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A constant Cyclotron Line Energy in 4U 0115+634

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We present a study of *RXTE* and *INTEGRAL* spectra of the transient 3.6 s X-ray pulsar 4U 0115+634 taken during a giant outburst in 2008 March/April. The spectra can be almost equally well modeled by two different semi-empirical continuum models, modified by an Fe Kα fluorescence line, interstellar absorption, and cyclotron resonance scattering features (CRSFs) located at ~10.7, 21.8, 35.5, 46.7, and 59.7 keV. One of these two models, the so called NPEX model, leads to an anticorrelation between the centroid energy of the fundamental CRSF E_0 and the X-ray flux F_X, in agreement with previous works. The other model, consisting of a simple exponentially cutoff power law modified by a Gaussian emission feature around 10 keV, however, leads to a constant value for E_0 for the observed fluxes and a comparatively narrow line shape. We show that the cyclotron line model component resulting from the NPEX fits rather contribute to the broadband continuum model. We conclude that the previously reported anticorrelation is probably due to an artifact of the particular modeling of the continuum.

"An INTEGRAL view of the high-energy sky (the first 10 years)" 9th INTEGRAL Workshop and celebration of the 10th anniversary of the launch,
October 15-19, 2012
Bibliotheque Nationale de France, Paris, France

*Speaker.

PoS(INTEGRAL 2012)020

1. Introduction

4U 0115+634 is an accreting high mass X-ray binary with a pulse period of ∼3.6 s [3]. This system consists of a neutron star which accretes matter from the O9e-type optical companion star V635 Cas [19], resulting in violent transient X-ray outbursts of this source. Owing to the high magnetic field strength on the surface of neutron stars, the electrons' motion perpendicular to the magnetic field lines is quantized into discrete Landau levels. The respective energies of the possibly resulting cyclotron resonance scattering features (CRSFs or cyclotron lines) in the X-ray spectra can be approximated by the 12-*B*-12-rule

$$E_{\mathrm{cyc}} = \frac{11.6B}{1+z}, \tag{1.1}$$

where E_{cyc} denotes the centroid energy of the fundamental CRSF in units of keV, B the magnetic field strength in units of 10^{12} G, and z the gravitational red shift. The centroid energies of the higher harmonics are given to first order by multiples of the fundamental line energy. Since the magnetic field of a neutron star can be approximated by a dipole, and E_{cyc} depends on the magnetic field strength, this energy is also a function of the height of the cyclotron line. Some X-ray binary pulsars with cyclotron lines show variability in the centroid cyclotron line energy. However, these changes of E_{cyc} are not uniform. There are sources showing a positive correlation between E_{cyc} and the X-ray flux F_{X} (e.g., Her X-1 [17]), and there are systems showing an anticorrelations between these two parameters (e.g., V 0332+53 [14]). As a third type of cyclotron sources, there are systems with a constant CRSF energy for all observed fluxes (e.g., MXB 0656–072 [9]). Theoretical models explain these different types of variabilities with different deceleration mechanisms for the accreted material in the accretion column [1, 7, 17]. Below a certain critical luminosity L_{crit}, the braking is dominated by gas pressure leading to a positive correlation between E_{cyc} and F_{X}. For luminosities above L_{crit}, the deceleration is mainly dominated by radiation pressure, resulting in an anticorrelation between these parameters. At intermediate luminosities, the deceleration of the accreted material is dominated by Coulomb interactions leading to a quite stable E_{cyc}.

With five cyclotron lines, 4U 0115+634 is the source with the highest number of detected CRSFs [6]. Therefore, until today, the X-ray spectra of this source have been studied in great detail, e.g., [5, 13, 18], and references therein. Many authors found an anticorrelation between the fundamental cyclotron line energy E_0 and the X-ray flux F_{X} [11, 13, 18]. This result indicates that 4U 0115+634 is located in the supercritical luminosity regime.

In this work we revisit the behavior of the cyclotron lines in 4U 0115+634, focussing on a giant outburst in 2008 March/April. As displayed in Fig. 1, this outburst lasted about 40 days and exceeded a flux of 200 mCrab in the *RXTE*/ASM band (2–12 keV). During this period, the source has been monitored regularly by *RXTE* and *INTEGRAL*.

For a description of the extraction process, an observation log, and a more detailed report of the analysis, see [12].

