SPECTRAL AND TIMING PROPERTIES OF THE LOW-MASS X-RAY BINARY 4U 0614+09 WITH XMM-NEWTON

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ABSTRACT

4U 0614+09 is a low-mass X-ray binary with a weakly magnetized neutron star primary. It shows variability on time scales that range from years down to \( \sim 0.8 \) milliseconds. Before the Chandra and XMM-Newton era, emission features around 0.7 keV have been reported from this source, but recent Chandra observations failed to detect them. Instead, these observations suggest an overabundance of Ne in the absorbing material, which may be common to ultracompact (\( P_{\text{orb}} \lesssim 1 \) hour) systems with a neon-rich degenerate dwarf secondary.

We observed 4U 0614+09 with XMM-Newton in March 2001. Here we present the energy spectra, both from the RGS and EPIC cameras, and the Fourier power spectra from EPIC high-time resolution light curves, which we use to characterize the spectral state of the source.

Key words: Missions: XMM-Newton – stars: neutron stars – X-rays: stars accretion, accretion disc

1. INTRODUCTION

4U 0614+09 is a low-luminosity X-ray binary. Thermonuclear (type I) X-ray bursts from 4U 0614+09 were observed by OSO 8 [\textsuperscript{1}] and WATCH [\textsuperscript{2}], identifying the central source as a neutron star (as opposed to systems with black-hole candidate primary).

In 4U 0614+09 the X-ray flux can vary by a factor of \( \sim 2 - 4 \) (e.g., van Straaten et al. 2000) on timescales of days to months. Using EXOSAT data, Barret & Grindlay [\textsuperscript{3}] found an anticorrelation between the high- and low-energy X-ray emissions in 4U 0614+09; this anticorrelation has been observed to extend up to 100 keV [\textsuperscript{4}].

Observation with RXTE have revealed strong quasi-periodic oscillations [\textsuperscript{5}].\textsuperscript{6} that extend up to \( \sim 1300 \) Hz kilohertz [\textsuperscript{7}]. These oscillations are thought to originate from matter in Keplerian orbit close to the central object. If this so, these quasi-periodic oscillations carry information about the strong gravitational field in the vicinity of the compact object.

The energy spectrum of 4U 0614+09 can be approximated by a combination of a power law (sometimes with an exponentially cut-off at high energies), and a soft component, both affected by interstellar absorption. The soft component fits a blackbody, and is interpreted as the combined effect of emission from the surface of the neutron star and the accretion disc. The power law component is assumed to originate via comptonization of soft photons by hot electrons in a corona around the neutron star.

In 4U 0614+09, observations with EINSTEIN’s Solid State Spectrometer have revealed emission features at \( E \sim 0.7 \) keV [\textsuperscript{8}]: these features are thought to originate in a corona around the neutron star or above the disc [\textsuperscript{9}].

Here we present a preliminary analysis of two observations of 4U 0614+09 carried out in March 2001 with the instruments onboard XMM-Newton. We discuss spectral (both continuum and line features) and timing properties of the source.

2. OBSERVATIONS AND RESULTS

XMM-Newton observed 4U 0614+09 on March 13 2001 in two occasions, starting at 10:38 UTC and at 12:38 UTC, respectively; the exposure times were \( \sim 11 \) ks, and \( \sim 17 \) ks, respectively. During the first observation data were collected with the Reflection Grating spectrometers (RGS) only, whereas during the second observation the European Photon Imaging Camera (EPIC) was also used. We will not discuss here the Optical Monitor data, and from the EPIC data, here we will only present results obtained with the MOS cameras.

In the observation in which the EPIC cameras were used, MOS 1 was operated in “full frame” (imaging) mode, in which data from all 7 CCDs are read out with a time resolution of 2.6 seconds, whereas MOS 2 was operated in “timing mode”; in this mode data from the central CCD are collapsed into a one-dimensional row to achieve a 1.5-millisecond time resolution. Both RGS cameras were operated in the standard “spectral mode” (read out of all 9 CCDs with a cycle of 5.7 seconds).

The raw data was processed using the standard SAS pipe-line. For our analysis we used the latest SAS version, v5.2.0 (20010917,1110).

In Figure 1 we show the MOS 1 image, from 0.3 to 12 keV. The source is relatively bright, and pile-up effects are apparent in the central parts of the image.
In Figure 2 we show the 0.3–12 keV light extracted from MOS 2 (timing) data. Because of the much faster read-out time, pile-up is not a problem here. Each point represents 64 seconds of data. There is a slight decrease of the source intensity as the observation progresses; the X-ray hardness (defined as the count rate ratio between the 0.3–4 keV band and the 4–12 keV band) is consistent with being constant during the whole observation (Figure 1).

