

# Orbital parameters of V 0332+53 from 2015 giant outburst data (Research Note)

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## ABSTRACT

We present the updated orbital solution for the transient Be X-ray binary V 0332+53, which we obtained by complementing historical measurements with the data from the gamma-ray burst monitor onboard *Fermi*. These were acquired during the outburst in June–October 2015. We modeled the observed changes in the spin-frequency of the pulsar and deduced the orbital parameters of the system. We significantly improved existing constraints and show that contrary to previous findings, no change in orbital parameters is required to explain the spin evolution of the source during the outbursts in 1983, 2005, and 2015. The reconstructed intrinsic spin-up of the neutron star during the latest outburst is found to be comparable with previously observed values and predictions of the accretion torque theory.

**Key words.** stars: neutron – X-rays: binaries – pulsars: individual: V 0332+53

## 1. Introduction

The bright X-ray transient source V 0332+53 was discovered by the Vela 5B satellite during an outburst in 1973 (Terrell & Friedhorsky 1984). Observations with EXOSAT ten years later allowed the position of the source to be determined (Stella et al. 1985). X-ray pulsations with a period of  $\sim 4.4$  s modulated by motion in an eccentric orbit ( $e \sim 0.3$ ) with a period of  $\sim 34.3$  d were detected (Stella et al. 1985). The optical counterpart of the X-ray pulsar has been identified to be a Be star (Honeycutt & Schlegel 1985) at a distance of  $\sim 7$  kpc (Negueruela et al. 1999).

Like other Be systems, V 0332+53 exhibits two types of X-ray outbursts with peak luminosities of  $\sim 10^{38}$  erg s<sup>-1</sup> and  $\sim 10^{37}$  erg s<sup>-1</sup> associated with enhanced accretion onto the neutron star from the Be circumstellar disk close to the periastron. The so-called normal or type I outbursts occur regularly as the neutron star passes through the Be disk and have comparatively low luminosity. Longer and more luminous type II or giant outbursts are rarer and are thought to be related to the formation of a stable accretion disk around the neutron star during a periastron passage (Okazaki et al. 2002; Martin et al. 2014). Four type II outbursts and a number of type I outbursts have been detected from the source so far (Terrell & Friedhorsky 1984; Tsunemi et al. 1989; Swank et al. 2004; Camero-Arranz et al. 2015; Doroshenko et al. 2015; Nakajima et al. 2015).

Orbital parameters of V 0332+53 were first determined by Stella et al. (1985) using the EXOSAT data. Later Zhang et al. (2005) and Raichur & Paul (2010) used *Rossi X-Ray Timing Explorer* (RXTE) and International Gamma-Ray Astrophysics Laboratory (INTEGRAL) observations performed during the 2004–2005 giant outburst to refine the orbital solution. These authors found a significantly higher projected semimajor axis  $a \sin i$  value than reported by Stella et al. (1985), which was associated with apsidal motion in the system.

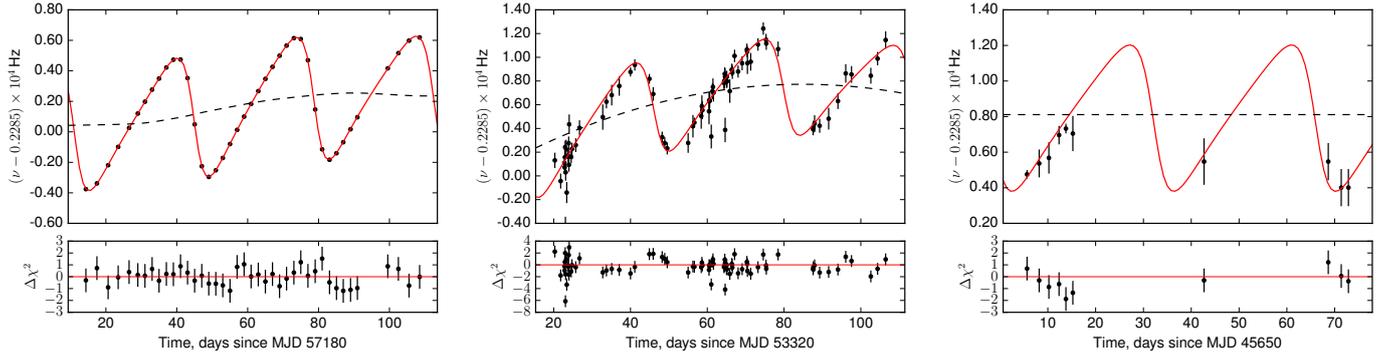
In this note we report on the analysis of timing properties of V 0332+53 during the most recent type II outburst, which took place in June–October 2015 together with older observations. We also provide the updated orbital solution for the system.

