A Cr-K EMISSION LINE SURVEY IN YOUNG SUPERNOVA REMNANTS WITH CHANDRA

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ABSTRACT

We performed a Cr-K emission line survey in young supernova remnants (SNRs) with the Chandra archival data. Our sample includes W49B, Cas A, Tycho, and Kepler. We confirmed the existence of the Cr line in W49B and discovered this emission line in the other three SNRs. The line center energies, equivalent widths (EWs), and fluxes of the Cr lines are given. The Cr in Cas A is in a high ionization state, while that in Tycho and Kepler is in a much lower one. We find a good positive correlation between Cr and Fe line center energies, suggesting a common origin of Cr and Fe in the nucleosynthesis, which is consistent with the theoretical predictions. We propose that the EW ratio between Cr and Fe can be used as a supplementary constraint on the progenitors’ properties and the explosion mechanism.

Key words: ISM: individual (W49B, Cas A, Tycho, Kepler) – supernova remnants

Online-only material: color figures

1. INTRODUCTION

The X-ray emission of young supernova remnants (SNRs) is predominantly from the ejecta heated by the reverse shock. Since the ejecta are metal abundant, their X-ray spectra usually show strong emission lines of heavy elements such as O, Ne, Mg, Si, S, Ar, Ca, and Fe. Many works have focused on these emission lines from young SNRs, e.g., W49B (Hwang et al. 2000b; Miceli et al. 2006), Tycho (Tsunemi et al. 1986; Hwang & Gotthelf 1997), Cas A (Tsunemi et al. 1986; Holt et al. 1994; Hughes et al. 2000; Hwang et al. 2000a), and Kepler (Hatsukade et al. 1999; Kinugasa & Tsunemi 1999; Cassam-Chenaï et al. 2004; Reynolds et al. 2007). Comparison of the abundance pattern of an SNR with the theoretical predictions could be used to constrain the properties of the corresponding supernova (SN; e.g., Hughes et al. 1995; Rakowski et al. 2006).

For a long time the K lines from heavy elements such as Ti, Cr, and Mn, which are expected to appear in 4–6 keV had not been detected in SNRs. The first and the only case, as far as we know, is the detection of the He-like lines of Cr and Mn in SNR W49B by the Advanced Satellite for Cosmology and Astrophysics (ASCA; Hwang et al. 2000b) and XMM-Newton (Miceli et al. 2006). Hwang et al. (2000b) proposed that Cr, Mn, and Ni would be the most promising heavy atomic species for future detection, since they are the most abundant elements next to Fe with K-shell emission lines at energies above ∼4 keV.

From nucleosynthesis theories (Woosley & Weaver 1994, 1995; Thielemann et al. 1996) we know that Cr is mainly formed from the decay of Fe during SN explosions. SNRs from type Ia explosions are the top candidates for the detection of Cr emission, as the progenitors are completely destroyed during the SN explosions and all material is ejected into interstellar space. The Cr line emission could also be detected in a core-collapse SNR, if there is a large fraction of Cr formed outside the mass cut. In this paper, we report a Cr line survey in the young and bright SNRs W49B, Cas A, Tycho, and Kepler using the abundant archival data collected by the Chandra X-ray observatory. We describe the observations and data analyses in Section 2. The results are given in Section 3, followed by a discussion in Section 4 and a summary in Section 5. Throughout this paper, the statistical uncertainties are given at 90% confidence level.

2. OBSERVATIONS AND DATA ANALYSES

SNRs are important observational targets for Chandra. For example, as one of the largest projects, Chandra has observed the Cas A SNR for a few times with a total exposure time of 1 Ms (Hwang et al. 2004). The Kepler SNR was also observed for 750 ks (Reynolds et al. 2007). In this paper, we collected almost all the available Chandra ACIS-S data of the four SNRs. The detailed observation information is listed in Table 1. The data were processed using the CIAO software package (version 3.4). We created new level 2 event files for all the observations we used, applying gain map, time-dependent gain, and charge transfer inefficiency corrections with the latest released calibration files (CALDB version 3.4.3 and ATOMDB version 1.3.1). The only exception is that the charge transfer inefficiency cannot be corrected for all the Cas A data since they are acquired in GRADED mode. Figure 1 shows the X-ray images of the four SNRs. Since the Cr line is very weak, we extracted the spectrum of each SNR from almost the entire source region, as illustrated in Figure 1. The background spectra were extracted from the off-source regions.

