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SEARCH FOR NEUTRON-CAPTURE GAMMA-RAY LINES FROM A0535+26 IN OUTBURST

Steven E. Boggs
Department of Physics and Space Sciences Laboratory, University of California, Berkeley, CA 94720; boggs@berkeley.edu
and
David M. Smith
Physics Department and Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064
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ABSTRACT

In 2005 May–June, the *Reuven Ramaty High Energy Solar Spectroscopic Imager* (*RHESSI*) observed the Be/X-ray binary system A0535+26 during a giant outburst, during which time its hard X-ray intensity reached several crab. This bright source presented a unique opportunity to search for redshifted neutron-capture lines from the surface of the neutron star. Such lines, if discovered, would strongly constrain the neutron star equation of state, motivating this search. An upper limit on the narrow, unredshifted line has been set at 6.5×10^{-4} photons $\mathrm{cm^{-2}\ s^{-1}}$, while width-dependent limits on a broadened, redshifted line are set in the range of $(4.0\text{–}10.5) \times 10^{-4}$ photons $\mathrm{cm^{-2}\ s^{-1}}$. To our knowledge, these are the first measured upper limits on redshifted 2.2 MeV emission from an accreting neutron star.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: individual (A0535+26) — stars: neutron — X-rays: binaries

1. INTRODUCTION

Matter accreting onto a neutron star can approach ion temperatures of 100 MeV, well exceeding nucleon binding energies. Collisions of these energetic nuclei with others within the accretion disk or the neutron star atmosphere will break apart nuclei heavier than hydrogen. Detailed descriptions of this spallation process can be found elsewhere (Bildsten et al. 1993; Jean & Guessoum 2001). A substantial population of free neutrons can be produced in these collisions, primarily through spallation of ^{4}He. These free neutrons have the potential to radiatively capture on hydrogen nuclei [H(n, γ)D], producing a characteristic 2.223 MeV photon. A number of authors have studied scenarios that would produce 2.2 MeV line emission in accreting X-ray binaries, including extremely broad, blueshifted lines from neutron capture within the accretion flow (Aharonian & Sunyaev 1984), narrow lines from neutron capture on the surface of the binary companion (Guessoum & Jean 2002; Jean & Guessoum 2001; Guessoum & Dermer 1988), and redshifted neutron capture on the surface of an accreting neutron star itself (Bildsten et al. 1993; Brecher & Burrows 1980; Reina et al. 1974). While detection of 2.2 MeV emission with any one of these three characteristics would provide useful information on nuclear reactions in accretion flows, the last possibility is especially interesting in that it would allow a direct measurement of the gravitational redshift of the neutron star, constraining the nuclear equation of state under these extreme conditions. The importance of these observations for constraining the nuclear equation of state constitutes a special motivation for our search.

Photons emitted with an intrinsic energy E in the thin atmosphere of an accreting neutron star of radius R and mass M experience a gravitational redshift for an observer at infinity to an energy E' given by

$$\frac{E'}{E} = \sqrt{1 - \frac{2M}{R}}, \tag{1}$$

where M and R are measured in units where $G = c = 1$. Measurement of E' for a known radiation of energy E would allow direct measurement of the gravitational redshift, constraining the ratio M/R to an uncertainty of

$$\Delta\left(\frac{M}{R}\right) = \frac{E'}{E}\,\Delta\left(\frac{E'}{E}\right). \tag{2}$$

This gravitational redshift would place significant constraints on the underlying equation of state. Neutron stars have central densities 5–10 times as high as laboratory nuclei; in those conditions exotic physics such as strangeness-bearing baryons, condensed mesons, or even deconfined quarks may appear (Lattimer & Prakash 2004 and references therein). These processes would be reflected in the equation of state (pressure-density, P-ρ, relation) for the neutron star material. Using the P-ρ relation for a given model, the equation of hydrostatic equilibrium can be numerically integrated to obtain the global mass-radius (M-R) relation for that equation of state, defining a single curve in the neutron star M-R diagram (Lattimer & Prakash 2004). The ratio M/R by itself cannot uniquely identify the nuclear equation of state, but it can potentially rule out a number of models and place strong constraints on the allowed masses and radii for the remaining ones. Measurement of this gravitational redshift combined with independent measurement of the mass M by other means, such as dynamical studies, would uniquely identify the underlying equation of state.

