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GRO J1008–57: a laboratory for accretion physics

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We present timing and spectroscopic results of three outbursts of the transient high mass X-ray binary GRO J1008–57 in 2005, 2007, and 2011. The orbital parameters from the literature are not in agreement with the measured pulse arrival times. We therefore updated the orbital solution, specifically the orbital period and the time of periastron passage, using pointed observations with *RXTE*, *Swift*, and *Suzaku*. We confirmed our results with an analysis of *RXTE*-ASM lightcurves. We show that GRO J1008–57's outbursts occur mostly at the same orbital phase and therefore make predictions of outbursts and, thus, scheduled observations possible.

The X-ray spectrum of GRO J1008–57 during an outburst can be well described by a cutoff power law with an additional black body at energies below 10 keV. We found that the same spectral model describes GRO J1008–57 during the rise and the decline of the outburst at fluxes changing by two orders of magnitude. In particular, the photon index of the power law and the black body flux show a correlation with the total X-ray flux. Other parameters such as the black body temperature and the folding energy are independent of flux and remain the same over all analyzed outbursts.

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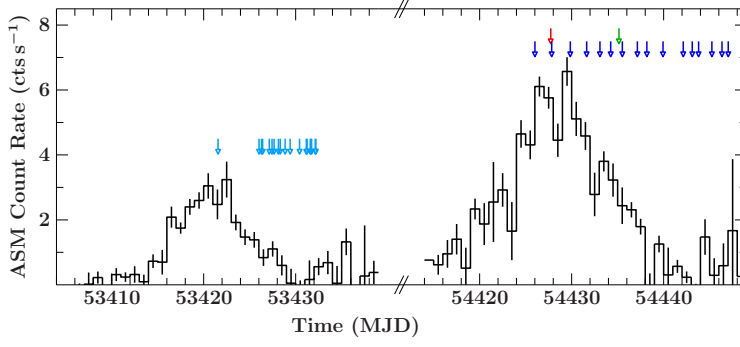


Figure 1: *RXTE*-ASM lightcurve of the outbursts of GRO J1008–57 in 2005 and 2007. Individual observations with *RXTE* (blue), *Swift* (red), and *Suzaku* (green) are indicated by arrows.

1. Introduction

There are neutron star X-ray binaries, where the magnetic field of the compact object is in the order of 10^{12} G. The matter accreted from the donor star is forced to follow the magnetic field lines onto the poles of the neutron star, where a hot spot forms. The thermal photons emitted by the hot spot and the accretion column above the surface are upscattered by the infalling, relativistic plasma [1]. In the accretion columns above the polar caps, shocks may form due to balancing between radiation pressure or Comptonization processes and gravitational pressure of the infalling matter [2]. Due to the lack of a working physical model the spectra of accreting neutron stars are in general modeled by a power law with an exponential cutoff at higher energies and soft components, such as a black body spectrum.

2. GRO J1008–57

The transient high mass X-ray binary GRO J1008–57 was discovered in 1993 during a strong X-ray outburst [12, 11]. This system contains a neutron star on a wide eccentric orbit around a B0e type companion [3], which features a circumstellar disk. If the neutron star is close to its companion matter can be accreted from that disk. This leads to strong X-ray outbursts close to periastron passage only, while the system stays in quiescence during most of the orbit. This is why the determination of the orbital parameters is challenging. In case of GRO J1008–57, X-ray outbursts are observed with a period of ~ 249 d, representing the orbital period of the binary [8].

The X-ray lightcurve of GRO J1008–57 shows regular pulsations of ~ 93.6 s [11], which led to the determination of the orbital parameters shown in Table 1 [4]. Due to the sparse observational coverage the orbital parameters were uncertain. The X-ray spectrum above 20 keV as recorded by *CGRO* and above 5 keV as recorded by *INTEGRAL* was modeled by an exponentially cutoff power law [5, 10, 4]. Furthermore, a high energy cyclotron absorption feature at 88 keV was claimed [10], but has not been confirmed yet. If this feature is present, GRO J1008–57 would be one of the most strongly magnetized accreting neutron stars known. At energies below 10 keV *Suzaku* observations have shown deviations from the pure power law continuum during an outburst of GRO J1008–57 in 2007 [9].