Cas A and Kepler have been observed for a few times spanning 4 to 5 months. We therefore carefully performed the analysis to eliminate the effect of any CCD performance evolution with time. Taking Cas A as an example, we first created source and background spectra as well as the corresponding RMF and ARF files for each of the nine observations (including IDs 4634, 4635, 4636, 4637, 4638, 4639, 5196, 5319, and 5320), and then combined them with FTOOLS.4 This process has taken into account the degradation of the CCD performance during the observation span. We noticed that there is no clear difference between the nine RMF files; therefore, the ARF files can be added with FTOOLS addarf. The total photon number of each source spectrum was taken as the corresponding adding weight.

4 http://heasarc.gsfc.nasa.gov/docs/software/f tools/
We performed a joint fit to the spectra of all the observations by using their respective RMF and ARF files, and found that the fitting results are consistent with those obtained by using the combined data and the added RMF and ARF. This demonstrates that the combining process works well and suggests that the gain is properly calibrated from observation to observation. The spectral fitting was done with XSPEC version 11.3.2 (Arnaud 1996).

The 0.5–8.0 keV spectra of the four SNRs are plotted in Figure 2. Apparently the spectrum of Cas A has the best statistics; therefore, we take it as an example to describe our spectral analysis process. We first fitted the continuum-dominant 4.2–6.0 keV spectrum with bremsstrahlung and power law models, respectively. In both cases, three linelike features appear in the residual distribution. In this case, we added three Gaussian components to account for these lines. The fitting models and residuals are plotted in Figure 3. The best-fit centroid energies of the three lines are 4.607, 4.878, and 5.635 keV, respectively. The power law model can represent the continuum emission better than the bremsstrahlung one, with $\chi^2 = 452.9$ versus 560.3 for 111 degrees of freedom (dof), although neither of the two fits is statistically acceptable. However, adapting different continuum models does not change the best-fit results of the line strength significantly, e.g., the equivalent width (EW) of the 5.635 keV line is 9.6 ± 0.87 eV with the power law model and 10.7 ± 0.95 eV with the bremsstrahlung. For the other three SNRs, the power law model also fits the continuum emission better than the bremsstrahlung model does. The latter model seems to overestimate the spectra at low energies, while underestimating at high energies. In this case, the power law model was used in the following fitting process to account for the continuum emission. We also note here that the 4.2–6.0 keV spectrum of Cas A is more complicated than the model we used. This will be further discussed in Section 3.2.

According to the Astrophysical Plasma Emission Code (APEC5), the two lines below 5.0 keV could be the He-like Ca-K emission, while the Ti-K emission could not be ruled out as it also emits around those energies. Unfortunately, Ti has not been considered in the currently available plasma codes, thus we cannot get the emissivities of the Ti lines to judge whether they represent these observed line features or not. Since the main topic of the current paper is Cr emission and the line candidates below 5.0 keV are beyond its scope, we only adopt the power law model for the continuum emission.
data above 5.0 keV for the analyses of the continuum and line emission. As an element of the Fe-group, Cr is closely related to Fe in its synthesis process (Woosley & Weaver 1994, 1995; Thielemann et al. 1996). A comparative study of the Fe and Cr emission should be important. Therefore we take the 5.0–7.5 keV spectra to study both the Cr and the Fe K lines in the following.

We note here that the systematic errors of the EWs and fluxes induced by using different continuum models and different energy ranges are included in the parameters’ confidence ranges.
in Tables 2 and 3. By fitting the 5.0–7.5 keV spectra of the four SNRs with bremsstrahlung to represent the continuum model, we can get the best-fit EWs and fluxes of the Cr and Fe emission lines along with their 90% statistical errors. Likewise, by fitting these spectra with the continuum energy extended down to 4.2 keV, we can also get another set of best-fit EWs, fluxes, and their confidence ranges. The final confidence ranges listed in Tables 2 and 3 cover those from the above two fittings and from fitting with a power law continuum model to the data in 5.0–7.5 keV.

