Multifrequency Observations of the Galactic Microquasars GRS1915+105 and GROJ1655-40

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The two galactic 'microquasars' with superluminal radio jets have been quite active during 1996, generating a variety of studies involving both NASA and ground-based observatories. GRS 1915+105 has displayed dramatic accretion instability in observations with RXTE, revealing X-ray light curves and emission states unlike anything previously seen. Variable QPOs in the range of 0.07–10 Hz have been monitored with the capability to track the individual oscillations. The QPO amplitude is as high as 40% of the mean flux, while both amplitude and phase lag increase with photon energy. The results imply a direct link between the QPO mechanism and the origin of the energetic electrons believed to radiate the X-ray power-law component. GRS1915+105 also displays a transient yet stationary QPO at 67 Hz. The other source, GRO J1655-40, is an optically established black hole binary. Recent optical reports include an excellent model for the binary inclination and masses, while an optical precursor to the April 1996 X-ray outburst has been measured. We report new results from recent RXTE observations. GROJ1655-40 has displayed both the canonical "soft/high" and "very high" X-ray states, with QPOs at 8–22 Hz during the latter state. In addition, there is a high-frequency QPO at 300 Hz. The rapid oscillations in these sources are suspected of providing a measure of the mass and rotation of the accreting black holes, although several competing models may be applied when evaluating the results.

1 Introduction

The two sources of superluminal radio jets [9 15 6] in the Galaxy, GRS1915+105 and GRO J1655-40 have been quite active during 1996. These X-ray sources were originally detected during May 1992 and July 1994, respectively, and they have persisted well beyond the typical time scale for X-ray transients [2]. Optical study of the companion star in GROJ1655-40 has yielded a binary mass function (3.2 $M_{\odot}$) that indicates an accreting black hole [1 13]. In the case of GRS1915+105, interstellar extinction limits optical/IR studies to weak detections at wavelengths > 1 micron [8]. The compact object in this system is supsected of being a black hole due to the spectral and temporal similarities with GROJ1655-40 and other black hole binaries. Both of these microquasars have now been detected with OSSE [4] out to photon energies of 600 keV.

Investigations of microquasars are motivated by several broad and interrelated purposes: to search for clues regarding the origin of relativistic jets, to probe the properties of the compact objects, and to understand the various spectral components and their evolution as the sources journey through different accretion states. Several research programs are described herein, with emphasis on new results from the Rossi X-ray Timing Explorer (RXTE).

2 RXTE Observations of GRS1915+105

The RXTE All Sky Monitor [7] began operation during 1996 Jan 5-13, and continuous observing with a 40% duty cycle has been achieved since 1996 Feb 20. GRS1915+105 was found to be bright and incredibly active [11], as ASM time series data revealed high amplitude modulations at 10-50 s. These results initiated a series of weekly pointings for the PCA and HEXTE instruments. The yield is approaching ten billion photons in an immensely complex and exciting archive that is fully available as 'public' data.

The ASM light curve of GRS1915+105 (1996 Feb 20 – 1997 Jan 23) is shown in Fig. 1. These results are derived using version 2 (1/97) of the model for the instrumental response to X-ray shadows through the coded masks. The top panel shows the normalized intensity for the full range (2–12 keV) of the ASM cameras, in which the Crab nebula produces 75.5 c/s. The vertical lines in the upper region show the times of the PCA / HEXTE observations in the public archive. Below this light curve, one of the ASM hardness ratios is displayed; $HR2$ is the ratio of normalized flux at 5–12 keV relative to the flux in the 3–5 keV band. The spectrum of GRS1915+105 is harder than the Crab ($HR2 = 1.07$). Since there is an anticorrelation between the count rate and $HR2$ in GRS1915+105, we caution against the presumption that the ASM flux is a direct measure of X-ray luminosity. During 1997, significant progress is expected from efforts to combine the ASM results with those of BATSE and radio monitors, including the newly organized Greenbank Interferometer project. This effort will build on earlier work [5] to investigate the multifrequency evolution of X-ray outbursts and radio flares.

