ROTATIONAL BROADENING OF ATOMIC SPECTRAL FEATURES FROM NEUTRON STARS

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ABSTRACT

The discovery of the first gravitationally redshifted spectral line from a neutron star (NS) by Cottam et al. has triggered theoretical studies of the physics of atomic line formation in NS atmospheres. Chang et al. showed that the hydrogenic Fe H α line formed above the photosphere of a bursting NS is intrinsically broad. We now include rotational broadening within general relativity and compare the resulting profile to that observed during type I bursts from EXO 0748-676. We show that the fine-structure splitting of the line precludes a meaningful constraint on the radius. Our fitting of the data show that the line-forming Fe column is log ($N_{\text{Fe},n=2}/\text{cm}^{-2}$) = $17.9^{+0.27}_{-0.42}$ and gravitational redshift $1 + z = 1.345^{+0.005}_{-0.008}$ with 95% confidence. We calculate the detectability of this spectral feature for a large range of spins and inclinations, assuming that the emission comes from the entire surface. We find that at 300 and 600 Hz only 10%-20% and 5%-10% of NSs would have spectral features as deep as those seen in EXO 0748-676.

Subject headings: line: formation — stars: abundances — stars: neutron — X-rays: binaries — X-rays: bursts

1. INTRODUCTION

The observation of gravitationally redshifted atomic absorption lines from the surface of the neutron star (NS) in EXO 0748-676 (Cottam et al. 2002, hereafter CPM02) provides a new constraint on the nuclear equation of state. By adding spectra of 28 type I X-ray bursts observed with XMM-Newton, CPM02 detected an absorption line at 13 Å during the peak of the burst, which moved to 13.75 Å as the surface temperature declined. They associated these features with hydrogen-like and helium-like Fe $n = 2 \rightarrow 3$ transitions, implying a gravitational redshift of $1 + z \approx 1.35$. Motivated by these observations, Bildsten et al. (2003, hereafter BCP03) explained why Fe can be present above the photosphere. They also discussed the microphysics of the resonant Fe H α line, showing that it is Stark broadened because of the large photospheric densities, $\rho \approx$ $0.1-1 \text{ g cm}^{-3}$ (Paerels 1997), and confirmed the conclusion of London et al. (1986) that the radiation field determines the Fe ionization balance.

Chang et al. (2005, hereafter CBW05) recently amplified these points and performed a self-consistent radiative transfer and statistical equilibrium calculation. They assumed that the Fe H α line-forming region is a thin layer above the continuum photosphere, as expected from the accretion-spallation scenario of BCP03. The H α line is a scattering-dominated resonance line with a fine-structure splitting of 20.7 eV, comparable to the observed width and the scale of rotational broadening of 24 eV for a 10 km NS rotating at 45 Hz. The lack of pulsations from this NS during accretion leads us to estimate that $B < (1-2) \times 10^9$ G needed for Zeeman splitting to play a role in the formation of the Fe H α line (Loeb 2003). CBW05 calculated the equivalent width (EW) as a function of the Fe column, $N_{\rm Fe}$, for varying effective temperatures and pressures in the thin

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⁵ Center for Radiophysics and Space Research, Cornell University, 104 Space Sciences Building, Ithaca, NY 14853; ira@astro.cornell.edu. line-forming region. To match the observed EW required, a total iron column of $N_{\rm Fe} \approx (1-3) \times 10^{20} \text{ cm}^{-2}$ was needed, higher than that predicted by BCP03 by a factor of a few.

In this Letter, we rotationally broaden the energy- and angledependent line profiles of CBW05 and compare them to the observations. We explain our method of calculating the rotational broadening in § 2 and show that the Schwarzschild+Doppler (S+D) approximation (Miller & Lamb 1998; Braje et al. 2000) is extremely accurate in reproducing the line profiles from the full general relativistic calculation, even up to 300 Hz. We fit the data in § 3 and show that the intrinsically broad line profile prohibits any meaningful constraint on the NS radius if the 44.7 Hz burst oscillation seen by Villarreal & Strohmayer (2004) is the spin frequency. At slow spins or at low inclinations, the line profile shape is set by both rotational broadening and fine-structure splitting, making it absolutely necessary to use realistic line profiles when modeling the lines in EXO 0748-676 or any other favorably oriented (and hence detectable) rapidly rotating NS. We confirm the importance of the intrinsic line profile in determining NS parameters by contrasting it with a simple line profile. We close § 3 by accurately determining the redshift and the amount of Fe in the upper atmosphere. We conclude in § 4 by summarizing our findings and discussing the likelihood that lines like those seen in EXO 0748-676 will be found in the more rapidly rotating NSs.