There have been attempts to search for such redshifted lines across many regions of the electromagnetic spectrum, with the most promising results to date coming from X-ray spectroscopy (Cottam et al. 2002). Neutron capture, and the subsequent 2.223 MeV line, has been discussed for over 30 years as a potential candidate for measuring this redshift (Bildsten et al. 1993 and references therein). Most theoretical studies of redshifted 2.2 MeV emission from accreting neutron stars have concentrated on Sco X-1, the brightest persistent X-ray binary in the sky. Theoretical estimates of the redshifted line emission from this source range from $(1\text{–}2) \times 10^{-6}$ photons $\mathrm{cm^{-2}\ s^{-1}}$ (Bildsten et al. 1993; Reina et al. 1974) to 3×10^{-5} photons $\mathrm{cm^{-2}\ s^{-1}}$ (Brecher & Burrows 1980). Bildsten et al. (1993) derive an upper limit on the expected emission for other sources, scaled to the Sco X-1 X-ray flux, of

$$F_{2.2} < 2 \times 10^{-5} \text{ photons cm}^{-2} \text{ s}^{-1} \times \left(\frac{Y}{0.25}\right)\left(\frac{100 \text{ MeV}}{E_i}\right)\left(\frac{F_{\rm X}}{F_{\rm Sco\ X\text{-}1}}\right), \qquad (3)$$

where Y is the He mass fraction of the accreted material, E_i is the accreted ion energy, and $F_{\rm X}$ is the X-ray intensity, relative to $F_{\rm Sco\ X\text{-}1} = 3 \times 10^{-7}$ ergs cm^{-2} s^{-1}. The best sources for potentially observing the redshifted 2.2 MeV line are those that are exceptionally bright and/or those accreting material exceptionally rich in He. In addition, we expect this line to be both rotationally and gravitationally broadened. Sco X-1, which is probably spinning at ∼300 Hz (White & Zhang 1997), would intrinsically produce a very broad line. More slowly rotating neutron stars, depending on their exact accretion geometry, can potentially produce much narrower redshifted lines (Ozel & Psaltis 2003), which would be easier to detect. To date, there have been no published constraints on the redshifted 2.2 MeV emission line from any source.

By contrast, there has been significant work on the search for narrow, unredshifted 2.223 MeV emission. This emission line is seen routinely in solar flare studies (e.g., Murphy et al. 2003). Using annual-scanning observations from the *Solar Maximum Mission*, Harris & Share (1991) were able to place the first significant constraints on 2.2 MeV emission from Sco X-1 of 1×10^{-4} photons cm^{-2} s^{-1}. An all-sky survey for 2.2 MeV emission was performed using the COMPTEL instrument on board the *Compton Gamma Ray Observatory*, which yielded significantly tighter constraints on a number of accreting neutron stars, including an upper limit on emission from Sco X-1 of 2.5×10^{-5} photons cm^{-2} s^{-1} (McConnell et al. 1997). This all-sky survey yielded only a single potentially significant source of 2.2 MeV emission, with a companion that remains unidentified. The possibility of seeing these narrow lines from neutron capture in the atmosphere of the secondary companion was originally proposed by Guessoum & Dermer (1988). The launch of the SPI γ-ray telescope on *INTEGRAL*, with improved line sensitivity and spectral resolution over COMPTEL, renewed theoretical interest in the potential of seeing these lines from accreting X-ray binaries (Jean & Guessoum 2001; Guessoum & Jean 2002). For these models, the 2.2 MeV line width is determined by the orbital parameters of the binary system (Jean & Guessoum 2001) and effectively unresolved with the *RHESSI* spectral resolution. Current work suggests that narrow-line emission could be marginally detectable by SPI for a handful of nearby X-ray binary sources under favorable conditions (Guessoum & Jean 2002). However, given the sensitivity of today's γ-ray telescopes, the hope for detecting narrow (or redshifted) lines from any typical source is slim.

