4U 0115+63:
A Bonanza of Cyclotron Resonance Scattering Features

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We report on an outburst of the high mass X-ray binary 4U 0115+634 with a pulse period of 3.6 s in 2008 as observed with *INTEGRAL* and *RXTE*. By analysing the lightcurves we derived an updated orbital period of the binary system. We also studied the pulse profile variations as a function of time and energy. We find evidence for phase lags at ∼11 and ∼22 keV. In our spectral analysis we found clear evidence for at least two cyclotron features. The continuum can be described by two different models, which lead to a fundamental difference in the behavior of the cyclotron features. We discuss possible reasons for this disagreement.

Introduction

4U 0115+634 is a transient X-ray pulsar with a Be star optical companion. Unlike ordinary B stars, Be stars host a circumstellar disc, resulting from fast rotation, magnetic loop, or non-radial pulsations. Material originating from the Be star's disc can be accreted onto the neutron star. The gravitational energy is released via electromagnetic processes close to the neutron star, where Compton scattering imprints a characteristic power-law spectral shape to the X-ray radiation.

On the surface of neutron stars, magnetic fields of the order of 10^{12} G can occur. As a consequence, the X-ray spectra of pulsars may exhibit broad absorption lines known as cyclotron resonance scattering features (CRSF) at a fundamental energy of $E_c[\mathrm{keV}] = 11.6 \times B[10^{12}\,\mathrm{G}] \times (1+z_g)^{-1}$ and harmonics, where z_g is the gravitational redshift. So far CRSFs have been detected in about 20 X-ray pulsars.

4U 0115+634 is one of the pulsars whose CRSFs have been studied in great detail (see, e.g., Wheaton et al. 1979, White et al. 1983, Nagase et al. 1991, Heindl et al. 1999, Santangelo et al. 1999, and Nakajima et al. 2006). In previous outbursts, CRSFs have been detected up to the fifth harmonic (Heindl et al. 2004, Ferrigno et al. 2009). This high number of detected CRSFs in 4U 0115+634 makes this system an outstanding laboratory to study the physics of cyclotron lines in X-ray pulsars.

The overall lightcurve of the 2008 outburst is shown in Fig. 1. The peak intensity reached ∼ 280 mCrab in the 2–10 keV energy band.

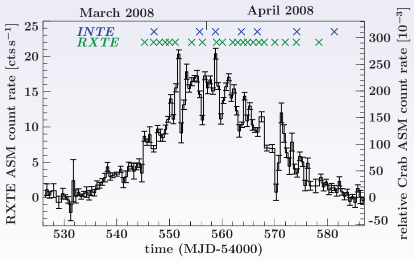

Figure 1. RXTE-ASM lightcurve of the 2008-outburst (2–10 keV energy band).

Orbital Ephemeris

Due to the orbital motion of the neutron star, its pulse period is periodically Doppler shifted. These shifted periods, calculated by epoch folding the PCA-lightcurves, can be used to determine the **orbital ephemeris** of the binary system.

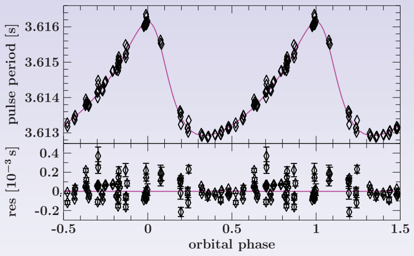

Figure 2. Doppler shifted pulse periods of 4U 0115+63 vs. the orbital phase together with the best fit ($\varphi = 0$ where pulse period is at maximum).

Therefore, we used the orbital parameters from Bildsten et al. (1997) ($a_x \sin i$ = 140.13(8) lt-sec, e = 0.3402(2) and ω = 47.66(9)°) except the epoch of periastron passage, T_0, which we determined from the fit. Assuming that P_{orb} is constant, the difference between our new T_0 and that from literature has to be a multiple of the orbital period P_{orb}. Thus we conclude $P_{\mathrm{orb}} = 24.31617^{+0.00005}_{-0.00007}$ d. Recently, Raichur & Paul (2010) found evidence for a nonzero time derivative of the longitude of periastron $\dot{\omega}$. How this evolution affects our results is still ongoing work.

Spectral Analysis

First, we checked the consistency of the 2008 data to previous results from Nakajima et al. (2006), who studied an outburst of 4U 0115+63 in 1999. They described the data with the NPEX model, which consists of a positive and a negative power law plus a high energy cutoff (Mihara, 1995). Furthermore two (or in some cases three) cyclotron absorption features are necessary to reproduce the observations well. We find that the new data can also be described by this model: Typical values for the fundamental line width are between 7 and 11 keV and the line energy varies between 10 and 15 keV.

