Identification of a 12–17 d time-scale in X-ray observations of GRS 1915+105

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ABSTRACT

Measurement of the energy emitted from accreting astrophysical systems provides an observational constraint on the plasma processes that may be operating within the disc. Here we examine the continual time-variation over the past 6 yr of the total X-ray flux from the microquasar GRS 1915+105. The application of differencing and rescaling techniques to *RXTE* All-Sky Monitor (ASM) data shows that the small amplitude fluctuations scale up to 12–17 d. A 17-d time-scale in the X-ray fluctuations corresponds to half the measured binary orbital period of this system (33.5 ± 1.5 d). While this may be coincidental, it is possible that these two time-scales may be linked by, for example, a turbulent cascade in the accretion disc driven by a tidally induced two-armed spiral shock corotating with the binary system. Temporal scaling is found only in the ever-present small fluctuations, and not in the intermittent larger-amplitude fluctuations. This is consistent with the basic model for this source which consists of a steady, cold outer disc and an unstable inner disc.

Key words: accretion, accretion discs – methods: statistical – X-rays: individual: GRS 1915+105.

1 INTRODUCTION

GRS 1915+105 was discovered in 1992 by the WATCH All-sky X-ray Monitor on board the *GRANAT* satellite (Castro-Tirado, Brandt & Lund 1992), and lies in the Galactic plane at a distance of 11–12 kpc (Mirabel & Rodríguez 1994; Fender et al. 1999). The extreme variability of the X-ray flux from its accretion disc, first noticed by Castro-Tirado et al. (1994), coupled with its jet emission (Mirabel & Rodríguez 1994, 1999; Dhawan, Mirabel & Rodríguez 2000; Chaty et al. 2001), makes it an ideal source for the study of accretion physics. At 14 ± 4 solar masses (Greiner, Cuby & McCaughrean 2001, hereafter referred to as G2001), it can thus be considered as a Galactic stellar-mass analogue of a massive extragalactic black hole system such as a quasar, hence the term 'microquasar'. The importance of microquasars as accessible astrophysical laboratories is discussed by Mirabel & Rodríguez (1999); for example, the proportionality of dynamic time-scales to mass implies that thousand-year

events in a quasar could be studied over minutes in a microquasar (see for example Mirabel et al. 1998).

Spectral states, quasi-periodic oscillations (QPOs) and the rich temporal variability of GRS 1915+105 are the focus of much research (see for example Nayakshin, Rappaport & Melia 2000; Belloni, Méndez & Sánchez-Fernández 2001; Klein-Wolt et al. 2002; Rodríguez et al. 2002; Ueda et al. 2002, and references therein). Before the measurements by G2001, mass estimates for GRS 1915+105 made use of the temporal and spectral similarity to microquasar GRO J1655−40 (Grove et al. 1998), another Galactic X-ray source with superluminal radio jets (Zhang et al. 1994) together with a binary mass function appropriate for a black hole (Bailyn et al. 1995). The radial velocity measurements performed by G2001 determined a mass of 14 ± 4 solar masses, leading the authors to suggest that the X-ray variability can be accounted for by instabilities in a radiation-pressure-dominated accretion disc near the Eddington limit. The observations of G2001 also constrain the mass of the donor star to 1.2 ± 0.2 solar masses, and its orbital period around the black hole to 33.5 ± 1.5 d.

There is now much evidence for the basic model of a cold, steady outer disc and an unstable, radiation-pressure-dominated inner disc in GRS 1915+105 (see for example Belloni et al. 1997a,b, and references therein). Hence there are two emitting regions to consider: an inner region that empties and refills on time-scales of s, perhaps due to a rapid local viscous-thermal instability (Lightman & Eardley

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1974; Belloni et al. 1997a; Janiuk, Czerny & Siemiginowska 2000); and a steadier outer region varying only over the much longer time-scale $t_{\rm visc}$ associated with viscous dissipation of bulk plasma flows. We may therefore expect $t_{\rm visc}$ to emerge as the longest time-scale over which correlation may be present in observations of the total luminosity; a recent study suggests $t_{\rm visc} \sim 10$ yr (Vilhu 2002).

