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Spectral and timing features in the ultra-compact X-ray binary 4U 0614+091

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We have studied the ultra-compact X-ray binary 4U 0614+091, which is a promising target for the instruments on board of International X-ray Observatory: the High Time Resolution Spectrometer (HTRS) and the Wide Field Imager (WFI) and an instrument on board of the Gravitas mission (General Relativistic Astrophysics VIa Timing and Spectroscopy). It is a bright source (L~3x10^{36} erg/s) consisting of a neutron star orbiting around a carbon-oxygen or oxygen-neon-magnesium white dwarf with an orbital period of around 50 min. We recently discovered an emission feature at ~0.7 keV in this source and interpreted this feature as a relativistically broadened reflection line of O VIII Lyα, caused by X-rays reflected off the accretion disc in the strong gravitational field close to the neutron star. This is the first time that a broad fluorescent O VIII Lyα line is seen in the X-ray binary. This source also shows strong kHz quasi-periodic oscillations (QPOs). By modeling the relativistically broadened oxygen line and simultaneously measuring kHz QPOs we can obtain two independent measurements of the inner radius of the accretion disc. Since 4U 0614+091 shows transitions from the low flux state to the high flux state, we will be able using future instruments to track the changes of the inner radius of the accretion disc obtained from modeling the oxygen line and measuring the QPOs and investigate the correlation between the two. In this way we will be able to test theoretical models for relativistically broadened reflection lines and kHz QPOs.

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1. Introduction

Ultra-compact X-ray binaries (UCXB) are a subclass of low-mass X-ray binaries (LMXBs). They consist of a neutron star or a black hole that accretes gas from a white dwarf. The unique characteristic of UCXBs is a very short orbital period, typically less than 80 minutes (the size of the system is around $1R_{\odot}$). An important process observed in LMXBs is reflection. Photons emitted by the neutron star, the jet nozzle, or flares above the disc can be reflected off the accretion disc giving emission lines and free-free continuum emission. If the infalling photons are reflected by the innermost part of the disc effects such as gravitational redshift and the relativistic Doppler effect [5] will broaden the reflection features in a characteristic way. The most prominent reflection line is the Fe Kα line at $\sim$ 6.4 keV and the second strongest is the O VIII Lyα line at $\sim$ 0.7 keV (assuming solar composition of the disc). Broad Fe Kα lines have been reported so far in a number of LMXBs including those containing a neutron star [4,10,12,13]. Detailed modeling of these reflection lines provides information about the inner radius and inclination of the inner part of the disc. Knowing the inner radius of the disc provides an upper limit on the radius of the neutron star. Measuring the radius together with the mass of the neutron star constrains the equation of state of the dense matter, which is one of the most challenging goals in studying neutron stars.

One of the currently available methods to determine the radius and the mass in the case where a neutron star is in an accreting binary system combines spectral and timing features, namely aforementioned relativistically broadened emission lines and kHz quasi-periodic oscillations (QPOs,[17]) The QPOs can be precisely measured, however their origin is not certain. The variability on very short time scales however indicates that the kHz QPOs are associated with the inner part of the disc. In almost all models for the kHz QPOs a kHz QPO with higher frequency (observations usually reveal two frequencies occurring at the same time) reflects the Keplerian orbital frequency of the accreting matter near the inner radius of the accretion disc. Therefore, it carries information about the inner radius of the accretion disc and the mass of the neutron star. If a relativistically broadened line is observed simultaneously with the kHz QPO then a measurement of the inner radius of the accretions disc and neutron star mass can be directly obtained.

We present a case of an ultra-compact X-ray binary 4U 0614+091 for which above described method can be applied. This source is a good target for the future instruments like the High Time Resolution Spectrometer (HTRS) and the Wide Field Imager (WFI) on board of the International X-ray Observatory and instrument on board of the Gravitas mission (General Relativistic Astrophysics VIa Timing and Spectroscopy). These instruments are designed to be able to simultaneously register spectral information with a decent spectral resolution, which is important in modeling the relativistically broadened lines and timing information with very high time resolution, essential for detecting the kHz QPOs.