The data analyzed here were obtained by *RXTE* during outbursts of GRO J1008–57 in 2005 February and 2011 April, and by *RXTE*, *Swift* and *Suzaku* during 2007 December. The 2005 and 2007 outburst lightcurves and the observation times are shown in Fig. 1. The lightcurves used

Table 1: Orbital parameters of GRO J1008–57 [4]. See Table 2 for updated values for P_{orb} and τ .

Eccentricity	$e = 0.68(2)$
Projected semi major axis	$a \sin i = 530(60) \text{ lt-s}$
Longitude of periastron	$\omega = -26(8)^\circ$
Orbital period	$P_{\text{orb}} = 247.8(4) \text{ d}$
Time of periastron passage	$\tau = \text{MJD}49189.8(5)$

for timing analysis (Section 3) were extracted with 1 s time resolution in case of *RXTE*, and 10 s resolution for *Swift* and *Suzaku*. Spectra were obtained from the top layer of PCA’s PCU2 and HEXTE’s cluster B. The extraction regions used to extract spectra from data by *Swift*-XRT and *Suzaku*-XIS took pile-up into account. In addition, spectra of *Suzaku*-PIN and -GSO are used for the spectral analysis (Section 4). For more details about the observations and the data extraction see [6].

3. Timing Analysis

Since the time of periastron passage as listed in Table 1 and the 2007 outburst, GRO J1008–57 orbited its companion 21 times. In order to check whether these orbital parameters are still valid, we analyzed the Doppler shifted pulse period during the outbursts in 2005 and 2007. The average pulse periods determined by epoch folding [7] are $93.698 \text{ s} \pm 0.007 \text{ s}$ and $93.737 \text{ s} \pm 0.002 \text{ s}$, respectively. The uncertainties are, however, too large to detect any significant changes over the outburst.

By analyzing individual pulse arrival times, the accuracy of the period measurements can be increased significantly. We determined the arrival times of individual pulses of GRO J1008–57 by matching the lightcurves with a reference pulse profile. To calculate this profile, we folded lightcurves with a good signal to noise ratio with the pulse periods we found through epoch folding. Due to the energy coverage and the sensitivity of each detector, an individual reference profile had to be created. Furthermore, we had to take the time variability of the pulse profile over the outburst into account. The model we used to fit the arrival time of the n^{th} pulse found in the lightcurve is given by

$$t(n) = t_0 + P_0 n + \frac{1}{2!} P_0 \dot{P} n^2 + \frac{1}{3!} (P_0^2 \ddot{P} + P_0 \dot{P}^2) n^3 + \frac{a_x \sin i}{c} F(e, \omega, \tau, \theta) \quad (3.1)$$

where P_0 is the pulse period at the reference time t_0 , and \dot{P} and \ddot{P} are the derivatives of the pulse period. The last term accounts for the Doppler effect of the orbital motion, where $a_x \sin i$ is the projected semi major axis of the neutron star and F the time delay function depending on the eccentricity e , longitude of periastron ω , time of periastron passage τ , and mean anomaly θ .

A first fit of the determined arrival times of the 2005 and 2007 outbursts with orbital parameters fixed to the values found in the literature (Table 1) showed large deviations from a constant pulse period. Since the observed pulse arrival times include intrinsic changes of the neutron star’s pulse period as well as the Doppler shift of orbital motion, we could not tell at this point if a change in pulse period is mimicked by the not well-known orbital parameters. In order to solve that issue, we simulated the influence of the uncertainties of the orbital parameters given in Table 1 on the measured arrival times. We found that the measured deviations from a constant pulse period are

Table 2: Parameters of a fit of Equation 3.1 to the arrival times determined from the lightcurves.

Orbital period	$P_{\text{orb}} = 249.465 \pm 0.017 \text{ d}$
Time of periastron passage	$\tau = \text{MJD } 54424.63 \pm 0.31$
Spin period during 2005	$P_{2005} = 93.67924 \pm 0.00010 \text{ s}$
Spin period during 2007	$P_{2007} = 93.71346 \pm 0.00028 \text{ s}$
Spin-up before MJD 54434.4819	$\dot{P}_{2007} = 0 \pm 25 \times 10^{-11} \text{ s s}^{-1}$
	$\ddot{P}_{2007} = 3.38 \pm 0.15 \times 10^{-14} \text{ s s}^{-2}$

most likely due to a slightly different orbital phase, either caused by a difference in the orbital period or the time of periastron passage. Thus, we extrapolated the time of periastron passage to 2007 and fitted those two parameters to the measured arrival times. This led to a good overall description of the data, if an additional spin-up at times of high luminosity of the source in 2007 was considered ($\chi^2_{\text{red}} = 1.33$ for 1112 dof). The parameters obtained are listed in Table 2.

