Draft version August 22, 2016
Preprint typeset using LaTeX style emulateapj v. 01/23/15

# X-RAY EMISSION FROM DUST IN SUPERNOVA REMNANTS

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*Draft version August 22, 2016*

## ABSTRACT

Interstellar dust is a crucial component in the interstellar medium (ISM). Large amount of refractory metals like iron are locked in interstellar dust grains. When interstellar shocks heat the ISM, these metals will be released to gaseous plasmas. Therefore, dust grains can be viewed as a reservoir of neutral atoms which continuously change the ionization state of the plasmas in shocks. Meanwhile, dust grains can be penetrated by hot thermal electrons and produce fluorescent lines. These two process will change the Fe K$\alpha$ profile significantly. We use updated atomic database and plasma code to calculate the Fe K$\alpha$ emissivity and spectra using the dusty non-ionization equilibrium (NEI) model. Our results show the Fe K$\alpha$ emissivity at 1 keV is lower than that in Borkowski 1997 (**?**). At 10 keV, the Fe K centroid shift is more than 140 eV, which can be distinguished by present X-ray telescopes. When next generation of calorimeter- based spectrometers are available, this dust fluorescent line can be identified in many hot dusty underionized plasmas, like the young supernova remnant Cas A.

*Keywords:* Interstellar dust, supernova remnants, fluorescent emission

## 1. INTRODUCTION

Young supernova remnants (SNRs) are typical hot X-ray emitting plasmas ($T_e \approx 10^7$ K). In such high temperature, high speed ions bombard on dust and remove atoms from their surface. This process, which is called physical sputtering, is the primary mechanism of dust destruction in the SNR (**?**). When temperature reaches ≈5 keV, not only ions make great influence on dust grains, thermal electrons can also effect dust's micro-structure by penetrating them. When electrons hit the dust, they can occassionally knock out inner-shell electrons that originally belong to atoms bounded in the dust. Following that, fluorescence line will be produced. These two processes make dust, especially iron dust, an important component in SNR's plasma when we analyse its X-ray spectra: Iron is an important refractroy element that is omninent in the universe, with 95% of them depleted on dust grains. When shockwave propangates through dusty plasma, these dust grains act like iron storage that constantly feed neutral iron to the gaseous plasma. This alter the ionic fraction of the plasma. In addition, iron has a high fluorescence yield (30%), thus dust could produce a large amount of fluorescence emission.

The most commonly used model to fit the SNR's plasma is the NEI model which consider only gaseous plasma. Simple as it is, this model omits the role of dust playing on the refractroy elements. In this paper, we calculate Fe K$\alpha$ emission from plasma using a dust-modified NEI model. The paper is organized as follow: In Section 2, we introduce our model; in Section 3, we describe the database and plasma code we use; In Section 4, we show the theoretical prediction of Fe K$\alpha$ X-ray emission; In Section 5, we predict some region in SNR that dust line may be detected directly when next generation X-ray spectroscopy are being used. A summary is provided in Section 6.

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## 2. DUST-MODIFIED NEI MODEL

Nonequilibrium ionization (NEI) model is frequently used to describe the plasma in young SNRs, since the shock heating time is limited and many heavy elements have not reach their equilibrium states. For example, at $10^7$ K, it took $\approx 3 \times 10^{11}$ cm$^{-3}$s for Fe to reach equilibrium, while young SNRs' typical ages are less than $10^{11}$ cm$^{-3}$s.

In classic NEI models, only gaseous phase are considered. However, for elements like irons, many iron atoms are lock in the dust grains and will be ejected slowly into ambious gas slowly. We consider only the major mechanism physical sputtering and assume the MRN size distribution of dust grains (**?**):

$$dn = a^{-3.5} da$$

with the largest radius to be 0.25 $\mu$m. Simulation shows when temperature reaches 1 to 10 keV, Fe dust grain has a sputtering rate of $r = 10^{-6}$ $\mu$myr$^{-1}$cm$^3$. Assuming every dust grain is a homogenious sphere, the fraction of Fe that left in dust is:

$$\begin{aligned} f(\tau) &= \frac{\int_0^{a_{max}-r\tau} \frac{4}{3}\pi a^3 da}{\int_0^{a_{max}} \frac{4}{3}\pi a^3 da} \\ &= 1 - 3.2\tau_{13}^{1/2} + 3\tau_{13} - \tau_{13}^2 + 0.2\tau_{13}^3 \end{aligned} \tag{1}$$

in which $\tau_{13} = 10^{13}$ cm$^{-3}$s. Adding this to NEI model:

$$\begin{aligned} dn/d\tau &= n_i df/d\tau \\ dn_1/d\tau &= -n_i df/d\tau - \alpha_1 n_1 + R_1 n_2 \\ &...... \end{aligned} \tag{2}$$