2. Spectral Analysis

A problem when analyzing X-ray spectra from accreting X-ray pulsars is the description of the broadband continuum. Mostly, semi-physical models consisting of some variant of a power law

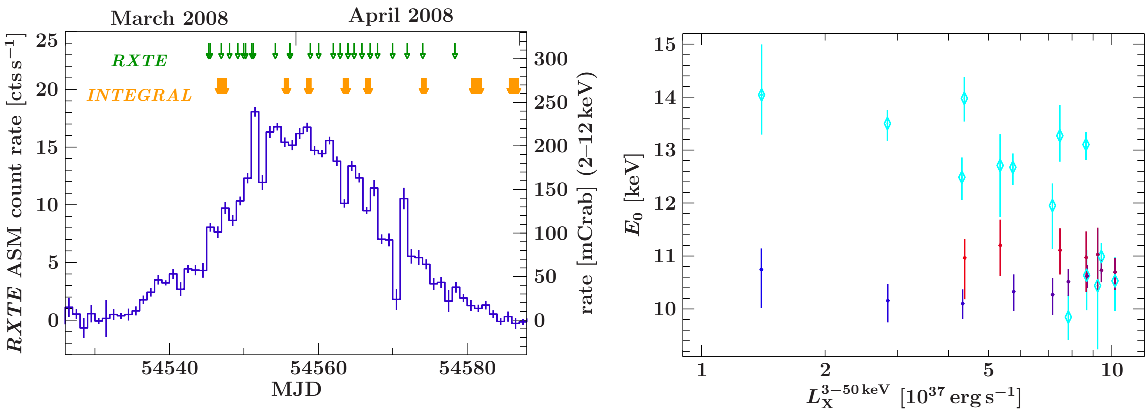

Figure 1: Left: *RXTE*/ASM light curve of the 2008 outburst of 4U 0115+634 in the 2–12 keV energy band. The arrows indicate the *RXTE* and *INTEGRAL* observations. Right: Fundamental cyclotron line energy versus the 3–50 keV X-ray flux. Cyan diamonds indicate the results when using the `NPEX` model. The color change from reddish to dark bluish data points indicates the temporal evolution of the results when using the `CutoffPL` continuum.

with a high energy exponential cutoff are used to describe the spectra [8]. The most simple model is the so called `CutoffPL`, which has the form

$$\texttt{CutoffPL}(E) \propto E^{-\Gamma} \exp\left(-\frac{E}{E_\mathrm{fold}}\right), \tag{2.1}$$

with the photon index Γ, and the folding energy E_fold [16]. Often more complex continuum models with a higher number of free parameters are used. One of these models is the so called `NPEX` model [10] of the form

$$\texttt{NPEX}(E) \propto \left(E^{-\Gamma_1} + \alpha E^{+\Gamma_2}\right) \exp\left(-\frac{E}{E_\mathrm{fold}}\right), \tag{2.2}$$

with photon indices $\Gamma_{1,2} \geq 0$. However, not all pulsars can be described perfectly even with such complex broadband continuum models. In some cases, an absorption- or emission-like feature remains around $\sim$10 keV. Although the origin of the so called "10 keV feature" is still not clear, it is usually modelled as an additive or multiplicative Gaussian line [2].

We furthermore modify the models with up to five cyclotron absorption features, i.e., we multiply the continuum model with pseudo-Lorentzian profiles given by

$$\texttt{CYCLABS}(E) = \exp\left(-\frac{\tau (W E/E_\mathrm{cyc})^2}{(E - E_\mathrm{cyc})^2 + W^2}\right), \tag{2.3}$$

where W denotes the width, and τ the optical depth of the feature. In the remainder of this work, the cyclotron line parameters are labelled with the number of the respective harmonic, where 0 corresponds to the fundamental line. Another feature required for a good description of the data is the Fe Kα fluorescence line at 6.4 keV. Finally, to account for the interstellar absorption, we use an updated version of TBabs [1] [20, 21].

[1] see http://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs/

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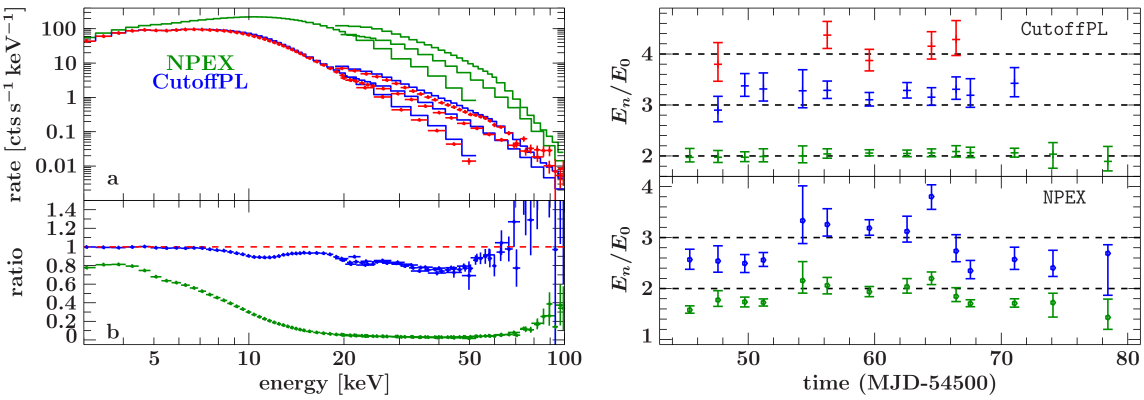

Figure 2: Left: **a** Exemplary PCA, HEXTE, and ISGRI spectra (red) together with the best fit models for the `CutoffPL` (blue) and `NPEX` (green) model. **b** Ratio between the spectra and the model. Right: Ratios of the cyclotron line energies of the higher harmonics with respect to E_0 for the `CutoffPL` and `NPEX`. The dashed lines indicate the integer values for these ratios.