To confirm the updated orbital period of $P_{\text{orb}} = 249.465 \text{ d}$, we analyzed the times of maximum flux of each outburst of GRO J1008–57 detected by *RXTE*-ASM. Figure 2 shows the orbital phases of the outburst times obtained by using our updated orbital ephemeris. Almost all detected outbursts agree with an orbital phase of about -0.03. Using the orbital parameters of [4] reveals, however, a linearly increasing outburst phase, which is unreasonable. Hence, GRO J1008–57 shows regular outbursts close before periastron with an orbital period of 249.465 d, making outburst predictions possible.

4. Spectral Evolution

The X-ray continuum of GRO J1008–57 was successfully described by a power law with an exponential high energy cutoff [5, 10, 4] as implemented as PLCUT in XSPEC/ISIS with the photon index Γ , the break energy E_{break} and the folding energy E_{fold} . Even when taking galactic X-ray absorption into account, this model did not describe the *Suzaku*-XIS spectra below 10 keV. We found that adding a black body component with a temperature around 1.8 keV led to a good description of the data between 1 to 100 keV (see Fig. 3). Although, there are slight deviations above 80 keV visible in *Suzaku*-GSO, which might hint at the claimed cyclotron line at 88 keV [10]. The data quality is, however, too low to constrain any line parameters sufficiently. The spectra also show an iron emission line at 6.4 keV.

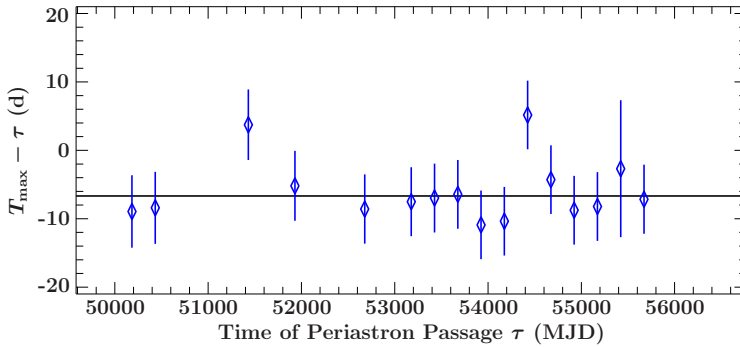


Figure 2: The time of periastron passage of each detected outburst of GRO J1008–57 in *RXTE*-ASM against the orbital phase of the outburst maxima in days using our updated orbital solution. Almost all outburst times are consistent in orbital phase.

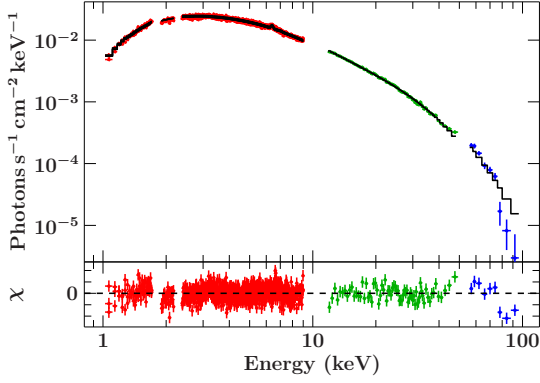


Figure 3: The unfolded *Suzaku*-XIS (red), -PIN (green) and -GSO (blue) spectra and model during the 2007 outburst of GRO J1008–57.

Table 3: Flux-independent parameters of a combined fit to the 2005, 2007, and 2011 outbursts of GRO J1008–57.

