SPECTRAL MODELING OF THE HIGH-ENERGY EMISSION OF THE MAGNETAR 4U 0142+614

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ABSTRACT

We present an empirical spectral modeling of the high-energy emission of the anomalous X-ray pulsar 4U 0142+614 based on simultaneous Swift and INTEGRAL observations from X- to γ-ray energies. We adopted models contained in the XSPEC analysis package, as well as models based on recent theoretical studies, and restricted ourselves to those combinations of up to three components that produced a good fit while requiring the lowest number of free parameters. Only three models were found to satisfactorily fit the 0.5–250 keV spectrum of 4U 0142+614: (1) a ~0.4 keV blackbody and two power laws, (2) a resonant cyclotron scattering model plus a power law, and (3) two log-parabolic functions. We found that only the latter two models do not overpredict the infrared/optical emission observed simultaneously from this XAP, and only the log-parabolic functions can naturally account for the upper limits set by COMPTEL in the γ-ray range. A possible interpretation of the two log parabola in terms of inverse Compton scattering of soft X-ray photons by very energetic particles is discussed.

Subject headings: pulsars: individual (4U 0142+614) — stars: magnetic fields — X-rays: stars

Online material: color figures

1. INTRODUCTION

Anomalous X-ray pulsars (AXPs) and soft γ-ray repeaters (SGRs) are peculiar classes of high-energy sources that share a number of properties: i.e., the emission of short bursts, slow rotation periods in a narrow range, secular spin-down, and an X-ray luminosity of ~10^{34}–10^{36} erg s^{-1} (see, e.g., Woods & Thompson 2006 for a review). AXPs and SGRs are believed to be neutron stars powered by ultrastrong magnetic fields (“magnetars”; Duncan & Thompson 1992; Thompson & Duncan 1995).

Spectral analysis is an important tool in magnetar astrophysics, since it can provide key information on the emission mechanism(s). The first attempts at modeling the spectra of AXPs were based on soft X-ray data (<10 keV) only. It was found that a blackbody (kT ~ 0.5–0.6 keV) plus a power law (photon index Γ ~ 2–4), or, limited to a few cases, two blackbodies (kT1 ~ 0.1 and kT2 ~ 0.8 keV) could successfully model the 0.5–10 keV emission. Even though the blackbody plus power-law spectral model has been frequently applied to the X-ray spectra of magnetar candidates, a convincing physical interpretation is still missing (for the power-law component in particular). Recent studies have attempted to overcome this limitation. Several authors showed that resonant cyclotron scattering of soft thermal photons emitted by the star surface may lead to the formation of the power-law tail observed in the soft X-rays (Thompson et al. 2002; Lyutikov & Gavriil 2006; Fernandez & Thompson 2007). Rea et al. (2007, and in preparation) presented an application of the Lyutikov & Gavriil (2006) resonant cyclotron scattering (RCS) model to AXPs and SGRs, showing that in a few sources this component alone can explain the X-ray spectrum below ~10 keV.

More recently, hard X-ray observations have shown that in some magnetar candidates (namely, 4U 0142+614, 1RXS J170849–400910, 1E 1841–045, 1E 2259+586, SGR 1806–20, SGR 1900+14; Kuiper et al. 2004, 2006; Mereghetti et al. 2005; Götz et al. 2006) a large fraction of the total flux is emitted at energies well above ~10 keV. The origin of these “hard” tails, that have so far been detected up to energies of ~250 keV, is still debated (see Beloborodov & Thompson 2007 and Baring & Harding 2007 for possible interpretations). Furthermore, in some cases they also emit at optical and/or infrared wavelengths (e.g., Hulleman et al. 2000; Israel et al. 2004; Durant & van Kerkwijk 2006).

Several AXPs have exhibited long-term variability both in their optical/infrared emission and in X-rays (Oosterbroek et al. 1998; Israel et al. 2002; Hulleman et al. 2004; Rea et al. 2005). Unavoidably, this introduces additional uncertainties in the modeling of broadband spectra based on observations at different wavelengths taken at different times.

The AXP 4U 0142+61 has been recently observed quasi-simultaneously in the hard X-rays (with INTEGRAL; see den Hartog et al. 2007), soft X-rays (with Swift-XRT; see § 2), radio, infrared, and optical (with the Westerbork Synthesis Radio Telescope and Gemini North; see den Hartog et al. 2007 and Durant & van Kerkwijk 2006b for details). Data from this and other campaigns show that most of the bolometric emission (>95%) revealed so far from these (and others) AXPs lies in the X-γ-ray energy range. Motivated by this we present here an empirical modeling of the 0.5–250 keV spectrum of 4U 0142+614 obtained during this quasi-simultaneous campaign (see § 2). In § 3 we discuss how the extrapolation of different models match the flux measured at other wavelengths. In particular, we note that only the fit with two absorbed log-parabolic functions is consistent with the 4U 0142+614 γ-ray upper limits and does not overestimate the observed optical/infrared emission. Some physical implications of our study are then briefly discussed.

