THE LIKELY ORBITAL PERIOD OF THE ULTRACOMPACT LOW-MASS X-RAY BINARY 2S 0918–549

JING ZHONG and ZHONGXIANG WANG
Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China; jzhong@shao.ac.cn, wangzx@shao.ac.cn

Received 2010 June 20; accepted 2010 December 14; published 2011 February 4

ABSTRACT

We report the discovery of the likely orbital period of the ultracompact low-mass X-ray binary (LMXB) 2S 0918–549. Using time-resolved optical photometry carried out with the 8 m Gemini South Telescope, we obtained a 2.4 hr long, Sloan $r'$ light curve of 2S 0918–549 and found a periodic, sinusoidal modulation at 17.4 ± 0.1 minutes with a semiamplitude of 0.015 ± 0.002 mag, which we identify as the binary period. In addition to 4U 0513−40 in the globular cluster NGC 1851 and the Galactic disk source 4U 1543–624, 2S 0918–549 is the third member of the ultracompact LMXBs that have orbital periods around 18 minutes. Our result verifies the suggestion that 2S 0918–549 is an ultracompact binary based on its X-ray and optical spectroscopic properties. Given that the donor in 2S 0918–549 has been suggested to be either a C–O or He white dwarf, its likely mass and radius are around 0.024−0.029 $M_\odot$ and 0.03−0.032 $R_\odot$, respectively, for the former case and 0.034–0.039 $M_\odot$ and 0.033–0.035 $R_\odot$ for the latter case. If the optical modulation arises from X-ray heating of the mass donor, its sinusoidal shape suggests that the binary has a low inclination angle, probably around 10°.

Key words: binaries: close – stars: individual (2S 0918–549) – stars: low-mass – stars: neutron – X-rays: binaries

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) constitute a large fraction of bright X-ray sources ($L_X \sim 10^{36}$ erg s$^{-1}$) in the Galaxy. These binary systems consist of an accreting compact star, either a neutron star or black hole, and a Roche-lobe-filling, low-mass companion. Thus far, approximately 200 LMXBs are known. Among them, there is a class called ultracompact binaries. Different from the majority of LMXBs which contain ordinary, hydrogen-rich mass donors, ultracompact systems are believed to consist of extremely low-mass, either hydrogen-poor or degenerate, companion stars (Nelson et al. 1986; Yungelson et al. 2002). As a result, while ordinary LMXBs have a minimum orbital period around 80 minutes (Paczynski & Sienkiewicz 1981; Rappaport et al. 1982), ultracompact systems can evolve to extraordinarily small binary separations with orbital periods as short as a few minutes (Podsiadlowski et al. 2002; Nelson & Rappaport 2003). These ultracompact LMXBs, along with their white dwarf analogs (the AM CVn binaries; see Warner 1995), represent extreme and exotic endpoints in binary and stellar evolution.

While the ultracompact systems had initially been assumed to be relatively rare, the number known has more than doubled to 11 (including 4 globular cluster sources) over the past few years, with a range of orbital periods from 11 to 55 minutes (Ma & Li 2009; Zurek et al. 2009). It is likely that there are more such binaries, because a few candidate systems have been identified either by their peculiar X-ray and/or optical spectral features (Juett et al. 2001; Nelemans et al. 2004; Wang 2004) or through their unusually low optical-to-X-ray flux ratios (Deutsch et al. 2000; Bassa et al. 2006; in’t Zand et al. 2007). To fully study and understand the ultracompact LMXB population, verification of those candidate systems are warranted. It has been shown that the indirect methods for ultracompact binary identification may not be reliable (Shahbaz et al. 2007). In order to verify their ultracompact nature, time-resolved photometry for detecting orbital periodic signals is needed. Moreover, once ultra-short orbital periods are found, properties of the binary systems can be further estimated (e.g., Wang & Chakrabarty 2004), helping our understanding of these systems. In an effort to verify the ultracompact nature of the proposed candidates, we have undertaken optical observations aiming to detect orbital flux modulations. We have successfully found the orbital period of the candidate 4U 1543–624 (Wang & Chakrabarty 2004). In this paper, we report our discovery of the likely orbital period of another candidate, 2S 0918–549.