This model describes the ionic fraction varying with ionization parameter $\tau = n_e t$.

## 3. PLASMA CODE

The calculation of theoretical spectra requires high-precision plasma code. Here we used the APEC v3.0

developed by Harvard-Smithsonian Center for Astrophysics. APEC v3.0 aims at calculating emission for hot, collosional plasma in non-equilibrium state, which matches our requirement for analyzing X-ray emission from SNR.

Compared to previous version, APEC v3.0 contain more precise information on auto-ionization and satellite lines. For example, the new column "ion_drv" describes which ion actually produces each line. Therefore, line emissivity should be multiplied by corresponding ion_drv's ionic fraction to get the precise total emissivity. In addition, it contains information of n=2 to n=1 fluorescence lines from Fe I to Fe XXIV that is omitted in previous version, which is crucial for our Fe K$\alpha$ calculation.

For fluorescence line from dust, we use **?**'s collisional K-shell ionization rate coefficient:

$$\begin{aligned} < v\sigma > &= 1.13 \times 10^{-7} (\mathrm{ryd/Ip})^{3/2} \beta^{1/2} \\ &\times \exp(-\beta)/(\beta + 0.4)\ \mathrm{cm^3 s^{-1}}, \end{aligned} \tag{3}$$

where 1 ryd is the Ryderberg constant 0.0136 keV, Ip is the K-shell ionization potential 7.112 keV, and $\beta = 1/T_e$. $< v\sigma >$ need to be multiplied by fluorescence yield 0.2026 and 0.1013 (double lines) and Fe solar aboundance to be compatible with the line emissivity (column "epsilon") in APEC.

## 4. NEW RESULTS

### 4.1. *ionic fraction and emissivity*

We compare the classic pure-gas NEI model with the dust modified NEI model, using 100% atomic gaseous Fe as initial condition for the former and 95% dust Fe and 5% atomic gaseous Fe for the latter. If dust is ignored, the ionic equilibrium timescale of Fe is $1 \times 10^{12}$ cm$^{-3}$s. However, most Fe is locked in dust grains (in ISM, 95% Fe is depleted onto dust, $n_i = 0.95$). Because the timescale of dust destruction is $1 \times 10^{13}$ cm$^{-3}$s, the plasma will not be in ionization equilibrium until $1 \times 10^{13}$ cm$^{-3}$s.

Fig. 1 to 4 show the ionic fraction varing with $\tau$.

When $\tau < 10^{10}$ cm$^{-3}$s, dust locked most Fe. If dust do not emit any X-ray photons, the whole plasma will have little K$\alpha$ emission. However, the atoms locked in dust grain can also emit fluorescence lines similar to neutral atoms. Therefore, the total emissivity is close to the pure-gas NEI model.

Dust has the most prominent effect on total K$\alpha$ emissivity when $\tau = 10^{10} - 10^{11}$ cm$^{-3}$s. At this time, for the pure-gas NEI model, Fe XVIII $\sim$ Fe XXIV, which have high K$\alpha$ emissivity, become the dominant ions. However, for dust NEI model, most Fe are still in solid state, whose emissivity is significantly smaller than high-ionized ions. Therefore, dust lowers the total K$\alpha$ emissivity.

When $\tau > 1 \times 10^{11}$ cm$^{-3}$s, dust has dropped to below half of its initial value, and the total emissivity is dominated by gas. Thus after that time, the total emissivities of the two models grow closer. When $\tau = 1 \times 10^{13} cm^{-3} s$, plasma reaches equilibrium in both model, thus the two emissivities become the same.