2. ROTATIONAL BROADENING

We compute the impact of rotational broadening on the intrinsic line profiles of CBW05 using two independent methods: a fully relativistic method that employs ray tracing in the spacetime of a rotating NS and an approximate method that retains the most important relativistic effects to lowest order in v/c. In the fully relativistic approach, the spacetime metric for rotating NSs with various spin frequencies, masses, and equations of state are computed numerically as described in Cadeau et al. (2005). Once the (nonspherical) surface of the NS has been located, geodesics connecting the surface to the observer are computed. We discretize the surface into small patches and calculate the zenith angle α between the local normal and initial photon direction in the locally comoving frame for each patch. We also calculate the solid angle $d\Omega$ subtended by the patch as seen by the observer and the redshift z_* . The redshift z_* includes both the gravitational redshift and

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FIG. 1.—Line profiles from an exact general relativity calculation (*thick lines*) and the S+D approximation (*thin lines*). We plot four different models with $v_s \sin i = 45$ Hz (*solid lines*), 100 Hz (*short-dashed lines*), 200 Hz (*dotted lines*), and 300 Hz (*long-dashed lines*). The intrinsic line profile (*dot-dashed line*) is the same for these models. We also plot the line profile for $v_s \sin i = 20$ Hz (*short-dash-long-dashed line*) to illustrate the line profile as it changes from being dominated by fine-structure splitting to being dominated by rotational broadening.

Doppler-like terms resulting from rotation. Since the intensity, I, is both a function of energy and $\cos \alpha$, the observed flux due to the patch is

$$dF_{\nu} = (1+z_*)^{-3} I[\nu(1+z_*), \cos\alpha] d\Omega.$$
(1)

The observed spectrum is found by summing over all visible patches. The technical details of the fully relativistic computational method are presented by C. Cadeau et al. (2005, in preparation).

We also use the simpler S+D approximation (Miller & Lamb 1998; Braje et al. 2000; see also Cadeau et al. 2005 and Poutanen & Gierliński 2003) to independently compute the spectrum. In the S+D approximation the metric is approximated by the nonrotating Schwarzschild metric, and appropriate Doppler factors correct for the rotation. To the lowest order in v/c, the redshift factor reduces to $1 + z_* = (1 + z)(1 - \delta)$, where $\delta = \beta \sin \zeta \sin \alpha \sin i$, $\beta = 2\pi R v_s / \{c[1 - 2GM/(Rc^2)]^{1/2}\}$ is the scale of rotational broadening, v_s is the observed spin of the NS, and $z = [1 - 2GM/(Rc^2)]^{-1/2} - 1$. The angle ζ is the azimuthal angle of the emitting patch about the vector pointing from the center of the star toward the observer. This angle is zero if the patch is in the plane defined by the spin axis and this vector.

A further simplification is the use of the Beloborodov (2002) approximation, $1 - \cos \alpha = (1 + z)^{-2}(1 - \cos \psi)$, where ψ is the bending angle. This allows the total observed flux to be written as the integral over all possible initial photon zenith and azimuthal angles,

$$F_{\nu} = (1+z)^{-1} (R/d)^2$$

$$\times \int d\zeta \int d(\cos \alpha) \ \cos \alpha \ \frac{I[\nu(1+z_*), \cos \alpha]}{(1-\delta)^3}, \quad (2)$$



