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CHANDRA DETECTION OF Fe XVII IN ABSORPTION: IRON ABUNDANCE IN THE HOT GASEOUS INTERSTELLAR MEDIUM

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ABSTRACT

The iron depletion level and the gas-phase iron abundance in the hot ($\sim 10^6$ K) interstellar medium (ISM) are critical to our understanding of its energy balance as well as the thermal sputtering, cooling, and heating processes of dust grains. Here we report on the first detection of the Fe XVII absorption line at 15.02 Å from the hot ISM in the spectrum of the low mass X-ray binary 4U 1820–303 observed with the *Chandra X-Ray Observatory*. By jointly analyzing this absorption line with those from O VII, O VIII, and Ne IX ions in the same spectrum, we obtain an abundance ratio as Fe/Ne=0.8(0.4, 2.1) in units of the Anders & Grevesse solar value (90% confidence intervals). We find that the result is robust with respect to different assumed gas temperature distributions. The obtained Fe/Ne abundance ratio, albeit with large uncertainties, is consistent with the solar value, indicating that there is very little or no iron depleted into dust grains, i.e., most of or all of the dust grains have been destroyed in the hot ISM.

Subject headings: ISM: abundances — ISM: dust — X-rays: ISM — X-rays: individual (4U 1820–303)

1. INTRODUCTION

As one of the most abundant refractory metals, iron is an important constituent of the interstellar dust grains and is believed to have the greatest fraction of its atoms depleted into dust grains (Sofia et al. 1994). Surveys in ultraviolet (UV) wavelength band indicate that $\gtrsim$70% of the iron in the cool and warm medium of the Galactic disk/halo could be locked up in solid grains, and only the remains can be probed through absorption lines of gaseous Fe II (see Savage & Sembach 1996 and references therein). Recent studies on X-ray absorption edges also provide evidence of iron depletion into dust grains in the interstellar medium (ISM; Juett et al. 2006).

Iron can be liberated from the dust to the gas phase through thermal sputtering. Theoretical calculations show that the sputtering caused by high velocity shocks ($v_s \simeq$ 50-200 km s^{-1}) could destruct several $\times$10% of grains in the ISM, and that with the presence of a magnetic field, grain-grain collisions can also be a very efficient process for dust grain destruction, specifically in the case of low-velocity shocks ($v_s \lesssim$100 km s^{-1}; Draine & Salpeter 1979; Jones et al. 1994). The dust grains can also be fragmented/destroyed through thermal evaporating in the hot ISM. The recycling of atoms back to the gas phase has been evidenced by the difference of the elemental abundance ratios in the Galactic halo from those in the Galactic disk, and by the ionization disparity of the shocked material at various post-shock distance (Jenkins & Wallerstein 1995; Savage & Sembach 1996). A comparison between the observed abundance ratio of (Mg+Fe)/Si in the dust of the halo clouds and that of the theoretical expectation, together with the observed correlation between the gas-to-dust ratio and the dust mass carried by Fe, indicates that the dust grain cores likely contain iron oxides and/or metallic iron. Some of these resilient cores can survive from the shock destruction during the dust processing in the ISM (Sembach & Savage 1996; Frisch & Slavin 2003).

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In the hot ISM, the knowledge of the exact amount of iron contained in dust grains, which is reflected in the gas-phase abundance of iron (e.g., Savage & Sembach 1996), is of great importance for understanding many astrophysical processes. For an emission spectrum of a solar abundance plasma at temperature $\sim 10^6$ K, the contributions of iron ions encompass about 50% of the total emitting energy and photons in the energy range from 10 eV to 2 keV. On the other hand, dust grains are an effective coolant of the hot gas. The thermal energy of the hot gas can be transferred to dust grains via the collisions between electrons and dust grains, resulting in bulk heating of the dust and infrared (IR) emission. For a solar abundance of the dust grains, the grain IR radiation is at least comparable to, and could be more than 10 times more efficient than, the gas X-ray emission in cooling the hot gas at temperature $\sim 10^6$ K (Dwek & Arendt 1992). Consequently, the existence of the iron-bearing dust in the hot ISM could alter the chemical composition of the hot gas, therefore, largely change the flux and the spectral shape of the hot gas radiation, affect the energy balance, change the cooling rate thus the lifetime of the hot gas, and eventually, adjust the star formation rate, in the whole ISM and affect the galactic evolution in general.