In this paper we apply the technique of differencing and rescaling to the GRS 1915+105 X-ray data, and show that this implies the existence of a fundamental time-scale for the system in the range 12–17 d. The technique of differencing and rescaling was used by She (1991) and She & Orszag (1991) to study a physical model of intermittency in turbulence, and by Mantegna & Stanley (1995) to investigate fluctuations in the value of a financial index. More recently, the method has been used by Greenhough et al. (2002) to compare accreting with non-accreting X-ray sources, and by Hnat et al. (2002) to quantify turbulence in the solar wind. In summary, we first construct a set of differenced series $Z(t, \tau)$ from the original series $y(t)$, for a range of values of the time-lag τ:

$$Z(t, \tau) = y(t) - y(t - \tau). \tag{1}$$

A set of probability distribution functions (PDFs) is then calculated for the amplitude of the differenced series Z, one for each value of τ, denoted by $P(Z, \tau)$. The best-fitting slope of $\log P(0, \tau)$ against $\log \tau$ defines the scaling exponent m. We then seek a common functional form of these PDFs by rescaling both axes such that

$$Z \rightarrow Z\tau^m = Z_s \quad \text{and} \quad P \rightarrow P\tau^{-m} = P_s. \tag{2}$$

If the separate PDFs for values of τ up to some $\tau_{\max}$ collapse on to one curve, this implies that the X-ray fluctuations are controlled by a single physical process on time-scales below $\tau_{\max}$.

This technique enables us to test in particular for the joint presence of temporal scaling and non-Gaussianity (Hastings & Sugihara 1993; Kantz & Schreiber 1997; Sornette 2000), which together are strong indications of correlated processes such as turbulence (Bohr et al. 1998). GRS 1915+105 is ideal for this type of statistical analysis in that (i) it remains active on very long time-scales, and (ii) this time-scale is very well separated from those associated with the inner disc.

2 SCALING OF GRS 1915+105 X-RAY DATA

2.1 Summary of the data

The raw X-ray data, provided by the All-Sky Monitor (ASM) on board the *RXTE* satellite (Swank et al. 2001), are held at the Goddard Space Flight Centre (GSFC) and can be accessed via their website.[1] Calibration is undertaken by the ASM/*RXTE* team and the processed data are freely accessible on their website[2] (Bradt et al. 2001), where there are 32 800 observations over the period from 1996 February 20 to 2002 April 12, which we plot in Fig. 1. Each point represents the total X-ray flux (measured by the number of counts during periods that last 90 s) integrated over the range 1.3–12.2 keV. The breakdown into three energy bands (1.3–3, 3–5 and 5–12.2 keV) is also available; we have carried out separate analyses of these components, which yield very similar results to those for the total flux which we present here. The source luminosity is sufficiently high to permit the neglect of instrument thresholds,
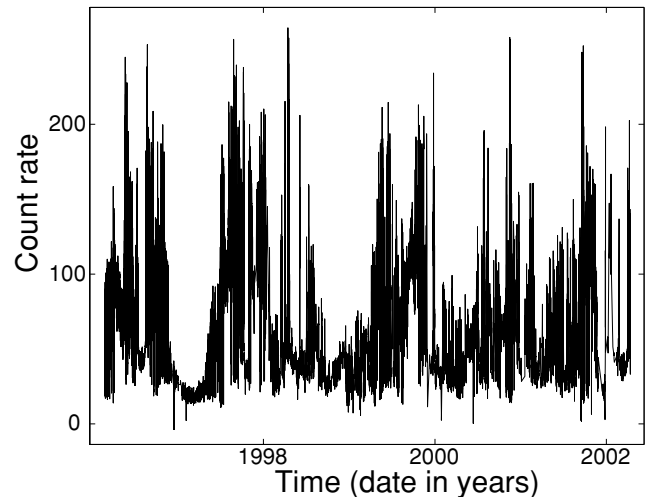
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[1] http://heasarc.gsfc.nasa.gov/docs/xte/asm_products.html
[2] http://xte.mit.edu/XTE/asmlc/ASM.html

Figure 1. X-ray time-series for GRS 1915+105, 1996 February 20–2002 April 12 (MJD 50133–52376); mean sampling interval 94 min. There are 32 800 data points, each of which is the number of counts in the range 1.3–12.2 keV observed in a 90-s interval. Data obtained by ASM on *RXTE* (Swank et al. 2001; Bradt et al. 2001).

uncertainties, and other sources in the field of view. Sampling intervals between the 90-s X-ray counting periods are distributed with a mean of 94 min, and 90 per cent of the intervals are below 193 min; the exact observation times are known and therefore we do not assume even sampling in our analysis. When differencing the X-ray intensities to construct $P(Z, \tau)$, we exploit the fact that each measured intensity is obtained at a precise time that is stated in the data set to within 0.1s. We use these sampling times to find intensities that were observed within $2^{\pm 0.1}\tau$ of the chosen value of τ. While the ASM data is not filtered prior to sampling, and hence the true frequency spectrum is distorted by aliasing, the differencing technique uses only time-domain information that accurately represents the true signal at the given times. We do not attempt any kind of interpolation.

