THE ASTROPHYSICAL JOURNAL, 574:L51–L55, 2002 July 20

DISCOVERY OF CYCLOTRON RESONANCE FEATURES IN THE SOFT GAMMA REPEATER SGR 1806−20

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Received 2002 May 1; accepted 2002 June 17; published 2002 June 26

ABSTRACT

We report evidence of cyclotron resonance features from the Soft Gamma Repeater SGR 1806−20 in outburst, detected with the *Rossi X-Ray Timing Explorer* in the spectrum of a long, complex precursor that preceded a strong burst. The features consist of a narrow 5.0 keV absorption line with modulation near its second and third harmonics (at 11.2 and 17.5 keV, respectively). The line features are transient and are detected in the harder part of the precursor. The 5.0 keV feature is strong, with an equivalent width of ∼500 eV and a narrow width of less than 0.4 keV. Interpreting the features as electron-cyclotron lines in the context of accretion models leads to a large mass-to-radius ratio ($M/R > 0.3\ M_\odot\ \mathrm{km}^{-1}$) that is inconsistent with neutron stars or that requires a low (5–7) × 10^{11} G magnetic field that is unlikely for SGRs. The line widths are also narrow compared with those of electron-cyclotron resonances observed so far in X-ray pulsars. In the magnetar picture, the features are plausibly explained as being ion-cyclotron resonances in an ultrastrong magnetic field that have recently been predicted from magnetar candidates. In this view, the 5.0 keV feature is consistent with a proton-cyclotron fundamental whose energy and width are close to model predictions. The line energy would correspond to a surface magnetic field of 1.0 × 10^{15} G for SGR 1806−20, in good agreement with that inferred from the spin-down measure in the source.

Subject headings: stars: individual (SGR 1806−20) — stars: magnetic fields — stars: neutron — X-rays: bursts

1. INTRODUCTION

Soft gamma repeaters (SGRs) are a unique class of slowly rotating pulsars ($P \sim$ 5–8 s) that glow quietly in X-rays (luminosity $L \sim 10^{35}$–10^{36} ergs s^{-1}) for several years and suddenly become vigorously active for a few weeks to months, emitting hundreds of short (∼0.1 s), bright ($L \sim 10^{39}$–10^{42} ergs s^{-1}) bursts of soft gamma rays (see, e.g., Hurley 2000 for reviews). Occasionally, SGRs also emit giant bursts that last for up to a few hundred seconds and exhibit remarkable pulsations that reveal their spin periods and confirm their nature as rotating neutron stars (Mazets et al. 1979; Hurley et al. 1999a; Ibrahim et al. 2001).

The lack of evidence for a binary companion or a remnant accretion disk made the energy source of SGRs elusive. Two competing models offer contrasting views on SGRs, as conventionally magnetized ($B \approx 10^{12}$ G) neutron stars powered by fossil accretion disks (Marsden et al. 2001) or as ultramagnetized ($B \approx 10^{15}$ G) neutron stars powered by their own magnetic field (*magnetars*; Duncan & Thompson 1992). Recently, strange/quark star models were also proposed for SGRs (Cheng & Dai 1998; Zhang, Xu, & Qiao 2000).

SGR 1806−20 is one of the four confirmed SGRs; three lie within the Milky Way (SGR 1900+14, SGR 1806−20, and SGR 1627−41), and one in the Large Magellanic Cloud (SGR 0526−66). The source was first detected by the *Prognoz 7*, *ISEE*, and Konus instruments in 1979 (Laros et al. 1986). A few years later, it underwent several periods of burst activity that were observed by different missions; this allowed a fairly accurate determination of the source position (Atteia et al. 1987; Laros et al. 1987). The latest episode of activity was closely monitored in 1996 with the *Rossi X-Ray Timing Explorer* (*RXTE*). During these observations, the source in quiescence was found to pulsate with a 7.47 s spin period and to spin down at a high rate (2.6 ms yr^{-1}). Interpreting the spin-down as being due to magnetorotational dipole losses leads to a magnetic field of ∼8 × 10^{14} G and a characteristic age of ∼1500 yr, typical of a young pulsar (Kouveliotou et al. 1998). SGR 1806−20 has been associated with the Galactic radio supernova remnant (SNR) G10.0−0.3 about 14.5 kpc away (Kulkarni et al. 1994; Corbel et al. 1997); however, this association, like those of other SGRs with SNRs (see Gaensler et al. 2001), was later questioned on the basis of Interplanetary Network and *Chandra* observations (Hurley et al. 1999b). Recently, a possible infrared counterpart was reported on the basis of *Chandra* observations (Eikenberry et al. 2001).

