DISCOVERY OF A 6.4 keV EMISSION LINE IN A BURST FROM SGR 1900+14
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ABSTRACT

We present evidence of a 6.4 keV emission line during a burst from the soft gamma repeater SGR 1900+14. The Rossi X-Ray Timing Explorer (RXTE) monitored this source extensively during its outburst in the summer of 1998. A strong burst observed on 1998 August 29 revealed a number of unique properties. The burst exhibits a precursor and is followed by a long (~10$^3$ s) tail modulated at the 5.16 s stellar rotation period. The precursor has a duration of ~0.85 s and shows both significant spectral evolution as well as an emission feature centered near 6.4 keV during the first 0.3 s of the event, when the X-ray spectrum was hardest. The continuum during the burst is well fit with an optically thin thermal bremsstrahlung spectrum with the temperature ranging from ~40 to 10 keV. The line is strong, with an equivalent width of ~400 eV, and is consistent with Fe Kα fluorescence from relatively cool material. If the rest-frame energy is indeed 6.4 keV, then the lack of an observed redshift indicates that the source is at least ~80 km above the neutron star surface. We discuss the implications of the line detection in the context of models for SGRs.

Subject headings: stars: individual (SGR 1900+14) — stars: neutron — X-rays: bursts

1. INTRODUCTION

Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are almost certainly young neutron stars with spin periods in the 5–10 s range and large spin-down rates. The SGRs occasionally and unexpectedly produce short energetic (>10$^{41}$ ergs s$^{-1}$) bursts of X-ray and gamma-ray radiation, and two of these sources (SGR 0526–66 and SGR 1900+14) have also produced so-called “giant flares,” like the famous March 5 event, with luminosities upward of 10$^{44}$ ergs s$^{-1}$. The persistent X-ray luminosities of both SGRs and AXPs are much larger than their spin-down luminosities, implying that some other source of energy powers the X-ray emission. The recent discoveries of X-ray pulsations from the SGR persistent X-ray counterparts (Kouveliotou et al. 1998, 1999; Hurley et al. 1999a) and their large period derivatives, $P \approx 10^{-10}$ s s$^{-1}$, when interpreted in the context of magnetic dipole radiation, have provided support for the hypothesis, first proposed by Duncan & Thompson (1992), that SGRs are magnetars, neutron stars with dipolar magnetic fields much larger than the quantum critical field $B_c = m_e c^2/\hbar \approx 4.4 \times 10^{13}$ G (see also Paczynski 1992; Thompson & Duncan 1995, 1996). It has also been suggested that AXPs may be magnetars, but in a later, less active evolutionary stage (Kouveliotou et al. 1998).

Marsden, Rothschild, & Lingenfelter (1999) suggest that the observed variations in $P$ from SGR 1900+14 are inconsistent with magnetic dipole spin-down and that the torque may be dominated by a relativistic wind, in which case a dipolar field may not have to be supercritical. More recently, Harding, Contopoulos, & Kazanas (1999) have computed the torque due to an episodic particle wind and suggested that a magnetar field can still be consistent with the observed spin-down rates and supernova remnant ages as long as the wind duty cycle and luminosity are within well-defined limits.

Attention has also been focused recently on accretion models for these sources (see Marsden et al. 1999a; Chatterjee, Hernquist, & Narayan 2000; Alpar 1999). These models suggest the spin-down torques may be due to disk accretion. However, direct evidence for such disks is extremely limited, and with daunting constraints on the presence of companions (Mereghetti, Israel, & Stella 1998; Hulleman et al. 2000) it seems unlikely that a binary companion could be the source of such material. These models also have difficulty explaining both the presence of bursts in SGRs and the apparently very quiet spin-down of at least some of the AXPs (see Kaspi, Chakrabarty, & Steinberger 1999; Baykal, Swank, & Stark 1998).

Although much evidence supports the magnetar hypothesis, recent findings have provided new challenges, and it remains for continued observations to either vindicate or disprove the hypothesis. In this Letter we describe recent X-ray spectral analysis of an unusual burst from SGR 1900+14, which provides the first strong evidence for line emission in an SGR burst. Here we focus on the evidence for both spectral features and spectral evolution during a precursor event to the strong burst observed with Rossi X-Ray Timing Explorer (RXTE) and BATSE on 1998 August 29 UT (see Ibrahim et al. 2000). We note that this event was also seen by the BeppoSAX gamma-ray burst monitor and Ulysses (K. Hurley et al. 2000, private communication).