Another possibility is to search for emission in exceptionally bright sources in outburst. In 2005 May, the Be/X-ray binary system A0535+26 began such a giant outburst (Tueller et al. 2005), with its hard X-ray intensity reaching several crab. A0535+26 is a well-studied X-ray pulsar with a period of 104 s (Rosenberg et al. 1975) and in a 111 day eccentric orbit with the Be star HDE 245770 (Li et al. 1979). The estimated distance to this system is 1.8 ± 0.3 kpc (Giangrande et al. 1980; Steele et al. 1998). Occasional giant outbursts are observed from this source, with peak X-ray fluxes reaching several crab over 50–100 days. Detection of cyclotron features at 110 keV has been well verified, with reports of a second, fundamental feature at ∼50 keV (Kendziorra et al. 1994) verified by recent *INTEGRAL* SPI observations (Kretschmar et al. 2005). For a historical overview of this well-studied system, see the review by Giovannelli & Graziati (1992). A0535+26 shows three typical intensity states (Kendziorra et al. 1994): quiescence, with flux levels below 10 mcrab ($L_{\rm X} < 10^{35}$ ergs s^{-1}); normal outburst, with flux levels between 10 mcrab and 1 crab; and giant outbursts, in which the system becomes the brightest X-ray source in the sky (several crab; $L_{\rm X} > 10^{37}$ ergs s^{-1}).

Only a handful of these giant outbursts from A0535+26 have been observed to date: 1975 April–May (Rosenberg et al. 1975), 1980 October (Nagase et al. 1982), 1989 March–April (Sunyaev et al. 1989), and 1994 February–March (Grove et al. 1995). The most recent giant outburst in 2005 May–June has been a highly anticipated event for the current generation of modern high-energy telescopes. Unfortunately, due the close proximity of the Sun to this source on the sky at the time of this giant outburst, most astronomical telescopes were unable to study this event due to solar pointing constraints. However, *RHESSI*, being a solar observatory, had an ideal view of this source in outburst (Smith et al. 2005). A detailed presentation of the *RHESSI* X-ray observations of this source will be presented elsewhere (W. Coburn et al. 2006, in preparation).

Here we report on the search for both a narrow 2.223 MeV emission line and a broad, redshifted emission line from A0535+26 with the *RHESSI* instrument during the peak of the giant outburst, 2005 May 18–June 25.

2. *RHESSI INSTRUMENT AND ANALYSIS*

RHESSI is a NASA Small Explorer satellite, designed to perform detailed spectroscopic imaging of X-ray and γ-ray emission (3 keV–17 MeV) from solar flares (Lin et al. 2002). *RHESSI* imaging is performed by two arrays of opaque one-dimensional grids separated by 1.5 m and co-aligned with the nine detectors (Zehnder et al. 2003). As the *RHESSI* spacecraft rotates (4 s period; axis aligned with the Sun), these grids modulate the count rate in the detectors, allowing imaging through rotational modulation collimator techniques (Hurford et al. 2002). Thus, *RHESSI* has high angular resolution (2″.3) in the 1° field of view of its optics. In addition, *RHESSI* sends down the energy and timing information for each photon, allowing detailed timing measurements.

The heart of the *RHESSI* instrument is the array of nine coaxial germanium detectors, each with a diameter of 7.1 cm and a height of 8.5 cm (Smith et al. 2002). *RHESSI* performs its imaging by photon timing, not positioning, so there is no spatial information for interactions within a detector segment—just energy and timing information. The detectors are electrically "segmented" into two monolithic sections, so that the front segments (∼1.5 cm thickness) perform as separate detectors, with separate electronics, from the rear segments (∼7.0 cm thick). *RHESSI* detectors are segmented in order to optimize performance over its broad energy band: solar X-ray and hard X-ray photons (<100 keV) will preferentially stop in the "fronts," while γ-rays (>100 keV) will preferentially interact in the "rears." The fronts have a typical threshold of 2.7 keV and a spectral resolution of roughly 1 keV at 94 keV. The rears have a typical threshold of 20 keV and a spectral resolution of 9.9 keV at 2.223 MeV at the time of these observations.