To date, while a great deal of evidence has gathered in favor of the magnetar model over other scenarios, the determination of the magnetic field strength in SGRs (Kouveliotou et al. 1998, 1999), although compelling, is still indirect (Marsden, Rothschild, & Lingenfelter 1999). Spectral signatures, on the other hand, promise decisive direct measurements of the field strength. In this Letter, we report evidence of absorption features in the X-ray spectrum of SGR 1806−20. The nearly harmonic line spacing is suggestive of a cyclotron origin. We use the line energy to derive the star's magnetic field and discuss the implications of this finding on current SGR models.

2. OBSERVATION AND DATA ANALYSIS

SGR 1806−20 entered an intense phase of bursting activity in 1996 November during which it was extensively monitored with *RXTE*. Proportional Counter Array (PCA) data were extracted from the HEASARC archives, and the high-resolution event mode data were used to construct the burst light curves. Among the bursts detected, we found one event that shows an unusual temporal profile with a long (≈0.5 s) multipeak pre-

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cursor followed by a bright burst (see Figs. 1*a* and 1*b*). The time history of this event shares a number of similarities with a remarkable burst from SGR 1900+14, where a 6.4 keV emission line was recently discovered in the burst precursor (Strohmayer & Ibrahim 2000; Ibrahim et al. 2001). In fact, (1) both bursts are preceded by a complex multipeaked precursor, and both precursors have similar temporal profiles that are different from typical SGR bursts; (2) both precursors are significantly longer than typical (∼0.1 s) SGR bursts; and (3) spectral evolution is detected in both precursors, while most bursts show a uniform spectrum.

Motivated by these similarities, we investigated in detail the spectral characteristics of the precursor. In order to subtract the background, we used a preburst persistent emission segment that is free from any bursting activity. We divided the precursor into four intervals and used the PCA data below 30 keV to fit the spectra of the different peaks separately. An absorbed power-law emission model provided a qualitatively acceptable fit to the data and revealed a moderate spectral evolution as shown in Figure 1*c*. The spectrum is harder in the second interval with a larger χ^2 than in the other three intervals. Absorbed bremsstrahlung models gave similar fits, with $kT \sim 30$ keV. The fit residuals (Fig. 2) show no significant structure in intervals 1, 3, and 4, but in interval 2, they suggest the presence of a narrow absorption feature near 5 keV. The fit was improved by adding a cyclotron absorption component, and the *F*-test gives a probability of 1.3×10^{-3} for a chance reduction of the *F*-statistic by 6.8 for a 5.0 keV absorption feature with a narrow width of 0.24 keV. The feature is significant at 3.2 σ.

Further inspection of the fit residuals suggested additional modulation around the second and third harmonics of the 5.0 keV feature and near 7 keV. The fit continued to improve with the successive addition of three absorption lines. The energies derived from the fit are 7.5, 11.2, and 17.5 keV, respectively. With all four lines included, the *F*-test gives an improved random probability of 2.2×10^{-4} for a chance reduction of the *F*-statistic by 6.2, corresponding to a 3.7 σ significance.

The spectrum and the predicted counts of the best-fit model are shown in the bottom panel of Figure 3, and the incident photon spectrum that would be implied by the model is shown in the top panel of Figure 3. The fit parameters for the four intervals and the characteristics of the line fits are given in Tables 1 and 2. The *F*-statistics given there are all in comparison with the absorbed power-law fit with no cyclotron resonance features.

