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Deep Eclipses in the Cataclysmic Variable 1RXS J020929.0+283243

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Abstract—Our observations with the 1.5-m Russian–Turkish Telescope (RTT150) in October 2005 as part of the program for identifying ROSAT X-ray sources revealed deep eclipses in the cataclysmic variable 1RXS J020929.0+283243 in Triangulum. We determined the orbital period of the binary (96.26 min) and the range of its magnitude variations ($V = 17.0–21^{m}.5$). Due to the favorable geometry (the orbital inclination is close to 90°), the light curve exhibits eclipses of the white dwarf by the secondary component and eclipses of the hot spot by the white dwarf itself.

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INTRODUCTION

Many of the 18 806 X-ray sources in the 1RXS catalog (Voges et al. 1999) remain unidentified or completely unstudied in the optical range even 15 years after the ROSAT all-sky survey (1990–1991). During our regular series of observations with the 1.5-m Russian–Turkish Telescope (TUBITAK National Observatory, Bakirlitepe) from October 15 through October 29, 2005, we studied several selected objects from the ROSAT catalog with uncertain optical identification or without any identification. The objective of these observations was to obtain deep multicolor BVR images of the fields around the sources with the simultaneous construction of their light curves in searching for variability on time scales of several minutes and hours. A typical observing session for each object involved taking 40 images with exposure times of 60–90 s in each band. The readout time of a complete $8' \times 8'$ frame from the ANDOR DW436 CCD array with 2×2 binning was 36.7 s. Simultaneously with the imaging, we constructed the light curves of several objects in the field of view with a time resolution of 96 or 126 s. If a source exhibited a marked variability, its observations were continued with a higher time resolution and longer series. This is how the variability of one of the stars in the region of 1RXS J020929.0+283243 was discovered.

THE PREHISTORY OF 1RXS J020929.0+283243

In the Hamburg Catalogue of optical identifications of bright X-ray sources from the ROSAT all-sky survey (Zickgraf et al. 2003), the object 1RXS J020929.0+283243 (below referred to as J0209+2832 for short) was identified with a quasar (QSO) based on the spectra and images obtained during the Hamburg survey of northern-sky quasars. The following coordinates are given for the QSO: $02^{h}09^{m}29^{s}.8$ $+28°32'28''$; its magnitude and color index are $B = 18.2$ and $B - R = -0.3$, respectively. At the same time, also based on spectroscopic data, Wu et al. (2001) called the object a cataclysmic variable. The spectrum accumulated during a 50-min exposure with the 2.16-m telescope exhibits a flat continuum from 4000 to 8000 Å, an intense hydrogen Balmer series, He I lines, and a strong He II 4686 Å line. As a result, the source is listed in the catalog of cataclysmic variables by Downes et al. (2001), a revised and appended edition of April 2005, only with the coordinates (02:09:29.86+28:32:29.6) and the photographic magnitude at maximum (18.4B), but without any information about its variability.

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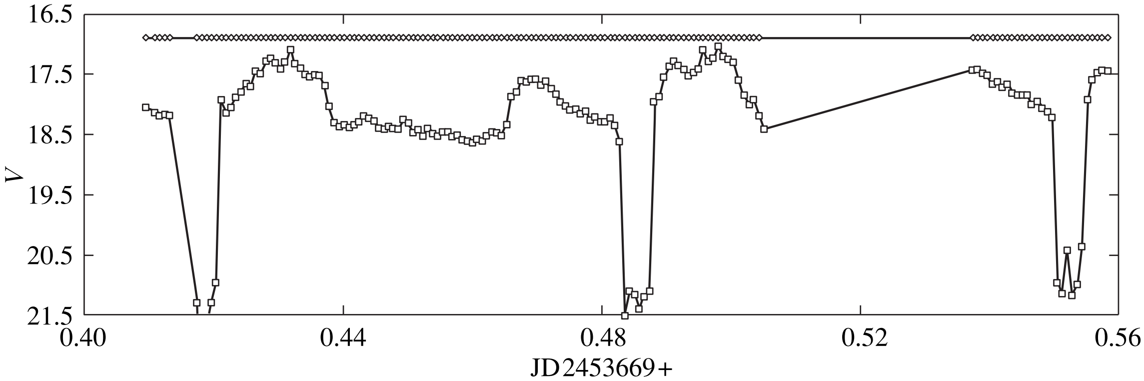

Fig. 1. Light curve of the cataclysmic variable J0209+2832 on October 25/26, 2005 (UT 21:50–01:30).

