1. INTRODUCTION

The dominant thermal flux during type I bursts and superbursts offer an ideal opportunity for studying neutron star (NS) properties through spectral measurements of their photospheres (e.g., London, Taam, & Howard 1984, 1986; Foster, Ross, & Fabian 1987). Although never confirmed, the reports by Waki et al. (1984), Turner & Breedon (1984), Nakamura, Inoue, & Tanaka (1988), and Magnier et al. (1989) of 4 keV absorption lines during type I bursts motivated theoretical work on the formation of the Fe Lyα line and edge (e.g., Foster et al. 1987; Day, Fabian, & Ross 1992). Cottam, Paerels, & Mendez (2002, hereafter CPM) observed the accreting NS EXO 0748−676 using the Reflection Grating Spectrometer (RGS) aboard the XMM-Newton satellite and claimed detection of hydrogen-like and helium-like Fe absorption features from the He-like Fe transition of hydrogenic Fe during type I bursts. This Letter is an initial study on the implications of the hydrogen-like feature and predictions for heavy-element abundances near the photosphere. The helium-like feature will be left for future work.

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XMM-Newton observed EXO 0748−676 for 335 ks, during which 28 type I X-ray bursts were seen. CPM combined the burst spectra and split them into a high-luminosity (part) and a low-luminosity (part), which covers the fading to the baseline L. In the high-L part, the detected absorption line was identified as the Hα transition of hydrogenic Fe. In the low-L spectrum, a line identified as the He-like Hα transition was seen. For these identifications, CPM measured the NS’s gravitational redshift at +z = 1.35, giving R = 4.4GM/c2 from the line centroid (neglecting the rotational corrections of Fujimoto 1985; Özel & Psaltis 2003). These spectra have photospheric temperatures kTeff,α ≈ 1.6 keV and kTeff,α < 1.4 keV, using the measured color temperatures (kTc = 1.8 keV and kTc < 1.5 keV; CPM) and correcting for the redshift and spectral hardening from Comptonization (London et al. 1986; Madej 1997).

In § 2, we calculate the Fe abundance when accretion is active, showing that proton spallation of Fe (Bildsten, Salpeter, & Wasserman 1992, hereafter BSW) naturally yields NFe ≈ 3.4 × 10^{19} cm^{-2} for accretion of solar-metallicity material. The spallation also produces large columns of elements with Z < 26, which could be observable via their photoionization edges during the cooling phase of the burst or a radius expansion burst. In § 3, we show that Stark broadening (Paerels 1997) dominates the Hα line equivalent width and that the measured equivalent width (properly redshifted to the NS surface) of Wline = 10 eV implies an Fe column of NFe ≈ (7−20) × 10^{20} cm^{-2} depending on line depth. However, these abundance calculations are highly uncertain due to non-LTE (NLTE) effects and resonant line transport, which we believe play an important role in the line formation. We summarize in § 4 and note that the radiative flux during the burst can levitate hydrogenic Fe.
The accretion gap, we presume that the impact angle and kinetic energy at 200–300 MeV nucleon\(^{-1}\) for the spallation cross section (i.e., that cross section for Fe\(^{56}\)) is calculable this nuclear cascade by following the evolution of nuclei as the nuclei sink, we due to neutron knockout reactions, about 10% of those Fe nuclei are \(^{55}\)Fe and 5% are \(^{54}\)Fe. The Fe column is comparable to the uniform solar abundance calculation because \(\sigma_{\text{ip}} \approx \sigma_{\text{ip}}\). Since many spallation reactions occur as the nuclei sink, we also found the abundances of all lower Z and A nuclei. We calculated this nuclear cascade by following the evolution of each isotope under the constraint that production equals destruction. The cross sections from Silberberg et al. (1998) were used. We found that the sum of all nuclei with 20 < Z < 26 outnumber Fe by a factor of 2.5–3.0 (see Table 1). In the absence of the BSW spallation scenario, these nuclei would not be present. The single most abundant heavy nucleus is \(^{56}\)Fe.

The immediate question that comes to mind is whether these spallation products can be detected. They may be detected via the H\(_\alpha\) lines, but those cross sections are rarely larger than twice those induced by protons; Ferrando et al. (1988) \(N_{\text{Fe}} = N_{\text{Fe}}\sigma_{\text{ip}}J_{\text{ip}}\), with the Fe deposition rate \(N_{\text{Fe}} = 2f_{J_{\text{ip}}/3}\), giving

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N_{\text{Fe}} = \frac{2f_{J_{\text{ip}}}}{3\sigma_{\text{ip}}} \approx 3.4 \times 10^{19} \text{ cm}^{-2} \left( \frac{f_{J_{\text{ip}}}}{3 \times 10^{-5}} \right) \left( \frac{600 \text{ mb}}{\sigma_{\text{ip}}} \right). \tag{1}
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eV per atom) integrated from $E = E_a$ to $1.3E_a$, which is independent of $Z$.

