Orbital Parameters of the High-Mass X-ray Binary 4U 2206+54

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We present new radial velocities of the high-mass X-ray binary star 4U 2206+54 based on optical spectra obtained with the Coudé spectrograph at the 2m RCC telescope at the Rozhen National Astronomical Observatory, Bulgaria in the period November 2011 – July 2013. The radial velocity curve of the HeI \( \lambda 6678 \) line is modeled with an orbital period \( P_{\text{orb}} = 9.568 \) d and an eccentricity of \( e = 0.3 \). These new measurements of the radial velocity resolve the disagreements of the orbital period discussions.

1 Introduction

4U 2206+54 (BD 53°2790; LS III +54 16) is a persistent high-mass X-ray binary star at a distance of 2.6 kpc (Blay et al. 2006). It was first detected as an X-ray source by the Uhuru satellite (Giacconi et al. 1972). The system also appeared in the Ariel V catalogue (Warwick et al. 1981). The mass donor is classified as an O9.5Vp star with a higher than normal helium abundance, underfilling its Roche lobe and losing mass via a slow but dense stellar wind, \( v \sim 350 \) km s\(^{-1}\) (Ribó et al. 2006). However, there are some metallic lines typical for a later-type spectrum (Negueruela & Reig 2001). The compact object is a neutron star (Torrejón et al. 2004) with spin period \( P_s = 5554 \pm 9 \) s (Finger et al. 2010).

The X-ray spectrum of 4U 2206+54 is typical for a neutron star accreting material onto its magnetic poles. The orbital period of the system is a subject of discussion. X-ray monitoring by RXTE has suggested an orbital period of 9.568 (Corbet & Peele 2001), but later SWIFT/BAT and RXTE observations found a modulation of about 19.25 d, twice of the 9.6-day period (Corbet, Markwardt & Tueller 2007). The combination of slow X-ray pulsations (Reig et al. 2009; Finger et al. 2010) and the spin-down rate of the neutron star (Reig, Torrejón & Blay 2012) suggests a strong magnetic field \( \sim 10^{14} \) G. If the high magnetic field is confirmed, then 4U 2206+54 will become the first kind of an accreting magnetar.

Here we present new optical spectroscopy and radial velocity measurements of 4U 2206+54.

2 Observations and data reduction

All data reported here are obtained by the 2m RCC telescope of the Rozhen National Astronomical Observatory, Bulgaria. 4U 2206+54 is observed between November 2011 and July 2013 with the Coudé spectrograph of the telescope. We used two gratings with resolutions of \( R = 30\,000 \) and \( R = 15\,000 \), respectively. The log of observations is given in Table 1.

The spectra are reduced in the standard way including bias removal, flat-field correction, wavelength calibration and correction for the Earth’s motion. Pre-processings and measurements of the radial velocities are performed using standard routines provided by IRAF. The spectra obtained within each observational night are processed and measured independently.

Our spectra include two prominent spectral features - H\( \alpha \) and HeI \( \lambda 6678 \) Å. The double-peaked H\( \alpha \) line is dominated by emission from the circumstellar disk of the donor star. We did not use H\( \alpha \) line to measure the orbit since its radial velocity measurements may be strongly affected by changes in the disk structure. The HeI \( \lambda 6678 \) line is less affected by changes in the disk, therefore we use only this line for radial velocity measurements.

Three examples of HeI \( \lambda 6678 \) line are plotted in Fig 1.

3 Orbital solution

The radial velocity curve was modeled with an eccentric orbital solution. We used the PHOEBE program (Prša & Zwitter-
Table 1  Observations of 4U 2206+54. Given here are as follows: the ID of the spectrum, MJD of the start of the exposure, the exposure time, the resolution of the grating (R30 for R=30 000 and R15 for R=15 000), the orbital phase folded with $P_{orb} = 9.568$ d, the radial velocity of the HeI $\lambda$6678 line, and (O - C) errors.

