Intrinsic spectra of the AXPs

De-extinction from model-independent measurement of interstellar column densities

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1 Introduction

Magnetars (Soft Gamma-ray Repeaters and Anomalous X-ray Pulsars) have been very exciting to research as of late, with their many and varied high-energy phenomena. They promise, with extreme magnetic, electrodynamic, energy, density and gravitational properties, to be ideal natural laboratories for unlocking the secrets of fundamental physics.

AXPs are X-ray bright, and the majority of investigations of them have thus been conducted in this band. A poorly constrained source of uncertainty in determining the true, intrinsic X-ray spectra, in particular at lower energies, is the amount of interstellar extinction. In previous studies, AXPs’ X-ray spectra have been fit with simple continuum models, deriving extinction column densities with small statistical errors. Different choices of model, however, produced a wide range of columns, each with statistically acceptable fits. The column density can thus be uncertain by as much as a factor of 2 (see, for example, the values of \(N_H\) for 4U 0142+61 in Juett et al. 2002).

The most often used and quoted model for AXP spectra is the sum of a black-body and a power-law. This accounts for the peak in the spectra around 2 keV and an extended tail to higher (\(\sim 10\) keV) energies. The model fails, however, at even higher energies (20–150 keV), where den Hartog et al. (2006) have found a rising power-law spectrum; and at lower energies, where an extrapolation of the model grossly over-predicts the optical emission (Hulleman et al. 2004). From a physical perspective, it is not clear why there should be a power-law component in the spectra of AXPs. Recent physical models, such as those presented by Lyutikov and Gavriil (2006) can account for a power-law like high-energy tail, but do not predict a soft part. In these models, the blackbody surface flux is modified by interactions in the outer atmosphere or magnetosphere, for exam-
ple through the inverse-Compton scattering of photons off high-energy particles. This creates an extended high-energy tail but leaves the spectrum at low energies (the Rayleigh-Jeans side of the blackbody spectrum) unaffected.

Here, we attempt to measure the interstellar extinction in a model-independent way, using individual absorption edges of the elements O, Fe, Ne, Mg and Si in X-ray spectra taken with XMM-Newton.

2 Data analysis

We searched the XMM-Newton archive for observations of all the AXPs. The XMM Newton observatory (Jensen 1999) provides data from three separate instruments simultaneously, but in this work we are concerned with the Reflection Grating Spectrometer (RGS) instruments (den Herder et al. 2001), which provide high-resolution spectra in the range 6–40 Å. We found a number of long observations for the four brightest AXPs (we omitted shorter data sets with few counts). For all these, RGS is used with the same instrumental setup, thus ensuring a fair comparison of the sources.

In order to improve the signal-to-noise ratio, we decided to merge the spectra from different observations of each object into averaged spectra. Here, we must raise a caveat: some AXPs—1E 1048.1-5937 in particular—are variable, and the spectral shape may be different in each observation. This, however, should not change our column estimates, since we fit in small spectral regions around each absorption edge.

For our measurements, we assume that it is possible to find small regions of a spectrum around an absorption edge, over which the intrinsic spectrum is continuous and well-described by a power-law. For each region, we fit a simple analytical edge model, using the latest edge energies and structure information from high signal-to-noise spectroscopy (Takei et al. 2002; Juett et al. 2006; Ueda et al. 2005). Figure 1 shows such a fit, in this case for Oxygen in the spectrum of 4U 0142+61.

We determine our uncertainties through the ‘bootstrap’ Monte-Carlo method (Press et al. 1992), by resampling the data 1000 times with replacement and taking the 68% confidence region from this.

3 Results and conclusions

Table 1 shows the measured column densities to the AXPs of the metals within our sensitivity range, with appropriate uncertainties. Table 2 shows the implied hydrogen columns. Note that the iron and silicon columns were not reliably determined in any case, so these are not used to derive the hydrogen columns, and that we assume the abundances given by Asplund et al. (2004), which fit with our relative abundances for 4U 0142+61 very nicely.

Although in some cases, the measurements do not seem significant, this in not a case where we are attempting to prove the existence of a feature which may or may not be there, but rather, it is a case where the location and shape of the feature is known a priori, and that interstellar extinction must surely exist and here our job is simply to quantify it. Thus, the equivalent hydrogen columns can be safely averaged together, and reddenings estimated through Predehl and Schmitt’s (1995) relation, AV = 5.6(NH/1022 cm−2)mag. The main systematic uncertainty in this is that of the appropriate abundances to use, and the gas-to-dust ratio. At the very least, the relative extinctions between the sources is well-determined, with 4U 0142+61 the least extincted, followed by 1E 1048.1-5937, 1E 2259+586 and 1RXS J170849.0-400910, in that order.

With these values of column densities, it is possible to reverse the process and derive the intrinsic spectra of the AXPs. In Fig. 2, we show the de-extincted spectra derived for all four AXPs under consideration. Two things are immediately apparent: they are not consistent in shape with one-another, and there is no continuation of the >2 keV power-law at low energies (the photon indices, measured from power-law plus black-body fits, of 2.4 to 4.0 correspond to slopes of α = −0.6, −0.1, 0.4, 1.0 [Fα ∝ λα], for 1RXS J170849.0-400910, 1E 1048.1-5937, 4U 0142+61 and 1E 2259+586 respectively). The spectra as shown have indices of approximately α = −3, −2, −2 and 0 respectively, if the low-energy tail is taken to be a power-law. The high-energy power-law clearly does not continue to low energies for any of the sources.

While there is no evidence of a rising power-law component at low energies, the spectra also do not decline as fast as would be expected if they were due to a black-body component. If the thermal emission arises from the neutron-star surface, as seems likely, this might simply reflect a range of