### 4.2. *centroid and spectra*

Different Fe ions emit K$\alpha$ photons with slightly different energy: Atomic Fe has fluorescent K$\alpha$ line centroided at 6.4 keV, while highly ionized ion Fe XXV emit 6.7 keV K $\alpha$ photons. Because dust has a great impact on ionic fraction at $\tau = 10^{10} - 10^{12}$ cm$^{-3}$s, and itself produces low-energy fluorescence lines, dust will also affect the centroid of the K$\alpha$ profile. We calculated flux-weighted centroid of K$\alpha$ profile, which is shown in Fig. 6. (technically, we chose strong lines, whose flux is greater than 1% of the strongest line.)

Fig. 7 shows the centroid shift. As expected, in $\tau = 10^{10} - 10^{12}$ cm$^{-3}$s, dust model has a much lower centroid than pure-gas model. At 10 keV, the difference reaches 140 eV at $5 \times 10^{10}$ cm$^{-3}$s.

We also compare the theoretical spectra of these two model. As shown in Fig. 8 and 9, at $\tau = 1 \times 10^{11}$ cm$^{-3}$s and T=1 keV, the dust fluorescence lines are prominent.

## 5. CAS A

Young SNRs are typical under-ionized X-ray emitting plasmas. In addition, strong IR emission from dust are detected in many of them. Cas A is one of the most studied SNR. In X-rays, there are three regions (north, east, west) has distinct Fe K$\alpha$ emission, but in the south, Fe K$\alpha$ flux is rather low. In IR,**?** found prominent [OIV]+[Fe II] emission lines in the south shell. Thus the south shell probably contains small amount of high-ionized Fe ions but high amount of iron dust. **?** fit Cas A X-ray spectra with vpshock model and found the average electron temperature and ionization parameters to be 2.2 keV and $2 \times 10^{11}$ cm$^{-3}$s respectively, which is the case that dust NEI model differs most with the pure-gas NEI model. In the south region marked in Fig. 10, the Fe K$\alpha$ centroid is $6.61 \pm 0.01$ keV, which is consistent with our dust-modified model. When the next generation of X-ray spectroscopy put into use, the unique dust Fe fluorescence line may be detect in this region directly.