The lower limit of the magnitude variations in the object, its orbital period, subtype, and the presence and recurrence of outbursts are unknown.

DETECTION OF ECLIPSES WITH RTT150

J0209+2832 was the third object observed in October 2005 as part of our program of searching for optical identifications of ROSAT sources. We detected an eclipse in the ninth image 20 min after the beginning of our observations, at 1:01 UT on October 23. No object was found at the position of the 18th-magnitude star with the limiting magnitude $V = 21$.

On October 23/24, the object was imaged in the V band with the same 1.5-min exposure time as that on the previous night. The eclipse began in the 31st of the 40 frames. Its depth was again below the limiting magnitude over 90 s. Therefore, to increase the signal at minimum light during the eclipse in the hope of finding the depth of the brightness decline, we decided to use a clear filter and to record only a part of the CCD array 400 of the 1024 pixels in height. This allowed the frame readout time to be reduced to 14 s. The total cycle of obtaining a single image at an exposure time of 50 s was 64 s. On October 25/26, we measured three minima to $21\overset{m}{.}2 - 21\overset{m}{.}5$. Figure 1 shows the light curve of J0209+2832 from 21:50 UT, October 25, to 01:30 UT, October 26, covering two orbital periods and three eclipses. Our observations of the three successive eclipses during the same night showed that the object has a period close to 95 min.

The light curve of the eclipse at 1:14 UT, October 26, is shown in Fig. 2. Note the brightness rise by $0\overset{m}{.}8$ (by a factor of $\sim$2) at the mideclipse. Such an effect has an analogue in the Solar System—the "central flash" during the occultation of a star by a planet or a planetary satellite with an atmosphere (e.g., the Saturnian satellite Titan). At the midevent, the atmosphere of the occulting body refracts the light from the brighter body, thereby serving as a spherical "lens" (Hubbard et al. 1993). For 1RXS J020929.0+283243, we may be dealing with a similar effect in the atmosphere of the companion star. The bending of light by an angle of $\sim 10°$ is needed for this, which requires a dense atmosphere.

DETERMINING THE ORBITAL PERIOD

During six nights, we detected nine eclipses in the object J0209+2832; their start times are given in Table 1. This allowed us to determine the binary period more accurately: 0.06685 days, or 96.26 min. Exactly 15 orbital periods elapses in 24 h 4 min, i.e., the eclipses on each succeeding night occur 4 min later than those on the preceding night.

The ephemeris (light elements) for the eclipses of the variable 1RXS J020929.0+283243 is:

$$T = 2\,453\,666.543 + 0.06685E.$$

The uncertainty in the period determined from our data is $\pm 0\overset{d}{.}00002$, or less than 2 s. The eclipse duration is 350 ± 30 s, or 0.06 of the orbital period.

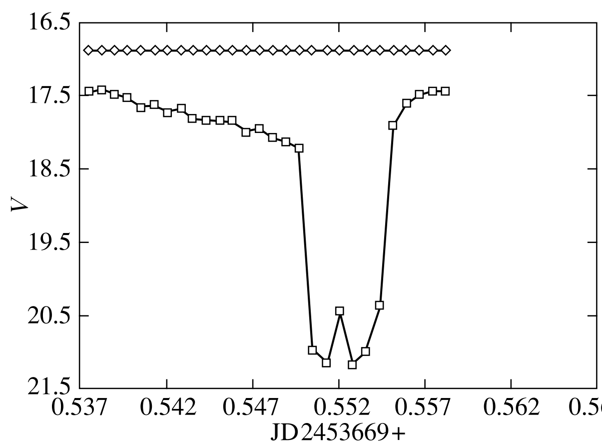

Fig. 2. Light curve of J0209+2832 during the eclipse on October 26, 2005 (UT 01:14).

Table 1.

Date, 2005	Time, UT	JD	Epoch No.
October 23	01:02	2453666.543	0
October 23	23:29	2453667.479	14
October 25	22:01	2453669.418	43
October 25	23:37	2453669.484	44
October 26	01:13	2453669.551	45
October 26	20:28	2453670.353	57
October 26	22:05	2453670.420	58
October 27	23:45	2453671.490	74
October 29	01:22	2453672.560	90

THE FIELD AND COMPARISON STARS

A $3' \times 2.5'$ image of the J0209+2832 field is shown in Fig. 3. The two bars mark the position of the cataclysmic variable. A color version of this image is accessible at http://hea.iki.rssi.ru/~denis/J020929analysis.html. To produce the color image, we used forty 90-s exposures in each of the R, V, and B bands taken on October 22, 23, and 26, respectively, at $1.3''$–$1.5''$ seeing. The coordinates of J0209+2832 measured relative to the UCAC2 stars are $\mathrm{RA} = 02^{\mathrm{h}}09^{\mathrm{m}}29^{\mathrm{s}}\!.82$, $\mathrm{Dec} = +28^\circ 32' 29''\!.1$ (J2000.0).