## 2. Data analysis and results

The most recent outburst of V 0332+53 in 2015 has been monitored with several instruments. However, the best timing information is provided by the gamma-ray burst monitor (GBM) onboard *Fermi* (Meegan et al. 2009), which measured the spin frequency of the source every one to three days throughout the outburst. The *Fermi*/GBM consists of 12 *NaI* and two *BGO* detectors providing full-sky coverage in the 8 keV–40 MeV energy range. It is designed to detect and localize gamma ray bursts. However, it also proved to be very useful for detection and monitoring of pulsed signals from X-ray pulsars. In particular, the *Fermi*/GBM team regularly publishes<sup>1</sup> spin histories of selected pulsars including V 0332+53 based on the analysis of CTIME data from *NaI* detectors in the 8–50 keV energy range.

Pulsations from V 0332+53 were first detected by GBM on MJD 57 194, and the data used in this publication cover the interval from 57 194 until MJD 57 290, that is, almost three full orbital cycles. The orbital modulation of the spin frequency superimposed by a spin-up trend is clearly visible in the raw data shown in Fig. 1. We used these measurements to constrain the orbital parameters and intrinsic spin evolution of the pulsar using the same approach as Zhang et al. (2005). In particular, we assumed that the slowly changing intrinsic spin of the neutron star is modified by Doppler effects that are due to the orbital motion. They used equations from Hilditch (2001) to calculate the magnitude of the frequency shift for a given set of orbital

<sup>1</sup> <http://gammaray.msfc.nasa.gov/gbm/science/pulsars.html>



**Fig. 1.** Observed pulse frequency modulated by orbital motion as measured with (*left to right*) *Fermi* GBM, RXTE and EXOSAT, and Tenma during the three major outbursts from the source. Reconstructed intrinsic pulsar frequencies (black dashed lines) modulated by motion along the orbit with best-fit parameters (red line) together with fit residuals are also shown.

parameters. Comparison of the observed frequency values with the model at different orbital phases allows then to constrain the orbital parameters of the system.

We emphasize that both the orbital modulation and the intrinsic variation of the pulsar spin frequency must be modeled. The intrinsic spin evolution of V 0332+53 during an outburst is rather complicated, as found by Zhang et al. (2005) and Raichur & Paul (2010), who had to include the second pulse period derivative to describe it adequately. In fact, this is expected because the accretion torque exerted onto the neutron star depends on the accretion rate, which changes dramatically during the outburst. We found that this is indeed also the case for the latest outburst.

As a result of the higher accuracy of individual frequency measurements, we were unable to adequately describe the spin history measured with *Fermi* GBM even when we included the third spin frequency derivative as a parameter. We note that including higher order derivatives is unfeasible as their magnitude quickly decreases, which makes the fit unstable. On the other hand, we found that using a smooth interpolating function defined by frequency values at fixed times  $T_i = \text{MJD } 57\,194, 57\,208, 57\,220, 57\,230, 57\,250, 57\,270,$  and  $57\,290$  (i.e., using the piecewise cubic hermite interpolating polynomial) provides a more robust description of the intrinsic spin evolution of the pulsar.

We also repeated the analysis of RXTE data carried out by Raichur & Paul (2010) and Zhang et al. (2005). We reconstructed the spin history of the pulsar during the giant outburst in 2005 using the epoch-folding period search and RXTE PCA light curves in the 3–21 keV energy range between MJD 53 332 and 53 432. We simultaneously fit the data from the 2005 and 2015 outbursts together with historical pulse frequency measurements reported by Stella et al. (1985) and Makishima et al. (1990) for the outburst in 1983–1984. Following Zhang et al. (2005), we included systematic uncertainties of  $7 \times 10^{-8}$  Hz and  $7 \times 10^{-6}$  Hz for *Fermi* GBM and RXTE/PCA data, respectively. A joint fit to the three datasets results in  $\chi^2_{\text{red}} = 1.02$  for 115 degrees of freedom. The best-fit results are presented in Fig. 1 and Table 1.

We wish to emphasize that contrary to findings by Zhang et al. (2005), it was possible to describe the spin evolution of the source during the three outbursts without assuming any change in orbital parameters. The results obtained are generally consistent with the values reported by Zhang et al. (2005) and Raichur & Paul (2010), with the exception of the orbital period value. We note that in our case the orbital period is better defined because

**Table 1.** Best-fit orbital parameters of V 0332+53 including the *Fermi* GBM data from the 2015 outburst (*left column*).