2.1. Energy Spectra

We used MOS 1 data to produce a spectrum of the source in the range 0.3 to 12 keV. To reduce the effects of pile-up, we extracted data from an annulus that does not include the center of the image (see Figure 1); we also produced the corresponding RMF and ARF files. We fitted the spectrum with different models, but we found that for energies above \( \gtrsim 1 \) keV, a simple power law (affected by interstellar absorption) fits the data quite well. However, for \( E \lesssim 1 \) keV there is an excess of emission above the power law. Although the addition of a soft component (we used blackbody or disc-blackbody emission) improves the fit, the soft component cannot fit completely the low-energy excess. A better fit (reduced \( \chi^2 = 1.12 \) for 962 d.o.f.) is obtained by fitting the data to a power law plus a gaussian line centered at 0.65 keV (in this case the soft component is not needed, statistically speaking), with an equivalent width of about 200-300 eV. In Figure 3 we show the MOS spectrum for which we have left the excess at 0.65 keV unfitted; the excess is apparent in the residuals plot. The best-fit parameters are shown in Table 1.

Figures 4a and 4b show the spectra extracted from both RGS cameras, fitted with the same model used to fit the MOS data. To compare the fits between RGS and MOS, we left all model parameters free; in this way, differences in the calibration between the three instruments become apparent as differences in the best-fit parameters in each spectrum. As already mentioned, the MOS and RGS observations are not simultaneous, so small changes in the source spectrum may also be responsible, at least in part, for any difference in the best-fit parameters. Given this caveat, the parameters that we obtained from the different instruments are in most cases very similar to each other. In particular, the excess emission above the power law fit in the MOS data is also present in the RGS data; the models fitted to the data in Figures 4a and 4b do include this feature, and therefore the excess is not apparent in the residuals. In all cases (MOS and RGS), the feature is significantly detected \((\gtrsim 10\sigma)\). However, it is worth mentioning that, if it really is an emission line or an emission-line complex, this feature is not resolved in the RGS spectrum.

Recently, Juett et al. 2001 (2001) have proposed that this low-energy excess in 4U 0614+09, and similar ones in three other low-mass X-ray binaries, may be attributed to an overabundance of Ne, and an underabundance of O in the absorbing material along the line of sight. Such an unusual abundance of Ne and O in 4U 0614+09 has already been reported by Paerels et al. (2001), based on LETGS Chandra data. Juett et al. proposed that this Ne/O overabundance with respect to solar, could be local to these objects, and could be related to the evolution history of the secondary star in the system. We therefore fitted the MOS and RGS data with a model consisting of a power law plus a blackbody, both affected by interstellar absorption, for which the relative abundances of O and Ne were
left as free parameters. In this case, we did not include the emission line-like feature. The fits are good, with reduce \( \chi^2 = 1.14 - 1.21 \) for 961 - 2577 d.o.f., and Ne / H and O / H abundances that are 0.4 - 0.5, and 2.0 - 2.9 solar, respectively.

Besides the 0.65 keV excess, the RGS spectra show other features, that are consistent with those already seen in this source with Chandra plus the Low-Energy Transmission Grating Spectrometer [Paerels et al. 2001]; most noticeable are the Ne K edge at \( \sim 14 \AA \) (RGS 2), the O K edge at \( \sim 22 \AA \) (RGS 1), and the 1s-2p atomic O absorption feature at \( \sim 23.5 \AA \) (RGS 1).

### 2.2. Power Spectra

We used MOS 2 “timing” mode data to produce a power spectrum for observation 2. We calculated the Fourier transform of contiguous 256 seconds long segments, up to a Nyquist frequency of 256 Hz without energy selection. The individual power spectra were then averaged to produce a single power spectrum of the whole observation. This power spectrum is shown in Figure [3], where we have subtracted the contribution of Poisson noise. The power spectrum is more or less flat up to \( \sim 1 \) Hz, and there it gradually steepens towards higher frequencies, which is typical of neutron star and black hole X-ray binaries in the so-called low (hard) state. In the case of low-luminosity neutron star binaries, like 4U 0614+09 (these binaries are also known as Atoll sources), this state is called “Island” (the names derive from the shape traced out by these sources in a color-color diagram; see Klis 1989).