| spectrum ID yyyyymmddxxx | MJD -start | Exp Time [min] | R   | Orbital Phase | $V_{\text{HeI}}$ [km s$^{-1}$] | (O - C) [km s$^{-1}$] |
|------------------------|-----------|----------------|-----|---------------|-------------------------------|-----------------|
| 20111108055 2455873.896963 20 | R15 | 0.272 | -24.8 | -1.8 |
| 20111108056 2455873.912325 20 | R15 | 0.274 | -20.3 | 2.9 |
| 20120706124 2456114.974316 20 | R15 | 0.469 | -71.8 | -1.5 |
| 20120706125 2456114.990791 20 | R15 | 0.470 | -79.8 | -9.6 |
| 20120707159 2456115.983374 20 | R15 | 0.574 | -94.2 | -16.5 |
| 20120707160 2456115.997523 20 | R15 | 0.576 | -84.3 | -6.6 |
| 20120708024 2456116.885644 20 | R15 | 0.668 | -89.3 | -13.8 |
| 20120708025 2456116.900287 20 | R15 | 0.670 | -81.6 | -6.6 |
| 20120709092 2456117.905134 30 | R15 | 0.775 | -88.3 | -19.4 |
| 20120709098 2456117.955419 30 | R30 | 0.201 | -34.2 | -9.6 |
| 20120830453 2456169.795944 30 | R30 | 0.198 | -27.5 | -2.6 |
| 20120830454 2456169.816999 30 | R30 | 0.201 | -34.2 | -9.6 |
| 20120927415 2456115.983374 20 | R15 | 0.128 | -54.4 | -21.7 |
| 20120927416 2456115.997523 20 | R15 | 0.129 | -41.8 | -9.4 |
| 20121005639 2456116.885644 20 | R15 | 0.092 | -37.8 | -0.7 |
| 20121005640 2456116.900287 20 | R15 | 0.094 | -35.5 | -1.3 |
| 20121006736 2456117.905134 20 | R15 | 0.096 | -46.2 | 16.5 |
| 20121006737 2456117.929325 20 | R30 | 0.064 | -51.8 | -11.1 |
| 20121025107 2456118.918291 20 | R30 | 0.045 | -28.5 | 14.4 |
| 20121025108 2456118.938901 20 | R30 | 0.047 | -29.4 | 13.7 |
| 20121104034 2456119.824752 20 | R15 | 0.092 | -37.8 | -0.7 |
| 20121104035 2456119.838901 20 | R15 | 0.093 | -35.5 | -1.3 |
| 20130102019 2456294.756762 20 | R15 | 0.259 | -9.4 | 13.0 |
| 20130102020 2456294.770866 20 | R15 | 0.260 | -8.1 | 14.5 |
| 20130123098 2456315.710368 20 | R15 | 0.444 | -50.7 | 15.6 |
| 20130520065 2456432.934320 20 | R15 | 0.700 | -58.8 | 15.1 |
| 20130521110 2456433.948816 20 | R15 | 0.806 | -64.8 | 1.8 |
| 20130521111 2456433.962972 20 | R15 | 0.808 | -61.6 | 4.8 |
| 20130525168 2456437.902431 30 | R15 | 0.220 | -23.9 | -0.7 |
| 20130619206 2456462.970446 20 | R15 | 0.840 | -60.9 | 2.9 |
| 20130718030 2456492.014043 20 | R15 | 0.875 | -51.7 | 8.9 |

For our orbital solution, we took $P_{orb} = 9.568$ d. In Sect.4.1, we discuss the reasons for this choice in more details.
Fig. 1 Examples of HeI λ6678 Å line. Below the spectra the individual IDs are given (see Table 1).

Table 2 Orbital parameters of 4U 2206+54.

| Parameter     | Value                  |
|---------------|------------------------|
| $P_{\text{orb}}$ (d) | 9.568*                 |
| $e$           | 0.30 ± 0.02            |
| $\omega$ (deg) | 61° 2.1 ± 1            |
| $\gamma$ (km s$^{-1}$) | -54.5 ± 1            |
| MJD$_0$ (HJD-2,450,000) | 5871.67 ± 0.05 |
| $K_1$ (km s$^{-1}$) | 30.5 ± 3              |
| $a_1 \sin i$ (R$_\odot$) | 3.76 ± 0.05       |
| $f(M)$ (M$_\odot$)    | 0.0232 ± 0.0045        |
| $\sigma$ (km s$^{-1}$) | 10.3                  |

*for the purposes of our orbital solution, we used this value.