The PCA observations of GRS1915+105 immediately showed dramatic intensity variations [3] with a complex hierarchy of quasi-periodic dips on time scales from 10 s to hours. Complex and yet repeatable 'stalls' in the light curve were preceeded by rapid dips in which the count rate dropped by as much as 90% in a few seconds. These variations were interpreted as an inherent accretion instability, rather than absorption effects, since there was spectral softening during these dips. There were also occasions of flux overshooting after X-ray stalls. These repetitive, sharp variations and their hierarchy of time scales are entirely unrelated to the phenomenology of absorption dips [3]. The dips represent large changes in an absolute sense; the pre-dip or post-dip luminosity in GRS1915+105 is as high as 2×10^{39} ergs cm^{-2} s^{-1} at 2-60 keV, assuming the distance of 12.5 kpc inferred from 21 cm HI absorption profiles [9].

The phenomenology of wild source behavior in GRS1915+105 has expanded since the first series of observations. Three examples are shown in Fig. 2. The Oct 7 display of quasiperiodic stalls preceeded by rapid dips (middle panel) is highly organized and repetitive, while the Jun 16 light curve (top panel) shows complex, interrupted stalls that are not preceeded by rapid dips. In the bottom panel, an entirely new type of oscillatory instability is displayed; hundreds of these ringing features were recorded during Oct 13 and 15 with a recurrence time near 70 s. During Oct 15 the recurrence time increases (see Fig. 2), leading to a long X-ray stall and subsequent flux overshoot. The nature of these astonishing X-ray instabilities is currently a mystery. Note, however, that most of the PCA observations show 'normal' light curves with variations limited to rapid flickering at 10-20 % of the mean rate.

A penetrating analysis of GRS1915+105 was made by investigating the X-ray power spectra and comparing them with the characteristics of the ASM light curve[10]. The shape of the broad-band power continuum and the properites of rapid QPOs (0.01 to 10 Hz) are correlated with the brightness, spectral hardness, and the long-term variations seen with the ASM. Four emission states were found, labelled in Fig. 1 as chaotic (CH), bright (B), flaring (FL), and low-hard (LH). We see QPOs and nonthermal spectral components during all four states, implying that they are new variants of the 'very high state' rarely seen in other X-ray binaries[17 16]. The combination of the intense QPOs and the high throughput of the PCA enabled phase tracking of individual oscillations. Four QPO cases were chosen from three different states [10], with frequencies ranging from 0.07 to 2.0 Hz. The results are remarkably similar: the QPO arrival phase (relative to the mean frequency) exhibits a random walk with no correlation between the amplitude and the time between subsequent events. Furthermore the mean 'QPO-folded' profiles are roughly sinusoidal with increased amplitude at higher energy, and with a distinct phase lag of ≈ 0.03 between 3 and 15 keV. At photon energies above 10 keV, the high amplitudes and sharp profiles of the QPOs are inconsistent with any scenario in which the phase delay is caused by scattering effects. Alternatively, it appears that the origin of the hard X-ray spectrum itself (i.e. the creation of energetic electrons in the inverse Compton model) is functioning in a quasiperiodic manner. These results fundamentally link X-ray QPOs with the most luminous component of the X-ray spectrum in GRS1915+105.

In addition to the frequent X-ray QPOs below 10 Hz, a transient yet 'stationary' QPO at 67 Hz has been discovered [10]. This feature is seen on 6 of the first 31 PCA observations of GRS1915+105. Typically, the amplitude is 1% of the flux and the QPO width is 3.5 Hz. This QPO exhibits a strong energy dependence, rising (e.g. on 1996 May 6) from 1.5 % at 3 keV to 6%

at 15 keV. One may attempt to associate this frequency with the mass and spin rate of an accreting black hole, but the competing models include such concepts as instabilities at the minimum stable orbit of $3Rs$, implying a mass of 33 $M_\odot$ for a nonrotating black hole[10], to relativistic modes of oscillation in the inner accretion disk, implying 10 $M_\odot$ for a nonrotating black hole[12].