Absorption features did not improve the fits significantly for the other three intervals. We studied the implications of instrumental effects in the PCA elsewhere, and we showed that for count rates less than 9×10^4 counts s^{-1}, pileup and dead-time effects are not sufficient to modify the spectrum, nor can they produce a spectral feature (Ibrahim et al. 2001; Strohmayer & Ibrahim 2000). The count rate during the main burst peaks exceeded this limit, and we therefore excluded them despite some evidence of absorption around 5 keV. The presence of the features in an interval with a moderate count rate and the fact that the features are present in part of the precursor and are not seen in intervals with comparable count rates and a similar number of counts strongly argue against significant instrumental effects. Besides, when fitted with a Gaussian, the 5.0 keV feature is strong, with an equivalent width of ∼500 eV, even larger than that of the 6.4 keV emission line from SGR 1900+14. This cannot be interpreted as being due to imperfections in the PCA response matrix. Numerical simulations also showed that random fluctuations could produce power-law spectra with a χ^2 as high as that of interval 2 in about 16% of the cases, but the fit residuals are randomly distributed and never showed a systematic structure similar to that of the real data.

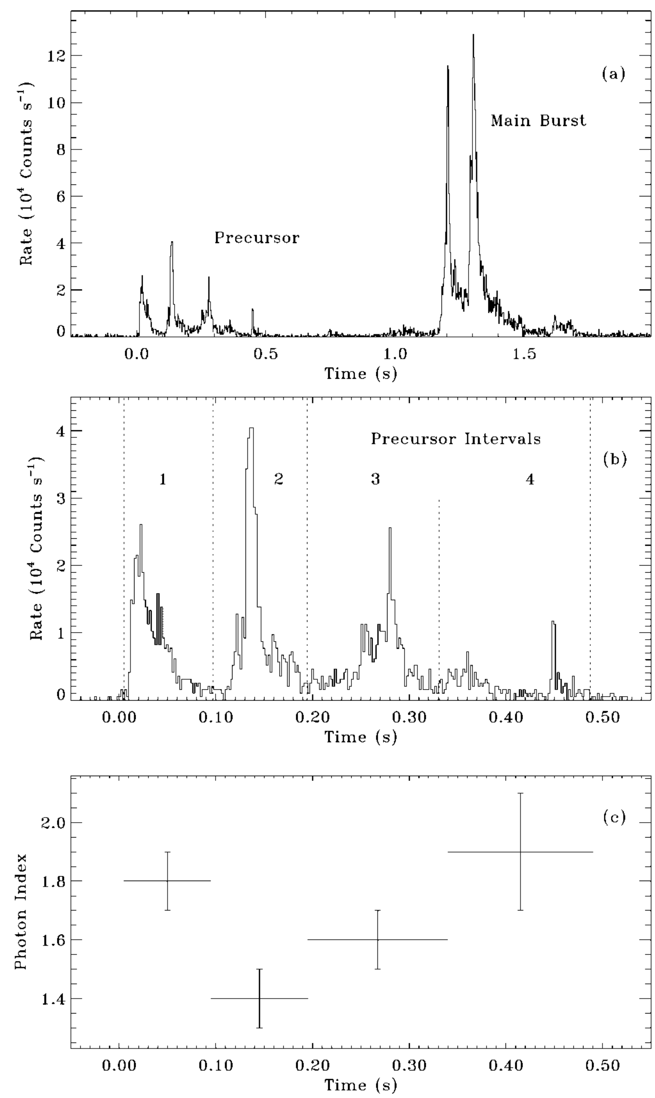

FIG. 1.—Time history of the outburst from SGR 1806−20 as seen by *RXTE*/PCA (2–60 keV). (*a*) Bright burst preceded by a long, complex precursor. (*b*) Precursor intervals used in the spectral analysis. (*c*) Evolution of the power-law photon index for the precursor intervals. T_0(UTC) = 9:13:43 on 1996 November 18.

Taking into account that the features appear in one spectrum out of the four examined, the chance probabilities for the single feature and the set of features are 5.2×10^{-3} and 8.8×10^{-4}, respectively. However, we have now looked at a large sample of bursts and found the 5 keV feature in the spectra of some other bursts as well. This will be reported in a follow-up paper (A. I. Ibrahim et al. 2002, in preparation).