The iron depletion level in the hot gas can be measured by modeling the iron emission lines or the absorption lines that the gas-phase iron ions imprint on the background point source spectrum, then comparing the iron abundance with the solar values. Directly measuring the IR emission of the dust in such environments is difficult due to the confusion with foreground cold dust in the Galactic disk along the line of sight. A recent study of the very soft (0.25 keV) X-ray diffuse background emission in the vicinity of the Sun suggests that the gas phase iron is $\sim$ 30% of the solar value (Sanders et al. 2001). However, given that the Sun may reside in a privileged location (i.e., the Local Hot Bubble), this depletion level may not be typical for the general hot ISM. Furthermore, the inferred emission measure is also sensitive to different adopted plasma emission models, and the less well known interaction between the solar wind ions with the local neutral ISM may further complicate the interpretations (e.g., Sanders et al. 2001; Pepino et al. 2004; Hurwitz et al. 2005). Absorption line studies, on the other hand, measuring the total column

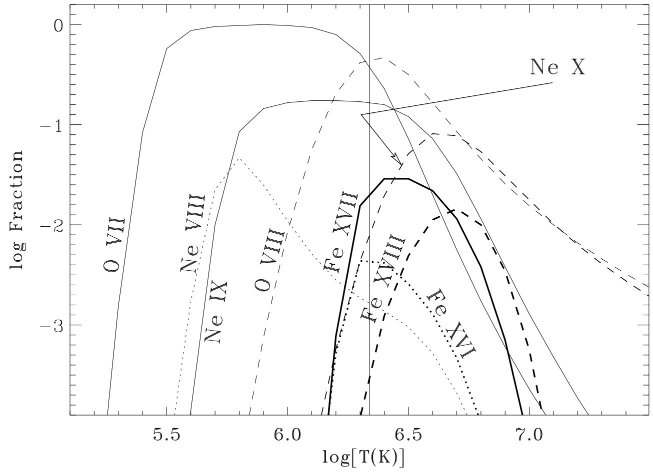

FIG. 1.— Ionization fractions of oxygen, neon, and iron ions as a function of temperature for a gas in the collisional ionization equilibrium state (Arnaud & Raymond 1992). The fractions of neon and iron have been scaled down with respect to the relative solar abundance ratio to oxygen. The *vertical line* indicates the best fit temperature (2.2×10^6 K) in the isothermal case for the absorbing gas toward 4U 1820–303.

density along the line of sight, are less affected by the different models and the charge exchanges between the solar wind and the local neutral gas, and, therefore, should provide a reliable measurement of the iron abundance in the hot ISM.

In this Letter, we present the first detection of the Fe XVII absorption line at ~ 15 Å from the hot ISM toward 4U 1820–303. Comparing the column density of Fe XVII with that of Ne IX, and with those of O VII and O VIII that we previously measured, we have derived a relative abundance ratio of Fe/Ne and then inferred the iron depletion level in the hot gas. Throughout the Letter, we adopt the solar abundances from Anders & Grevesse (1989), [3] and quote the errors at 90% confidence levels for single varying parameters until otherwise specified.

2. SOURCE, OBSERVATIONS, AND THE EXISTING RESULTS

4U 1820–303 is a bright low mass X-ray binary residing in the globular cluster NGC 6624 (Galactic coordinates l, b = $2.^\circ79, 7.^\circ91$) and its distance has been determined as 7.6 ± 0.4 kpc (Kuulkers et al. 2003), meaning that it is very close to the Galactic center and is located ~ 1 kpc above the disk plane.

The *Chandra X-Ray Observatory* has observed this source three times with different instrumental configurations. The observation log, data reduction and analysis procedures have been described in detail in Yao & Wang (2006, hereafter Paper I), and here, we summarize absorption line detections and relevant absorption line diagnostic results.