2. RXTE OBSERVATIONS

On 1998 August 29 at 10:16:32.5 UT a bright burst was observed during RXTE pointed observations of SGR 1900+14. The burst is unusual in that it showed a rather long (~1 s) precursor and a long decaying tail modulated with strong 5.16 s pulsations, similar in this respect to the giant flare that occurred on 1998 August 27 (see Hurley et al. 1999b). Here we describe in detail the spectral properties of the precursor. We used data from the proportional counter array (PCA) in an event mode that provides the time of each good X-ray event and its energy in one of 64 bins across the 2–90 keV PCA response. The event was also observed by BATSE (Ibrahim et al. 2000).

Figure 1 shows the time history in the entire PCA bandpass of the precursor with 2 ms time resolution ($\Delta t = 1/512$ s). The precursor is rather long (~0.85 s) compared to typical SGR burst durations and comprises several peaks. Multiplied compositions are not atypical for such bursts. Not only is the pre-
is measured from MJD (Terrestrial Time). The rise vertical dashed lines denote the intervals used in the spectral analysis. Time the full 2±90 keV PCA bandpass, and the sampling rate was 512 Hz. The

from SGR 1900

cursor itself rather long, but the main burst lasted \( \approx 3.5 \) s, quite long for an SGR burst. In order to investigate the precursor’s spectrum we accumulated data in five independent intervals. These are labeled in Figure 1. We chose five intervals as a trade-off between having sufficient signal in each interval and a desire to search for spectral changes within the burst. We further chose the interval boundaries so that each interval would contain the same number of counts and therefore yield spectra of similar statistical quality. We used a \( \approx 1000 \) s segment of preburst data as a background estimate. Thus, our results describe the spectrum of the burst emission alone. We note, however, that there are very few background counts in the accumulated spectra. Thus, in terms of the derived spectral shape, including the presence of narrow spectral features, the background is essentially negligible.

We began by fitting the accumulated spectra with an optically thin thermal bremsstrahlung (OTTB) model including photoelectric absorption (brems \( \times \) wabs in XSPEC v10.0), a spectral form that has often been used to characterize SGR bursts. We found that the OTTB model provides an adequate description of the continuum in all the intervals. In the first two intervals, inspection of the residuals suggested a narrow excess in the vicinity of 6.4 keV. We then added these two intervals together and fit the combined spectrum with the same model. To quantitatively assess the significance of the excess we added a narrow Gaussian emission line to the model and evaluated the significance of the change in \( \chi^2 \) using the \( F \)-test (see Bevington 1992). Since the width of the feature is of the same order as the PCA instrumental width, we are justified in using a narrow line (i.e., a zero-width Gaussian). We also checked a posteriori that allowing a finite width did not produce a significant decrease in \( \chi^2 \). Our analysis indicates that the narrow line significantly improves \( \chi^2 \), and we find a single-trial significance for the 6.4 keV feature of \( 3.8 \times 10^{-3} \) using the spectrum accumulated during intervals 1 and 2. Table 1 summarizes the spectral fits to all five intervals, both with and without the line component, and includes the \( F \)-test probabilities. Figure 2 shows the residuals (data – model, in units of standard deviations) as a function of channel energy for the sum of intervals 1 and 2 using only the best-fitting OTTB continuum model (Fig. 2a) and the continuum plus Gaussian line at 6.4 keV (Fig. 2b). After modeling the feature at 6.4 keV we still see a weaker excess near \( \approx 13 \) keV. If we model just this feature while ignoring the 6.4 keV excess, we find an \( F \)-test significance for the additional two parameters of only 0.075, so statistically it is much less compelling than the 6.4 keV feature; however, we note that the fitted centroid is consistent with a harmonic relationship to the 6.4 keV feature.

We did not find any evidence for significant excesses in the residuals from intervals 3–5. To emphasize this, we also show in Figure 2c the residuals from a fit to the sum of intervals 4 and 5 using the OTTB model, which reveal no evidence for an excess. We note that the OTTB continuum is much softer in these intervals than the first two (see Table 1 and Ibrahim et al. 2000).

At the PCA count rates observed during the precursor, dead time effects are not entirely negligible. We have shown elsewhere (Ibrahim et al. 2000) that for the observed rates during the precursor, the effects of dead time—and in this case, more crucially, pulse pileup—are not sufficient to explain the observed changes in the spectral continuum, nor can pileup itself produce a narrow spectral feature.