2. UCXB 4U 0614+091: XMM-Newton observation

2.1 Relativistically broadened O VIII Lyα line

The ultra-compact X-ray binary 4U 0614+091 consists of a neutron star [16] orbiting around a white dwarf with a period of $\sim$ 50 min [15]. Optical spectra of this source show an enhancement of the disc material in oxygen and carbon [11], which suggests that the donor star is either a carbon-oxygen or an oxygen-neon-magnesium white dwarf. Theory predicts that in the case that disc material is overabundant in oxygen, photons reflected off the disc will give a spectrum where

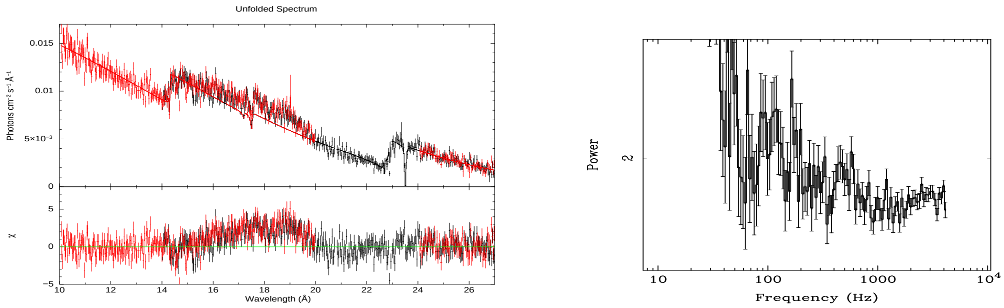

Figure 1: *Left panel*: the RGS1(black) and RGS2(red) spectrum of 4U 0614+091 with continuum model overlayed [7]. The spectrum shows a broad emission feature with a peak at ~ 19 Å, coincident with the position of the O VIII Lyα line. Residuals from the fit are plotted in the units of standard deviation. *Right panel*: Power spectrum of 4U 0614+091 obtained from EPIC-pn timing data that was obtained simultaneously with the spectroscopic observations shown in the left panel. Note the upper kHz QPO at ~ 500 Hz [9].

the most prominent line is the O VIII Lyα line [1]. A recently discovered broad emission feature at ~ 0.7 keV (18Å) in XMM-Newton [7] data of this source was therefore interpreted as a relativistically broadened O VIII Lyα reflection line (see Fig. 1, left). Schulz et al. [14] found a similar feature in Chandra spectra of 4U 0614+091, confirming beyond doubt that the feature is not due to calibration uncertainties. Schulz et al. [14] additionally found variations in the position of the centroid of this feature on a time scale of days. This is the first time that a broad fluorescent O VIII Lyα line has been seen in an X-ray binary. Recently, a similar emission feature at ~ 0.7 keV was also discovered in the UCXB 4U 1543-624 [8]. Similar to 4U 0614+091 optical spectra of 4U 1543-624 show enhancement of oxygen and carbon in the accreting material [11].This reflection feature can be used as a tool to probe the geometry of the inner part of the disc.

2.2 kHz QPO

The kHz QPOs have been observed in the power spectra of a number of accreting neutron stars [17]. RXTE data on 4U 0614+091 often show one or two kHz QPOs [18]. We detect the kHz QPO in the same XMM-Newton data set in which the broad oxygen line was found (see [6] for analysis of the EPIC-pn data in timing mode). The peak is at $\nu \approx 500$ Hz and the FWHM ≈ 150 Hz (see Fig. 1, right). The source was also observed by RXTE, simultaneously with XMM-Newton. Boutelier et al. [3] found consistent results on the kHz QPO properties and suggested that the observed kHz QPO is most likely an upper one. Therefore according to the theoretical models this kHz QPO is associated with the Keplerian orbital frequency of the accreting matter and can be used to constrain the mass and the radius of the neutron star.