Parameter	This work	RP10	Z05
$P_{\text{orb}}$ , d	33.850(3)	36.5(3)	34.7(4)
$a \sin(i)$ , lt s	77.8(2)	82.5(9)	86(10)
$e$	0.371(5)	0.417(7)	0.37(12)
$\omega$ , deg	277.4(1)	283.5(9)	283(14)
$T_{\text{PA}}$ , MJD	57 157.38(5)	53 330.58(6)	53 367(1)
$K_X$ , km s $^{-1}$	53.9(2)	–	59(7)
$f(M)$ , $M_{\odot}$	0.44(1)	–	0.58(23)

**Notes.** Values obtained by Raichur & Paul (2010; RP10) and Zhang et al. (2005; Z05) are also shown for reference. All uncertainties are at a  $1\sigma$  confidence level.

the periastron passage time is very well constrained in both the RXTE and *Fermi* datasets and the number of orbital cycles between the two outbursts is known. Other discrepancies likely arise from the different assumptions on the intrinsic spin frequency of the pulsar coupled with insufficient orbital phase coverage and limited accuracy of individual spin frequency measurements in previous studies.

**Implications for the binary orbit.** We have shown that it is possible to describe the outbursts in 1983, 2005, and 2015 assuming no change in the orbital parameters, thus resolving the discrepancy in  $a \sin(i)$  values reported by Stella et al. (1985) and Zhang et al. (2005). The discussion by Zhang et al. (2005) regarding a possible apsidal motion in the system is thus not required anymore. We conclude, therefore, that there is no evidence for apsidal motion in the system.

On the other hand, the low  $a \sin i$  value reported by Stella et al. (1985) led Negueruela et al. (1999) to conclude that the Be companion in V 0332+53 must be strongly undermassive. Indeed, assuming  $a \sin i \sim 50$  lt s, the projected rotational velocity of the Be star measured by Negueruela et al. (1999)  $v_* \sin i_* \sim 100\text{--}200$  km s $^{-1}$  implies  $i_* \geq 12^\circ\text{--}24^\circ$  if the intrinsic rotational velocity of the star is below the break-up value  $v_* \leq 0.8v_{\text{break-up}} \sim 480$  km s $^{-1}$ . For the orbital parameters reported by Stella et al. (1985) this indeed implies a strongly undermassive optical companion with  $M_* \leq 5\text{--}7 M_{\odot}$ , unless its equatorial plane is misaligned with the orbital plane of the system (Negueruela et al. 1999). For the larger  $a \sin i \sim 78$  lt s found in this work, the same considerations imply  $M_* \leq 8\text{--}50 M_{\odot}$ , which is compatible with the expected mass of a Be star (for any

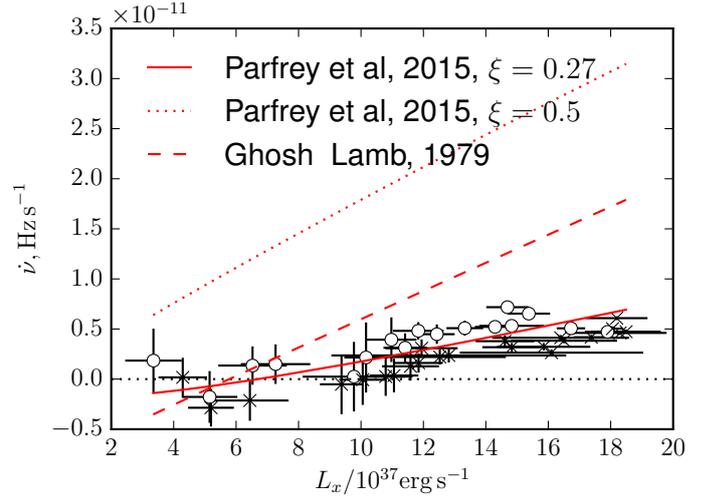
assumed inclination compatible with  $v_* \leq 0.8v_{\text{break-up}}$ ). We conclude, therefore, that there is no evidence either for a tilt between its equatorial plane and orbital plane of the system.

**Intrinsic spin evolution.** When the orbital parameters of the system are determined, it is possible to study the intrinsic spin evolution of the pulsar and thus probe the accretion torques acting on the neutron star. To estimate the spin frequency time derivative, we corrected the observed frequency values for motion in the binary system using the ephemeris obtained above and calculated the frequency derivative, comparing the measurements in adjacent time intervals (propagating the uncertainties). The average spin-up rate of  $\dot{P}_{\text{spin}} \sim 5 \times 10^{-6} \text{ s d}^{-1}$  in the 2015 outburst is comparable with  $\dot{P}_{\text{spin}} \sim 8 \times 10^{-6} \text{ s d}^{-1}$  reported by Zhang et al. (2005) for the 2005 outburst.