To estimate the variability of the source during our observation, we fitted the power spectrum with a function consisting of two lorentzians. The central frequencies of these two lorentzians are \( 1 \) \( \pm \) 0.7 Hz, and the FWHM are 2.0 \( \pm \) 0.3 Hz, and 9.8 \( \pm \) 0.6 Hz, respectively. The total rms variability (integrated from 0 to \( \infty \)) is 31.7 \( \pm \) 1.6 %. This value is consistent with those in other atoll sources, and in particular in 4U 0614+09, in the island state (see, e.g., Mendez et al. 1997; van Straaten et al. 2000).

### Table 1. Fits to the X-ray spectra of 4U 0614+09

| Instrument | Observation Date | \( N_H \) \( [10^{22} \text{ cm}^{-2}] \) | \( \Gamma \) [photon index] | \( E_{\text{peak}} \) [keV] | \( \text{EqW} \) [eV] | Flux \( ^1 \) | \( \chi^2/\text{dof} \) |
|-----------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| RGS 1     | 13/03/2001 10:38 UTC | 0.351 \( \pm \) 0.003 | 2.078 \( \pm \) 0.020 | 0.66 \( \pm \) 0.01 | 205 \( \pm \) 30 | 6.24 \( \times \) \( 10^{-11} \) | 1.20/2578 |
| RGS 2     | 13/03/2001 10:38 UTC | 0.405 \( \pm \) 0.005 | 2.317 \( \pm \) 0.020 | 0.60 \( \pm \) 0.02 | 305 \( \pm \) 70 | 5.93 \( \times \) \( 10^{-11} \) | 1.11/2536 |
| MOS 1     | 13/03/2001 12:38 UTC | 0.316 \( \pm \) 0.003 | 1.955 \( \pm \) 0.050 | 0.65 \( \pm \) 0.01 | 289 \( \pm \) 50 | 1.17 \( \times \) \( 10^{-10} \) | 1.12/962 |

\(^1\) Unabsorbed 2-10 keV flux in erg cm\(^{-2}\) s\(^{-1}\). 1-\( \sigma \) errors are indicated.

Our XMM-Newton observations of the low-mass X-ray binary 4U 0614+09 found the source in the so-called island state, during which the energy spectrum fits a relatively flat power law (photon index \( \sim 2 \)), and the power spectrum shows a broad-band component that extends up to \( \sim 1 \) Hz, with high rms variability (\( \sim 31 \% \) in this case).

Striking from the spectral fits is the excess emission (above the power law emission) at \( \sim 0.65 \) keV that is apparent both in the MOS and RGS spectra. A similar excess has been reported by Christian et al. (1994) using the solid state spectrometer aboard EINSTEIN, and White et al. 1997 using the solid state imaging spectrometers aboard ASCA. The low-energy excess reported by Christian et al. 1994 is centered at around 0.77 keV, and has an equivalent width of \( \sim 40 \) eV. In our case the excess is centered at a slightly lower energy (\( \sim 0.65 \) keV), and we measure a larger equivalent width (200 - 300 eV). Christian et al. propose that this excess could be due to emission by Ly\( \alpha \) O VII and He-like O VIII, and Fe XVII - Fe XIX in a corona around the central object. Similar emission has been detected recently from other X-ray binaries, e.g. EXO 0748-67 (Cottam et al. 2001a) and 4U 1822-37 (Cottam et al. 2001b). In those cases, however, the emission lines are narrow. It is possible that the excess that we measure is due to Oxygen radiative recombination continuum produced by transitions of continuum electrons to the ground state (e.g., Liedahl & Paerels 1996).

![Figure 3. MOS spectrum of 4U 0614+09. The fit model is a power law (see Table 1 for model parameters). The excess at 0.65 keV has been left unfitted for this plot.](image)
Figure 4. Energy spectra of 4U 0614+09 extracted from both RGS cameras, fitted with the same model used to fit the MOS data. In this case the excess emission at ~ 0.65 keV has been fitted using a gaussian.

Alternatively, it is possible that this line-like “feature” is a consequence of assuming that the abundance of the absorbing material along the line of sight is solar. In fact, the feature disappears when an overabundance of Ne/O in the absorbing material with respect to the solar abundance is considered. If, as suggested by [Juett et al. 2001](#), this overabundance occurs in the vicinity of the binary system, these results are relevant within the evolutionary scenario of this, and similar X-ray binaries.

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Figure 5. Fourier power spectrum of 4U 0614+09, produced from MOS 2 “timing” mode data; the Poisson noise contribution has been subtracted. The blue solid line is the best fit to the data, consisting of a combination of two lorentzians, which are indicated by the red dashed line, and the green dotted line, respectively.

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