2. OBSERVATIONS AND SPECTRAL MODELING

We used Swift X-Ray Telescope (XRT) data obtained on 2005 July 11–12 for an on-source exposure time of 7400 s in the photon-counting (PC) mode (that produced a standard two-dimensional image). The data were analyzed with the FTOOL
Fig. 1—4U 0142+614 soft and hard X-ray spectrum fitted with (from left to right) a blackbody plus two power laws (§ 2.1), the RCS model plus a power law (§ 2.2), and two log-parabolic functions (§ 2.3). Upper row shows the unfolded spectrum and the residuals of the fits: the black lines and plus signs represent the data, the residuals, and the overall model, and the dashed lines represent the single components. The lower row shows the relative unabsorbed fitted models: the gray dashed lines represent the single components, the black lines represent the overall model, and the gray arrows indicate the COMPTEL upper limits from den Hartog et al. (2006). [See the electronic edition of the Journal for a color version of this figure.]

Fig. 2.—4U 0142+614 soft and hard X-ray spectrum fitted with an absorbed blackbody plus a power law and a bremsstrahlung (top), and an absorbed resonant scattering model plus a bremsstrahlung (bottom). Both models give an unsatisfactory reduced $\chi^2 > 2$. [See the electronic edition of the Journal for a color version of this figure.]

2.1. The Canonical Empirical Model

This is the empirical model, which is usually adopted for AXP spectra and consists of a single blackbody and two power laws. For 4U 0142+614 the best fit gave a blackbody temperature of 1.8 response matrices). We extracted photons from an annular region (3 pixels inner radius, 30 pixel outer radius) in order to avoid pile-up contamination, and we considered standard grades for the PC mode 0–12.

For the hard X-ray part of the spectrum we used INTEGRAL data taken by the IBIS/ISGRI instrument (20–250 keV energy range) quasi-simultaneously with the Swift XRT data. These consist of 868 ks divided in 265 science windows collected between 2005 June 29 and July 17 in a pointed observation (see den Hartog et al. 2007).

We fitted (making use of XSPEC 11.3 and 12.1) the X-/γ-ray spectrum of 4U 0142+614 by using any combination of the following components: (1) for the soft X-ray part, two blackbodies, a blackbody plus a power law, a neutron star atmosphere model (nsa model, only available for a maximum magnetic field of $B = 10^{13}$ G), a comptonized blackbody (compbb), a disk blackbody (diskbb), a log-parabolic function, a RCS model (as in Rea et al. 2007, and in preparation); and (2) for the hard X-ray part, a power law, a bremsstrahlung model (bremss), and a log-parabolic function. In all cases we included photoelectric absorption (abundances set to solar values from Lodders 2003) and a constant to account for cross-calibration uncertainties in the two instruments.

All combinations, except for the three models discussed below (see also Figs. 1 and 2, and Table 1), gave unsatisfactory reduced $\chi^2$ values ($\chi^2 > 1.8$). All of the three models that successfully reproduced the spectrum required eight free parameters. Of course, we found that other models, involving components not listed above (e.g., a cutoff power law instead of the hard X-ray power law), gave satisfactory results. However, in all of those cases more than eight free parameters were required.
$kT \approx 0.42$ keV, a very steep power law below $\sim 10$ keV with $\Gamma = 3.77$, and a flatter power law for the high-energy part of the spectrum, $\Gamma = 0.73$ (see also Kuiper et al. 2006; den Hartog et al. 2007). We also tried a slightly more general model, which includes a cutoff around 300 keV, in the attempt to make the extrapolation of the canonical model compatible with the existing upper limits above $\sim 1$ MeV (note that we did not include the MeV upper limits in the fit). We found that the quality of the fit did not improve much despite the addition of one more free parameter in this modeling. Note that the model consisting of two blackbodies plus a power law did not provide a good fit, mainly because the two blackbodies alone cannot account for the soft X-ray part of the emission.

### 2.2. The Resonant Cyclotron Scattering Model

This combination makes use of the RCS model based on the spectra computed by Lyutikov & Gavriil (2006) and recently implemented in XSPEC by Rea et al. (2007). As shown by Rea et al. (2007, and in preparation), this component can well explain the soft X-ray emission of a few magnetars, whereas an additional power law is required for sources of this class that have a strong hard X-ray emission. The model parameters, together with the ranges over which each parameter was allowed to vary, are: the velocity of the magnetospheric $e^-$ currents (in units of $c$) $0.1 \leq \beta_{\text{rel}} \leq 0.5$; their (Thomson) scattering optical depth, $1 \leq \tau_{\text{opt}} \leq 10$; and the temperature of the seed surface emission (assumed to be a blackbody), $0.1 \prec kT \prec 3$ keV.