We have detected highly ionized O VII, O VIII, and Ne IX Kα, and O VII Kβ absorption lines, which are produced in the hot ISM rather than in the circumstellar gas associated with the binary system (Paper I; see also Futamoto et al. 2004; Juett et al. 2006). Modeling these lines with our absorption line model, *absline* (Yao & Wang 2005), we have constrained dispersion velocity of the hot gas [v_b = 255(165, 369) km s^{-1}], column densities of O VII, O VIII, and Ne IX. We have also obtained the abundance ratio of Ne/O in the hot gas, which is consistent with the solar value. For a gas at temperature about $10^6 - 10^7$ K, the population of each abundant iron ion contained in the gas, e.g., Fe XVI, Fe XVII, and Fe XVIII,

[3] The "real" solar abundances are still under debate (e.g., Asplund et al. 2005; Antia & Basu 2006), so we still use the old values.

TABLE 1
STRONG TRANSITION LINES OF FE XVII AND FE XVIII

Ion	Transition	λ (Å)	f_{ij}
Fe XVII	$2s^22p^6(^1S)-2s^22p^54d(^1P^0)$	12.123	0.53
Fe XVII	$2s^22p^6(^1S)-2s^22p^53d(^1P^0)$	15.015	2.31
Fe XVII	$2s^22p^6(^1S)-2s^22p^53d(^3D^0)$	15.262	0.63
Fe XVIII	$2s^22p^5(^2P^0)-2s^22p^4(^1S)3d(^2D)$	14.121	0.90
Fe XVIII	$2s^22p^5(^2P^0)-2s^22p^4(^1D)3d(^2P)$	14.203	0.57
Fe XVIII	$2s^22p^5(^2P^0)-2s^22p^43d(^2D)$	14.361	0.93

is distributed in a narrow temperature range (Fig. 1); therefore, a well confined gas temperature or its distribution is crucial for inferring the total iron in the hot gas. The detection of multiple absorption lines in this sight line enables us to obtain such a constraint. For instance, if the intervening gas is in the collisional ionization equilibrium (CIE) state (Arnaud & Raymond 1992) and isothermal, its temperature can be determined as $T = 2.2 \pm 0.3 \times 10^6$ K (Paper I).

3. Fe XVII ABSORPTION LINE AND IRON ABUNDANCE IN THE HOT ISM

We searched for the ionized iron absorption lines at the corresponding rest frame wavelengths in the wavelength range between 2 and 25Å in the spectrum obtained in Paper I. The Fe XVI absorption lines are expected to be very weak (the oscillation strength $f_{ij} < 10^{-6}$), and are not considered further in this work. Table 1 lists the strong lines ($f_{ij} > 0.5$) of ions Fe XVII and Fe XVIII. We only detected a significant Fe XVII absorption line at 15.02Å (Fig. 2), and did not see any clear sign for the other lines listed in Table 1. These detection results are not surprising. The constrained hot gas temperature favors the Fe XVII population, and the transition of the 15.02 Å line is strongest (Fig. 1; Table 1). Therefore, the Fe XVII absorption line at ~ 15.02 Å is expected to be at least 4 times stronger (in terms of equivalent width [EW]) than the others.

We use different models to characterize the Fe XVII absorption line at 15.02Å. The negative Gaussian model gives the line centroid as 15.008(14.999, 15.018) Å or 132(-50, 314) km s^{-1}, line width as $\sigma < 280$ km s^{-1} or $v_b < 396$ km s^{-1}, and its EW as 5.1(2.9, 7.3) mA.

We then fit the line with our *absline* model, which adopts the Voigt function as line profile and allows a joint analysis of multiple absorption lines (see Yao & Wang 2005; Paper I; Wang et al. 2005 for further discussion). The fit is as good as with a Gaussian model, and the obtained line position is also identical. Connecting the v_b with those of O VII, O VIII, and Ne IX lines (since the non-thermal broadening dominates, we therefore ignore the tiny differences of the thermal broadening in different elements), we obtain the column density of the Fe XVII as $\log[N_{\rm FeXVII}({\rm cm}^{-2})] = 15.0(14.7, 15.2)$. [4]