N_{H}	$= 1.63 \pm 0.03 \times 10^{22} \text{ cm}^{-2}$
kT	$= 1.783 \pm 0.025 \text{ keV}$
E_{break}	$= 5.79 \pm 0.13 \text{ keV}$
E_{fold}	$= 17.66 \pm 0.32 \text{ keV}$
W_{2005}	$= 45 \pm 10 \text{ eV}$
W_{2007}	$= 25 \pm 3 \text{ eV}$
W_{2011}	$= 66 \pm 5 \text{ eV}$

The *RXTE*- and *Swift* spectra confirm that the model used above describes the data well. Since *RXTE* monitored the source during the decay of the 2005 and 2007 outbursts, we used this model to reveal the spectral evolution of GRO J1008–57. Although the *Swift* and *Suzaku* observations were some days apart, the respective hydrogen column densities obtained are consistent with $1.63 \pm 0.03 \times 10^{22} \text{ cm}^{-2}$, which is consistent with the galactic value found by the 21 cm surveys¹. Because *RXTE*-PCA is not able to detect significant changes in absorption column density, we have fixed this parameter for the evolution fits. Inspection of contour maps showed that some continuum parameters are correlated with each other, but seem to be constant within the uncertainties over the outbursts. In particular, the black body temperature kT , the break energy E_{break} , and the folding energy E_{fold} remain constant, even between the 2005 and 2007 outbursts. In addition, the iron line flux is strongly correlated with the source flux, which implies that the equivalent width W does not change during an outburst.

To constrain all parameters, which seem to be independent of flux and outburst, we performed a combined fit using all available data of the 2005 and 2007 outbursts of GRO J1008–57. Since we know that the outbursts of GRO J1008–57 can be predicted (see Section 3), we scheduled *RXTE* observations during the onset of a predicted outburst in 2011 April to reveal spectral differences between the rise and decline of an outburst. The only free parameters in each individual observation were the power law photon index Γ and its flux F_{PL} (between 15 and 50 keV), as well as the black body flux F_{BB} . In addition, we allowed the iron line equivalent width W to vary between all outbursts. The quality of this fit is remarkably good with $\chi^2_{\text{red}} = 1.06$ for 3641 dof. The flux-independent parameters are shown in Table 3. Looking at the evolution of Γ and F_{BB} , we find that those parameters clearly correlate with the power law flux F_{PL} (see Fig. 4). Using these correlations, the spectrum of GRO J1008–57 can be described by knowing the power law flux between 15 and 50 keV only, independently of the rising or declining part of an outburst.

Detailed results will be presented in a forthcoming paper [6].

¹<http://heasarc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl>

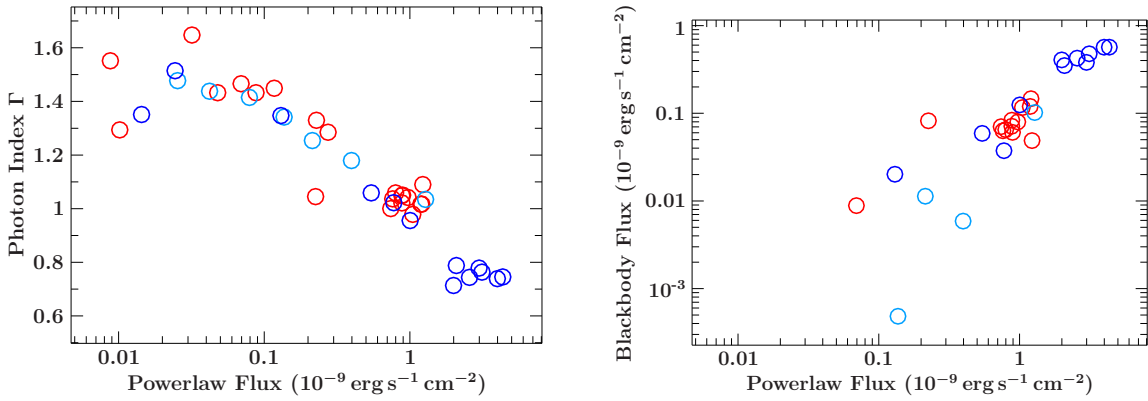


Figure 4: Power law flux F_{PL} dependencies of the photon index Γ (left) and black body flux F_{BB} . The correlations hold for different outbursts and phases (dark blue: decline in 2007, light blue: decline in 2005, red: rise in 2011).

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