3 Recent Observations of GRO J1655-40

During much of 1995 and early 1996, GRO J1655-40 was in a low or quiescent accretion state, permitting a clear optical view of the companion star (near F4 IV). Orosz and Bailyn[13] improved the determinations of the binary period (2.62157 days) and the mass function. They further measured the 'ellipsoidal variations' arising from the rotation of the gravitationally distorted companion star. Their analysis, using B,V,R, and I bandpasses, provide an exceptionally good fit for the binary inclination angle (69.5 deg) and the mass ratio. From these results, they deduce masses of 7.0 ± 0.2 and 2.34 ± 0.12 $M_\odot$ for the black hole and companion star, respectively.

The ASM recorded a renewed outburst from GRO J1655-40 that began on 1996 April 25. The ASM light curve (Feb 1996 to Jan 1997) is shown in the lower half of Fig. 1. With great fortune, our optical campaign had lasted until April 24, and Orosz *et al.* has shown[14] that optical brightening preceeded the X-ray ascent by 6 days, beginning first in the I band and then accelerating quickly in blue light. These results provide concrete evidence favoring the accretion disk instability as the cause of the X-ray nova. Theorists may now attempt to model the brightness gradients and delay times in the effort to develop a deeper understanding of this outburst.

The ASM $HR2$ measures (Fig. 1) show an initially soft spectrum that becomes brighter and harder for several months during mid outburst. The PCA observations from our GO program confirm this evolution, as the power-law component (photon index ≈ 2.6) dominates the spectrum during the brightest cases. The great majority of PCA measurments of GRO J1655-40 follow single tracks on the intensity:color and color:color diagrams, with a positive correlation between hardness and brightness.

PCA power spectra show transient QPOs in the range of 8–22 Hz that are clearly associated with the strength of the power-law component. Using a PCA-based hardness ratio, PCA_HR2 = flux above 9.6 keV / flux at 5.2–7.0 keV, we detect QPO in the range of 8–22 Hz whenever $PCA\_HR2 >$ 0.22. Furthermore, in the 7 'hardest' observations ($PCA\_HR2 > 0.3$), there is evidence of a high-frequency QPO near 300 Hz. In Fig. 3 we show the sum of PCA power spectra in these 3 intervals of PCA_HR2, illustrating the QPO centered at 298 Hz. The Poisson noise has been subtracted, with inclusion of deadtime effects [10]. The integrated feature has a significance of 14σ, a width of 120 Hz, and an amplitude near 0.8%. Applying the 'last stable orbit' model to this feature yields a mass of 7.4 $M_\odot$ for a non-rotating black hole. While this is astonishingly similar to the optically determined mass, we caution that other models can give similar results in the case of significant black hole rotation. We further note that none of the models discussed [10] for the high-frequency QPOs in GROJ1655-40 and GRS1915+105 adequately address the spectral signature of this oscillation, which is more directly associated with the power law component rather than the disk (thermal) component. Nevertheless, the fact of these QPOs, which almost certainly originate very near the accreting compact objects, will remain a vigorous research topic throughout the RXTE Mission.

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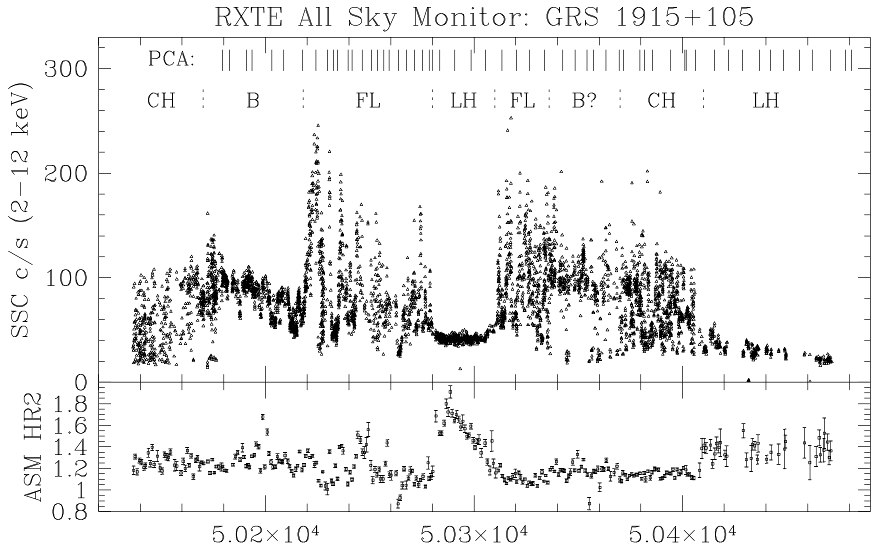