The LMXB 2S 0918–549 is a bright X-ray source ($L_X \sim 10^{36}$ erg s$^{-1}$) and has been detected by all major X-ray satellites (see Juett & Chakrabarty 2003 and references therein). On the basis of comparison of its X-ray spectrum with that of the known ultracompact LMXB 4U 1626−67, the source has been suggested to be an ultracompact binary with a neon-enriched degenerate donor (Juett et al. 2001; Juett & Chakrabarty 2003). Probably because the binary has a low inclination angle (generally $i < 60^\circ$; Frank et al. 2002), no orbital signals were found in X-ray observations of the source (Juett & Chakrabarty 2003). The optical counterpart to 2S 0918–549 was identified by Chevalier & Ilovaisky (1987), $V = 21$, $B − V = 0.3$. Based on its optical-to-X-ray flux ratio, the orbital period of the binary has been suggested to be $\lesssim 60$ minutes (Juett & Chakrabarty 2003). The source distance is probably 4.1–5.4 kpc, estimated from type-I X-ray bursts detected from the source (in’t Zand et al. 2005).

2. OBSERVATIONS AND DATA REDUCTION

Time-resolved imaging of 2S 0918–549 was carried out on 2008 December 5 using the 8 m Gemini South Telescope. The instrument was the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004), whose detector array consists of three 2048 × 4608 EEV CCDs. We used only the middle CCD chip (CCD 02) for imaging. The pixel scale is 0.073 pixel$^{-1}$, while the detector was 2 × 2 binned for our observation. A Sloan $r'$ filter with the central wavelength at 6300 Å was used. We obtained 179 continuous frames with an exposure time of approximately 24.5 s. Including 24 s readout time for each exposure, the total length of the observation was approximately
optical counterpart to 2S 0918\textasciitilde{}549. The nearby star labeled as \(N\) is \(1\)'5 away from the target. The star labeled as \(C\) was used as a check star.

The observing conditions during the early part of our observation (first 59 frames) were relatively poor, with the average seeing (FWHM of the point-spread function (PSF) of the images) being \(\lesssim 1\)'0 and a few frames having as large as \(1\)'3\textasciitilde{}1\)'5 seeing. For the remaining part, the conditions were good with most of the frames having \(\lesssim 0\)'8 seeing.

We used the IRAF packages for data reduction. The images were bias subtracted and flat fielded. The bias and flat frames were from GMOS baseline calibrations taken during the same night.

We performed PSF-fitting photometry to obtain brightnesses of our target and other in-field stars, with the photometry program DOPHOT (Schechter et al. 1993) used. A finding chart of the target field is shown in Figure 1. As identified by Chevalier \& Ilovaisky (1987), there is a nearby star (labeled as \(N\)) \(1\)'5 away from our target. To avoid possible contamination from this nearby star caused by the poor observing conditions during the early part of our observation, we positionally calibrated the first 59 frames to a reference image that was combined from three high-quality frames. The positions of star \(N\) and 2S 0918\textasciitilde{}549 were determined in the reference image, and were fixed at the positions for photometry of the first 59 frames. At last we excluded three frames among them from the data. From the three frames, the brightness measurements of star \(N\) and other in-field stars obtained were not consistent with the average brightnesses from other frames, and we note that the three frames have the seeing of \(1\)'3\textasciitilde{}1\)'5.

Differential photometry was performed to eliminate systematic flux variations in the images. Three isolated, nonvariable bright stars in the field were used. The brightnesses of our targets and other stars in each frame were calculated relative to the total counts of the three stars. A field star labeled as \(C\) (see Figure 1) was used as a check star, as it was nonvariable and had similar brightness to our target.

Because we did not request observations of standard stars for flux calibration in our Gemini program and also no standard stars were imaged in the same filter by the Gemini South telescope within at least half a month before and after our observation, we used the \(BV\) magnitudes of star \(N\) measured by Chevalier \& Ilovaisky (1987) to obtain absolute magnitudes of the target and other stars. The transformation formula between \(r\)' and \(BV\) magnitudes given by Fukugita et al. (1996) was used. We found an average \(r\)' magnitude of 20.95 \(\pm\) 0.16 for 2S 0918\textasciitilde{}549, where the uncertainty comes from the relatively large uncertainties on the \(BV\) magnitudes of star \(N\) in Chevalier \& Ilovaisky (1987). We note that with the same transformation, \(r\)' = 20.94 for 2S 0918\textasciitilde{}549 in Chevalier \& Ilovaisky (1987), which indicates that the binary has not had significant changes in its optical brightness. The average \(r\)' magnitude of star \(C\) was 20.98 \(\pm\) 0.16 \(\pm\) 0.02, where 0.02 mag is the standard deviation of star \(C\) measured from 176 frames.