Following the procedure we established in Paper I, we probe the abundance ratio of Fe/Ne in the hot gas. Since neon is a noble element, it is very unlikely depleted into dust grains. Therefore we take it as the reference element. In fact, we have obtained a Ne/O ratio that is consistent with the solar value (Paper I), and the following inferred Fe/Ne is essentially the same as Fe/O in units of solar value. Assuming that the absorbing gas is in a CIE state and isothermal, we jointly an-

[4] This column density, together with the dispersion velocity v_b constrained in jointly analyzing oxygen and neon lines (§2), can reproduce the EW measured with Gaussian model.

alyze the Fe XVII line with the O VII, O VIII, and Ne IX Kα lines and the O VII Kβ line, requiring the common absorbing gas to be of the same temperature. We fix the neon abundance at the solar value, and let the abundances of oxygen and iron be free parameters. In this way we constrain the hydrogen column density to $N_{\rm H} = 7.9(5.0, 10.2) \times 10^{19}$ cm^{-2}, the temperature to $T = 2.2(1.9, 2.5) \times 10^6$ K, and the abundance ratio to O/Ne = 0.9(0.5, 1.3) solar for the absorbing hot gas, which are identical to those reported in Paper I. In addition, we obtain the abundance ratio of Fe/Ne as 0.8(0.4, 2.1) solar. Considering the dependence of the Fe XVII population on T (Fig. 1), we calculate the confidence contours of Fe/Ne versus T, which is presented in Figure 3a.

Next, we investigate the effects on the inferred Fe/Ne ratio if the above isothermal assumption of the intervening gas is relaxed. Since the absorption samples almost the entire Galactic disk from the Sun into the Galactic bulge, it is possible that the hot gas consists of different temperature components. Here we examine two simple temperature distributions. In each case, we first interpolate the ionization fractions at different temperatures, assuming the gas to be in CIE state, and then calculate the column density for each ion. To get a better constraint, we also add the undetected Kα Ne X (12.134 Å) absorption line in the joint fit. This line, except for the detected line absorptions from oxygen, neon, and iron ions, is the next most expected one from a different ion to be observed in the spectrum with high counting statistic because of its anticipated large column density (Fig. 1) and large transition coefficient ($f_{\rm ij}$ = 0.416), and is particular useful for constraining the upper boundary to the gas temperature. In the first case, we assume that the hot gas temperature distribution follows a logarithmic Gaussian form, as a natural extension of the isothermal single temperature case,

$$\mathrm{d}N_{\rm H}(T) \propto \exp\left[\frac{-(\log T - \log T_0)^2}{2(\sigma_{\log T})^2}\right] \mathrm{dlog}(T), \qquad (1)$$

where the mean temperature T_0 is equivalent to T in the isothermal case, and $\sigma_{\log T}$ is the dispersion of $\log T_0$. Under this assumption, we obtain $T_0 = 2.0(1.8, 2.4) \times 10^6$ K and