The efficiency of RCS drops above $\sim 10$ keV, but even in the $6$–$10$ keV energy range the addition of another model component is required to fit the X-ray spectrum of 4U 0142+614. We find a best fit of the whole 0.5–250 keV spectrum with a RCS plus power-law model with a surface temperature of $kT \approx 0.33$ keV, magnetospheric plasma parameters of $\beta_{\text{rel}} \approx 0.22$ and $\tau_{\text{opt}} \approx 1.84$, and a power-law index of $\Gamma \approx 0.67$. The RCS component dominates the emission below 6 keV.

### 2.3. The Log-Parabolic Model

The log-parabolic model is an empirical model commonly used to fit blazars’ spectra, but also has been successfully applied to a few radio pulsars displaying hard X-ray emission, e.g., the Crab and the Vela pulsars (Kuiper et al. 2001; Massaro et al. 2006b, 2006a). We applied this model to our data and found that it fits well the soft and hard X-ray spectrum of 4U 0142+614 (see also Kuiper et al. 2006). Log-parabola spectra (Landau et al. 1986) can be obtained when relativistic electrons are accelerated by a statistical acceleration mechanism in which the probability of acceleration depends on energy and cool via synchrotron losses (Landau et al. 1986; Massaro et al. 2004) or by inverse Compton scattering of synchrotron seed photons.

The log-parabolic spectral distribution can be regarded as the simplest generalization of a power-law distribution, as it comprises a mild symmetric spectral curvature. We adopted the following expression, \[ F(E) = KE^{-\alpha - \beta \log E}, \]
where $E$ is the energy in keV, $\alpha$ is the photon index at 1 keV energy, and $\beta$ controls the curvature of the parabola in a log-log representation. The log parabola peaks at $E_{\text{p}} = 10^{(2-\alpha-\beta) E}$, its free parameters, besides the normalization constant $K$, are $\alpha$ and $\beta$ or, equivalently, $E_{\text{p}}$ and $\beta$.

The two log parabolas we fitted have peaks at $\sim 1.32$ and 412 keV and curvatures of $\beta = -2.52$ and $-0.7$. They provide a very good fit to the data, and have the same number of free parameters as the models discussed above (see Fig. 1 and Table 1).

### 3. DISCUSSION AND INTERPRETATION

We have shown that among spectral models with a relatively limited number of free parameters ($N_{\text{fit}} = 8$), only three successfully fit the X-ray spectrum of 4U 0142+614 (see § 2). The 0.5–250 keV fluxes we derived are consistent among all the three best models. The value of $N_{\text{fit}}$ in the RCS and log-parabolic models is closer to the value measured for this source using X-ray edges in grating spectra ($\sim 6 \times 10^{21}$ cm$^{-2}$; see Durant & van Kerkwijk 2006a).

Comparing the extrapolations of these models with the radio, infrared, and optical fluxes measured from quasi-simultaneously as well as $\gamma$-ray upper limits obtained around 0.2 MeV by COMPTEL (den Hartog et al. 2006, 2007), we found that the canonical model (§ 2.1) overpredicts all of them. The RCS model (§ 2.2) and the two log parabolas (§ 2.3) are an improvement over the canonical model, since they do not overpredict the low-energy emission. In any case, the optical/infrared emission of 4U 0142+614 (and likely of other magnetar candidates) accounts for only less than 5% of the overall source luminosity and might be due to secondary processes as compared to those responsible for the $X$-$\gamma$-ray flux. The optical emission is pulsed, so it is likely to be nonthermal in origin (Kern & Martin 2002). On the other hand, the infrared emission can be ascribed to a fossil disk (see e.g., Wang et al. 2006) reprocessing a fraction of the soft/hard X-ray emission of the magnetar.