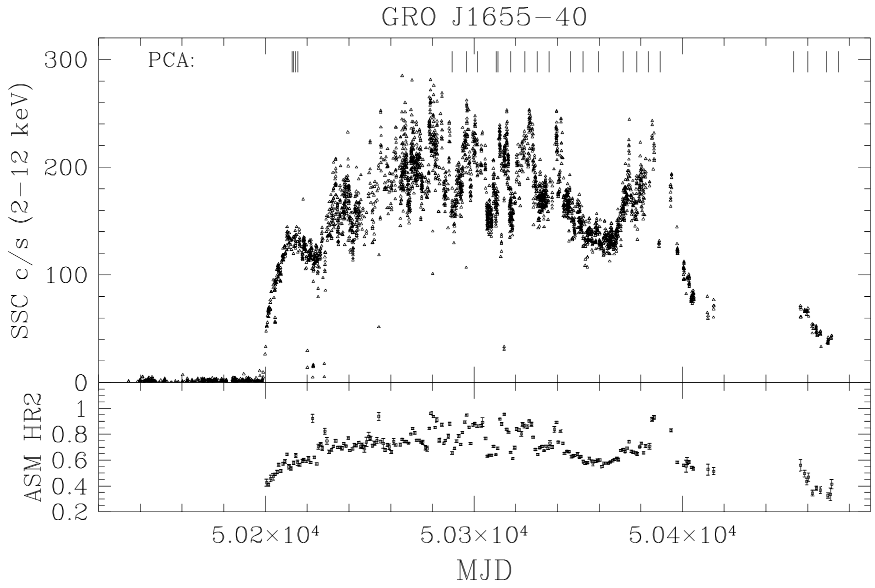

Figure 1: RXTE ASM light curves and hardness ratio of GRS1915+105 and GRO J1655-40.