In order to search for 2.2 MeV emission from A0535+26, we treat the nine *RHESSI* rear segments as monolithic γ-ray spectrometers and search for a line signal from the source during the interval of the giant flare that is not present in the

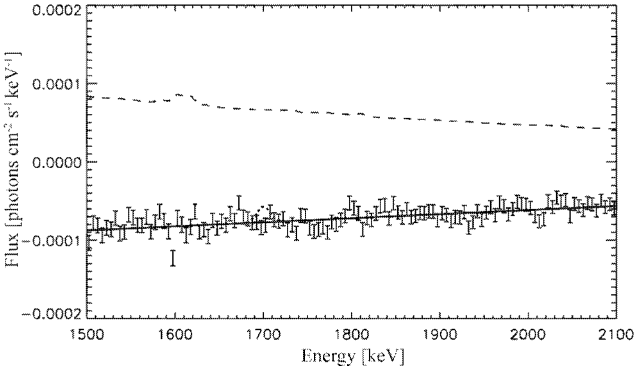

Fig. 1.—Background-subtracted spectrum of A0535+26, corrected for the *RHESSI* effective area, over the 1.5–2.1 MeV range covering the expected range for redshifted emission. The dashed line shows the average *RHESSI* background for these observations (counts cm^{-2} s^{-1} keV^{-1}), scaled by a factor of 0.2, for comparison. The background subtraction technique has oversubtracted the underlying continuum, so we search for redshifted lines relative to the best linear fit through this residual spectrum, shown by the solid line. The dotted line shows a typical 3 σ upper limit for a 0.5% broadened line.

RHESSI background data during intervals beforehand and afterwards. This technique is similar to that used to successfully study the Galactic ^{26}Al γ-ray line emission (Smith 2003), with the major difference being that Earth occultation was used in that case to modulate the constant diffuse Galactic flux. For this analysis, *RHESSI* data for time intervals when A0535+26 was visible in the sky (i.e., not occulted by the Earth) for the time interval May 18–June 25 are divided into 1 minute (hence spin-averaged) spectra, binned according to two orbital parameters that characterize background variations: longitude of the ascending node of the current orbit, and orbital phase since the ascending node. These coordinates define a particular spot on the Earth, but with a memory of the recent history of the spacecraft trajectory—most usefully, how recently and deeply the spacecraft passed through the South Atlantic Anomaly. Likewise, a library of background spectra was created using the identical binning technique, but for time periods before A0535+26 went into outburst, April 16–May 14, and after the giant outburst, July 10–August 7. For each 1 minute source spectrum, the appropriate background library spectrum was subtracted and the residuals were added together to form the final background-subtracted count spectrum (Smith 2003). This average residual spectrum was corrected for the *RHESSI* effective area and the effects of radiation damage in order to determine the residual incident photon spectrum. The residual from this background subtraction technique is on the order of 2% of the overall background flux.

3. RESULTS

Figure 1 shows the *RHESSI* background-subtracted 1.5–2.1 MeV spectrum of A0535+26. This energy band encompasses a reasonable range for expected energies for the redshifted 2.223 MeV lines from the surface of a neutron star, with radii ~1.8–9.3 times the Schwarzschild radius for the star (Lattimer & Prakash 2004). The scaled background spectrum is shown for comparison. (Note that the background flux is measured relative to the total detector area, not the effective area.) As can be seen clearly in this plot, the background subtraction routine that we have used has oversubtracted the underlying continuum with residuals ~2% the background level, although it has done well in removing the background lines. However, this oversubtraction does not significantly affect our search for linelike features. In order to search for line features, we first fit the overall 1.5–2.1 MeV residual spectrum to a single linear polynomial (shown in Fig. 1). We searched for Gaussian lines relative to this linear background fit. The expected line profile will depend on both rotational and gravitational broadening effects (Ozel & Psaltis 2003). Due to the slow rotation of A0535+26, rotational broadening will be negligible, but the expected line width (dominated by gravitational broadening) will depend on the detailed geometry of the emission region on the neutron star. Since we do not know the energy or width of the redshifted 2.2 MeV line a priori , we attempted the fit over a grid of line energies and widths. For fixed widths of $\Delta E/E_o = 0.5\%$, 1%, 2%, and 5% FWHM, we scanned the energy band, fixing E_o over the 1.5–2.1 MeV range in 5 keV steps. From the best-fit Gaussian for each of these line energies and widths, we can determine the amplitudes and uncertainties on the measured line intensities.