The two log parabolas (§ 2.3) are the only model that naturally

### TABLE 1 Parameter Values of the 4U 0142+614 Best Spectral Models

| Model          | BB + 2PL Model | RCS + PL Model | 2 log-parabolic Model |
|---------------|---------------|---------------|----------------------|
| Parameter     | Value         | Parameter     | Value                | Parameter     | Value                |
| $N_{\text{fit}}$ | $0.96^{+0.08}_{-0.06}$ | $N_{\text{fit}}$ | $0.63^{+0.04}_{-0.04}$ | $N_{\text{fit}}$ | $0.73^{+0.01}_{-0.01}$ |
| Constant      | 0.96          | Constant      | 0.90                 | Constant      | 0.87                 |
| $kT$ (keV)    | $0.42^{+0.01}_{-0.002}$ | $kT$ (keV)    | $0.335^{+0.002}_{-0.001}$ | $E_{\alpha}$ (keV) | $1.32^{+0.05}_{-0.05}$ |
| BB flux       | $1.53^{+0.05}_{-0.04}$ | $\tau_0$     | 1.84                 | $\beta_1$     | $-2.52^{+0.08}_{-0.04}$ |
| $\Gamma_{\text{soft}}$ | 3.77          | $\beta_0$     | 0.22                 | log $P_1$ flux | $3.9^{+1.1}_{-1.1}$ |
| $\Gamma_{\text{hard}}$ | 0.75          | $\Gamma_{\text{hard}}$ | 0.67                 | $E_{\sigma_2}$ (keV) | 412^{+20}_{-20} |
| $P_{\text{log-par}}$ flux | 7.80          | RCS flux      | 3.2                  | $P_{\text{log-par}}$ flux | 1.8^{+2}_{-2} |
| $P_{\text{log-par}}$ flux | 1.84          | Total abs. flux | 2.4                  | Total abs. flux | 3.5^{+2}_{-2} |
| Total flux    | 2.70^{+0.1}_{-0.1} | Total flux    | 10.3                 | Total flux     | 5.7^{+1.4}_{-1.4} |
| $\chi^2$ (dof) | 1.04 (48)     | $\chi^2$ (dof) | 1.01 (48)            | $\chi^2$ (dof) | 1.00 (48)            |

Notes.— Best-fit parameters for the 0.5–250 keV spectral modeling of 4U 0142+614. Errors are at 1 $\sigma$ confidence level. Fluxes (if not otherwise specified) are unabsorbed and in units of $10^{-6}$ erg cm$^{-2}$ s$^{-1}$. RCS, BB, PL$_{\text{soft}}$, and log $P_1$ fluxes are for the 0.5–10 keV energy band, while PL$_{\text{hard}}$ and fluxes refer to the 20–250 keV band. Total fluxes are in the 0.5–250 keV band. The value of $N_{\text{fit}}$ is in units of $10^{32}$ cm$^{-2}$. The constant parameter, which accounts for the intercalibration, assumes Swift/XRT as a reference.
accounts for the fast decline of the spectrum in the γ-rays implied by the COMPTEL upper limits. Nevertheless, in the other two models these limits would not be violated if the hard X-ray power law was characterized by a cutoff at ~300 keV (although this would require an additional free parameter in the fit). Note that in a detailed physical model the high-energy power law may indeed quickly decline around ~300 keV, e.g., as a result of the maximum energy up to which the spectrum of the emitting particles extends.

Thompson & Beloborodov (2005) recently proposed that the hard X-ray magnetar emission may be attributed to bremsstrahlung photons emitted by a thin surface layer heated up to ~100 keV by returning currents. However, we find that the 4U 0142+614 spectrum is harder at high energies than envisaged this scenario (Fig. 2). A bremsstrahlung model seems hardly compatible with the hard X-ray spectrum of this source and the COMPTEL upper limits.

Although two log-parabolic functions are often used to model a synchrotron self-Compton (SSC) emission, in the case at hand this interpretation appears unlikely for several reasons. First, it is difficult to reconcile the soft part of the X-ray spectrum with synchrotron emission, since the low-energy log parabola has a curvature of β = −2.52, which translates into a curvature of ~12 for the eγ spectrum. This is very close to the cutoff curvature of the high-energy synchrotron emission of a single particle. Moreover, we performed detailed simulations (see Tramacere 2002; Tramacere & Tosti 2003 for details) in order to infer which local magnetic field and electron density is needed to power the 4U 0142+614 emission by a SSC mechanism. We obtained B ~ 108 G and n~ 1015 cm−3, respectively. A charge density of the same order is predicted in the simple twisted magnetosphere model by Thompson et al. (2002) but close to the neutron star surface. Instead, the low value of the magnetic field requires that such eγ are located at an altitude of several hundred kms in the magnetosphere. We may speculate that inverse Compton scattering by a population of relativistic particles high up in the magnetosphere may explain the hard X-ray emission of magnetars for other (than synchrotron) spectral distributions of seed photons, e.g., that produced by the RCS model. Interestingly, the presence of highly relativistic particles well above the star surface has also been suggested by Thompson & Beloborodov (2005). These authors pointed out that seed positrons injected at ~100 km above the surface can undergo runaway acceleration and upscatter X-ray photons above the threshold for pair production.

In this Letter we introduced and fitted spectral models as purely empirical laws. As in many other studies where the total emission of X-ray pulsars is modeled, no attempt was made to separately fit the spectral behavior of the pulsed and the non-pulsed components. A more extensive study based on data of other magnetar candidates and attempting a more detailed physical interpretation of these results is in progress and will be reported elsewhere.

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