3. RESULTS

In Figure 2, the obtained light curves of 2S 0918\textasciitilde{}549, star \(N\), and the check star \(C\) are shown. A periodic modulation in the light curve of 2S 0918\textasciitilde{}549, while with a low amplitude, is clearly visible. To determine its period, we applied a phase-dispersion minimization technique (Stellingwerf 1978) with 16 bins of the full phase interval (0,1) used. The resulting periodogram is shown in Figure 3. The \(\Theta\) statistic indicates the detection of a periodicity and its two harmonics. Fitting the region near the first minimum with a parabola (Stellingwerf 1978), we found the period \(P = 17.4\) minutes.

In order to quantify the overall periodic modulation in the light curve, we fit the light curve with a sinusoid. The best fit has reduced \(\chi^2 = 2.3\) for 172 degrees of freedom (dof), and from the best fit we found \(P = 17.38 \pm 0.13\) minutes and a semi-amplitude of 0.014 \(\pm\) 0.002 mag. The large \(\chi^2\) value is mainly caused by large scattering of the first 56 data points due to the poor observing conditions. Excluding them and fitting the remaining data points, we found the reduced \(\chi^2 = 1.2\) for 117 dof (\(P\) was fixed at 17.4 minutes). The obtained semi-amplitude was 0.015 \(\pm\) 0.002 mag, not having significant changes. Therefore, the modulation can be described by a sinusoid with a semi-amplitude of 0.015 mag. The folded light curve at \(P = 17.4\) minutes as well as the best-fit sinusoid are shown in Figure 4. The time at the maximum of the sinusoidal fit (phase zero) was MJD 54805.23281 \(\pm\) 0.00027 (TDB) at the solar system barycenter.
Figure 3. Phase-dispersion minimization periodogram. The positions of the minimum Θ statistic at 17.4 minutes and its two harmonics are indicated by arrows.

Figure 4. r′ light curve of 2S 0918−549 folded at 17.4 minutes. Two cycles are displayed for clarity. The solid curve indicates the best-fit sinusoid with a semiamplitude of 0.015 ± 0.002 mag. The first 56 data points that were excluded from the fit are shown as crosses.

4. DISCUSSION

Using Gemini high time-resolution imaging we obtained an accurate optical light curve of 2S 0918−549 and have discovered a periodic flux modulation in the light curve. A low-amplitude modulation is clearly visible and appears to be coherent. Given the known X-ray and optical properties of 2S 0918−549, it is very likely that we have verified the ultracompact nature of this binary and its orbital period is around 17.4 minutes (see discussion below). In addition to 4U 0513−40 in the globular cluster NGC 1851 (Zurek et al. 2009) and the Galactic disk source 4U 1543−624 (Wang & Chakrabarty 2004), 2S 0918−549 is the third member of the ultracompact binaries that have orbital periods around 18 minutes.

We use the discovered orbital period to estimate the mass and radius of the donor. Since the mean density of a Roche-lobe-filling companion is determined by the binary period, our 17 minute period defines a mass–radius (M–R) relation for the companion, shown as the solid curve in Figure 5. In the current light curve we obtained, no asymmetry is clearly seen. In either case since superhump periods are only a few percent longer than the corresponding orbital periods, the orbital period of 2S 0918−549 is around 17.4 minutes.

Considering that the periodic modulation arises from the companion star, the inner face of the companion star in 2S 0918−549 is heated by X-ray emission from the central neutron star and its type-I X-ray bursts detected from the source possibly indicates that the donor instead is a helium white dwarf (in’t Zand et al. 2005). In any case, to compare the donor to stellar models, we use the M–R relations for different types of white dwarfs provided by Deloye & Bildsten (2003). Because extremely low-mass white dwarf donors in ultracompact systems may be thermally bloated compared to cold stars, affecting their M–R relation (Bildsten 2002; Deloye & Bildsten 2003), we show both cold and hot solutions for pure He, C, and O white dwarfs in Figure 5. A helium white dwarf with a mass of 0.034–0.039 M⊙ and a radius of 0.033–0.035 R⊙, or a C/O white dwarf with a mass of 0.024–0.029 M⊙ and a radius of 0.03–0.032 R⊙ can fit in the Roche-lobe-filling donor.