FIG. 2.—Line profiles at R = 10 km for several different models compared to the data. We plot best-fitting line profiles for $\nu_s = 0$ Hz (*dotted line*), 44.7 Hz (*short-dashed line*), 100 Hz (*long-dashed line*), and 300 Hz (*dot-dashed line*) for $R \sin i = 10$ km. We also show the continuum model of CPM02 (*solid line*) and the data (1 σ error bars).

where *R* is the NS radius and *d* is the distance. The results for emission from the entire NS surface with the intrinsic line profile of the fully relativistic calculation of CBW05 and the S+D approximation are shown in Figure 1. They are in excellent agreement, and the tiny deviations are mainly due to our neglect of relativistic aberration. The linear change to the metric in v/c due to frame dragging (Hartle 1967; Hartle & Thorne 1968) suggests an observable effect on the line at spin frequencies near 300 Hz as $\beta \sim 0.1$. However, the frame-dragging term enters into the linebroadening calculation as a second-order effect in v/c, preserving the validity of the simple S+D approximation. Only at very high spin frequencies does frame dragging have the potential of producing observable effects (Bhattacharyya et al. 2004).

Of greater relevance is the relative size of the fine-structure splitting and the scale of rotational broadening. At 45 Hz, the scale of rotational broadening is 24 eV for a 10 km NS, which is similar to the fine-structure splitting of 20.7 eV for the Fe H α line. At slower and faster rotation rates, fine-structure splitting dominates rotational broadening and vice versa. Hence, the line profile can change dramatically near 45 Hz. We illustrate this effect in Figure 1, where we plot the line profile for $v_s \sin i = 20$ Hz (*short-dashed–long-dashed line*), which is dominated by fine-structure splitting.

3. FITS TO EXO 0748-676 AND IMPLICATIONS

The simplicity and accuracy of the S+D approximation allows for a rapid and detailed exploration of the parameter space. We assume emission from the entire surface. Emission concentrated near the spin axis would also give narrow line profiles (Bhattacharyya et al. 2004), but we do not consider this possibility. We fit our models to the co-added spectra and continuum model from CPM02. We focus on a narrow range between 12 and 14 Å and plot these points in Figure 2. The 13.25 Å feature in the continuum fit is due to a Ne IX resonant transition in the circumstellar model. Taking the continuum model as the background flux, we overlay some models for $v_s = 0$, 44.7, 100, and 300 Hz for R = 10 km. To set the scale of Stark broadening, we take a background density of $n_p = 10^{23}$ cm⁻³, which is appropriate for a uniform Fe abundance above the continuum photosphere (CBW05). From these models, large spins, i.e., $v_s \sin i = 300$ Hz, are ruled out. Secondly, the intrinsically broad line profile, which is similar to the width of the observed line, prohibits a meaningful limit on R for $v_s = 44.7$ Hz.

We also performed a detailed exploration of the parameter space. Using the data between 12.6 and 13.3 Å, we overlay our line profiles on the continuum model to test the goodness of fit. Varying $\nu_s \sin i(R/10 \text{ km})$, 1 + z, and $N_{\text{Fe}, n=2}$, the best fit gives $\chi^2 = 11.01$ for 17 degrees of freedom. By itself, the continuum model gives $\chi^2 = 24.9$. The best-fit parameters are $\nu_s \sin i(R/10 \text{ km}) = 32 \pm 19 \text{ Hz}$, $1 + z = 1.345 \pm 0.004$, and $\log (N_{\text{Fe}, n=2}/\text{cm}^{-2}) = 17.9 \pm 0.2$. The errors indicated are 1 σ values derived from the covariance matrix.

To develop a more detailed understanding of the parameter space, we marginalize our three-parameter joint probability distribution function (PDF) over two parameters at a time and plot the resulting one-dimensional PDFs for each parameter in Figure 3. The 68%, 95%, and 99% central confidence intervals for the intrinsic line profiles for $\nu \sin i(R/10 \text{ km})$ ($R \sin i$ for $\nu_s = 44.7 \text{ Hz}$) are 11–52 Hz (0.25–11 km), 4–84 Hz (0.09–19 km), and 2–122 Hz (<27 km), respectively. For the best measured value of 1 + z = 1.345, a 1.4 M_{\odot} NS with R = 9.2 km falls within these limits.