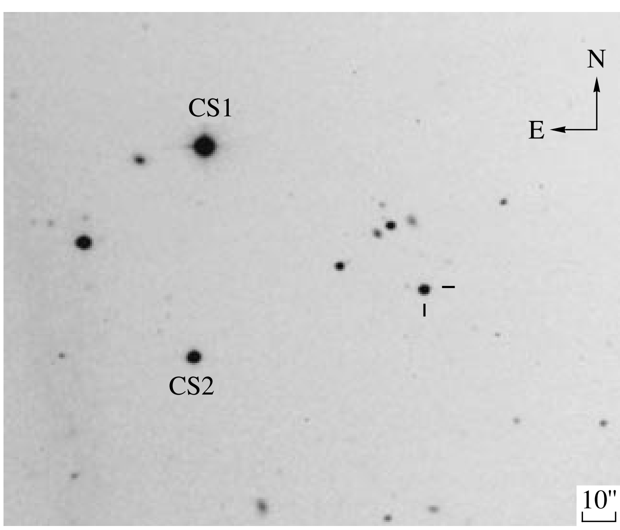

Fig. 3. Finding chart for J0209+2832. The two bars mark the position of the cataclysmic variable.

The two stars closest to J0209+2832 in color index designated in the figure as CS1 and CS2 were used as the comparison stars to construct the light curves. Data on all three objects from the USNO-A2.0 catalog are given in Table 2.

The V magnitudes of the comparison stars during our observations were 14.5 and 16.9.

ARCHIVAL OBSERVATIONS

To check the star for variability in previous years, we searched for optical images of the sky field under consideration in the archive of the Near-Earth Asteroid Tracking program, NEAT (Pravdo et al. 2005; Teegarden et al. 2003). Short exposures (30–60 s) gave a hope of detecting eclipses with a probability of ~1/16. Two eclipses were found on the 15 NEAT images available for five nights (December 26 and 29, 1997; October 13, 2001; November 25 and December 11, 2002): on December 26, 1997, at 06:42 UT and on November 25, 2002, at 03:59 UT. It should be noted that in the former case, the star was exactly at the boundary of two detector fragments with different sensitivities; therefore, whether this eclipse was real is still open to question.

In the remaining NEAT images, the star's magnitude varies over the range 16.9–$17^{m}\!.6$. However, the image obtained at 06:28 UT on December 26, 1997, is of greatest interest: it is the only image in which J0209+2832 is brighter than comparison star 2 by 0.5 magnitudes and fainter than comparison star 1 by only $1^{m}\!.6$. In December 1997, the variable was probably in a high state with an enhanced accretion rate, and the amplitude of its light curve exceeded 5^{m} (16.4–21.5).

We also checked the four available images of J0209+2832 in the Palomar sky survey: on October 29, 1989, and September 17, 1991, in red light (R) with an exposure time of 80 min and on September 24, 1987, and September 15, 1993, in blue light (B) with an exposure time of 60 min. We detected no outbursts brighter than $16^{m}\!.5$.

INTERPRETING THE LIGHT CURVE

The binary J0209+2832 is a pair of a white dwarf with an accretion disk plus a red M6 V star. The data by Beuermann et al. (1998) and Howell et al. (2001) indicate that the donor star in a binary with a period of 1.6 h must have the spectral type M6 V, a mass close to $0.15 M_\odot$, and a radius close to $0.15 R_\odot$. Judging by the 6-min eclipse duration, the inclination is most likely larger than 75°–80° for all masses of the white dwarf within the range 0.45–$1.2 M_\odot$.

Assuming the absolute magnitude of the M6 V red dwarf to be $M_V = 15.5$–16.0, we can estimate

Table 2.

Star	USNO-A2.0 ID	R.A.	Dec	R	B
J0209+2832	U1125_00693000	$02^h09^m29^s.82$	$+28°32'30''.6$	18.7	18.4
Comp. star 1	U1125_00693400	02 09 34.77	+28 33 12.5	14.3	14.6
Comp. star 2	U1125_00693422	02 09 35.05	+28 32 10.0	16.3	16.7

the distance to the binary from its brightness at the eclipse minimum, $21^m.5$, as 160–250 pc. In this case, for the white dwarf with a disk, the absolute magnitude is estimated to be $M_V = 11.0$–11.5.