TABLE 1

Redshifted 2.2 MeV Line, 3 σ Upper Limits, 1.5–2.1 MeV

$\Delta E/E$ (FWHM) (%)	Flux (photons cm^{-2} s^{-1})
0.5	4.0×10^{-4}
1.0	5.0×10^{-4}
2.0	6.4×10^{-4}
5.0	10.5×10^{-4}

For this range of redshifted energies and widths, we see no significant (>3 σ) linelike features in the background-subtracted spectrum. The 3 σ upper limits are very weakly energy dependent over this range, so that we can identify a single upper limit for each line width over this energy band. These are listed in Table 1. In Figure 1 we show for comparison what the 3 σ upper limit looks like; for example, assuming a relatively narrow width of $\Delta E/E_o = 0.5\%$, we set a 3 σ upper limit on redshifted 2.2 MeV emission over the 1.5–2.1 MeV range of 4.0×10^{-4} photons cm^{-2} s^{-1}. These 3 σ limits apply to any single redshifted energy within this energy range, as opposed to the probability that there is a line anywhere in that range.

Figure 2 shows the background-subtracted 2.150–2.300 MeV spectrum of A0535+26, which includes the unredshifted 2.223 MeV line energy. Our background subtraction technique has slightly oversubtracted a higher energy background line at 2.244 MeV; however, there is no significant sign of a residual,

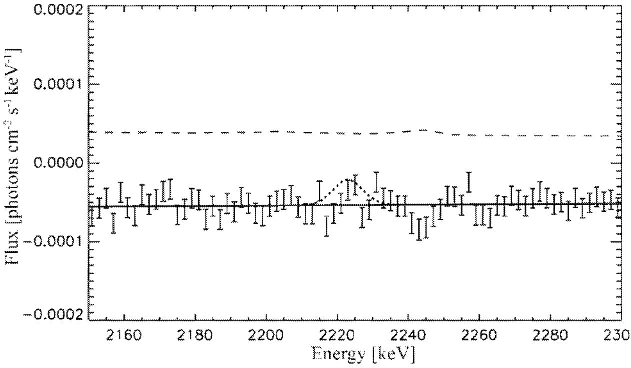

Fig. 2.—Background-subtracted spectrum of A0535+26 around the unredshifted 2.223 MeV line energy. The average *RHESSI* background, scaled by a factor 0.2, is shown for comparison (*dashed line*). Once again, the continuum background has been oversubtracted, so we search for a narrow line relative to the best linear fit through the residual spectrum (*solid line*). The dotted line shows our 3 σ upper limit on the narrow 2.223 MeV line emission.

narrow 2.223 MeV line at the rest energy. From the best-fit Gaussian of this residual spectrum, fixing the Gaussian line energy at 2.223 MeV and the Gaussian width at the instrumental resolution of 9.9 keV FWHM, we measure a flux of $(1.5 \pm 1.7) \times 10^{-4}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, corresponding to a 3 σ upper limit on this narrow line of 6.5×10^{-4} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

4. DISCUSSION

During the period of these observations, the hard X-ray emission from A0535+26 varied around a few crab, $F_X = (0.6\text{–}1.1) \times 10^{-7}$ ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (W. Coburn et al. 2006, in preparation), corresponding to $L_X = (2\text{–}4) \times 10^{37}$ ergs s^{-1}. Given the current most optimistic estimates, the broad, redshifted 2.2 MeV line from this source should not have been detectable with *RHESSI*. Unfortunately with the solar pointing constraints, *INTEGRAL* SPI, which would have been significantly more sensitive than *RHESSI* to this point source emission, was unable to observe A0535+26 at the time of this giant outburst.

Our upper limit represents the first measured constraint on this broad, redshifted 2.2 MeV emission. While this observation did not significantly constrain the models of redshifted emission (nor the gravitational redshift), it demonstrates some of the techniques required for this type of search. In addition, while our narrow-line constraint is significantly above the upper limits set by COMPTEL during its all-sky survey (McConnell et al. 1997), it is the first constraint of this emission on an accreting neutron star in outburst.

The potential of constraining the neutron star equation of state remains strong motivation for continuing work on these γ-ray observations of accreting neutron stars. If *RHESSI* (or SPI) were to measure one of these lines, it would constrain the neutron star mass-to-radius ratio to a level of ~0.05%. Given the sensitivities of this current generation of γ-ray instruments, we will have to rely on searching for these lines from sources in outburst, such as A0535+26.

Looking toward the future, the next-generation γ-ray instrument the *Advanced Compton Telescope* (*ACT*) will achieve factors of 50–100 improvements in sensitivity over *INTEGRAL* SPI. With this high sensitivity, *ACT* will be able to systematically study these redshifted 2.2 MeV lines from many accreting neutron stars, both persistent sources and those in outburst.

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