Modulation of an optical light curve for LMXBs generally arises from the companion star that is heated by the central X-ray source, with the visible area of the heated face varying as a function of orbital phase and the superior conjunction of the companion star corresponding to the observed brightness maximum of the light curve (e.g., van Paradijs & McClintock 1995). It has also been realized that compact LMXBs with extreme mass ratios (such as ultracompact binaries) are potential superhump sources (Haswell et al. 2001). The variation in the light curve of a superhump binary arises from an elliptical accretion disk, which is developed when the disk extends beyond the 3:1 resonance radius and precesses in the inertial frame due to the tidal force of a secondary star (e.g., Whitehurst & King 1991). Without an independent determination of the binary period (see, e.g., Wang & Chakrabarty 2010), we cannot distinguish between the two possibilities for the modulation seen in 2S 0918−549. A superhump modulation may have an asymmetric shape (e.g., Wang & Chakrabarty 2010). However, in the current light curve we obtained, no asymmetry is clearly seen. In either case since superhump periods are only a few percent longer than the corresponding orbital periods, the orbital period of 2S 0918−549 is around 17.4 minutes.
effective temperature can be estimated. The 0.1–200 keV X-ray luminosity $L_X$ is $1.9 \times 10^{30} d_X^2$ erg s$^{-1}$, where $d_X$ is the source distance assumed to be 5 kpc and the unabsorbed X-ray flux \( F_X = 6.4 \times 10^{-10} \) erg s$^{-1}$ cm$^{-2}$ given by in’t Zand et al. (2005) is used. The fraction $f$ of the X-ray energy absorbed by the companion is $f = \eta_4 (R_3/D_3)^2/4 \approx 0.004 \eta_4 (R_3/0.032 R_\odot)^2 [1 + (q/0.021)]^{-2/3}$, where $\eta_4 \approx 0.5$ is the fraction of the received X-ray energy absorbed by the companion, $R_3$ is the radius of the companion, and $D_3$ is the binary separation distance ($D_3 \sim 1.7 \times 10^{10}$ cm for orbital period $P_{\text{orb}} = 17.4$ minutes). The mass ratio $q = M_3/M_\odot$, where $M_\odot$ is the neutron star mass and we assume $M_2 = 0.03 M_\odot$ and $M_3 = 1.4 M_\odot$. Following Arons & King (1993), the effective temperature of the companion’s inner face is $T = (f L_X/\pi R_3^2 \sigma)^{1/4} \approx 46,000 d_X^{1/2}$ K, where $\sigma$ is the Stefan–Boltzmann constant. The visible area of this hot face varies as a function of the orbital phase, yielding a modulation of $[1 + \sin^2(i \sin^2(2\pi t/P_{\text{orb}}))]$, where $i$ is the inclination angle of the binary (see details in Arons & King 1993). Using such a modulation function, we can test how the observed modulation is generated. The extinction to the source $A_V \simeq 1.65$, estimated from $A_V = N_H/1.79 \times 10^{21}$ cm$^{-2}$ (Predehl & Schmitt 1995) by using hydrogen column density to the source $N_H = 2.95 \times 10^{21}$ cm$^{-2}$ (Juett & Chakrabarty 2003). By adding a constant flux component (arising from the accretion disk) to the modulation function and fitting the dereddened light curve of 2S 0918−549 with the modulation function, we find $i \sim 0^\circ$. The estimated low inclination angle is consistent with the non-detection of orbital signals at X-ray energies, which generally indicates $i \lesssim 60^\circ$ (Frank et al. 2002), and likely explains the low-amplitude modulation in the light curve. In order to fully explore properties of the binary by fitting the optical modulation, an advanced binary light curve model is needed (e.g., Deloye et al. 2008; Z. Wang et al. 2011, in preparation).

As a separate check, we also estimate the distance to 2S 0918−549. Mass transfer in ultracompact binaries is driven by gravitational radiation, and a mass transfer rate in 2S 0918−549 can be estimated to

\[
\dot{M} \simeq 6.2 \times 10^{-10} \frac{L_\odot}{\text{yr}^{-1}} \left( \frac{M_3}{1.4 M_\odot} \right)^{2/3} \left( \frac{M_2}{0.03 M_\odot} \right)^2 \left( \frac{P_{\text{orb}}}{17.4 \text{ minutes}} \right)^{-8/3}.
\]

Since $L_X = GM_{\text{ms}} \dot{M}/R_\odot = 4\pi d^2 F_X$, the unabsorbed 0.1–200 keV X-ray flux of 2S 0918−549 would imply $d \sim 9$ kpc, where conservative mass transfer onto a 1.4 $M_\odot$ neutron star is assumed and $R_\odot \approx 10$ km is the neutron star radius. The distance value is larger than the 4.1−5.4 kpc range derived from type-I X-ray bursts. We note that $M_\odot$ is sensitive to $M_2$. For example, if $M_2 = 0.024 M_\odot$, where an oxygen white dwarf has to be assumed, the distance could be lowered to 7 kpc. A larger X-ray flux can also help lowered the distance. As recorded in an ASCA X-ray observation in 1995, approximately seven times larger X-ray flux was detected (Juett & Chakrabarty 2003; in’t Zand et al. 2005). If that ASCA flux is considered, the distance would be lowered to ~4 kpc. However, given the known X-ray flux history of 2S 0918−549, its 2–10 keV flux has been stable and around $10^{-10}$ erg s$^{-1}$ cm$^{-2}$ (in’t Zand et al. 2005), suggesting that the ASCA flux was only a one-time event.