3. RESULTS

3.1. W49B

In the analysis of the ASCA spectrum, Hwang et al. (2000b) found evidence of the He-like Cr and Mn lines near 5.69 and 6.18 keV, and the existence of these lines was confirmed by XMM-Newton (Miceli et al. 2006). From the spectra (Figure 2, top left and Figure 4, top left), we can see that the Cr and Mn lines are also detected with Chandra. We fitted the 5.0–7.5 keV spectrum with a power law model plus three Gaussian components to account for the continuum, Cr, Mn, and Fe lines, respectively. Eliminating the Gaussian component for Cr (or Mn) leads to an increasing of $\chi^2$ by 93.4 for dof 68 to 222.9/62 for data in 5.0–6.0 keV. This represents a significant detection of the Cr-K line emission, and its best-fit parameters are listed in Table 2 as well.

The requirement of two Gaussian components for the Fe-K complex is probably due to the Doppler shift variation across the whole remnant. Spatially resolved X-ray spectroscopy of Cas A by both XMM-Newton (Willingale et al. 2002) and Chandra (Yang et al. 2008) shows that different parts of this remnant are moving with different line of sight velocities, with typical value of $\pm 1000$ km s$^{-1}$. Considering this, we selected two regions based on the Doppler shift map from the XMM-Newton observation (Willingale et al. 2002), as illustrated in Figure 1. The spectra of the two regions are given in Figure 5. They were fitted with a power law plus two Gaussian components, representing the continuum, Cr and Fe-K line emission. The Cr line is very significant in both spectra. Adding a Gaussian component for Cr leads to the reduced $\chi^2$ decreasing from 993.8/65 to 222.9/62 for data in 5.0–6.0 keV. This represents a significant detection of the Cr-K line emission, and its best-fit parameters are listed in Table 2 as well.

3.2. Cas A

The 5.0–7.5 keV spectrum of Cas A is shown in Figure 4 (top right). It was fitted with a power law (for continuum) plus three Gaussian components (for the lines). Two Gaussian components were used to represent the Fe-K complex since it cannot be well fitted by a single Gaussian profile. The centroid energies for these two Gaussian components are 6.600 ± 0.001 keV and 6.659 ± 0.001 keV, with their widths 100 ± 2 eV and 72 ± 7 eV, respectively. The centroid energy of the Fe-K complex listed in Table 2 is the emission measured weighted mean value, while the flux and EW are the sums of the two components. The third Gaussian component is for the 5.635 keV line mentioned in Section 2. Adding the third Gaussian leads to a much better fit (see Figure 3), with the reduced $\chi^2$ decreasing from 993.8/65 to 222.9/62 for data in 5.0–6.0 keV. This represents a significant detection of the Cr-K line emission, and its best-fit parameters are listed in Table 2 as well.
complex of Cas A. The centroid energies of the Cr line in the two regions are $5.590^{+0.008}_{-0.007}$ and $5.657^{+0.010}_{-0.008}$ keV, with a separation similar to that of the two Fe-K lines. The Cr and Fe ejecta are thus probably moving with similar velocity. We noticed that the Fe-K line from a small region of Cas A also cannot be well represented by one Gaussian component (see Figure 5, residual...
Figure 6. Line center energy of Cr vs. Fe in W49B, CasA, Tycho, and Kepler. The errors of the Fe line are not plotted, since they are almost within the size of the symbols. The stars represent the line center energy of Cr and Fe in various ionization states, as given in Table 4.

(A color version of this figure is available in the online journal.)

distribution), suggesting small velocity difference even within such a scale (see Figure 7 in Willingale et al. 2002).

On the other hand, the existence of more than one strong Fe-K line that cannot be resolved with Chandra ACIS could also contribute to the broadening of the Fe-K line in Cas A. Various Fe-K lines around this energy have been clearly displayed in the spectra of the cataclysmic variables V1223 Sagittarii (Mukai et al. 2001) and U Geminorum (Szkyd et al. 2002) using data collected by the High Energy Transmission Grating onboard Chandra. The centroid energy difference of the two Gaussian components in Cas A is about 60 eV, which is comparable with the difference of the He-like triplet of Fe-K lines (∼65 eV). Higher energy resolution spectra from future missions will help us to resolve the Fe-K complex.