The single-trial significance for the 6.4 keV feature is about \( 4 \times 10^{-3} \). We did analyze a number of independent intervals, so in estimating an overall detection significance we must pay a trials penalty. Although the lines were detected in the first intervals examined, we can be conservative and use six trials, one for each of the five independent intervals and one for the spectrum obtained by adding intervals 1 and 2. Even with this conservative number of trials we still have a significance of \( 2.4 \times 10^{-4} \), a robust detection. That the line is present during only a portion of the burst and not in intervals with similar count rates only tenths of seconds apart provides a solid argument that the feature is not instrumental. Furthermore, the line has large equivalent width (EW), much larger in fact than any previously reported imperfections or residuals that could plausibly be attributed to the PCA response matrix (FTOOLS V4.2 and PCA response matrix generator MARFRMF V3.2.1; K. Jahoda et al. 2000, private communication). All these ar-

![Table 1](image_url)

**TABLE 1**

| Interval          | \( kT \) (keV) | \( n_{\text{H}} \) \((10^{25} \text{ cm}^{-2})\) | \( E_0 \) (keV) | \( f \) \((\text{cm}^2 \text{s}^{-1})\) | Equivalent Width (eV) | \( P_{F,\text{test}} \) | \( \chi^2 \) | Degrees of Freedom |
|-------------------|----------------|---------------------------------|----------------|----------------|---------------------|----------------|-------------|-------------------|
| 1 + 2 (line)      | 33.8 ± 4.1     | 3.8 ± 0.7                        | 6.48 ± 0.14    | 0.24 ± 0.05   | 414 ± 95           | 3.8 \( \times \) 10^{-3} | 18.5        | 30                |
| 1 + 2 (no line)   | 26.9 ± 2.6     | 4.9 ± 0.7                        | ...            | ...            | ...                | ...            | ...         | 36.5              |
| 1 (line)          | 42.6 ± 9.2     | 3.9 ± 1.0                        | 6.40 ± 0.22    | 0.30 ± 0.11   | 398 ± 140          | 1.68 \( \times \) 10^{-2} | 19.5        | 26                |
| 1 (no line)       | 38.4 ± 5.9     | 5.0 ± 1.1                        | ...            | ...            | ...                | 2.67 \( \times \) 10^{-3} | ...         | 28                |
| 2 (line)          | 23.8 ± 3.1     | 3.3 ± 1.3                        | 6.56 ± 0.18    | 0.20 ± 0.06   | 440 ± 130          | 1.1 \( \times \) 10^{-3} | 13.5        | 23                |
| 2 (no line)       | 18.9 ± 2.4     | 4.9 ± 1.2                        | ...            | ...            | ...                | 23.3           | ...         | 25                |
| 3                 | 15.9 ± 1.4     | 4.1 ± 0.8                        | ...            | ...            | ...                | 34.5           | ...         | 32                |
| 4                 | 11.8 ± 0.9     | 3.9 ± 0.8                        | ...            | ...            | ...                | 16.7           | ...         | 27                |
| 5                 | 20.4 ± 2.1     | 5.1 ± 1.0                        | ...            | ...            | ...                | 29.0           | ...         | 29                |
Fig. 2a—Residual plots (data−model, in units of standard deviations) using the OTTB fit from the sum of the first two intervals in the precursor. Panel (a) shows the residuals using only the best-fitting continuum model and shows a strong excess at ≈6.4 keV, while panel (b) includes the continuum and the Gaussian line at 6.4 keV. Also shown in panel (c) are the residuals from an OTTB fit to the sum of intervals 4 and 5, which reveal no evidence for line emission during this interval.

Arguments provide very strong evidence that the line feature at 6.4 keV is real and therefore intrinsic to the source.

3. SUMMARY AND DISCUSSION

The spectral behavior reported above is unique in several ways. First, a narrow spectral feature in an SGR burst has not to our knowledge been previously reported, and second, the burst also shows a dramatic spectral softening. Strohmayer & Ibrahim (1998) demonstrated that some bursts from SGR 1806−20 also show significant spectral evolution. Interestingly, the earlier result from SGR 1806−20 is similar in that the trend is for hard to soft evolution. Finally, the line feature is present only during the hardest spectral intervals, suggesting a possible connection between these properties.

The presence of line emission during an SGR burst raises a host of interesting questions concerning the production mechanism and has many implications for models of SGRs. It is beyond the scope of this Letter to attempt an exhaustive description of possible models; rather, we qualitatively discuss several possibilities.

Of the various models proposed for SGR bursts, the most often discussed have been the magnetar model (Thompson & Duncan 1995) and models based on sudden accretion (see Colgate & Petschek 1981; Epstein 1985; Colgate & Leonard 1993; Katz, Toole, & Uhrhu 1994). To date there has been little direct evidence to support accretion scenarios. An intriguing possibility, however, is that the line is due to fluorescence of iron in relatively cool material located near the neutron star. Such features have been observed in a number of astrophysical systems, including accreting X-ray pulsars and magnetic cataclysmic variables (see White, Nagase, & Parmar 1993; Ezuka & Ishida 1999 and references therein). In the X-ray pulsars some portion of the line EW is correlated with the observed absorbing column, $n_H$, indicating that some of the line EW is due to fluorescence in the absorbing material, most likely the stellar wind from the secondary. In some circumstances there is evidence for an uncorrelated EW, indicating an additional source of fluorescing material, and it has been suggested that matter might accumulate in the Alfvén shell (Inoue 1985; Basko 1980) or perhaps an accretion disk (see Bai 1980).