The spin-up rate of the neutron star is expected to be correlated with the accretion rate. Therefore, we also estimated the accretion rate for each time interval for which the spin-up rate was determined. In particular, we multiplied the average *Swift*/BAT count rate in the 15–50 keV energy range during the respective time interval by the factor  $1.5(1) \times 10^{-7} \text{ erg s}^{-1} \text{ cm}^{-2}$  to calculate the flux. This factor was calculated based on the comparison of the daily average *Swift*/BAT count rates and flux in the 3–100 keV range measured during the pointed *NuSTAR* observations on MJD 57 223, 57 275, and 57 281. A detailed analysis of the pointed observations will be presented elsewhere, and here we only wish to mention that all observations lasted for  $\geq 0.4 \text{ d}$  and exhibited little variability within this time. The observed energy fluxes were calculated based on the fitting of the spectra in 3–80 keV energy range using the cutoff power-law model and a cyclotron line feature with two harmonics as described in Tsygankov et al. (2006) and Lutovinov et al. (2015). The accretion luminosity and accretion rate  $L_x = GMM/R = 4\pi d^2 F_x \sim 9.3 \times 10^{38} r_{\text{BAT}}$  can then be estimated from the observed flux  $F_x$  or BAT count rate  $r_{\text{BAT}}$  assuming a distance to the source of 7 kpc and standard neutron star parameters ( $M = 1.4 M_\odot$ ,  $R = 12 \text{ km}$ ). We find that the spin-up rate is indeed correlated with the observed X-ray flux as illustrated in Fig. 2.

Several accretion torque models describing the spin evolution of a neutron star accreting from a disk have been proposed. The model by Ghosh & Lamb (1979) invokes angular momentum transport from a neutron star to an accretion disk threaded by the magnetic field lines. As can be seen in Fig. 2, this model predicts a somewhat higher spin-up rate than observed (assuming the magnetic field of the neutron star is  $B = 3.5 \times 10^{12} \text{ G}$ , which corresponds to the highest cyclotron line energies reported by Tsygankov et al. 2006). The discrepancy is not large, however, and could be reconciled if we assume that the accretion rate is overestimated by a factor of two.

In a more recent study, Parfrey et al. (2015) argued that the angular momentum is removed from the neutron star by the electromagnetic outflow along the field lines opened by differential rotation of the magnetic field and the accretion disk. The total torque in this model depends strongly on the magnetospheric radius, which is assumed to constitute a fraction of the Alfvénic radius  $r_a = (\mu^4/2GMM^2)^{1/7}$  for spherical accretion, that is,  $r_m = \xi r_a$  with  $\xi \leq 1$ . The value of  $\xi \sim 0.5$  is expected from MHD simulations for disk accretion (Long et al. 2005; Bessolaz et al. 2008; Zanni & Ferreira 2013). However, in this case, the model predicts a significantly higher spin-up rate for V 0332+53 than observed. To match the observations with the model prediction, we can either assume that the accretion rate is overestimated by a factor of ten (which is unlikely) or that the  $\xi$  must be reduced by



**Fig. 2.** Observed spin-up rate as a function of source X-ray luminosity for the rising (circles) and declining (diamonds) parts of the 2015 outburst. Model predictions after Ghosh & Lamb (1979) and Parfrey et al. (2015) are also shown for reference.

factor of two (i.e.,  $\xi = 0.27$  as presented in Fig. 2), which could signify that the disk pushes farther out into the magnetosphere than expected.

### 3. Conclusions

We analyzed the *Fermi* GBM spin history of V 0332+53 during the giant outburst in 2015 together with historical data from previous outbursts in 1983–1984 and 2004–2005. Our results are generally consistent with earlier estimates by Zhang et al. (2005), Raichur & Paul (2010) and similar to the preliminary findings by the *Fermi* GBM team (based only on the data from the latest outburst).

For the first time we succeeded in describing the spin evolution of the source during all three outbursts with no change in orbital parameters between them, thus resolving a long-standing discrepancy between the orbital solutions reported by Stella et al. (1985), Zhang et al. (2005), and Raichur & Paul (2010). Therefore, our results do not support the suggestion by Zhang et al. (2005) regarding the possible apsidal motion in the system. We note also that in the light of the updated ephemeris, the conclusion by Neugeruela et al. (1999) regarding the misalignment of the system orbital plane and the Be star’s equatorial plane is not supported by the data. We were also able to significantly improve the accuracy of the orbital solution.

We find the intrinsic spin evolution of the pulsar to be complicated, with the spin-up rate being correlated with the accretion rate. The observed spin-up is qualitatively consistent with existing torque models assuming the neutron star has a magnetic field of  $\sim 3 \times 10^{12} \text{ G}$ , as determined from cyclotron line energy, although model uncertainties and the uncertainty in the system accretion rate prevent us from any conclusions regarding the preferred torque model.

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