3. Combining spectral and timing features observed in the UCXB 4U 0614+091

Once both a relativistically broadened line and the upper kHz QPO is observed simultaneously the mass of the neutron star and inner radius of the accretion disc can be measured. Here we are illustrating the method by using the result obtained by fitting a Laor profile to the feature at 19Å [7]. The best fit value of the inner radius of the accretion disc reported in [7] is $R = 14 \pm 1 GM/c^2$. One should however keep in mind (see the discussion in [7]) that modeling the feature at ~19Å using a model that takes into account only relativistic broadening is probably an oversimplification. The measured frequency of the kHz QPO is $\nu = 492.9 \pm 29.2$ Hz [3]. Combining both measurements under the assumption that the frequency of the kHz QPO reflects the motion on the Keplerian

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Table 1: Simulation showing the exposure time needed in order to measure the inner radius of the accretion disc accurately using the WFI on IXO or the Gravitas instrument. Two possible models are used: one takes into account only the relativistic broadening (Laor profile) the other takes into account also the additional broadening effect-Compton scattering. Two values of the inner radius of the accretion disc are simulated namely $6R_g$ and $15R_g$ ($R_g = GM/c^2$).

WFI	GRAVITAS
10 ksec using reflection model	
$6.0^{+0.3}_{-0.6}R_g$ $15.0^{+1.1}_{-0.8}R_g$	$6.8 \pm 1.0R_g$ $14.4^{+0.7}_{-1.0}R_g$
0.5 ksec using Laor profile	
$5.5^{+0.8}_{-0.5}R_g$ $13.9^{+0.3}_{-1.5}R_g$	$5.9^{+1.0}_{-1.9}R_g$ $14.7^{+1.5}_{-1.3}R_g$

orbit we can calculate the mass of the neutron star, namely $M = \upsilon^3/2\pi G\nu = 1.25 \pm 0.15M_\odot$, where $\upsilon = (GM/R)^{1/2}$ is the velocity of the particles obtained from the measurement of the inner disc radius using the broad O VIII Lyα line. The inner radius of the accretion disc (hence an upper limit on the radius of the neutron star) can also be calculated, namely $R = \upsilon/2\pi\nu = 25.9 \pm 1.6$ km. This upper limit is however not the most constraining we can obtain, since the observed kHz QPO does not have the highest frequency measured in this source. The region where this kHz QPO and also a broad O VIII Lyα is formed is therefore further from the neutron star than in the case of the kHz QPO with the highest frequency.

Additionally using kHz QPOs observed in this source an upper limit on the mass and radius of the neutron star can be calculated using the fact that the radius at which the kHz QPO with the highest frequency occurs is higher or equal to the radius of Innermost Stable Circular Orbit ($6GM/c^2$). The condition is as follows $M < c^3/(2\pi 6^{3/2}G\nu)$ [2]. Hence for the largest kHz QPO observed in this source $\nu = 1224$ Hz [3] we get an upper limit on the mass: $M < 1.8M_\odot$ and radius $R < 16$ km. It seems that the result obtained by using a relativistically broadened line and kHz QPO are in agreement with the constraint obtained from kHz QPOs only.

4. Relativistically broadened O VIII Lyα and kHz QPOs - future instruments:

4.1 HTRS

The HTRS instrument was designed to have a decent spectral resolution at ~6.4 keV together with very high time resolution in order to be able to measure the kHz QPOs. The instrument is aimed to study simultaneously the relativistically broadened Fe Kα line (at ~6.4 keV) and kHz QPOs occurring in AGNs and X-ray binaries. In the case of 4U 0614+091 our goal is to use the relativistically broadened O VIII Lyα line at 0.7 keV in combination with the kHz QPOs observed in this source. The kHz QPOs will clearly be detectable using this instrument. As far as the relativistically broadened O VIII Lyα is concerned, Fig.2 (left panel) shows that it will certainly be possible to detect this line, however a spectral resolution of ~100 eV at ~0.7 keV is not sufficient to constrain the parameters of the model like inner radius of the accretion disc.