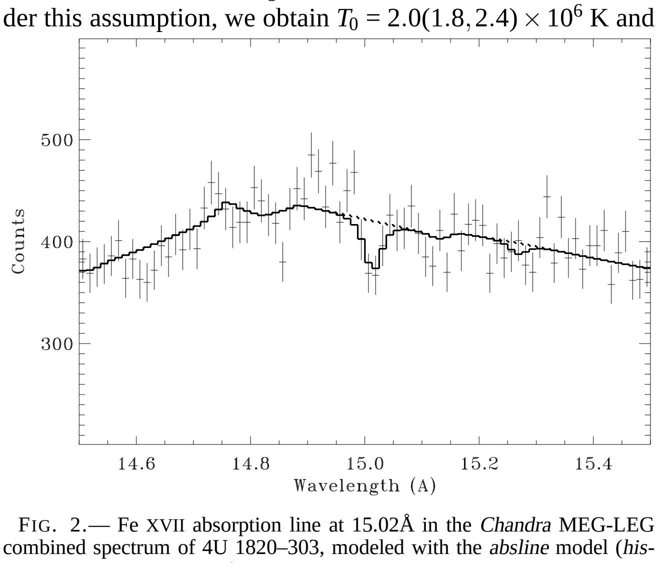

FIG. 2.— Fe XVII absorption line at 15.02Å in the *Chandra* MEG-LEG combined spectrum of 4U 1820–303, modeled with the *absline* model (*histogram*). The *dip* at 15.26 Å indicates the expected amount of absorptions for the second most significant Fe XVII line (Table 1). The dotted line indicates the smooth continuum level around the line. The model has been convolved with the instrumental response, and the binsize is 12.5 mÅ. The apparent bump on the blue-side of the line may be due to the imperfect calibration near the hot pixel. For the detail information of the co-added spectrum and the continuum fit, please refer to Paper I.

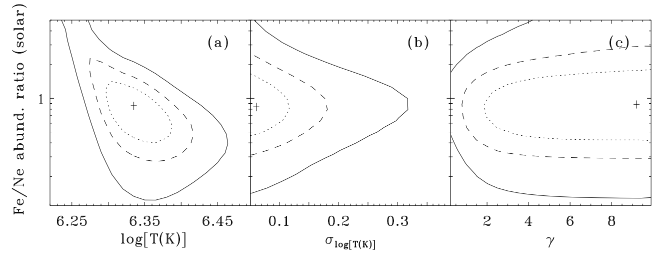

FIG. 3.— The 68%, 90%, and 99% confidence contours of (a) the abundance ratio of Fe/Ne (in units of solar value) vs. gas temperature T, (b) Fe/Ne vs. temperature dispersion, and (c) Fe/Ne vs. power-law index γ for the isothermal case, log-Gaussian temperature distribution, and the power-law temperature distribution, respectively.

$\sigma_{\log T} < 0.15$, and the abundance ratio Fe/Ne = 0.8(0.4, 2.3) solar. In Paper I, we have demonstrated that since an isothermal absorbing plasma is adequate to describe the observation, the additional free parameter $\sigma_{\log T}$ cannot be fully constrained in the spectral fitting, and there is an apparent correlation between T_0 and $\sigma_{\log T}$ (see Fig. 4 in Paper I) due to the large value of $N_{\rm OVIII}$. But the inferred Fe/Ne is insensitive to different $\sigma_{\log T}$ values, as illustrated in the confidence contours of the Fe/Ne ratio versus $\sigma_{\log T}$ (see Fig. 3b).

In the second case, we assume that the hot gas temperature distribution follows a power-law (PL) form,

$$dN_{\rm H}(T) = \frac{N_{\rm H0}(\gamma+1)}{T_0}(T/T_0)^{\gamma} dT. \qquad (2)$$

This simple characterization of the temperature distribution can be derived, for example, naturally from an exponential disk model (Yao & Wang 2007), where $N_{\rm H0}$ is the total hydrogen column density along the sight line, T_0 is the Galactic mid-plane temperature, and the PL index γ is the ratio of the temperature to density scale heights. Our joint analysis gives $N_{\rm H} = 7.5(5.3, 10.0) \times 10^{19}$ cm^{-2}, $\gamma > 2$, and $T_0 = 2.4(2.1, 3.4) \times 10^6$ K. Again, although the extra free parameter γ can vary in a large range, the constrained abundance ratio Fe/Ne=0.9(0.4, 2.0) solar is insensitive to γ. Fig. 3c shows the confidence contours of the Fe/Ne ratio versus the PL index γ.

4. DISCUSSION

We detect a significant Fe XVII absorption line at $\sim$ 15.02 Å in the *Chandra* spectrum of 4U 1820–303. A joint analysis of this line with the detected highly ionized oxygen and neon lines, all interstellar in origin and observed in the same spectrum, gives the abundance ratio of Fe/Ne in the hot ISM component, which, although with large errors, is consistent with the solar value. In addition, this result appears to be unaffected by the different gas temperature distributions adopted. We conclude that there is no evidence for substantial depletion of iron into dust grains in the hot ISM. This is in contrast to cooler phases of the ISM where iron is usually found to be heavily depleted (Sembach & Savage 1996; Juett et al. 2006). Grain cores containing iron oxides are generally rather resilient and it is quite difficult to liberate the iron from these cores (Sembach & Savage 1996; Frisch & Slavin 2003). This solar value of Fe/Ne ratio, if confirmed, thus suggests that likely all of the dust in this very hot ISM phase (T $\gtrsim 10^6$ K) has been destroyed by frequent and/or severe shocks during the dust grain processing in the ISM.