3.3. Tycho & Kepler

The 5.0–7.5 keV spectra of Tycho and Kepler are shown in Figure 4. We first fitted the spectrum of Tycho with a power law (for continuum emission) plus one Gaussian component (for the Fe-K line). A linelike structure came out around 5.45 keV in the residual distribution. As the neutral Cr-K line is near 5.4 keV while the H-like Cr-K line is around 5.9 keV (see Table 4), this structure might be the Cr line in relatively low ionization state. In this case, we added a Gaussian component there, and the reduced $\chi^2$ decreased from 36.6/21 to 11.4/18 in 5.0–6.0 keV. For the Kepler spectrum in the same energy range, adding a Gaussian component around 5.46 keV also leads to a reduction of the reduced $\chi^2$ from 47.6/24 to 27.8/21. Finally, the 5.0–7.5 keV spectra of Tycho and Kepler were fitted with a power law (for continuum) plus two Gaussian components (one for the Cr line and the other for the Fe line). The fitting models and residual distribution are also given in Figure 4.

The best-fit parameters for the Cr and Fe lines are listed in Table 2, along with their confidence ranges. Although there are big uncertainties in the EWs and fluxes of Cr lines in both Tycho and Kepler, the detection of these lines is significant, judging from the changes of $\chi^2$ mentioned above and the lower limits of the confidence ranges. From Table 2, we can see that the centroid energies of the putative Cr lines in Tycho and Kepler are about 200 eV lower than those of W49B and Cas A. This will be further discussed in Section 4.1.

4. DISCUSSION

4.1. The Ionization State and Spatial Correlations between Cr and Fe

The different line center energies of the Cr emission lines in these SNRs reflects that the ionization states of Cr in these SNRs are dissimilar. The Cr in W49B is in relatively high ionization state since its line center energy is $5.656^{+0.014}_{-0.016}$ keV (see Table 2). For Cas A, the centroid energy of the Cr line is $5.635^{+0.007}_{-0.005}$ keV, which also suggests a high ionization state of Cr. The center energies of the putative Cr lines in Tycho and Kepler are about 200 eV lower than those of W49B and Cas A. If these lines do come from Cr, it should be in a relatively low ionization state (see Table 4). We noticed that the Fe-K line center energies in Tycho and Kepler are both around 6.44 keV. This implies low ionization states of Fe as well, as suggested by previous observations (Tsunemi et al. 1986; Hwang et al. 1998; Hwang et al. 2002; Kinugasa & Tsunemi 1999).

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Table 4

| Element | Neutral | B-like | Be-like | Li-like | He-like | H-like |
|---------|---------|--------|---------|---------|---------|--------|
| Cr      | 5.420   | 5.533  | 5.580   | 5.657   | 5.665   | 5.916  |
| Fe      | 6.405   | 6.549  | 6.617   | 6.652   | 6.674   | 6.966  |

Notes.

- $K\alpha$ line energy.
- Line energy with transition from level 2p to 1s.
- Ly$\alpha$ line energy.
- http://www.camdb.ac.cn/e/spectra/spectra_search.asp.
- Mewe et al. (1985).

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$^a$ See Mewe et al. (1985); http://www.camdb.ac.cn/e/spectra/spectra_search.asp.
In Figure 6, we plot the Cr line center energy versus that of the Fe line in these four SNRs. The theoretical centroid energies of Cr and Fe K lines in different ionization states given in Table 4 are overplotted in the same figure. Obviously, there is a positive correlation between the two line center energies both theoretically and observationally. We can conclude from Figure 6 that the emission lines around 5.46 keV in Tycho and Kepler are from Cr. Meanwhile, the Cr in Cas A and W49B might be He/Li-like, while Ne-like or an even lower ionization state in Tycho and Kepler. Since the line center energy is closely related to the ionization ages of the emitting plasma, such a positive correlation implies that the ionization ages of Cr and Fe are closely related to each other.