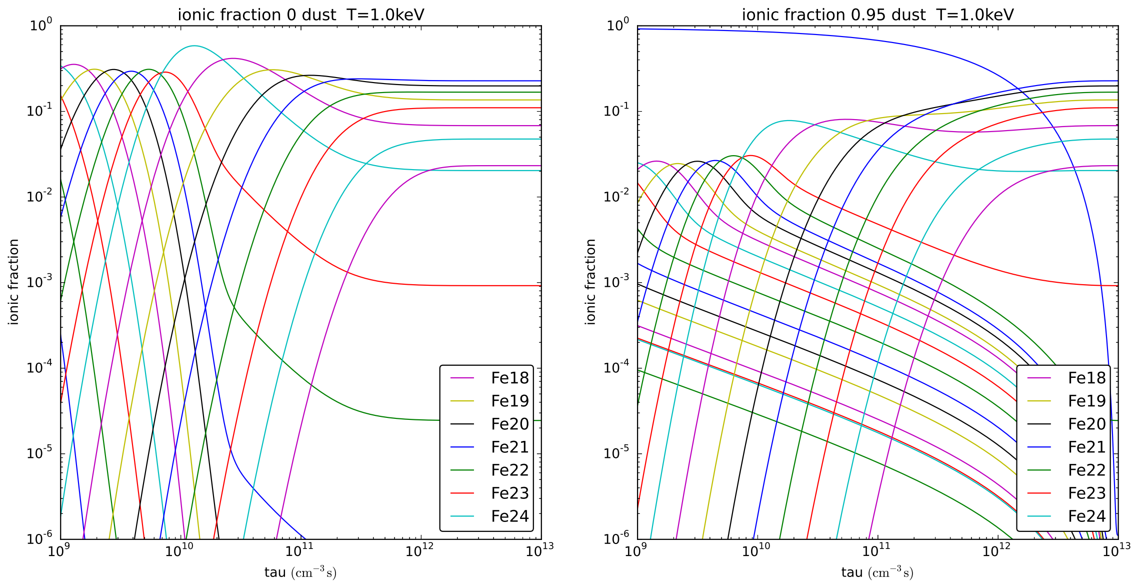


**Figure 1.** Ionic fraction varying with $\tau$ at 1 keV.

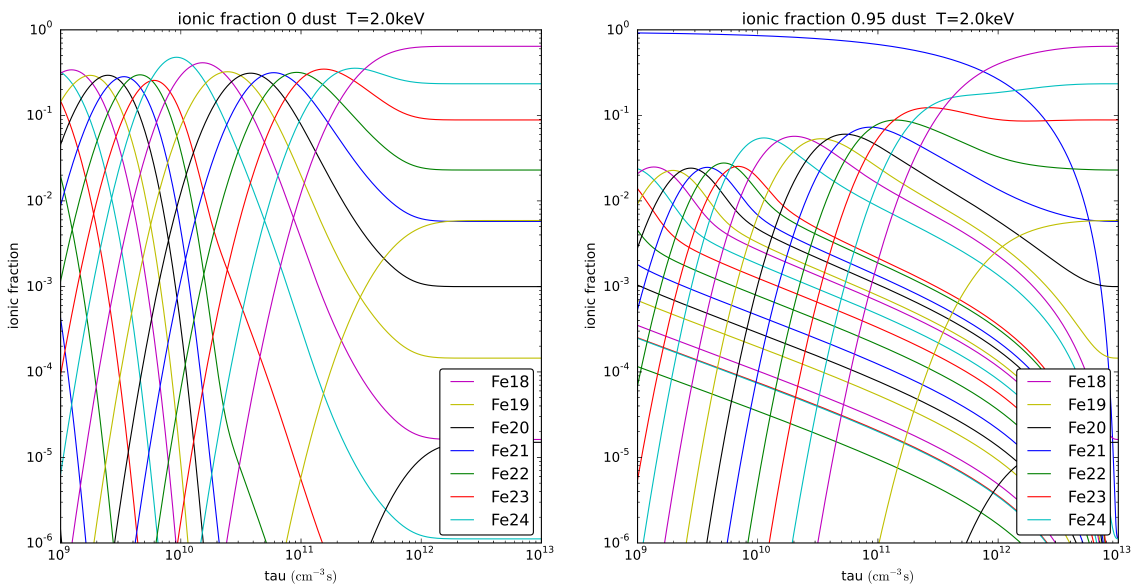


**Figure 2.**

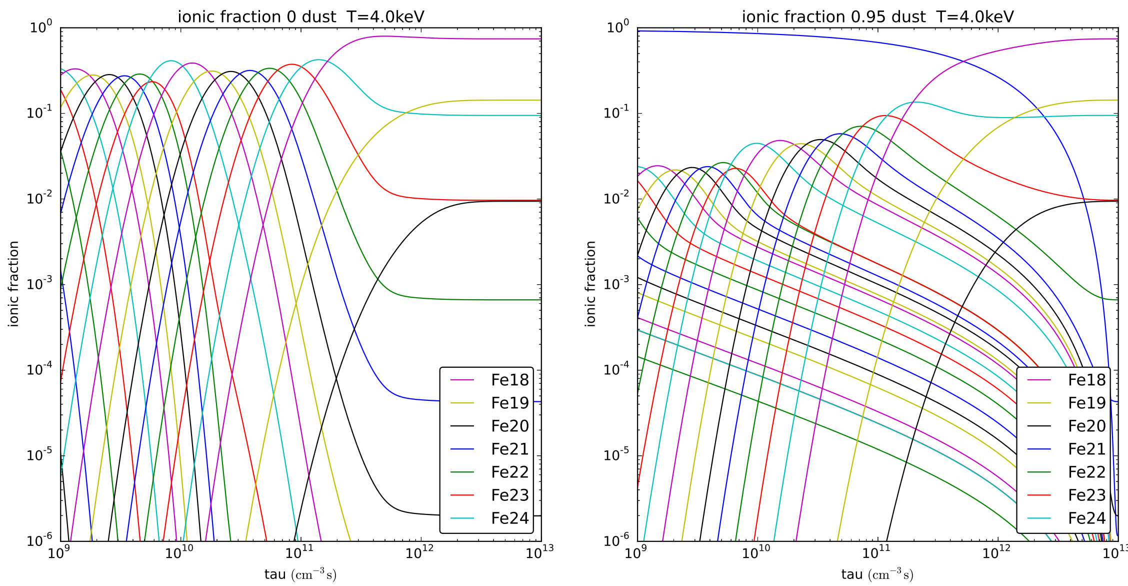


