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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. This 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 % 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 revealed 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: 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 the gravitational radiation (Taam et al. 1980). Losing the angular momentum, systems evolve into those with shorter orbital periods, smaller secondaries, and hence lower mass-transfer rates. When the secondary star becomes degenerate, decrease of mass leads to expansion of the secondary, and then, increase of the orbital period. The above scenario has been applied to explain the observed 'period minimum' of about 80 min, and has widely been 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 *Röntgen Satellite (ROSAT)* X-ray telescope

(Voges 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 the 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 HeI emission and TiO absorption bands, the latter being typical for M-type stars. The other state is the bright one in which the hydrogen lines appear in absorption. On the basis of these observations, this object has been classified as a dwarf nova (DN), a sub-group of CVs which experiences repetitive outbursts with typical amplitudes of 2 – 5 mag (Warner 1987). The DN outbursts are considered as the suddenly enhanced release of the gravitational energy induced by the thermal instability of an accretion disc (Osaki 1996).

Here we report 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.

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), Nollenweg (3), Walhostraat (3), Clovis (10), Jyvaskylan (2), and Potenza (1). The exposure time is 30 – 120 s. After the dark subtraction and flat fielding on the images, we performed aperture photometry and obtained differential magnitudes of the object using a comparison star of 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 can obtain magnitudes almost equal to R_c system from observations at Kyoto in which we use unfiltered ST-7E CCD camera since the sensitivity peak of the camera is near that of R_c system and the color of the object is $B - V \sim 0$. Heliocentric corrections to 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 with a rate of 0.25 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 started on 2001 November 9 as seen in figure 1a. The brightness then gradually declined for about one week and returned to the quiescent level around 2001 November 18.

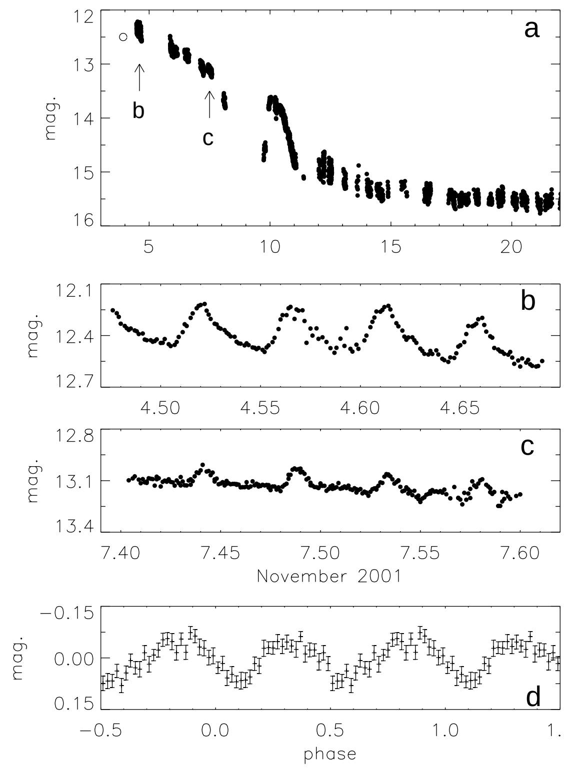

Fig. 1. Figure 1. Light curve of 1RXS J232953.9+062814 during the outburst on 2001 November. a: The whole light curve of the outburst. The abscissa and ordinate denote the date and R_c magnitude, respectively. The open circle denotes the discovery of this outburst with the visual estimation performed 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 the 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 magnitude, respectively. The epoch of the phase is arbitrary.

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 figure 1b and 1c. The humps have the common profile of the 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 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.

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 are generally a few percent longer than the orbital period, which is now interpreted as the beat phenomenon between the orbital period and the period of slow apsidal motion of an elongated accretion disc caused by the tidal torque from the secondary star (Whitehurst 1988; Osaki 1989). Using the light curve in quiescent phase (November 19 – December 4), our PDM period analysis yielded the period of 64.210 ± 0.023 min. The period of the humps during the outburst is 4.036 ± 0.015 % longer than this quiescent period. As shown in figure 1d, the profile of modulations during the quiescent phase is a double-peaked sinusoidal curve which is completely different from those during the outburst, and hence, indicates their different nature. In conjunction with these two periodicities, we conclude that the humps observed during the outburst are genuine superhumps. We furthermore identify the photometric period during quiescence with the orbital period. It is also supported by the spectroscopic period of 64.2 ± 0.1 min during quiescence[1]. 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 the absolute magnitude