Table 1 shows EW$\alpha$ assuming the element is present at the level implied by the spallation scenario and finding the amount of it in the hydrogenic ground state from Saha equilibrium for $kT = 1.2$ keV. As the burst cools or during a radius expansion burst, these edges could become prominent, and the entry of $\tau_{\alpha,\text{max}}$ in Table 1 presumes that all of the spallation-created elements have at least one bound electron. It is intriguing to note that these edge energies and EW$\alpha$ are close to those previously reported by Waki et al. (1984), Turner & Breeden (1984), Nakamura et al. (1988), Magnier et al. (1989), and Kuulkers et al. (2002).

3. ESTIMATED IRON ABUNDANCES FROM OBSERVED EQUIVALENT WIDTHS

We now estimate the Fe column needed to give the H$\alpha$ line observed by CPM. Motivated by our accretion scenario, we initially presume that this line forms in a thin isothermal layer of Fe in LTE at temperature $T$ above the hotter continuum photosphere. The observed redshift implies a surface gravity of $\log g \approx 3 \times 10^{14}$ cm s$^{-2}$ (1.4 $M_\odot/M$). Although rapid rotation ($\approx 100$ Hz) might explain the observed line width ($\approx 40$ eV), the line’s equivalent width depends most strongly on the intrinsic broadening mechanisms. The scale for thermal Doppler broadening is $\Delta E_{\alpha}/E_0 = (kT/\pi m_e e^2)^{1/2} \approx 1.5 \times 10^{-3} (kT/1$ keV)$^{1/2}$. The natural line width, $\Gamma = 5 \times 10^{11}$ s$^{-1}$ (BS), is given by the spontaneous decay rate for the 3 $\rightarrow$ 1, 2 transitions, which in units of the thermal Doppler shift is $\alpha = \pi T/2E_\alpha \approx 0.3$.

We now show that Stark broadening is larger by an order of magnitude than either of these effects for the H$\alpha$ transition. Stark broadening results from the shift of line energies due to the electric field from neighboring ions, $e\ell_i n_i$, where $\ell_i = (4\pi n_i/3)^{-1/3}$ is the mean ion spacing (Mihalas 1978). The energy perturbation from the linear Stark effect is $\Delta E_\alpha = e^2 \Delta x/\ell_i^2$, where $\Delta x$ is the size of the orbital. Using the linear Stark effect is justified since its energy shift at the densities and temperatures considered exceeds that of the degeneracy-breaking Lamb shift for the relativistic H-like ion (BS). For the $n = 3$ state of Fe at a Thomson depth unity, we find $\Delta E_{\alpha}/E_0 = 1.5 \times 10^{-3}$, an order of magnitude larger than thermal Doppler.

Since the majority of the intrinsic line width is attributed to Stark broadening, $N_{Fe}$ must be found from the measured EW given by the curve of growth (Mihalas 1978),

$$W = 2A_0 \Delta E \int_0^\infty \frac{\eta(\alpha)}{1 + \eta(\alpha)} d\alpha,$$

where $W$ is the EW in energy units, $A_0$ is the normalized line depth at line center, $\Delta E$ is the intrinsic energy width (in our case the Stark shift), $\eta$ is the ratio of the line opacity to the continuum opacity, and $\alpha = E/E_\alpha$. We use the electric field distribution for a uniform ion sea (e.g., the Holtsmark distribution, $W_{Fe}$; Mihalas 1978), giving $\eta(\alpha) = \eta_0 W_{Fe}(\alpha)$, where $\eta_0 = N_{b,Fe}/N_{Fe} \sigma_{\text{line}}/N_{Fe} \sigma_{\text{th}}$ is the ratio of line optical depth to continuum optical depth at line center. Depending on density, either thermal Doppler or Stark broadening dominates, so we convolve the Holtsmark distribution with the Voigt profile to cover the complete range of densities. We also ignore Debye screening effects on the electric field distribution since the deviation from the Holtsmark distribution is small for the typical $T$ and $\rho$.

Because rotational broadening acts to lower the apparent line depth and is likely to be important, the observed value of $N_{Fe} \approx 0.3$ is a lower limit. Indeed, the true line depth could be significantly larger than 0.3. However, such a large value of $N_{Fe}$ is difficult to understand for realistic temperature gradients and presuming LTE. For a gray atmosphere (a reasonable approximation for the temperature profile of a type I burst atmosphere) $A_0$ attains a maximal value of 0.2 when the Fe resides at very low column depths. The resolution of this dilemma may be the role of NLTE effects and resonant line transport in the H$\alpha$ line. Resonant line transport could generate such an absorption feature with a large line depth without invoking large temperature contrasts as in LTE (Jefferyes 1968). NLTE effects clearly play a role in determining abundances from the EW measurements. For instance, an immediate measure of the role of NLTE effects is that the radiative ionization rate for the Fe ground state exceeds the collisional ionization rate (London et al. 1986), complicating the ionization balance for Fe.