Dust grains pre-existing in the ISM or formed in supernova ejecta can be destroyed by their generated forward and reverse shocks and subsequently, in heated hot gas. By studying the iron abundance via the far-UV Fe II absorption lines, Sembach & Savage (1996) find that while more than 99% of iron is depleted into dust grains in the cold disk of the Galaxy, the iron depletion is $\sim 80\%$ in warm clouds of the Galactic halo. They attribute this difference to the dust grain disruption by the supernova (SN) shocks when circulating the grains between the Galactic disk and halo. If the hot ISM is believed to be heated from the cool ISM, it should have experienced shocks much more frequently and/or much more violently than the warm halo clouds. Therefore it is natural to expect that many more grains, even including the resilient iron-rich cores, could have been destroyed in such harsh environments. More recently, Strickland et al. (2004) have obtained an abundance ratio of Fe/O from the diffuse extraplanar halo emission of many disk galaxies like our own, which is $\sim 40\%$ solar. This result, although subject to different thermal plasma models adopted and the different thermal properties assumed for the emitting hot gas in the data analysis, clearly rules out the depletion pattern found by Sembach & Savage (1996) in the cold and warm gas of the Galactic disk and halo, further supporting the scenario that more iron has been released back to gas phase.

The above interpretation may not be entirely unique and in some cases is subject to systematic effects introduced by line-of-sight variations and intrinsic X-ray source properties. Claims like an overabundance of heavier elements relative to oxygen in neutral matter towards the Galactic center direction presumably caused by a significant contribution of Type Ia SNe in the Galactic bulge (Ueda et al. 2005) would elevate the contribution of iron in the hot gas phase as well. In this respect the result by Juett et al. (2006) that iron is significantly depleted in the cool phase in line of sight towards 4U 1820–303 and that Ne/O is close to the solar value is an important indicator that conditions are not so unusual. Abnormal heavy element abundances have been observed in microquasars (e.g., Cyg X-1: Schulz et al. 2001, Juett et al. 2004; GRS 1915+105: Lee et al. 2002, GX 339-4: Miller et al. 2004). In all these systems, the observed overabundance pattern of the heavy elements relative to oxygen can also be interpreted as the different photoionization structures of these elements in the intrinsic absorbing material (Schulz et al. 2002; Lee et al. 2002). Futamoto et al. (2004) and Juett et al. (2004, 2006) already argued successfully that this is likely not the case for 4U 1820–303.

As a final note, we point out that the absorption path length toward 4U 1820–303 passes through the Galactic bulge region where the soft X-ray background emission in the 0.75 keV band is greatly enhanced (Snowden et al. 1997). This enhancement indicates that the emitting plasma is either of a high temperature or of a dense emitting region, or both. Recently, we have obtained an exponential scale height of ~ 2 kpc and the mid-plane density of $\sim 2.4 \times 10^{-3}$ cm^{-3} for the hot gas toward Mrk 421 (Galactic coordinates l, b = $179.^{\circ}83, 65.^{\circ}03$) in a joint-analysis of absorption and emission data at the same time (Yao & Wang 2007). This characterization, if typical for the general hot ISM, only accounts for $\sim 30\%$ of the observed absorption toward 4U 1820–303, meaning that a large portion of the absorption originates from the Galactic bulge. Therefore, the gas phase abundance ratio of Fe/Ne presented in this letter could be biased because of the remarkable absorption contribution from the bulge, where the metal abundance pattern may not be as the same as that in the overall ISM. Nevertheless, we present here a feasible way to infer the gas phase iron abundance in the hot ISM that potentially affects our understanding of the cooling/heating process in the ISM in general. To obtain a global picture of the gas phase iron abundance in the hot gas, high quality absorption data along other sight lines that are away from the Galactic bulge region are therefore required.

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