Nakajima et al. (2006) found an anti-correlation between the X-ray luminosity of the source and the fundamental cyclotron line energy, which was confirmed by Tsygankov et al. (2007) using a different continuum model. In Fig. 3, we show our results, which confirm this anti-correlation using also the 2008 outburst. In the NPEX model the fundamental CRSF shows exactly the same behavior in the two outbursts. An interesting feature in this anti-correlation is a peculiar hysteresis effect never reported before. During the brightening phase, the fundamental energy E_1 is shifted systematically to higher values compared to the dimming phase. Another feature is a saturation like effect: During the maximum of the outburst, E_1 remains nearly constant.

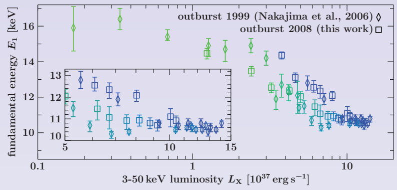

Figure 3. Fundamental CRSF energy vs. 3–50 keV X-ray luminosity using the NPEX model. Bluish data points correspond to the brightening phase while the greenish ones show the dimming phase of the outburst.

Another model that describes the broadband spectra of 4U 0115+63 during previous outbursts is the High Energy Cutoff Powerlaw together with a broad Gaussian emission feature at ∼10 keV as reported in Ferrigno et al. (2009). This continuum model can be successfully applied also to the data of the 2008 outburst and is well suited to characterize the cyclotron features at ∼11 and ∼22 keV.

Fig. 4 shows the dependence of the spectral parameters on the 3–50 keV X-ray luminosity. The Cutoff Energy E_{cut} was fixed to values ∼4–5 keV and the width of the Gaussian σ_G to 3 keV. The values for the width of the CRSFs are, compared to those achieved using NPEX, lower and much closer to those predicted by theoretical simulations of CRSFs. **The cyclotron line energies remain approximately constant within our ability to measure them, whereas the spectral variability can be ascribed to a variation of the continuum parameters.**

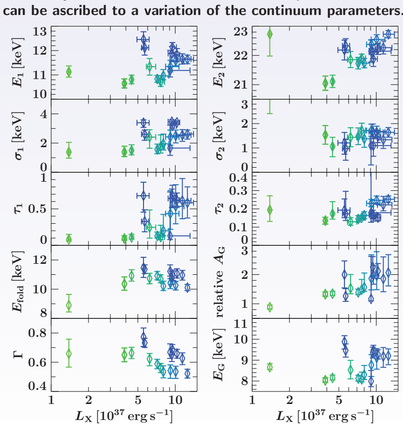

Figure 4. CRSF-and continuum parameters against 3–50 keV X-ray luminosity for the 2008 outburst. The colours are the same as in Fig. 3.

Pulse Profiles & Phase Lags

Fig. 5 shows colour coded pulse profiles for one exemplary observation of the 2008 outburst of 4U 0115+63. In agreement with previous work (Bildsten et al. 1997, and Ferrigno et al. 2009) the morphology of the pulse profiles change dramatically below ∼7 keV. This behavior is also observed in other X-ray pulsars, e.g. GRO J1008–57 (Kühnel et al. in prep.; see also poster "GRO J1008–57: High precision timing and spectral evolution") or 4U 1909+07 (Fürst et al. 2011).

Furthermore this plot clearly shows a shift in the pulse phase of the profile's main peak towards lower values at ∼11–13 keV and also at ∼20–25 keV. Ferrigno et al. (2011) showed that such phase lags are associated with the presence of CRSFs at these energies. A quantitative determination of the position of this phase lags for all observations of the 2008 outburst reveals no temporal variability of these parameter during this epoch. This result is inconsistent with the time dependence of E_1 obtained using the NPEX spectral model.

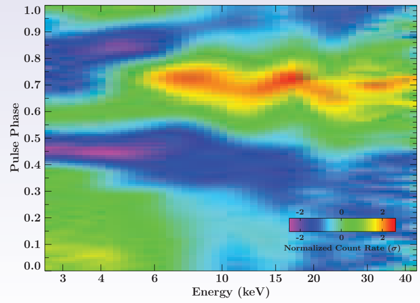

Figure 5. A cut in y-direction through this plot provides a colour coded pulse profile of 4U 0115+63 for a certain energy.

Conclusions

We find two models which describe the spectra of 4U 0115+63 of the 2008 outburst equally well in terms of χ^2_{red}: the NPEX model and a Powerlaw with High Energy Cutoff plus a Gaussian like bump centered at ∼10 keV. In both models, two cyclotron absorption features are clearly detected at ∼11 and ∼22 keV.

However, the behavior of the CRSFs is fundamentally different in these two models. While we see a hysteresis-like anti-correlation between E_1 and L_X in the NPEX model, such correlation disappears in the alternative model. There are a number of reasons which favour the use of this alternative model:

- the cyclotron lines do not contribute significantly to the shape the continuum as in the NPEX model;
- the behavior of the first harmonic is in good agreement with the behavior of the fundamental line;
- the line energy evolution is compatible with the phase lags in the pulse profiles.

We applied the alternative model also to the data of the 1998 outburst, finding similar results. A paper is in preparation reporting this analysis and the pulse phase resolved behavior of the spectral parameters.

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