Since an emission line has been detected in SGR 1900+14 in a similar event, we checked this possibility also for present data. Visual inspection of the spectrum may be actually suggestive of a peak around 7 keV. However, the addition of a Gaussian emission line provided a marginal improvement in the fit with respect to an absorbed power law, with a confidence level (CL) of only 74%.

3. DISCUSSION

The presence of electron-cyclotron features in X-ray pulsars was first predicted by Gnedin & Sunyaev (1974) and discovered

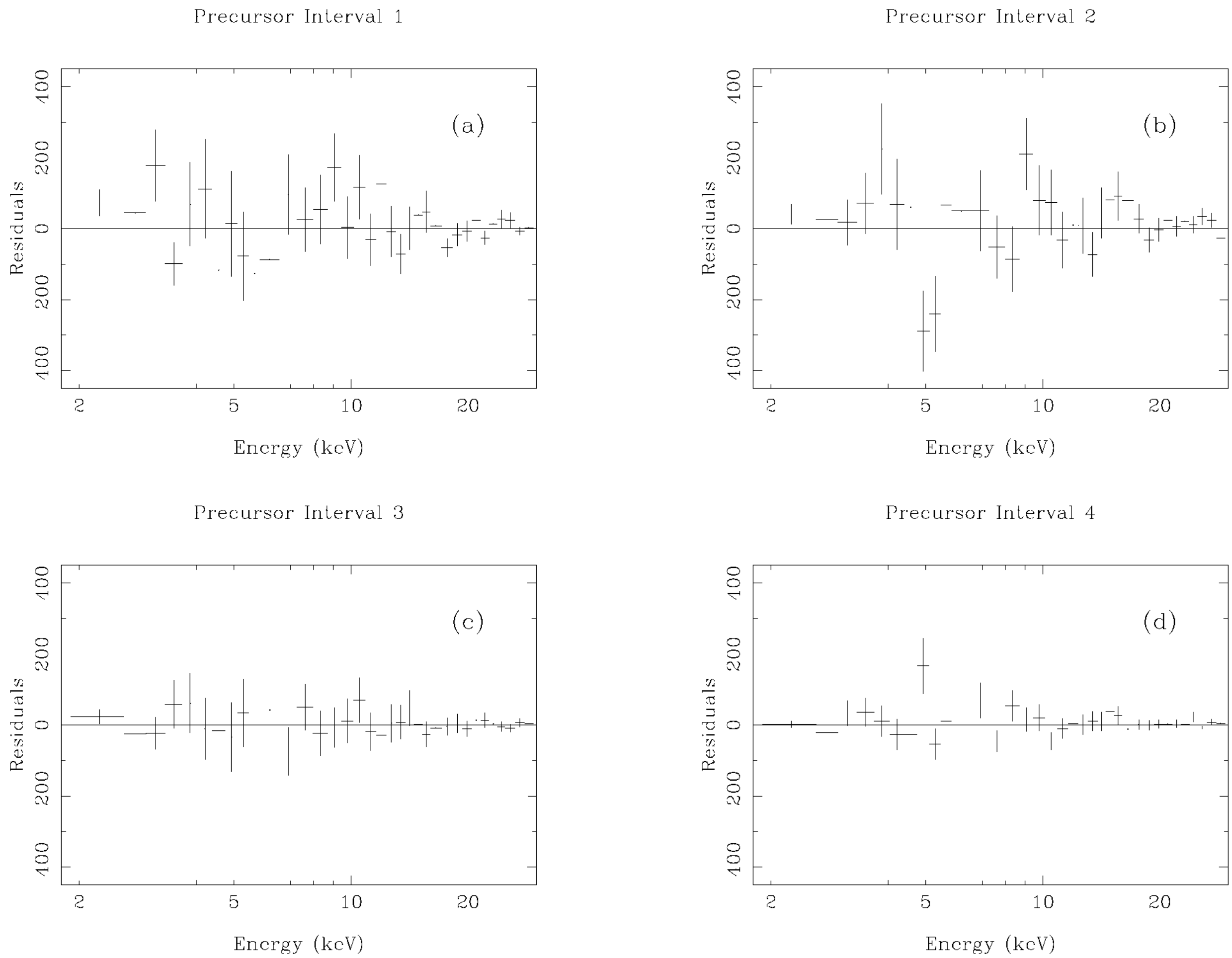

FIG. 2.—Residuals of the four precursor intervals when fitted with an absorbed power-law model. The residuals are significant in interval 2 but are random in intervals 1, 3, and 4.