Photometry with a time resolution of ∼10 s will make it possible to measure the size of the white dwarf from the duration of the decline and rise in brightness at the beginning and the end of an eclipse. Based on our data, we can only place an upper limit on the size of the compact object (∼30 000 km), since the eclipse ingress and egress are sharp at the exposure times used: the partial phase lasts less than 60 s (probably no more than 30 s). The brightness decline to $18^m.5$ at phase 0.3–0.75 (taking $\Phi = 0$ as the mideclipse) is most likely attributable to the hot spot on the white dwarf going behind the limb.

J0209+2832 AND THE ECLIPSING POLAR SDSS J0155+0028

The orbital period of ∼0.06685 days is typical of the UGSU-subtype stars (Samus et al. 2004). However, none of the known stars of this subtype exhibits $4^m.5$-deep eclipses. Moreover, among the 599 cataclysmic variables with known orbital periods as of July 2005, only one has a larger amplitude of the brightness variations. The magnitude–eclipse depth diagram constructed using data from version 7.5 of the Ritter–Kolb catalog is shown in Fig. 4. The star's magnitude at a normal maximum (mag1 in Ritter–Kolb notation) is plotted along the horizontal axis; the magnitude difference between the mideclipse and the brightness maximum (mag2–mag1) is along the vertical axis. It should be particularly noted here that mag1 given by Ritter and Kolb for some of the stars (e.g., V Sge) is actually the magnitude in an intermediate outburst, while mag2 is the magnitude in quiescence. Therefore, many data points in the diagram should be displaced downward. As a result, SDSS J0155+0028 (Schmidt et al. 2005) with an average eclipse depth of $\sim 5^m$ remains the only real close analog of J0209+2832. This object is worth discussing in more detail.

Eclipses of the cataclysmic variable SDSS J015543.40+002807.2 were detected in August 2002 (Dubkova et al. 2003). At the time of their discovery, their amplitude was more than 5 magnitudes (from 15.2 to $>20^m$). However, the brightness at minimum in October 2003 was not higher than $\sim 18^m$ (Schmidt et al. 2005). Clearly, the binary SDSS J0155+0028 can be in high and low states with different accretion rates. Our analysis of the archival observations shows that the brightness of J0209+2832 also varies appreciably on long time scales. Comparison of the light curves for the two objects also reveals common features: a rise in brightness before the eclipse, maximum light after the egress, a decline by $\sim 1^m$ at phase 0.2–0.3, and fine variability features. The eclipse duration for both binaries is ∼6 min. Moreover, the spectrum of SDSS J0155+0028 has unique features that allow it to be taken for a quasar, just as happened in our case! J0209+2832 may be a "close relative" of the eclipsing polar SDSS J0155+0028. However, each object has unique features of its own. In particular, the eclipses of J0209+2832 appear symmetric at a 64-s time resolution, while the brightness of SDSS J0155+0028 declines gradually, in 3 min, and the egress is as sharp as that for J0209+2832. In addition, J0209+2832 exhibits no dip at phase 0.9 that in SDSS J0155+0028 was explained by the eclipse of the accretion stream.

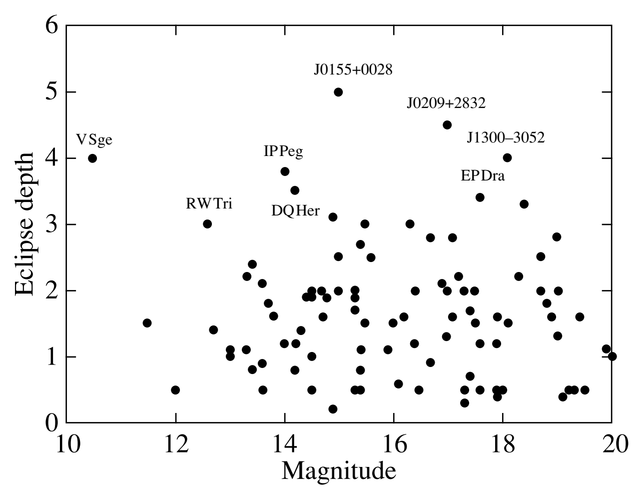

Fig. 4. Magnitude–eclipse depth diagram for cataclysmic variables. See text for more detail.

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