**Figure 3.**

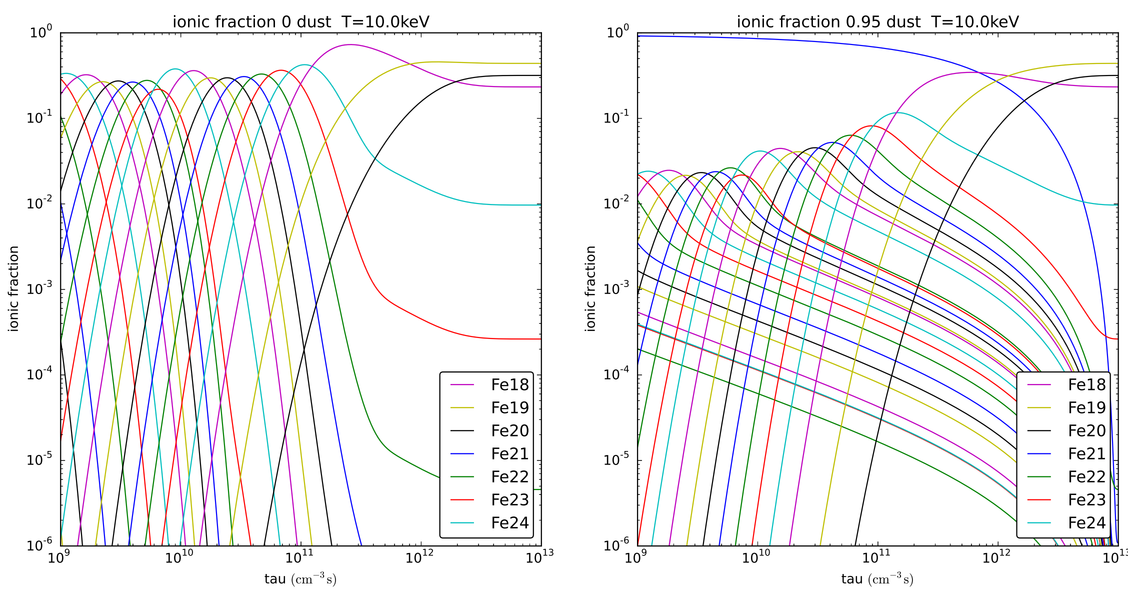


**Figure 4.**

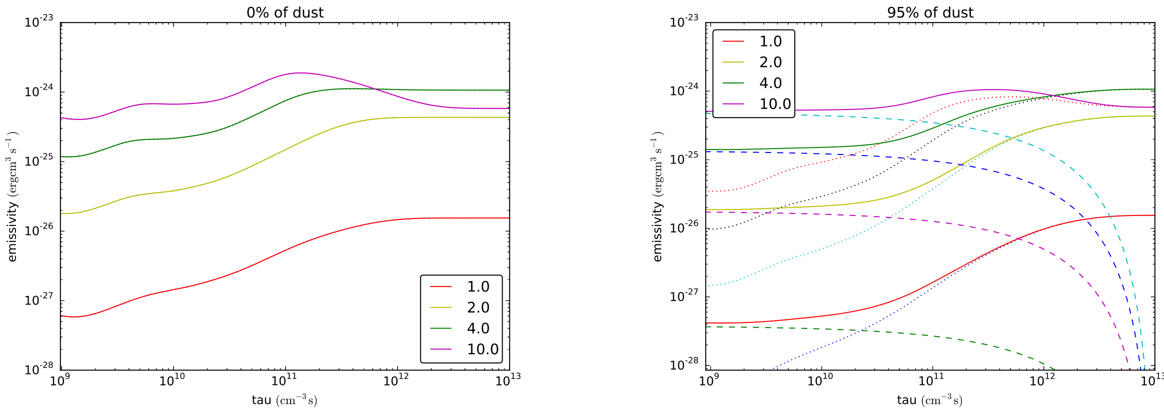


**Figure 5.**

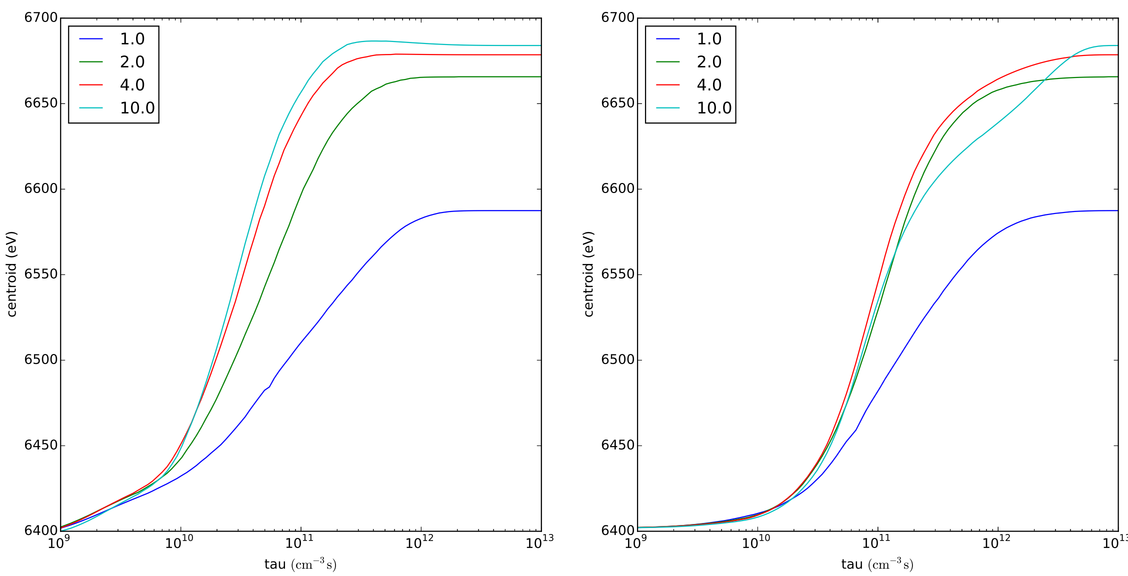


**Figure 6.** Centroid of the Fe K$\alpha$ profile varying with $\tau$. The centroids are flux-weighting average of strong lines, whose emissivity larger than 1% that of the strongest line. Left: pure-gas model. Right: dust model.