2.2 Results

In Fig. 2(a) we plot the probability of the smallest fluctuations, $P(0, \tau)$, as a function of τ. The straight lines on the double logarithmic axes indicate that $P(0, \tau)$ is a power-law function of τ up to $\tau \approx 2^{7.5}$. This corresponds to a time-scale of 12 d, as this value of τ represents $2^{7.5}$ times the mean sampling interval of 94 min. This break in scaling appears to be a robust feature of the data. For example, Fig. 2(b) shows the variance $\sigma^2(\tau)$ of the set of all fluctuations for a given value of τ; that is, the variance of the differenced data from which the PDFs $P(Z, \tau)$ are calculated. It implies the existence of scaling for τ up to 2^8, corresponding to 17 d. Our key result is that there is a clear break in scaling between the 7.5th and 8th octaves, corresponding to a time-scale of 12–17 d. We emphasize that 12–17 d is not a periodicity in the X-ray luminosity but a time-scale at which a break in the scaling of its statistical properties is observed. In Figs 2(a) and (b) a second scaling region emerges between octaves 7.5 and 10.5. This represents a rather restricted range of time-scales, however, and will not be considered further in this paper.

We next use the slope $m = -0.08$ of the linear fit over the lower range of time-scales in Fig. 2(a) to carry out rescaling, as described at equation (2), for fluctuations of size Z. Fig. 3(a) shows a collapse
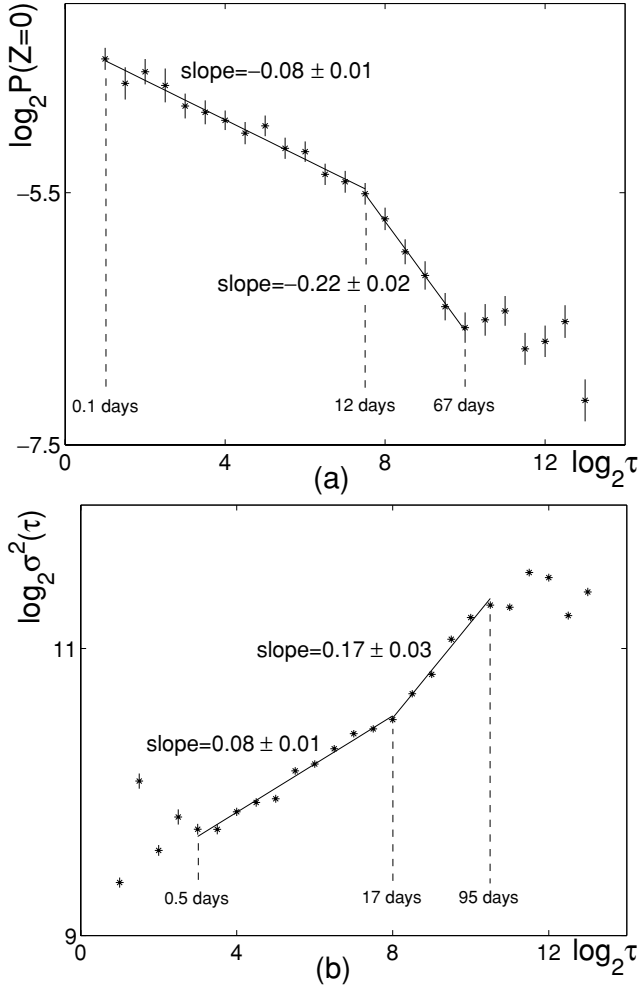
Figure 2. (a – upper panel) Dependence of the probability of the smallest-amplitude fluctuations (differences), $P(0, \tau)$, on differencing time interval τ. This is a logarithmic plot of $P(0, \tau)$ against $\tau = j\tau_0$, where j steps up in integer powers of two and $\tau_0 = 94$ min. Vertical error bars indicate a factor of $\pm 1/\sqrt{N}$, where N = number of pairs of data points separated by τ that are used to calculate $P(0, \tau)$; horizontal error bars of $\pm 2^{0.1}$ indicate the range of τ separating data points used to obtain $P(Z, \tau)$. The slope $m = -0.08$ is used to derive Fig. 3. (b – lower panel) Dependence of the variance, $\sigma^2(\tau)$, of the set of differences (Z, τ) on differencing time interval τ; error bars are calculated as in (a). The slopes of the solid lines in both plots are calculated from linear regression with 95 per cent confidence intervals. Taken together, the plots suggest that scaling extends from 0.5 d to 12–17 d.

on to one curve for $|Z_s| < 30$, implying that small fluctuations follow the same scaling, but large fluctuations beyond $|Z_s| \approx 30$ clearly do not scale in this way. In Fig. 3(b) we show that the scaling regime indicated in Fig. 3(a) is peaked, long-tailed, and definitely non-Gaussian, which is suggestive of turbulent behaviour (Bohr et al. 1998).