The best-fitting orbital parameters are listed in Table 2. In Fig. 2, we plot the radial velocity curve, the best-fitting solution, and the residuals of the fit. We found $P_{\text{orb}} = 9.55 \pm 0.05$ using the Phase Dispersion Minimization method (Stellingwerf 1978), which is not an improvement over Corbet & Peele (2001).

4 Discussion

4.1 Orbital period

The orbital periods of the Be/X-ray binaries are in the range from $\sim 10$ d to $\sim 1$ year. For example, SAX J2103.5-4545 has the shortest known orbital period among the Be/X-ray binaries: $P_{\text{orb}} = 12.7$ d (Camero Arranz et al. 2007).

The orbital period of 4U 2206+54 is still not well determined. X-ray observations revealed two possible values for the orbital period: $P_{\text{orb}} = 9.568 \pm 0.004$ d and $P_{\text{orb}} = 19.25$ d (Corbet & Peele 2001; Corbet, Markwardt & Tueller 2007).

We found $P_{\text{orb}} = 9.55 \pm 0.05$ using the Phase Dispersion Minimization method (Stellingwerf 1978), which is not an improvement over Corbet & Peele (2001).

We have measured the EW(H$\alpha$) in our spectra in order to find a clue for the real orbital period of 4U 2206+54. Our minimum and maximum values for the EW(H$\alpha$) are 0.51 Å and 3.12 Å respectively. Blay et al. (2006) have measured a maximum value of EW(H$\alpha$) of 7.3 Å. According to Fig. 15 in Reig (2011), the orbital period of the system should be the shorter one: $P_{\text{orb}} = 9.568$ d.

Moreover, in Fig. 4 we plot the radial velocities of the HeI λ6678 line folded with the two possible orbital periods. It is clearly visible that shorter orbital period modulate the data better than the longer orbital period. If the $P_{\text{orb}} = 9.568$ d is confirmed, 4U 2206+54 will become the Be/X-ray binary with the shortest orbital period. It will be another addition to the peculiar features that divert the system from the classical Be/X-ray binaries.

4.2 Orbital eccentricity

There is a group of Be/X-ray binaries (X Per, GS 0834-430, KS 1947+300, XTE J1543-568, and 2S 1553-542) characterized by very low eccentricities: $e \leq 0.2$ (Reig 2011). Their low eccentricity requires that the compact object received a much lower kick velocity at birth than previously...
3 Orbital geometry of 4U 2206+54 showing the relative orbits of the 10.7 M$_{\odot}$ donor star and the 1.4 M$_{\odot}$ neutron star. The relevant phases of the periastron, apastron, and the conjunctions are marked. The center of the mass is indicated with a cross.

assumed by current evolutionary models (Pfahl et al. 2002). These objects have $P_{orb} \geq 30$ d.

Most of the Be/X-ray binaries have moderately eccentric orbits with $e \geq 0.3$. For them the tidal force acts as a decelerator of the rotation of the mass donor in order to reach an equilibrium state, i.e. a circular and synchronized orbit (Stoyanov & Zamanov 2009).

It will be interesting to check whether the rotation of the mass donor is pseudosynchronized with the orbital motion of the compact object in the case of massive and short-period system such as 4U 2206+54.

5 Conclusions

On the basis of radial velocity measurements of the HeI $\lambda 6678 \, \text{Å}$ line, we measured the orbital parameters of the high-mass X-ray binary star 4U 2206+54. We found that the orbit of the system should be eccentric with $e = 0.3$, if the orbital period is 9.568 d. We discussed the probability that 4U 2206+54 is a Galactic Be/X-ray binary with the shortest orbital period known up today.

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