To describe the spectra of 4U 0115+634, we apply both, the `NPEX` and the `CutoffPL` model to each observation, with the latter modified by the 10 keV feature in emission [4]. Both models give a good description of the observed spectra with respect to χ^2_{red}, but for the `CutoffPL` the quality of the fit is slightly better. In agreement with earlier work [11, 13, 18], we find cyclotron absorption features at ~10.7, 21.8, 35.5, 46.7, and 59.7 keV. One important difference between these two fits is the behavior of the fundamental cyclotron line (see Fig. 1). While the `NPEX` model leads to the previously found anticorrelation between E_0 and F_X, the `CutoffPL` model exhibits a rather constant E_0 for all observed X-ray fluxes. Also, for `NPEX` the width of the fundamental cyclotron line W_0 often exceeds 5 keV, while for the `CutoffPL` model it is ~2 keV or less. A constant E_0, however, is in contrast to all previous results for 4U 0115+634, e.g., [11, 13, 18].

3. Behavior of the fundamental cyclotron line

As described in the previous section, the behavior of E_0 with respect to F_X completely changes when using different continuum models. Given that the fits with `NPEX` and the `CutoffPL` give similarly good results, what is the difference between these two approaches and where does the difference in the cyclotron line behavior come from?

The resulting fundamental cyclotron line, when using `NPEX` is rather broad compared to the `CutoffPL`. Such broad lines can strongly influence the continuum fit. To illustrate this impact on the broadband continuum, panel **a** of Fig. 2 displays the best fit models for `NPEX` (green) and the `CutoffPL` (blue) when turning the CRSFs off, i.e., setting the parameter τ for all cyclotron lines to zero. Panel **b** of this figure displays the ratio between the spectra and the best fit models after turning off the cyclotron lines. For the `CutoffPL` model plus 10 keV feature, the cyclotron lines manifest by sharp absorption lines at the respective cyclotron energies. In contrast, for the `NPEX` model the pseudo-Lorentzians obviously strongly influence the broadband continuum shape rather than describe narrow cyclotron lines. Thus, the observed variation of the fundamental cyclotron line with flux when using the `NPEX` model accounts for changes in the broadband continuum, rather than being a real physical effect of the cyclotron lines. For the fits with CutoffPL, the change of the spectral broadband shape reveals itself through the significant variation of the continuum parameters Γ and E_{fold}.

Another problem regarding the NPEX fit are the ratios of the energies of the higher harmonics and E_0. These ratios turn out to deviate strongly from integer values. Slightly non-integer values are expected when taking relativistic quantum mechanics into account, while such strong deviations as seen when using NPEX can only be explained by complex and more exotic assumptions [15, 16]. For the CutoffPL fits, these ratios are mostly in agreement with integers or differ only slightly. These ratios are displayed in Fig. 2 for both continuum models used.

To exclude a possible influence of the continuum parameters on the fundamental cyclotron line energy for the CutoffPL fits, we calculated confidence contours between E_0 and the parameters of the 10 keV feature, Γ, E_{fold}, and W_0. These fits reveal no relevant cross correlations between E_0 and any other free fit parameter.

4. Summary and Discussion

In this work we have shown that the X-ray spectra of 4U 0115+634 can formally be described by several continuum models almost equally well. However, using different continuum models, in this case the NPEX model and the CutoffPL modified by the 10 keV feature, results in a different behavior of the fundamental cyclotron line energy E_0. While there is an anticorrelation between E_0 and the X-ray flux F_X when using NPEX, E_0 stays constant when using CutoffPL. We have shown that the cyclotron line model component strongly influence the broadband continuum model when using NPEX. We conclude that the previously found anticorrelation between E_0 and F_X is caused by variations of the broadband continuum and that the centroid energy of the fundamental cyclotron line actually stays constant within uncertainties in the observed flux ranges.

5. Acknowledgements

This research has been funded by the Bundesministerium für Wirtschaft und Technologie under Deutsches Zentrum für Luft- und Raumfahrt grants 50OR0808, 50OR0905, 50OR1113, and 50OR1007, and by the Deutscher Akademischer Austauschdienst. MTW is supported by the US Office of Naval Research. IC acknowledges financial support from the French Space Agency CNES through CNRS. SMN and JMT acknowledge support from the Spanish Ministerio de Ciencia, Tecnología e Innovación (MCINN) through grant AYA2010-15431 and the use of the computer facilities made available through the grant AIB2010DE-00057.

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