a few years later by Trümper et al. (1978) and Wheaton et al. (1979). All observed cyclotron lines have been detected above 10 keV and are interpreted as electron features, with inferred magnetic fields $B \sim (1\text{–}3) \times 10^{12}$ G (Cusumano et al. 1998; Heindl et al. 1999; Santangelo et al. 1999). The presence of cyclotron features in SGRs would resolve a host of issues concerning the nature of these peculiar objects. SGRs have been considered as either ultramagnetized neutron stars powered by the dissipation of their own B-field (Duncan & Thompson 1992) or conventional neutron stars powered by accretion from a very faint companion or a fossil disk (Marsden et al. 2001). Here we discuss the implications of our observation in light of these models.

In a strong magnetic field and depending on the physical conditions in the emitting/absorbing matter, cyclotron features from electrons, protons, and other ions could in principle be observed. Possibly atomic absorption lines could also be present, e.g., redshifted iron at 5 keV, but no model generating such high flux and high temperature at a layer deeper than absorbing heavy atoms has been proposed. In a typical neutron star with $B \approx 10^{12}$ G, as invoked in accretion-powered models, the fundamental electron-cyclotron resonance lies at $E_e = 11.6(1+z)^{-1} \times (B/10^{12}\ \mathrm{G})$ keV, where $(1+z)^{-1} = (1 - 2GM/Rc^2)^{1/2}$ is the gravitational redshift factor at the star surface. Proton and α-particle resonances, on the other hand, would be undetectable in X-rays because of their very low energy ($E_{p,\,\mathrm{He}} \sim 2\text{–}5$ eV). Interpreting the 5.0 keV feature as an electron-cyclotron resonance originating close to the surface of a typical $B \approx 10^{12}\text{–}10^{13}$ G neutron star would require a very large gravitational redshift $(1+z)^{-1} < 0.4$ (or $z > 1.5$), with a mass-to-radius ratio $M/R > 0.3\ M_\odot\ \mathrm{km}^{-1}$. Such values are inconsistent with neutron stars, for which $M/R < 0.23\ M_\odot\ \mathrm{km}^{-1}$ as imposed by causality (Lat-

TABLE 1
SPECTRAL RESULTS FOR THE PRECURSOR

Interval	Photon Index	N_H ($\times 10^{22}$ cm^{-2})	χ^2/dof	F-Statistic/CL (%)
1	1.8 ± 0.2	21.4 ± 4.1	35/32	…
2	1.4 ± 0.1	18.8 ± 3.7	40/32	…
3	1.6 ± 0.1	18.2 ± 3.5	12/32	…
4	1.9 ± 0.2	26.7 ± 7.5	31/32	…
2 (one line)	1.5 ± 0.2	18.7 ± 3.4	23.5/29	6.8/99.87
2 (four lines)[a]	1.6 ± 0.2	21.1 ± 4.9	13/24	6.2/99.97

[a] The line widths are held fixed at the best-fit values shown in Table 2.