The PDF for $v_s \sin i(R/10 \text{ km})$ is asymmetric toward zero and hence prohibits setting a meaningful lower limit due to the intrinsic width of the line set by its fine structure. Had we ignored the instrument shape of the line and had adopted a black line profile, which is a narrow line with zero flux about the line center and a fixed EW = 0.1 Å (Fig. 3, *dashed line*), we would set misleading constraints on the NS parameters. Using this black line profile, we can constrain $v \sin i(R/10 \text{ km}) = 47-102 \text{ Hz}$, which for a 44.7 Hz rotator gives $R \sin i = 10.4-23 \text{ km}$. These misleading constraints highlight the importance of using the intrinsic line profile to fit for NS parameters. The limitations of simple line profiles have also been discussed previously by Villarreal & Strohmayer (2004).

The 68%, 95%, and 99% central confidence intervals of log ($N_{\text{Fe},n=2}/\text{cm}^{-2}$) are 17.69–18.05, 17.48–18.17, and 17.34–18.26, respectively. The corresponding values of N_{Fe} are (1.4–3) × 10²⁰, (0.9–4.0) × 10²⁰, and (0.8–4.8) × 10²⁰ cm⁻². At 68% confidence, these values are within a factor of 3–6 times the solar metallicity photospheric value, $N_{\text{Fe}} \approx 5 \times 10^{19} \text{ cm}^{-2}$ (CBW05), and within a factor of 5–10 times the accretion-spallation value of $N_{\text{Fe}} \approx 3.4 \times 10^{19} \text{ cm}^{-2}$ (BCP03). At 99% confidence, we may require a column of a factor of up to 10 times larger. Our estimate from this likelihood analysis agrees with the simple EW estimate of CBW05. In addition, the NLTE value of N_{Fe} is likely to be larger (London et al. 1986) and may demand either supersolar metallicity or radiative levitation (CBW05).

The 68%, 95%, and 99% central confidence intervals of 1 + z are 1.342–1.348, 1.337–1.350, and 1.334–1.353, respectively. We have also calculated the corresponding confidence intervals for R/M, which gives $R = 6.592-6.670(M/M_{\odot})$ km, $6.565-6.722(M/M_{\odot})$ km, and $6.542-6.766(M/M_{\odot})$ km. Since we fit a rotationally broadened profile to the data, our measurement of 1 + z is immune to beaming effects, which Özel & Psaltis (2003; see also Bhattacharyya et al. 2004) point out



FIG. 3.—Marginalized probability distribution functions for 1 + z, $v_s \sin i(R/10 \text{ km})$, and $N_{\text{Fc},n=2}$ normalized so that their peak is unity. For the marginalized PDF of $v_s \sin i(R/10 \text{ km})$, we also display on the top axis the value of $R \sin i$ for $v_s = 44.7$ Hz. In addition, we plot the marginalized PDF of $v_s \sin i(R/10 \text{ km})$ for a black line profile with fixed EW of 0.1 Å (*dashed line*). We also show the 95% (*dotted line*) central confidence intervals for each parameter.

can skew the measurement of the redshift if the line energy is taken from the flux minimum (or combinations of minima).

4. SUMMARY AND CONCLUSIONS

Using the intrinsic Fe H α line profiles calculated by CBW05, we calculate rotational broadened line profiles to compare to the observed lines in EXO 0748–676 (CPM02). We show that the line profiles generated by the simple S+D approximation accurately reproduce the ones from a fully relativistic ray-tracing method described briefly in § 2.

Assuming that the burst emission comes from the entire surface of the NS, we constrain the Fe column in the line-forming region (log $N_{\text{Fe},n=2}/\text{cm}^{-2} = 17.9^{+0.27}_{-0.42}$). We also find that the redshift is $1 + z = 1.345^{+0.005}_{-0.008}$. The NS spin is $v_s \sin i(R/10 \text{ km}) = 32^{+52}_{-28}$ Hz for a fiducial NS radius of 10 km. These errors denote 95% confidence intervals. Fixing $v_s = 44.7$ Hz (Villarreal & Strohmayer 2004), we find that the radius is effectively unconstrained by the observed line due to the intrinsic width set by fine-structure splitting, an effect missed by simple line profiles.