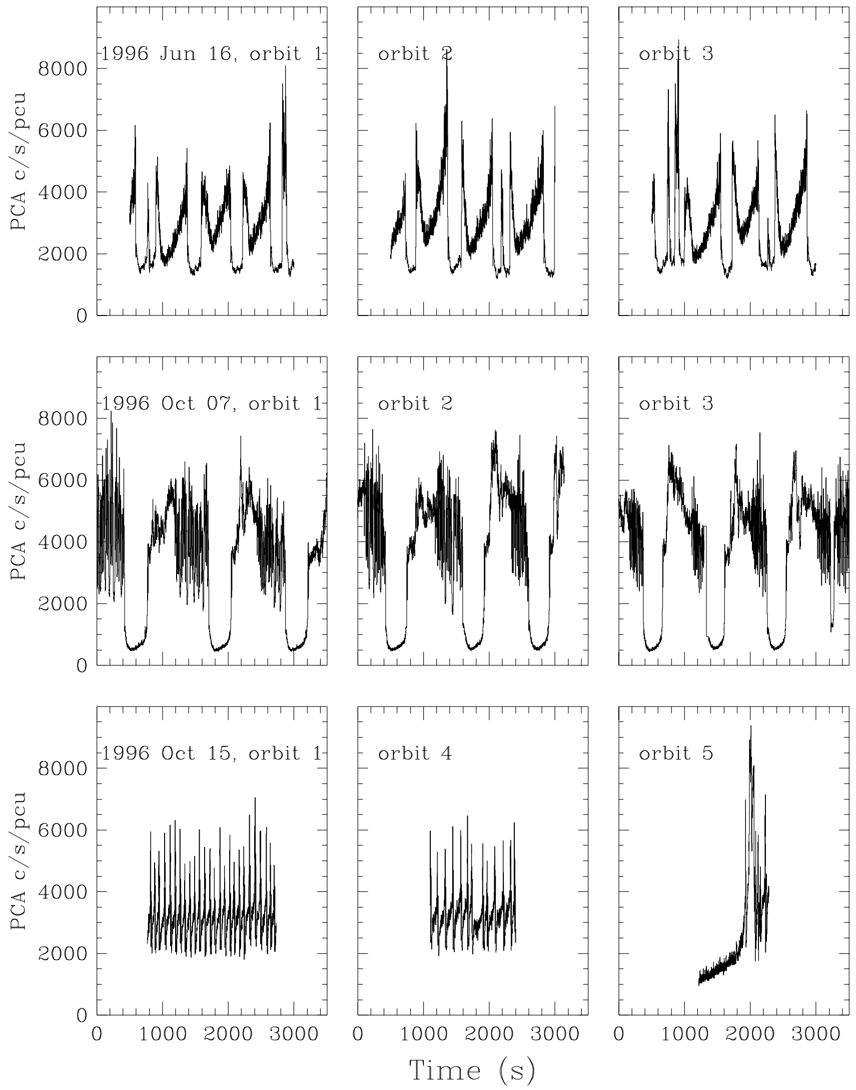

Figure 2: Samples of PCA light curves showing dramatic variability in GRS1915+105 (2–30 keV). The adjacent panels along each row display source measurements from different satellite orbits during the same observation.

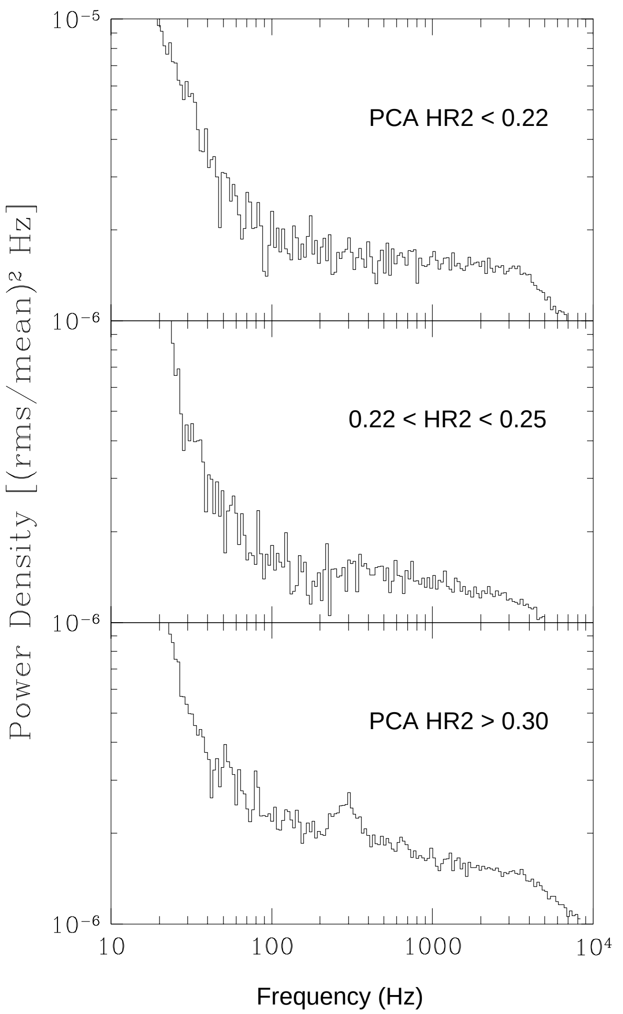

Figure 3: PCA power spectra of GRO J1655-40 in which 20 observations are combined into 3 intervals of PCA_HR2 (see text). A QPO appears at 300 Hz during the 7 observations with the hardest X-ray spectra.