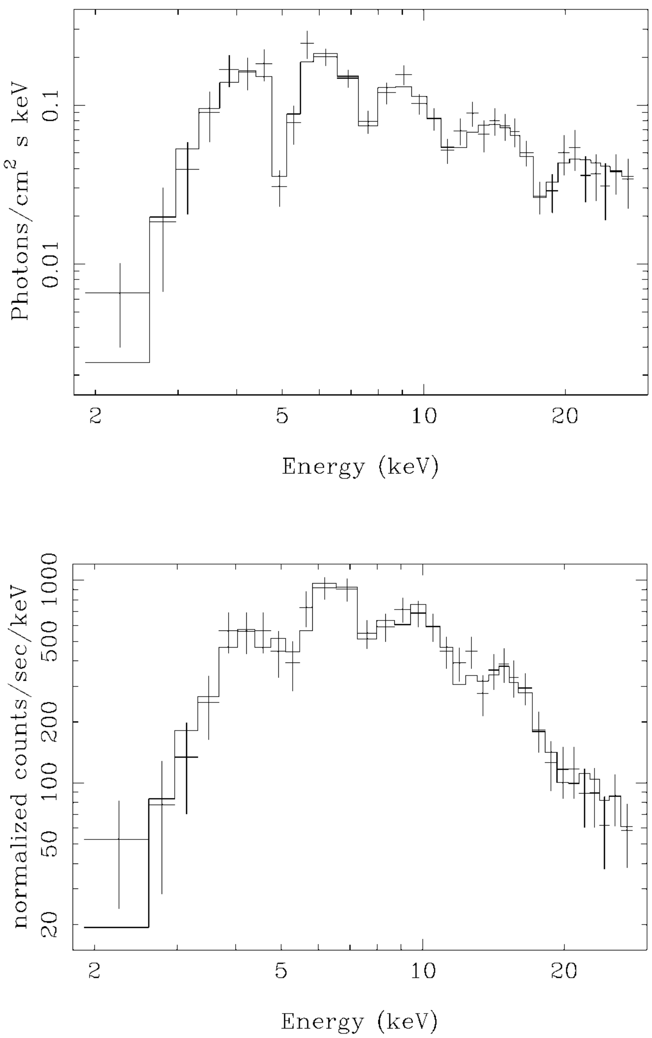

FIG. 3.—Spectrum and best-fit continuum model for the second precursor interval, with four absorption lines (*RXTE*/PCA, 2–30 keV). *Bottom*: Pulse-height spectrum with the model predicted counts (*histogram*). *Top*: Model (*histogram*) and the estimated photon spectrum for the best-fit model.

timer et al. 1990). Interestingly, these values are consistent with a more compact form of matter such as strange/quark stars; however, no predictions for spectral features from such objects have been made yet (Cheng & Dai 1998; Zhang et al. 2000). Fields below 4×10^{11} G are ruled out since they imply $z < 0$. For the 5.0 keV feature to be an electron-cyclotron resonance from a neutron star with acceptable mass and radius, the surface magnetic field could only be in the narrow range of (5–7) × 10^{11} G, in apparent contrast to plausible values for SGR 1806−20 ($B \sim 10^{13}$ G) within the accretion model (see Fig. 2 in Rothschild, Marsden, & Lingenfelter 2000) and well below the average value in ordinary radio pulsars. The pulsar *B*-field distribution shows that ~20% of the population has $B \lesssim 6 \times 10^{11}$ G (e.g., Hartman et al. 1997; Regimbau & de Freitas Pacheco 2001). The rarity of SGRs as opposed to the larger population of pulsars with such a magnetic field also argues against this possibility.

Moreover, electron-cyclotron features in the spectra of accreting pulsars show large thermal broadening (ΔE is approximately a few keV) because of the low electron mass in comparison with those of ions. Although the physical conditions in SGRs are not necessarily the same as in X-ray pulsars, broadening of the cyclotron line is to be expected in any case for typical electron energies ≈1–10 keV. For the 5.0 keV fundamental, the estimated width would be $\Delta E \approx 1.5$ keV. On the contrary, the observed feature is much narrower ($\Delta E \approx 0.24$ keV). The 1 keV resolution of the PCA detector at 5 keV makes it difficult to precisely resolve features with widths ≲1 keV. However, the 90% upper limit on the 5.0 keV feature width is 0.4 keV, still narrower than any known electron feature. All of the preceding considerations indicate that the interpretation of the observed 5.0 keV feature in terms of an electron-cyclotron line seems unlikely, although it cannot be completely ruled out on the basis of present data.

TABLE 2

BEST-FIT PARAMETERS FOR THE LINE FEATURES

Line Feature	Energy (keV)	Width (keV)	Depth
1	5.0 ± 0.2	0.24 ± 0.1	1.9 ± 0.6
2	7.5 ± 0.3	0.45 ± 0.2	1.2 ± 0.4
3	11.2 ± 0.4	1.2 ± 0.5	0.9 ± 0.3
4	17.5 ± 0.5	1.1 ± 0.7	1.0 ± 0.4

NOTE.—The cyclotron absorption model is described in Mihara et al. 1990.

