Search for cyclotron absorptions from magnetars in the quiescence with *XMM-Newton*

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In this work, we perform the detailed analysis of absorption features in spectra of magnetar candidates observed by XMM-Newton satellite. No significant line-like feature has been found. This negative result may indicate the possible presence of smoothing out the absorption features mechanisms.

Introduction

Magnetars are strongly magnetized neutron stars powered with a super-strong magnetic field (see e.g. [1, 2] for a review). There are two classes of objects which properties could be described in terms of the magnetar model: Anomalous X-ray Pulsars (AXPs) and Soft Gamma Repeaters (SGRs). It is generally assumed that such sources spin down by magnetic dipole radiation. The inferred values of the surface magnetic field strength $10^{14} - 10^{15}$ G are larger than the so-called *critical* magnetic field $B_{crit} \equiv m_e^2 c^3/e\hbar = 4.4 \cdot 10^{13}$ G where the effects of quantum electrodynamics should be taken into account. This makes magnetars to be the unique natural laboratories to test such superstrong magnetic fields.

However, no direct measurements of magnetic fields in magnetars have been presented so far. It was suggested in [3] to search for proton cyclotron harmonic, which should appear in the x-ray band (2-10 keV) due to the presence of the strong magnetic field:

$$\hbar\omega_p^{cycl} = 0.63\,(1+z)^{-1}\left(\frac{B}{10^{14}G}\right)\ \text{keV}. \tag{1}$$

Here $\hbar\omega_p^{cycl}$ denotes the *observed* energy of the cyclotron feature, $(1+z)^{-1} = \left(1 - 2GM/rc^2\right)^{1/2}$ is the gravitational redshift (~ 0.8 for a typical neutron star), B is the magnetic field strength. Previous search revealed some features during flares and high states, which could be treated as cyclotron features, in the spectra of 7 among 19 magnetar candidates (see Table 1).

Summarizing the results of Table 1, we note that the most of the absorption features were mainly observed during flaring stages and with moderate-resolution instruments such as RXTE/PCA. It was also announced about the absence of the absorption features in the *quiescent* spectra of AXP 4U 0142+614, [16], although they were predicted in earlier theoretical works [18, 19]. The aim of this paper is to provide more extended search for cyclotron features in the quiescent spectra of magnetars. For such an analysis, a combination of good energy resolution and large effective area is necessary. Therefore, we concentrate on EPIC cameras onboard *XMM-Newton* satellite, extending the earlier results of [16, 14], where the same instruments were used.

The Method and Results

In this work, we used all publically available XMM-Newton/EPIC observations with all three cameras (e.g. MOS1, MOS2 & PN) in the *Imaging* mode. It was done to ensure the better statistics and to prevent possible calibration uncertainties which may occur in *Timing* mode. All event lists were cleaned from soft proton solar flares using the standard routine `http://www.sr.bham.ac.uk/xmm2/xmmlight_clean.csh` v. 3.3. Source and background regions were substracted manually from the image. Pile-up checking was carried out with the

Table 1: Parameters of the previously detected absorption-like features found in magnetar candidates. 'MC' denotes Monte Carlo simulations; `gauss` or `cyclabs` denotes the `Xspec` model describing the absorption feature.

Object	Energy, keV	Significance, method	Instrument	Notes	References
1E 2259+586	5, 10	–	GINGA/LAC	during flux increase	[4]
SGR 1806-20	5.0, 7.5, 11.2, 17.5	3.3σ, `gauss`, F-test (for a set of features)	RXTE/PCA	in the harder part of a precursor	[5], [6][1]
4U 0142+614	4, 8, 14	–	RXTE/PCA	emissions, in the most energetic among a sequence of bursts	[7]
1E 1048-5937	14	3.9σ, `gauss`, MC	RXTE/PCA	emission, in a burst	[8]
	13	3.3σ, `gauss`, MC	RXTE/PCA	emission, at one part of a bursts tail	[9]
XTE J1810-197[2]	12.6	4.5σ, `gauss`, MC	RXTE/PCA	emission in a burst tail	[10]
1RXS J1708-4009	8.1	2.95σ, `cyclabs`, MC	*Beppo*SAX	the longest observation (200ks), during rising phase	[12], [13], [14]
SGR 1900+14	6.4[3]	3.7σ, `gauss`, F-test	RXTE/PCA	during precursor to the main burst	[15]

[1] In this work there is a significance estimation of a 5 keV feature (3σ, C-statistic), which appeared in a variety of bursts, whereas the set of features appeared only in one bursting episode of the long precursor.

[2] It was also reported about an absorption-like feature around 1.1 keV in the XMM-Newton/EPIC spectra, which has more readily been interpreted as an absorption edge than a cyclotron absorption, however (see [11]).

[3] There was also a weak excess near 13 keV, but the authors found it to be insignificant and interpreted the line as Fe K-α emission.

Table 2: The results of our analysis. In spite of the significant improvement of the χ^2 value, Monte Carlo simulations did not reveal significant features.

Object	Obs. ID	Energy, keV	Width, eV	Significance, σ
1E 1547.0-5408	0402910101	2.7	13	1.94
1E 2259+586	0057540201	2.2	7	1.36
XTE J1810-197	0161360401	2.6	4	1.07

`epatplot` procedure. If the predicted ratios of the single-to-double events were not equal to 1 within the `epatplot` error interval, such observations were not included in the subsequent analysis. After taking all reductions 41 high-quality observations for 12 objects remained.