The optical flux of a CV is dominated by the emission from an accretion disc particularly in the short period systems which have a very low-luminosity secondary. Since the emission from the disc is proportional to the mass-transfer rate, absolute magnitudes (M_V) of CVs are a good indicator of 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.$=$23h29m54s.23 and Dec. $= +06°28'12''.4$ using the template stars in USNO-A2.0 catalogue (Monet 1998). On the other hand, we obtained the position in 1951.6 using USNO-A2.0 catalogue, in which it is reported to be R.A. $=$23h29m54s.357 and Dec.$= +06°28'10''.35$. From these positions, we obtained a significant proper motion of ΔR.A.$= 38\,{\rm mas\,yr}^{-1}$ and ΔDec.$= 41\,{\rm mas\,yr}^{-1}$. To calculate a secure upper-limit of the distance, we neglect the radial velocity and consider the transverse velocity of this object to be $100\,{\rm km\,s}^{-1}$ which corresponds to the maximum expected velocity dispersion of CVs (Harrison et al. 2000). With the above proper motion, it yields the distance of < 380 pc.

In the framework of the disc instability model for DN outbursts, peak luminosities strongly depend on the amount of the mass stored in the disc, namely the size of the disc and the binary system (Osaki 1996). The well-known empirical law of $M_V({\rm peak}) = 5.74 - 0.259 P_{\rm orb}({\rm hr})$ 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 the peak absolute magnitude of 5.46 mag. With the observed apparent magnitude of 12.41 mag, we calculate a lower-limit of the distance to be ~ 245 pc neglecting intersteller extinction and the term of the inclination of the disc.

The above two estimations of the distance are consistent each other and yield the quiescent absolute magnitude of $+7.8 < M_V < +8.8$ using the 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 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 contradict with the standard evolutionary scenario

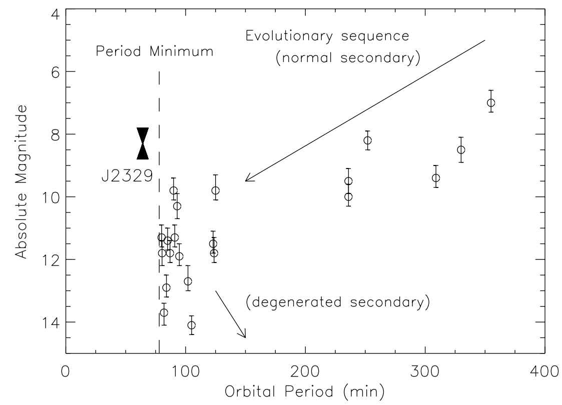

Fig. 2. Absolute magnitude of CVs on the function of their orbital period. We show the lower and upper-limit of the quiescent brightness of 1RXS J232953.9+062814 as filled triangles and mark as 'J2329'. Open circles denote DNe listed in Sproats et al. (1996). The arrows are schematic evolutionary sequences expected from theoretical models in which the orbital angular momentum is continuously removed from systems due to the 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 at 78 min.

[1] http://www.kusastro.kyoto-u.ac.jp/vsnet/Mail/vsnet-alert/msg06851.html

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 (Marks et al. 1996). On the other hand, the strong hydrogen emission lines seen in the quiescent optical spectrum indicate that this object belongs to not this class, but ordinary hydrogen-rich CVs.

Besides the high mass-transfer rate, another notable feature is the large superhump excess of 4.04 %. Both theoretically and empirically, systems with smaller mass ratio ($q = M_2/M_1$) are generally expected to have smaller superhump escesses (Patterson 2001). We can understand it with the weak tidal effect from quite low-mass secondary stars in short-period systems. This superhump excess of is one of the largest one in SU UMa stars, and thus indicates unexpectedly large mass ratio of this system. The empirical relation yields $q = 0.19$ (Patterson 2001). On the other hand, although the quiescent optical spectrum indicates the presence of a secondary star with the effective temperature similar to 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 with moderate mass star is heated by the UV − X-ray flux from the accretion disc. In this case, we expect the 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; Augusteijn et al. 1993). V485 Cen and 1RXS J232953.9+062814 have some noteworthy common features, that is, the short duration of outbursts, the rebrightening phenomenon, and the relatively strong He I emission (Olech 1997). We thus propose that these two objects establish the first sub-class below the period minimum in hydrogen-rich CVs. 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 on the late evolution of compact binaries. To determine the hydrogen and helium contents in this system will provide a clue for its nature since a system with moderately hydrogen-deficient secondary star is proposed to have a shorter period minimum (Nelson et al. 1986). Since the high mass-transfer rate implies a short recurrence time of outbursts, the continuous monitoring of this object is strongly encouraged. Our first results on the superhump evolution in this system will be reported in the forthcoming paper. The bright apparent magnitude of this new object provides the unique chance for us to perform detailed observations of its secondary star and to study the evolutionary status of this class, which have been difficult only with the faint source V485 Cen.

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