period minimum with a high mass-transfer rate. The evolutionary status and the driving mechanism of the angular momentum removal of this class make a new issue concerning the late evolution of compact binaries. Theoretical calculations imply that the period minimum depends on the opacities and hydrogen fraction in the secondary of CVs (Sienkiewicz 1984; Nelson et al. 1986). A system with a moderately hydrogen-deficient secondary is predicted to have a shorter period minimum and a larger mass-transfer rate before reaching its period minimum. It is thus possible that such a secondary star causes the atypical system parameters of 1RXS J232953.9 + 062814. Only with equivalent widths of hydrogen and helium estimated from optical spectra, however, it is difficult to determine their fraction in the secondary. Our discovery of this object with a bright apparent magnitude will provide a unique chance for us to perform detailed observations, including a determination of the primary and secondary masses, and thereby to study the evolutionary status of this class, which has been difficult with only the faint source V485 Cen.

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