The above ionization state correlation suggests that the Cr and Fe ejecta are colocated, which is also supported by the spectra of the blueshift and redshift regions in Cas A. As shown in Section 3.2, the Cr and Fe ejecta are probably moving with the same velocity as implied by the centroid energies of the Cr and Fe lines from these two regions. Meanwhile, the EW ratio of the Cr line to the Fe line in the blueshift region spectrum is 0.82%, while it is 0.91% in the redshift one. They are both consistent with the overall value (0.85±0.18%; see Table 2) within the confidence range. This is further evidence that Cr and Fe are colocated.

According to the nucleosynthesis theory (Woosley & Weaver 1994, 1995), $^{50}$Cr is generated by explosive oxygen and silicon burning, while $^{52,53}$Cr are the products of $^{52,53}$Fe decay in explosive silicon burning. The most abundant Fe is $^{56}$Fe decayed from $^{56}$Ni, which is also produced mainly from explosive silicon burning. Among all the isotopes of Cr, $^{52}$Cr is the most abundant, and its production is generally at least one order of magnitude greater than the others (Nomoto et al. 1984; Woosley et al. 1995). In this case, most of the Cr would be located near and thus share a similar ionization time with Fe in SNRs. Cayrel et al. (2004) observed a number of so-called “first stars,” i.e., very metal-poor dwarfs and giants. They found that the scatter of the Cr/Fe values of these stars is very small, indicating that the production of Fe and Cr are very closely linked. Our results are consistent with the theoretical predictions and further strengthen the previous observational statement in a different way.

### 4.2. Using the Cr to Fe EW Ratio to Constrain the SN Explosion Process

Many theoretical calculations of nucleosynthesis have included Cr for both Ia (Woosley & Weaver 1994; Iwamoto et al. 1999) and core-collapse SNe (Woosley & Weaver 1995; Thielemann et al. 1996; Maeda & Nomoto 2003). In order to compare with these models, we need the mass (or abundance) ratio between Cr and the other elements. Hwang et al. (2000b) interpolated the He/α emissivity of Cr from those of Si, S, Ar, Ca, and Fe, using the Raymond–Smith (RS) code for the 2 keV plasma in collisional ionization equilibrium (CIE), and then calculated the Cr abundance of W49B. They found that the Cr and Fe abundances are consistent with a solar ratio, corresponding to an atomic number ratio $1.0\%$ of Cr to Fe (Anders & Grevesse 1989) and thus a mass ratio $M_{\text{Cr/Fe}} \sim 0.9\%$. Cr and Fe in Tycho and Kepler are in relatively low ionization state, and as emissivities in these states are not well calculated for elements such as Si, S, Ar, Ca, and Fe. It is difficult to intergrade the Cr emissivity as done by Hwang et al. (2000b). However, according to the discussion in Section 4.1, Cr and Fe are spatially correlated and thus have similar temperatures and ionization ages, therefore the EW ratio of the Cr and Fe K lines (EW$_{\text{Cr/Fe}}$) would be a good representation of the mass ratio of these two elements. Considering this, we use the EW ratio for the discussion below.

From Table 2, we can see that EW$_{\text{Cr/Fe}}$ of these four SNRs differ from one another. This ratio might be used to constrain the properties of the corresponding SNe. Badenes et al. (2006) have made detailed comparisons of the X-ray spectra of the type Ia SNR Tycho with the theoretical models. They found that the one-dimensional delayed detonation model can well reproduce its X-ray emission. From numerical calculations, the standard SNe Ia models, i.e., carbon deflagration and Chandrasekar mass models (e.g., W7, W70 etc.; Nomoto et al. 1984) often yield relatively small $M_{\text{Cr/Fe}} (< 1\%$). Nomoto et al. 1997; Iwamoto et al. 1999). Multidimension models based on W7 also give similar $M_{\text{Cr/Fe}}$ (Travaglio et al. 2004, 2005). On the other hand, the delayed detonation models (WDD, CDD etc) produce much larger $M_{\text{Cr/Fe}} (> 2\%$), and $M_{\text{Cr/Fe}}$ decreases as the transition density increases (Nomoto et al. 1997; Iwamoto et al. 1999). Therefore, our observational results of Tycho suggest that there should be a deflagration-detonation transition at some stage of Tycho’s SN explosion, which further confirm the results of Badenes et al. (2006). Meanwhile, we favor a relatively small transition density, probably 1.7 × 10$^7$ g cm$^{-3}$ (Nomoto et al. 1997; Iwamoto et al. 1999). This is also consistent with that suggested by Badenes et al. (2006, 2.2 × 10$^7$ g cm$^{-3}$).