We now show that the small fluctuations that exhibit scaling are continually present, whereas the large fluctuations are not. Fig. 4 provides representations of: panel (a) the full X-ray time-series for GRS 1915+105; (b) the small fluctuations that lie between the dot-dash lines ($|Z_s| < 30$) in Fig. 3; and (c) the large fluctuations ($|Z_s| > 30$) only. Dots are the data points at which the fluctuations terminate, that is the latter points of the pairs that are differenced to construct $P(Z, \tau)$. Thus, for example, in Fig. 4(a) there is a dot for every
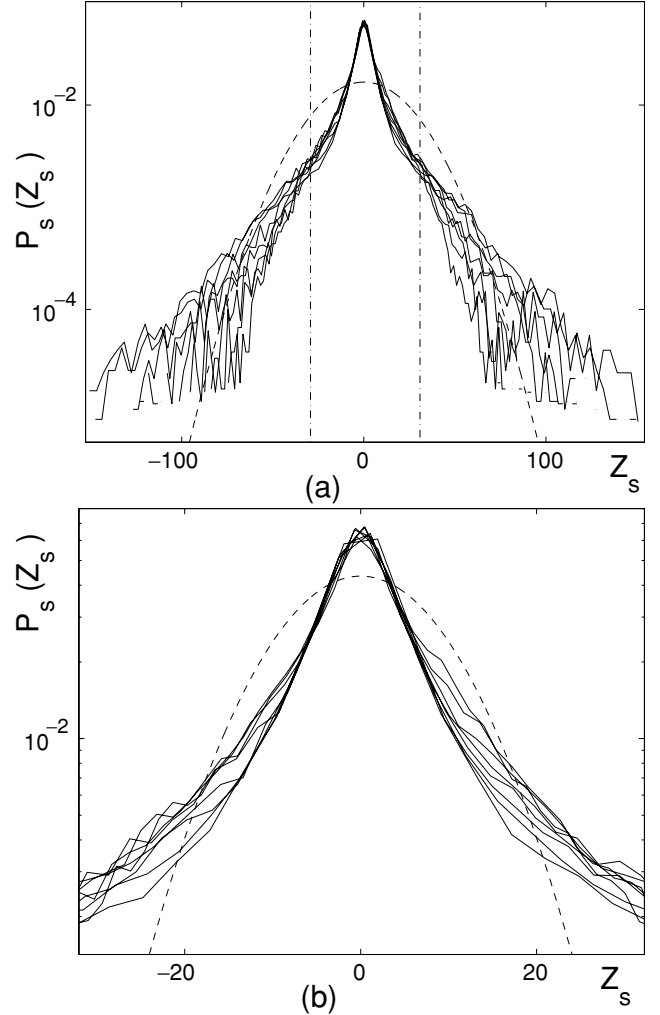
Figure 3. (a – upper panel) Rescaled PDFs of differenced time-series, where Z_s denotes the differences rescaled according to τ and m as at equation (2). Curves are plotted for time intervals $\tau = j\tau_0$ where j steps up in integer powers of two and $\tau_0 = 94$ min; $j_{\max} = 8$ (=17 d). The PDFs collapse on to one non-Gaussian curve between the dot-dashed lines at $|Z_s| = 30$, indicating that only the small fluctuations exhibit temporal scaling. For comparison purposes, the dashed line is the Gaussian fit to curve $j = 1$ for all Z_s. (b – lower panel) Peak region of (a) enlarged to display detail, with Gaussian (dashed line) fitted to curve $j = 1$ for $|Z_s| < 30$ only.

raw data point, whereas in (b) we plot one dot only for each pair of intensities whose rescaled difference Z_s lies between $Z_s = \pm 30$. It is clear that the small scaling fluctuations arise from all parts of the time-series, whereas the larger non-scaling fluctuations are sometimes absent (notably for long periods in 1997 and 1998–1999).