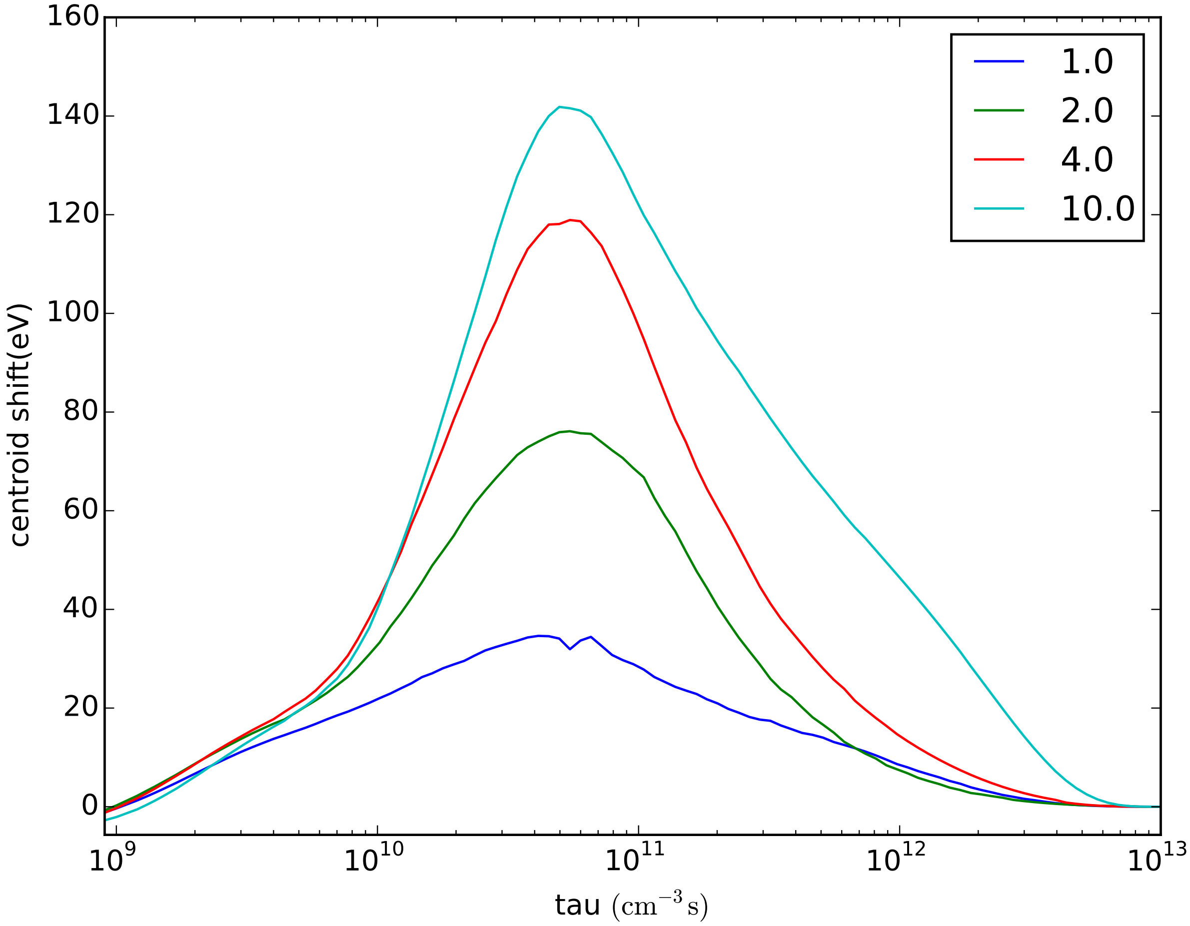


**Figure 7.** Centroid ifference between the two model.

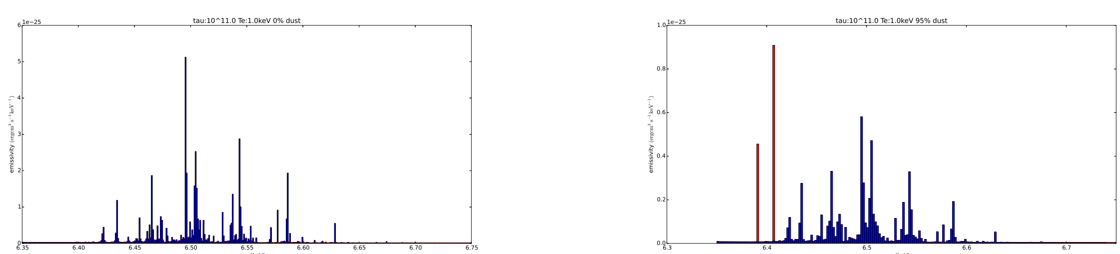


**Figure 8.** Theoretical spectra of the two model (Left: pure-gas, Right: dust) at 1 keV, $\tau = 1 \times 10^{11}$ $\mathrm{cm}^{-3}\mathrm{s}$. The dust double lines are prominent in these parameters.