To describe the continuum, we chose `blackbody + powerlaw` model modified by `Xspec` photoelectric absorption model `phabs`. After the fitting procedure, we moved through the spectrum, adding cyclotron absorption with cyclotron absorption model `cyclabs` with a step of the central energy of 100 eV and looked for the χ^2 increase when setting the depths of the harmonics to zero. This robust analysis revealed three spectra from three different objects to have possible cyclotron absorptions. To estimate the significances of absorption features, we followed the procedure described in [17], by running Monte Carlo simulations of the spectra with the help of `Xspec` procedure `fakeit` and calculating the percentage of the spectra which are fitted without `cyclabs` component. The results are summarized in the Table . The spectra of the magnetar candidate with the highest cyclotron feature significance detected are presented in figures 1 and 2. Using this procedure, we found the significances of all absorption features to be below the margin 3σ detection limit.

Conclusions

Though initial theoretical works [18, 19] have predicted a proton cyclotron feature of equivalent width $0.7 - 0.75\ \hbar\omega_p^{cycl}$, in subsequent paper [20] it has been shown that vacuum polarization effects strongly suppress the cyclotron absorption feature, giving the equivalent width about an order of magnitude lower. It should also be noted that the theoretical calculations of the equivalent width of the cyclotron feature were done for a local patch of the neutron star surface. Phase averaged spectra, like those we are using here, would include contributions from various magnetic field strengths, directions and effective temperatures, which would further suppress the cyclotron feature. The results of our analysis indicate the absence of the significant cyclotron absorptions in the quiescent spectra of the magnetar candidates observed with *XMM-Newton*, what could be interpreted due to combination of the two above-mentioned effects.

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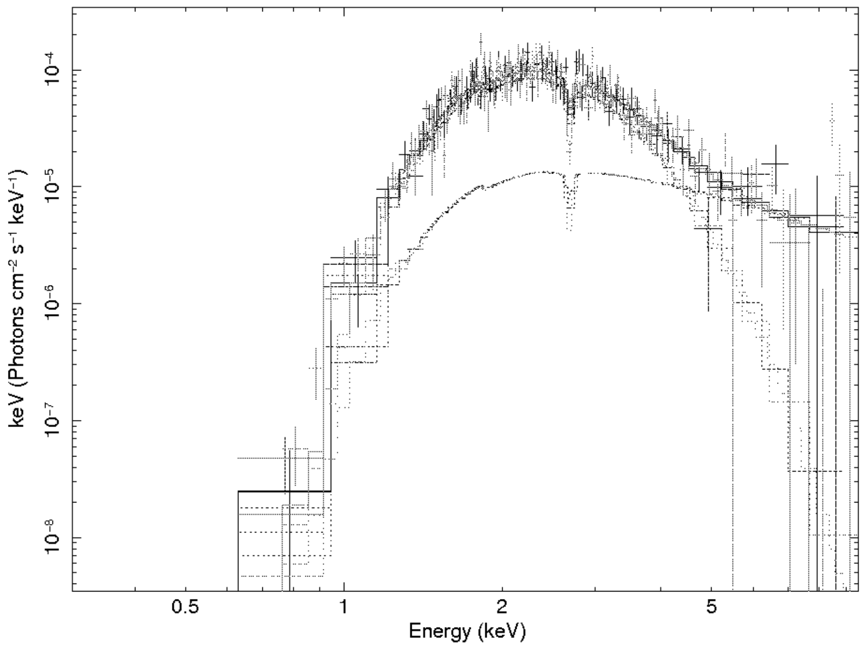

Figure 1: The spectrum of 1E 1547.0-5408 with the highest significance of a cyclotron absorption of 1.94σ estimated from the Monte Carlo simulations. The data are fitted with model `phabs*(blackbody+powerlow)*cyclabs` (see page 2).

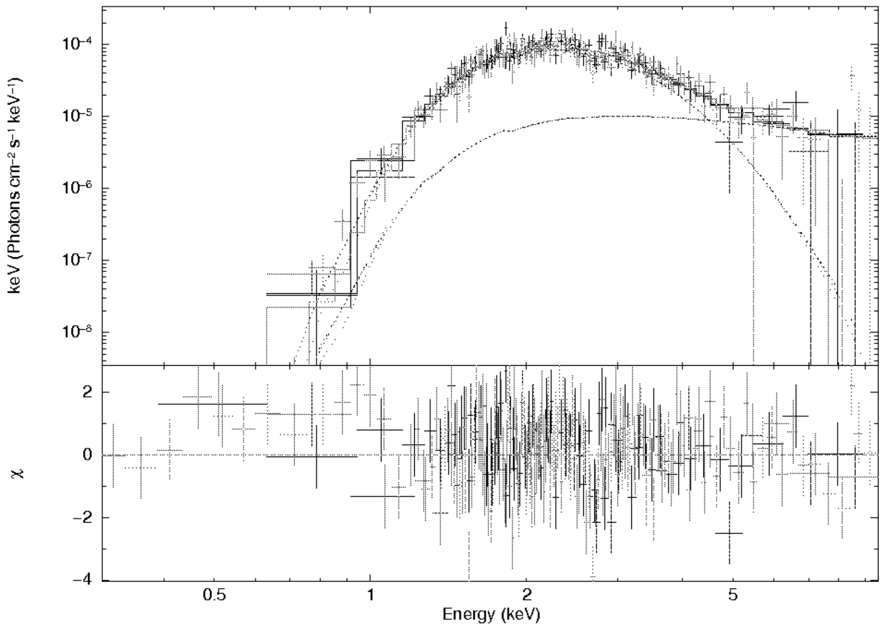

Figure 2: The same as in Fig. 1 but without adding a cyclotron absorption. The model residuals are shown in bottom part of the figure.