Cas A has been identified as the remnant of a core-collapse SN. The recent study of its progenitor implies the mass to be 15–25 $M_\odot$ (Young et al. 2006). According to the calculations of spherical models by Thielemann et al. (1996), a 20 $M_\odot$ progenitor gives a $M_{\text{Cr/Fe}}$ of 1.2%, which is higher than our measured value. However the nonspherical explosion may lead to a smaller $M_{\text{Cr/Fe}}$ (Maeda & Nomoto 2003). It has already been suggested that the explosion of Cas A is asymmetric, based on the jet structure (Hwang et al. 2004) and the Doppler map (Willingale et al. 2002). Meanwhile, a bigger progenitor mass would lead to a smaller mass cut and thus smaller $M_{\text{Cr/Fe}}$, since Cr is mainly produced in the incomplete Si-burning zone (Umeda & Nomoto 2002). Therefore, we support a higher progenitor mass (Young et al. 2006) and the asymmetric explosion scenario for Cas A.

The classifications of W49B and Kepler are not conclusive. For W49B, Hwang et al. (2000b) compared the relative abundances of Mg, S, Ar, Ca, Fe, and Ni to Si, and suggested that W49B may have a type Ia progenitor. However, they claimed that a low mass (13–15 $M_\odot$) type II progenitor is also possible. The Chandra image of W49B shows a bipolar jet, which was taken as evidence for a gamma-ray burst (GRB) remnant.\(^7\) This was further supported by multiband observations (Keohane et al. 2007). The nucleosynthesis calculation for bipolar core-collapse SN explosions (Maeda & Nomoto 2003) generally predicts an EW$_{\text{Cr/Fe}}$ of 1.0 ± 0.5%, which matches the observations perfectly (Hwang et al. 2000b; Miceli et al. 2006; this paper). Kepler tends to be identified as a type Ia SNR (Reynolds et al. 2004). If so, the small EW$_{\text{Cr/Fe}}$ would favor the carbon deflagration models (W7, W70 etc) rather than those involving detonation (Nomoto et al. 1997; Iwamoto et al. 1999; Travaglio et al. 2004, 2005).

The above discussions are based on the overall mass ratio of Cr to Fe in an SNR. It is possible that in these SNRs there is still a fraction of Fe and Cr that has not been overtaken by the reverse shock and so is invisible in X-rays. However, according to our discussion in Section 4.1, Cr and Fe should be well mixed, so

\(^7\) http://chandra.harvard.edu/press/04_releases/press_060204.html
the observed EW ratio of Cr to Fe could represent the overall Cr to Fe mass properly. Therefore the main conclusions are reliable no matter what fraction of Fe is observed.

5. SUMMARY

We performed a Cr-K line survey with the Chandra data in young SNRs W49B, Cas A, Tycho, and W49B. We confirmed the Cr line in W49B, and gave a consistent flux and line center energy with respect to the previous results. Then we report, for the first time, the detection of Cr lines in Cas A, Tycho, and Kepler. We conclude that Cr in Cas A is in a high ionization state similar to that of W49B, while Cr is in a low ionization state low in Tycho and Kepler. We find that Cr and Fe have similar ionization states and are colocated in these four SNRs. The reason might be that Cr and Fe are synthesized by the same process deep inside the progenitor. We propose that the EW ratio of Cr to Fe might be used as an supplementary constraint on the properties of the SN explosions. For the type Ia SNR Tycho, EW\textsubscript{Cr}/EW\textsubscript{Fe} favors the delayed detonation model with relatively small transition density ($1.7 \times 10^7$ g cm$^{-3}$) from deflagration to detonation. This is consistent with the model suggested by Badenes et al. (2006) from the comparison of Tycho’s X-ray spectra with theoretical calculations. The relatively small EW\textsubscript{Cr}/EW\textsubscript{Fe} in Cas A and W49B suggests their asymmetric explosions, which is also consistent with the previous results. If we adopt the type Ia origin for Kepler, its small EW\textsubscript{Cr}/EW\textsubscript{Fe} could be attributed to the carbon deflagration explosion.

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