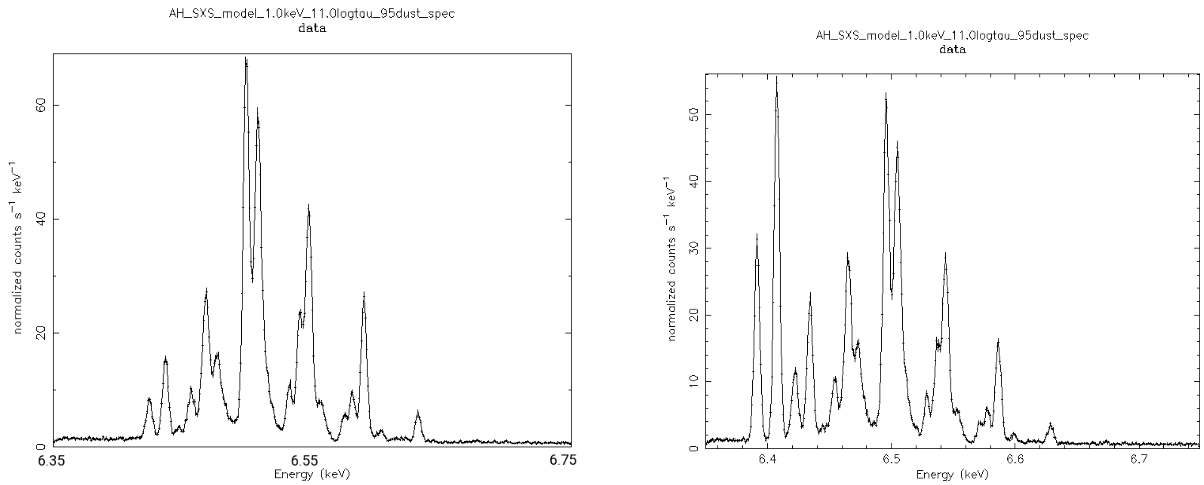


**Figure 9.** Fig. 8 after responsing by Astro-H SXS, simulated by Simx.

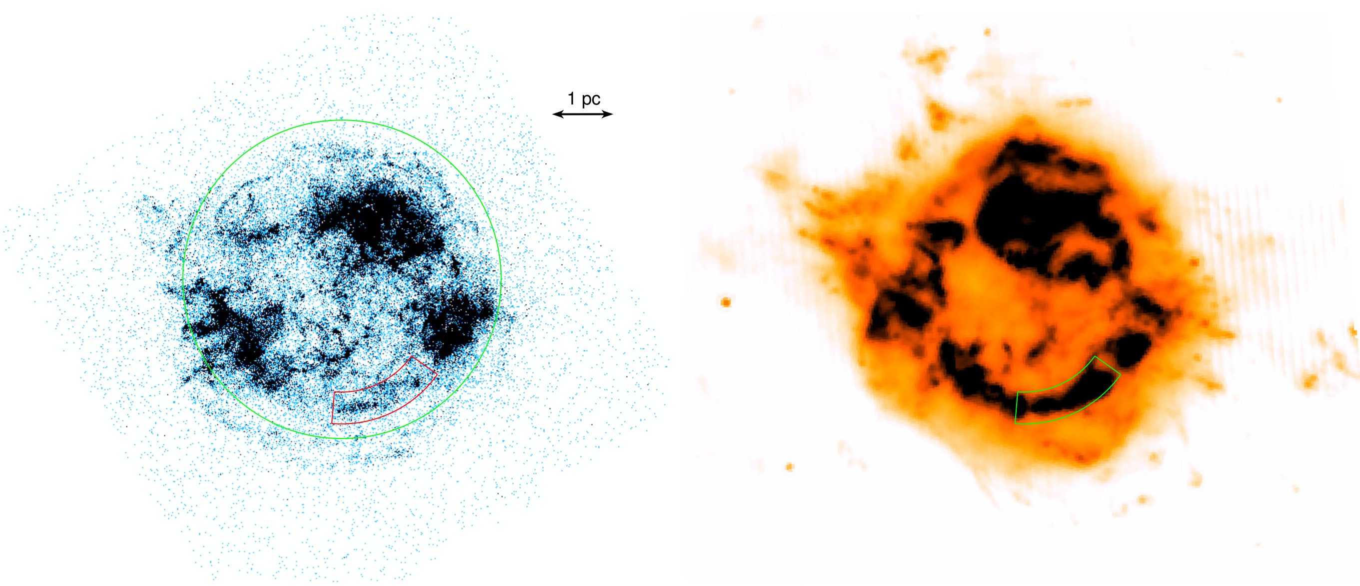


**Figure 10.** Cas A. Left: Chandra image in K $\alpha$ energy band. Right: Spizter image with $24\mu m$ (Fe II emission line) filter. The green circle is the boundary between ISM and ejecta. The spectra of the south region has K$\alpha$ line centered at $6.61 \pm 0.01$keV, which is consistent with the dust model.