3 DISCUSSION AND CONCLUSIONS

Using the differencing and rescaling technique, 12–17 d emerges as a resilient time-scale in the total X-ray luminosity (1.3–12.2 keV) of GRS 1915+105, and is shown to originate in only the small luminosity fluctuations. This is consistent with the accepted model of a cold (low emission and variability) outer disc that is stable over (viscous) time-scales well above those of the inner disc; only in the outer disc could processes evolve without interruption over periods of days.
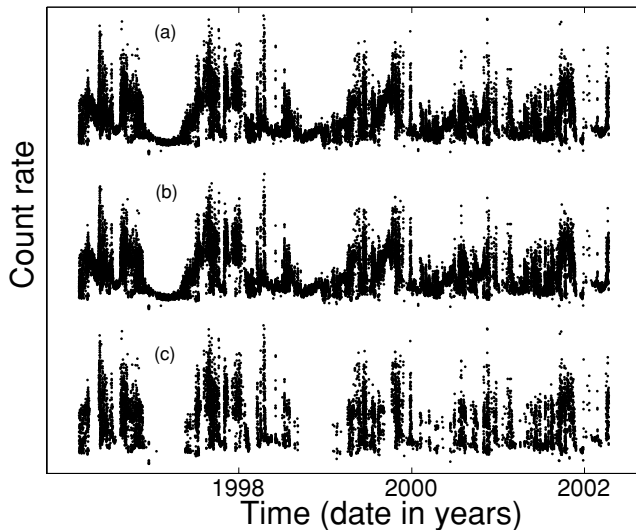
Figure 4. X-ray time-series plotted using dots to identify the origin of fluctuations of different sizes; (a) all fluctuations (all data points), (b) small fluctuations only (between the dot-dashed lines in Fig. 3), (c) large fluctuations only (outside the dot-dashed lines in Fig. 3). This plot shows that only the small fluctuations originate from all parts of the time-series, and Fig. 3 shows that only these fluctuations exhibit scaling.

It is also intriguing that 17 d is approximately half the binary period (33.5 ± 1.5 d) of this source. Although this may be coincidental, it is interesting to speculate on its possible physical significance. For example, this result lends some support to an interpretation in terms of tidally driven waves which we now describe. Lubow, Pringle & Kerswell (1993) review fluid experiments beginning in the 1970s, in which it was found that a dynamical instability can arise in a fluid whose base state is non-circular; Goodman (1993) originally applied this idea to tidally distorted accretion discs in close binary systems. The instability is caused by a perturbation in the frame rotating with the binary at angular frequency Ω_B. Trailing waves can couple via the tidal mode to generate a leading wave, which can then reinforce the original disturbance via the tidal distortion. Vishniac & Zhang (1996) use more detailed disc models to confirm Goodman's findings, and Ryu, Goodman & Vishniac (1996) show how the instability can become global (for other types of instability see, for example, Caunt & Tagger 2001).

In the mode with the largest amplitude, the surface density varies slowly with radius and has an angle and time dependence given by $\sin (2\theta - 2\Omega_B t)$ (Lubow et al. 1993). Differential rotation within the disc shears this disturbance into a two-armed spiral shock that corotates with the binary; amplification caused by the inwardly increasing velocity is balanced by dissipation (Blondin 2000). This tidally induced shock wave has been shown numerically to be a robust feature of the accretion discs of binary systems (Blondin 2000 and references therein), and their possible contribution to the light curves of intermediate polars was demonstrated by Murray et al. (1999). There exist, in addition, many observations of spiral shocks in binaries (see for example Baptista, Haswell & Thomas (2002) and references therein) and in active galactic nuclei (AGN) (Rouan et al. 1998 and references therein, for example). It is plausible that the periodic stirring effect of the rotating shock could drive a turbulent cascade (Goodman 1993; Bohr et al. 1998) in which plasma is heated by viscous dissipation within vortices covering a range of spatial and temporal scales smaller than those of the driving process, and with non-Gaussian fluctuations. It is this dissipation,

spatially integrated across the accretion disc, that drives the X-ray emission. Our observations are consistent with the hypothesis that in the present case of turbulence in a bounded system, the temporal scaling properties – and in particular the upper time-scale of 12–17 d – persist in the X-ray signal. With two spiral arms each rotating with a period of $T_B = 2\pi/\Omega_B$, one would therefore expect to observe temporal scaling up to $T_B/2$ in observations of the total luminosity. For GRS 1915+105, $T_B/2 = (33.5 \pm 1.5)/2 = 17 \pm 1$ d.

Our principal result thus provides quantitative constraints on models for transport and heating in the accretion disc of GRS 1915+105, and our analysis also suggests possible physical mechanisms that may be at work.

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