4.2 WFI and GRAVIAS

Another option is to use the Wide Field Imager (WFI) which is also available on board of the IXO mission. Its spectral resolution at 6.4 keV is similar to the spectral resolution of HTRS, however at ~0.7 keV the spectral resolution of the WFI is significantly better than spectral resolution of

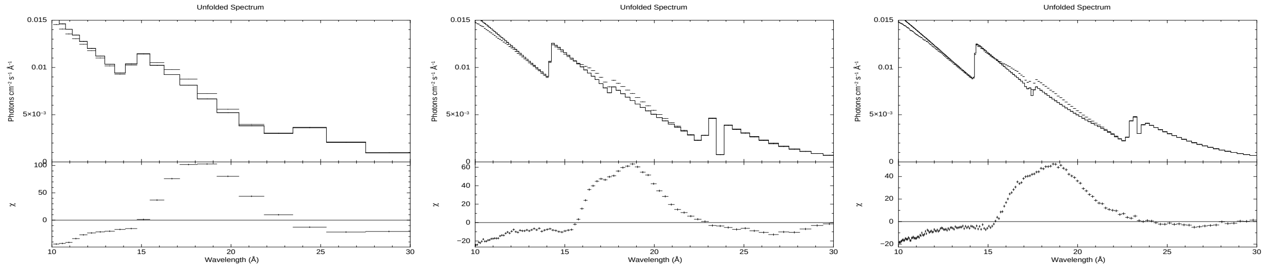

Figure 2: Simulated 10 ksec spectra using response matrixes from HTRS, WFI and Gravitas instruments. In the simulation we used a power-law component and a relativistically broadened reflection model used to fit the XMM-Newton data. Residuals from the fit are plotted in units of the standard deviation. For illustration purposes we fitted the spectrum with an absorbed power-law only. *Left panel*: **HTRS** spectrum, note a low spectral resolution ~100 eV at ~0.7 keV (19Å) of the instrument *Middle panel*: **WFI** spectrum, note significantly better spectral resolution, comparable with the resolution of the instrument on Gravitas. *Right panel*: **GRAVITAS** spectrum.

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the HTRS (see Fig.2, middle panel). Therefore the WFI instrument seems much more promising for modeling the relativistically broadened emission lines occurring in the soft part of the spectrum, like the O VIII Lyα discovered recently. The WFI instrument has however a disadvantage which is a rather low (comparing to HTRS) count rate level of ~1e4 counts/sec with < 10 % pile-up (the limit for HTRS is ~1e6 counts/sec). Since 4U 0614+091 is an Atoll source, which means that it is changing its state, from the low flux state to the high flux state, the flux in the high flux state is approximately 3 times higher than in the low flux state. The observation performed by XMM-Newton was taken when the source was in the low flux state and it would corresponds to ~5e3 counts/sec when measured by the WFI instrument. In the high flux state 4U 0614+091 could still be observed with the WFI though probably with a larger fraction of events which are piled-up.

An instrument on board of the Gravitas mission has a similar spectral resolution to the WFI instrument and the time resolution as well as count rate level with < 10% pile-up similar to HTRS. Therefore for the purposes of studying relativistically broadened lines occurring at the soft part of the spectrum ~1 keV and combining them with the timing properties the Gravitas mission seems to have the best instrument. Although the same results can also be obtained by using WFI and HTRS instruments simultaneously.

In order to have a decent signal to noise ratio required to model the relativistically broadened O VIII Lyα using currently available instruments (on board of Chandra and XMM-Newton) we need rather long exposures (>100 ksec). Thanks to the high effective area of the future missions we will be able to obtain the same result with much shorter exposure time. Our simulation shows (see Tab.1) that we can accurately determine the inner radius of the accretion disc using a relativistically broadened reflection model (which takes into account broadening not only by relativistic effects but also by Compton scattering) with exposure time of only 10 ksec. If the broadening of the observed line is only due to relativistic effects (model with the Laor profile) then we would need an exposure time of 0.5 ksec in order to determine the inner disc radius accurately.

5. Conclusions

The UCXB 4U 0614+091 is a good candidate to study the physics of neutron stars. It shows a relativistically broadened line and kHz QPO, which provide direct information about the mass and radius of the neutron star. Using future instruments like HTRS in combination with the WFI or the instrument on Gravitas we will be able to constrain the mass and radius of the neutron star using the relativistically broadened oxygen line and the kHz QPO. Additionally we will be able to track the position of the inner disc radius with changing state, which will give multiple constraints of the neutron star mass and radius at which the kHz QPO and the relativistically broadened line was formed. This in turn will provide a good test for the models for relativistically broadened lines and kHz QPOs.

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