Other transitions simultaneously confirm the redshift measurement and may provide meaningful constraints on the radius. CBW05 calculated the line profiles for the associate $Ly\alpha$ transition and Pa α transition. The EWs of the Fe Ly α and Pa α lines were $\approx 15-25$ eV and $\approx 7-10$ eV, respectively. The Pa α transition is obscured by interstellar absorption. CBW05 points out that the Ly α line profile is dominated by rotational broadening. Hence, a sufficiently deep observation of the Ly α transition would provide a good constraint on the radius of EXO 0748-676. The helium-like Fe $n = 2 \rightarrow 3$ transition may provide some additional constraints on EXO 0748-676, but the intrinsic line profile is not known. This is critical in modeling this feature, but it is beyond the scope of this work. Spectral modeling of the continuum emission during type I X-ray bursts has also been used to determine NS parameters (Shaposhnikov & Titarchuk 2004; Shaposhnikov et al. 2003 and references therein). Redshift measurements and spectral modeling used in combination would set very tight constraints on NS parameters.

Although EXO 0748-676 is rotating slowly among lowmass X-ray binaries (LMXBs), more rapid rotation does not necessarily make spectral lines undetectable. If a rapidly rotating NS is viewed more face-on, the spectral lines will be narrower. Hence, more rapid rotators may just constitute a smaller population of NSs with detectable features. We illustrate this in Figure 4, where we plot the fraction of sky denoted by $\Omega/4\pi$ over which the line minimum exceeds values 10% and 30% below the continuum. We assume the same intrinsic line profile as that of the observed H α line on EXO 0748-676 for a NS value of R_{∞} of 10, 15, and 20 km. We use R_{∞} instead of R because R_{∞} is a convenient way of absorbing the factor of 1 + z in the scale of broadening, β . These lines follow a very simple trend, which we now derive. Up to a certain rotation rate, these lines are always detectable. For sufficiently large rotation rates, the FWHM of the line is $\propto v_s \sin i$. Since the EW is conserved, the line minimum is $\propto (\nu_s \sin i)^{-1}$. Therefore, the maximum inclination for line minima greater than a certain strength is $\sin i_{\text{max}} \propto v_s^{-1}$, which limits the fraction of sky over which this line would be detectable. Hence, the larger effect of rotational broadening with higher inclination broadens the line and weakens line minima unless emission is restricted to the rotational pole (Özel & Psaltis 2003; Bhattacharyya et al. 2004).

For a fiducial value of $R_{\infty} = 10-15$ km, 10%–20% of NSs with spins of 300 Hz would have spectral features similar to EXO 0748-676, where the line minimum is about 30% below the continuum. At 600 Hz, the percentage is reduced by a factor of 2. For these favorably spinning and oriented NSs (line minimum $\approx 30\%$), the line profile is set by both rotational broadening and fine-structure splitting. Therefore, burst studies of NSs with spins near 300 Hz may yield at least one other example of atomic spectral lines from NSs. For these most favorable systems, the intrinsic line profile is absolutely necessary in order to model these lines and perform meaningful measurements from the observations. Of the presently known LMXBs with X-ray bursts, a very promising target is 4U 1728-34, which spins at 363 Hz (Galloway et al. 2003) and exhibits bursts at a fairly regular rate. A recent model of the NS-accretion disk geometry (Shaposhnikov et al. 2003) estimates the value of i to be around 50°. At this inclination, the line minimum is 7% below the continuum. For smaller inclinations of $i = 30^{\circ}$ and 10° , the line minimum would be 10% and 26%, respectively.

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FIG. 4.—Fraction of sky for which the line minimum is 10% (*thin lines*) and 30% (*thick lines*) below the continuum as a function of spin. We fix the Fe H α line to the observed EW from EXO 0748–676 and plot the line for NS $R_{\infty} = 10$ km (*solid lines*), 15 km (*dotted lines*), and 20 km (*dashed lines*).

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