To resolve the role of NLTE effects, the radiative transfer equation must be solved self-consistently for both the resonant transport of the H$\alpha$ and Ly$\alpha$ lines with detailed balanced of the Fe ionization and excitation in the strong radiation field of a type I burst. For now, we simply present results for $N_{Fe} \approx 0.3$, which is set by observations and $A_0 = 0.2$, which is characteristic of a gray atmosphere.

We calculate the $N_{Fe}$ required to reach $W_{Fe} = 10$ eV assuming all Fe resides at the column depth, $y = P/g$. We assume LTE and that the dominant states for Fe are either fully ionized or in the hydrogenic ground state or helium-like ground state to approximate the partition function. For radial infall, with the Fe layer between $kT = 1.2$–1.4 keV and $A_0 = 0.3 (0.2, N_{Fe} = 7 (20) \times 10^{20}$ cm$^{-2}$. This temperature range is consistent with the absence of helium-like Fe in the high $T$ phase of the burst (CPM). Since the occupation of the $n = 1$ state exceeds that in $n = 2$ by $\sim 10^{-2}$, we also calculate $W_{Ly\alpha}$ for the implied $N_{Fe}$ values. For this line, thermal Doppler and natural line broadening dominate Stark broadening (Madej 1989).

When $kT = 1.2$–1.4 keV and the Fe resides at the pressure implied by radial accretion, $W_{Ly\alpha} < 30$ eV. Foster et al. (1987) also calculated $W_{Ly\alpha}$ for a uniformly distributed Fe abundance at the solar value and found that it would not exceed 30 eV. It would require an $A_0 \approx 1$ to give a Fe column consistent with that calculated from spallation. However, such large temperature contrasts (and hence such large values of $A_0$) are not possible in these atmospheres, and we need to understand the NLTE line transport problem before we can address this apparent inconsistency.

Day et al. (1992) pointed out that a uniform presence of Fe at the solar value would create an observable photoionization edge. The Fe column required to produce the observed H$\alpha$ line would yield enormous edges. However, NLTE effects would weaken the strength of these photoionization features significantly (London et al. 1986). The reported broad spectral features in the 6–9 keV range (van Paradijs et al. 1990; Stromayer & Brown 2002) during type I bursts and superbursts need to be reanalyzed as possible Fe photoionization edges.

4. SUMMARY AND CONCLUSIONS

Active accretion in the context of a beam hitting the atmosphere naturally gives $N_{Fe} \approx 3 \times 10^{19}$ cm$^{-2}$, which depends only on the physics of proton spallation of Fe. In this scenario,
heavy elements with $Z < 26$ are produced in quantities comparable to Fe and may be observed via their photoionization edges or atomic lines (see Table 1) during the cooling phase of type I bursts or superbursts. Our initial LTE calculations have found that an Fe column of $\approx 7 - 20 \times 10^{20} \text{ cm}^{-2}$ is needed to produce the measured $\nu_{\text{in}}$ of CPM. However, until a more complete calculation of the resonant line transport for the $\text{H}\alpha$ and $\text{Ly}\alpha$ line has been undertaken in this strong radiation environment, we cannot say whether this factor of 20 discrepancy is certain.

Throughout this paper, we have presumed that Fe is present because of active accretion during the burst. However, the radiative force on hydrogenic Fe in the ground state is

$$F_{\text{rad}} = \int \sigma_{\text{e}} F_{\text{e}} c dE,$$

where $F_{\text{e}}$ is the flux per photon energy at the $\text{Ly}\alpha$ transition ($E = 6.9 \text{ keV}$). Since $F_{\text{e}}$ is nearly constant across the line, $F_{\text{rad}} = \pi \hbar e^2 f_{1-2} F_{\text{e}} / m_e c^2$ in the optically thin limit (Michaud 1970), where $f_{1-2} = 0.42$ is the oscillator strength from BS. If $F_{\text{e}}$ is given by a blackbody, then at $kT_{\text{eff}} = 1 \text{ keV}$, the radiative acceleration on Fe is $a_{\text{rad}} \approx 10^{15} \text{ cm} \text{s}^{-2}$, a factor of 3 larger than $g$. The radiative force will be even larger for realistic type I burst spectra, which are harder than a blackbody at the observed $T_{\text{eff}}$ (London et al. 1986; Pavlov, Shibanov, & Zavlin 1991). The Fe diffusion time is less than the burst duration, so there is adequate time for the accelerated Fe to reach a new diffusive equilibrium. The calculation of the resulting Fe column, which could well saturate the line and lower the radiative force, is beyond the scope of this Letter, as it requires a simultaneous solution of the radiative transfer and the Fe diffusion equations, like that done for hot white dwarfs (e.g., Chayer, Fontaine, & Wesemael 1995).

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