The appearance of lines in the disk accretors, Her X-1 and Cen X-3, indicates that a disk can also be an efficient reprocessor. The fluorescent lines from accreting X-ray pulsars are strong with EWs greater than 100 eV. This is at least qualitatively similar to the feature described here. If the line is due to 6.4 keV iron emission in the rest frame, then the fluorescing material cannot be the stellar surface itself because of the absence of any significant redshift. Assuming the rest-frame en-
nergy of the line is 6.4 keV, we can place a 90% confidence lower limit of \(\approx 80\) km on the altitude of the fluorescing material above a typical neutron star (\(M = 1.4 M_\odot\) and \(R \approx 10\) km). Note that this estimate also ignores any possible effects of a magnetar strength field on the line spectrum. However, the question remains as to the source of the fluorescing material.

SGR giant flares likely produce a hot, optically thick electron-positron plasma in the magnetosphere (Thompson & Duncan 1995). Energy from the radiating plasma will likely be conducted onto the surface of the star, which increases the crust temperature, and may also blow off a baryon wind (Thompson & Duncan 1995). It is conceivable that an ablation process caused either by the precursor itself or perhaps by the giant flare that occurred on 1998 August 27 may have ejected enough iron-rich material into the neutron star environment to produce the fluorescence. Somewhat related processes have been discussed in the context of the putative iron lines from gamma-ray burst afterglows (see Piro et al. 1999; Ghisellini, Lazzati, & Campana 1999). The SGR phenomenon reported here could conceivably be similar but on a smaller scale.

The apparent changes in spin-down rate observed in SGR 1900+14 (Marsden et al. 1999b) have been used to argue for the presence of circumstellar material to produce the spin-down torques. This material might be comoving ejecta from the supernova explosion (Marsden et al. 1999a) or perhaps a fall-back accretion disk (see Chatterjee et al. 2000; Alpar 1999). It is possible that such material could be the source of a fluorescence line. Another clue would seem to be the disappearance of the line as the continuum softens. This appears to be qualitatively consistent with fluorescence as the line mechanism, as the line strength will depend on the number of photons above the Fe K edge absorbed in the fluorescing material, and as the spectrum hardens (softens) this quantity will increase (decrease).

Although the weaker excess at \(~13\) keV is not compellingly significant on its own, the harmonic relationship with the 6.4 keV feature is suggestive of cyclotron emission from accreting pulsars (see Nagase 1989; Dal Fiume et al. 2000).

For magnetar-strength fields electron cyclotron transitions would lie above an MeV, well above the bandpass of RXTE/PCA. However, R. C. Duncan & C. Thompson (2000, private communication) have recently pointed out the following mechanism involving proton and alpha particle cyclotron transitions. In the magnetar model, the giant flare on August 27 produces a hot (\(T \sim\) MeV) trapped fireball in the stellar magnetosphere. Heavy nuclei are ejected from the stellar surface into this fireball, where they photodissociate and subsequently settle to form a thin layer of light elements on the stellar surface. In the August 29 precursor that follows, radiative heating of the star’s surface gives rise to emission at the cyclotron fundamental of each ion, separated by a factor 2 in frequency. If the 6.4 keV line is the He\(^+\) cyclotron fundamental, then the implied surface field strength is \(2.6 \times 10^{15}\) G. This estimate takes into account a redshift correction from the surface of a canonical neutron star. The alternative interpretation of the lines as first and second proton harmonics in \(1.3 \times 10^{15}\) G seems less plausible. In any case, the surface field strength somewhat exceeds the dipole field strength deduced from the spin-down of SGR 1900+14; but note that the multipeaked pulse profile in the tail of the August 27 flare gives evidence for stronger higher order multipoles (Thompson et al. 1999). More work is required to determine if this model can account for the observed line EW and other details, but it is an intriguing possibility.

It is sometimes difficult to draw firm conclusions based on a single example; however, our results argue strongly for detailed spectral studies of the whole sample of bursts observed with RXTE from SGR 1900+14, a project we are pursuing. Studies with instruments possessing greater spectral resolution (such as Chandra and XMM if they can handle the high fluxes) may hold great promise for further testing the magnetar hypothesis for SGRs.

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