The Gemini queue mode observation was carried out under the program GS-2008B-Q-78. The Gemini Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (US), the Science and Technology Facilities Council (UK), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil), and CONICET (Argentina). This research was supported by the starting funds of the Shanghai Astronomical Observatory, National Natural Science Foundation of China (11073042), and National Basic Research Program of China (973 Project 2009CB824800). Z.W. is a Research Fellow of the One-Hundred-Talents project of the Chinese Academy of Sciences.

Facility: Gemini:South (GMOS)

REFERENCES

Arons, J., & King, I. R. 1993, ApJ, 413, L121
Bassa, C. G., Jonker, P. G., in’t Zand, J. J. M., & Verbunt, F. 2006, A&A, 446, L17
Bildsten, L. 2002, ApJ, 577, L27
Chevalier, C., & Ivaisky, S. A. 1987, A&A, 172, 167
Deloye, C. J., & Bildsten, L. 2003, ApJ, 596, 1217
Deloye, C. J., Heinke, C. O., Taam, R. E., & Jonker, P. G. 2008, MNRAS, 391, 1619
Deutsch, E. W., Margon, B., & Anderson, S. F. 2000, ApJ, 530, L21
Frank, J., King, A., & Raine, D. J. 2002, Accretion Power in Astrophysics (3rd ed.; Cambridge: Cambridge Univ. Press)
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Haswell, C. A., King, A. R., Murray, J. R., & Charles, P. A. 2001, MNRAS, 321, 475
Hook, I. M., Jørgensen, I., Allington-Smith, J. R., Davies, R. L., Metcalfe, N., Murowinski, R. G., & Crampton, D. 2004, PASP, 116, 425
in’t Zand, J. J. M., Cumming, A., van der Sluyts, M. V., Verbunt, F., & Pols, O. R. 2005, A&A, 441, 675
in’t Zand, J. J. M., Jonker, P. G., & Markwardt, C. B. 2007, A&A, 465, 953
Juett, A. M., & Chakrabarty, D. 2003, ApJ, 599, 498
Juett, A. M., Psaltis, D., & Chakrabarty, D. 2001, ApJ, 560, L59
Ma, B., & Li, X. 2009, ApJ, 698, 1907
Nelemans, G., Jonker, P. G., Marsh, T. R., & van der Klis, M. 2004, MNRAS, 348, L7
Nelson, L. A., & Rappaport, S. 2003, ApJ, 598, 431
Nelson, L. A., Rappaport, S. A., & Joss, P. C. 1986, ApJ, 304, 231
Paczynski, B., & Sienkiewicz, R. 1981, ApJ, 248, L27
Podsiadlowski, P., Rappaport, S., & Pfahl, E. D. 2002, ApJ, 565, 1107
Predehl, P., & Schmitt, J. H. M. M. 1995, A&A, 293, 889
Rappaport, S., Joss, P. C., & Webbink, R. F. 1982, ApJ, 254, 616
Schechter, P. L., Mateo, M., & Saha, A. 1993, PASP, 105, 1342
Shahbaz, T., Watson, C. A., & Hernandez-Peralta, H. 2007, MNRAS, 376, 1886
Stellingwerf, R. F. 1978, ApJ, 224, 953
van Paradijs, J., & McClintock, J. E. 1995, in X-ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 58
Wang, Z. 2004, PhD thesis, Massachusetts Institute of Technology, MA
Wang, Z., & Chakrabarty, D. 2004, ApJ, 616, L139
Wang, Z., & Chakrabarty, D. 2010, ApJ, 712, 653
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge Astrophys. Ser. Vol. 28; Cambridge: Cambridge Univ. Press)
Whitehurst, R., & King, A. 1991, MNRAS, 249, 25
Yungelson, L. R., Nelemans, G., & van den Heuvel, E. P. J. 2002, A&A, 388, 546
Zurek, D. R., Knigge, C., Maccarone, T. J., Dieball, A., & Long, K. S. 2009, ApJ, 699, 1113