In the magnetar model ($B \gtrsim 10^{14}$ G), electron-cyclotron lines lie at very high energy $E_e \gtrsim 1$ MeV, out of range of the *RXTE*/PCA, whereas proton and α-particle resonances come within reach, with fundamentals at $E_p = 6.3(1+z)^{-1}(B/10^{15}\ \mathrm{G})$ keV and $E_{\mathrm{He}} = 3.2(1+z)^{-1}(B/10^{15}\ \mathrm{G})$ keV. In this picture, the 5.0 keV feature is plausibly a proton-cyclotron fundamental with an implied magnetic field $B = 7.9 \times 10^{14}(1+z)$ G. For a typical neutron star with $M = 1.4\ M_\odot$ and $R = 10$ km, the surface field strength in SGR 1806−20 is $B = 1.0 \times 10^{15}$ G, in very good agreement with the value ($B \sim 8 \times 10^{14}$ G) derived from the spin-down measure (Kouveliotou et al. 1998). The features at 11.2 and 17.5 keV are consistent with the second and third harmonics, but with a slight deviation that could be due to emission from a region with a different magnetic field and/or redshift. Electron-cyclotron features with slightly anharmonic spacing have been seen in transient X-ray sources (Heindl et al. 1999). Another possibility is that the 17.5 keV line is associated with the proton spin-flip transition at $E_p^S = 17.6(1+z)^{-1}(B/10^{15}\ \mathrm{G})$ keV (Thompson 2002; Zane et al. 2001). However, this interpretation seems less plausible since the rates for spin-flip transitions should contain an additional factor $E_p/m_p c^2 \ll 1$ with respect to transitions with conserved spin projection.

In recent years, the growing evidence for the existence of magnetars has stimulated several studies on the presence of ion-cyclotron features in the X-ray spectra of SGRs (Bezchastnov et al. 1996; Thompson 2002; Zane et al. 2001; Ho & Lai 2001). Our results on the energy and width of the fundamental feature are consistent with estimates by Zane et al. (2001). However, the continuum underlying the cyclotron features reported here is either nonthermal or bremsstrahlung for $kT >$ 20 keV and probably originates in the star's magnetosphere. In this respect, ion-cyclotron lines may naturally form in the magnetar model of Thompson & Duncan (1995) as primary photons, produced in the pair fireball, cross an optically thick baryon-loaded sheath, located at $\lesssim 2R$. The presence of hard photons with energy greater than the fundamental harmonic would also enhance the transitions between Landau levels and would thus make cyclotron features stronger (Gnedin & Sunyaev 1974).

Similar to proton-cyclotron resonances, α-particle resonances could also be present. For the same value of B as implied by the observed proton fundamental, the α-particle second harmonic would overlap the proton fundamental, and the third harmonic would be consistent with the observed feature at 7.5 keV. The α-particle fundamental would lie at 2.4 keV, too close to the lower end of the *RXTE*/PCA energy range to be separated from low-energy cutoff effects. Further observations with instruments possessing higher spectral resolution and lower bandpass energy could resolve the α-particle fundamental and confirm or disprove this conjecture.

Cyclotron features offer a new diagnostic tool for probing SGRs. Further analysis and new observations promise to shed new light and broaden our understanding of these enigmatic objects. This will potentially open new avenues for testing quantum electrodynamics predictions and exploring new physical effects unique to ultrastrong magnetic fields, which is one of the main reasons why SGRs are distinctively important.

We thank K. Hurley and T. Strohmayer for their careful reading and important comments on this Letter. We are also grateful to G. Pavlov, C. Thompson, R. Duncan, and C. Miller for useful remarks and discussions. A. I. I. thanks S. S.-H. and the Department of Physics at the University of Manitoba, where this work was partly done, for their hospitality. S. S.-H. acknowledges support from the Natural Sciences and Engineering Research Council (NSERC) and from a University Research Grant (URGP) at the University of Manitoba.

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