Fe K lines in the nuclear region of M82

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ABSTRACT

We study the spatial distribution of the Fe 6.4 and 6.7 keV lines in the nuclear region of M82 using the Chandra archival data with a total exposure time of 500 ks. The deep exposure provides a significant detection of the Fe 6.4 keV line. Both the Fe 6.4 and 6.7 keV lines are diffuse emissions with similar spatial extent, but their morphology do not exactly follow each other. Assuming a thermal collisional-ionization-equilibrium (CIE) model, the fitted temperatures are around 5–6 keV and the Fe abundances are about 0.4–0.6 solar value. We also report the spectrum of a point source, which shows a strong Fe 6.7 keV line and is likely a supernova remnant or a superbubble. The fitted Fe abundance of the point source is 1.7 solar value. It implies that part of the iron may be depleted from the X-ray emitting gases as the predicted Fe abundance is about 5 times solar value if assuming a complete mixing. If this is a representative case of the Fe enrichment, a mild mass-loading of a factor of 3 will make the Fe abundance of the point source in agreement with that of the hot gas, which then implies that most of the hard X-ray continuum (2–8 keV) of M82 has a thermal origin. In addition, the Fe 6.4 keV line is consistent with the fluorescence emission irradiated by the hard photons from nuclear point sources.

Key words: atomic processes – plasmas – galaxies: individual: M82 – galaxies: starburst – X-rays: ISM.

1 INTRODUCTION

Galactic-scale outflows (superwinds), driven by stellar winds from massive stars and core-collapse supernovae (SN) from active star-forming galaxies, represent an important feedback process of galaxy evolution (e.g. Lehnert & Heckman 1995; Veilleux, Cecil & Bland-Hawthorn 2005). Their mechanical and thermal energies regulate further star formation and modify the shape of the galaxy luminosity function (e.g. Benson et al. 2003). The superwinds will eject metals and enrich halo gases and intergalactic medium (e.g. Songaila 1997; Pettini et al. 2001; Tumlinson et al. 2011). However, due to its high temperature, low density and especially the contamination of dense point sources residing in the star-forming region, the hot plasma driving superwinds is hard to observe.

The prototype starburst galaxy M82 (located at 3.6 Mpc), with a powerful superwind detected on scales up to 10 kpc, is an ideal target to study the driving plasma of superwinds. With the sub-arcsec spatial resolution of Chandra, Griffiths et al. (2000) detected diffuse hard X-ray emission in the nuclear region of M82. They also detected an emission line around 5.9–6.9 keV, which is likely due to the Fe line at 6.7 keV. This is expected in the scenario of superwinds (Chevalier & Clegg 1985), which predicts a metal-enriched hot plasma at temperatures of $10^7$–$10^8$ K. The corresponding Fe abundance is about 0.3 solar abundance if assuming a thermal spectrum. Strickland & Heckman (2007) examined and discussed Fe lines of M82 in detail. They found that the Fe 6.7 keV line luminosity is consistent with that expected from the enrichment of previous SN ejecta. They also reported a marginal detection of the Fe 6.4 keV line, which is a fluorescent line of the neutral-like Fe.

The Fe 6.7 keV line is important to understand the driving plasma of superwinds. It is the most prominent emission line at such high temperatures, and thus the best tracer of the metal enrichment. If all the Fe produced by massive stars are mixed in the hot plasma, the expected Fe abundance will be around five times solar abundance, in contrast to the observed 0.3 times solar abundance (Strickland & Heckman 2007). It then implies there is other contribution to the diffuse continuum, in addition to the thermal continuum, or part of the Fe is depleted from the X-ray emitting gases.

In previous studies, the nuclear region of M82 is taken as a whole and no spatial analysis has been done due to the limited statistics (the total exposure is less than 50 ks). In this Letter, we present a detailed spatial study of the Fe 6.7 keV line of M82 with 500 ks of Chandra archival data, which is a factor of 10 longer than that used in previous studies. The deep data allow a significant detection of the Fe 6.4 keV line, which is informative to study the coexistence of cold molecular and hot gases. We also report a point source showing the Fe 6.7 keV line, which provides strong implications for the mixing level of Fe produced by massive stars.
This Letter is structured as follows. We describe the data reduction in Section 2 and the analysis results in Section 3. The implications of the results are discussed in Section 4. The errors quoted are for the 90 per cent confidence level throughout this Letter.

2 OBSERVATION DATA

We use eight archival Chandra observations (ObsID 5644 by PI T. Strohmayer and the others by PI D. Strickland) listed in Table 1, all of which are observed with ACIS-S3. After removing the period of flares, the effective exposure time is about 500 ks, which allows a detailed spatial study of Fe lines. The data reduction is performed using the CIAO software (version 4.5).

The nuclear region of M82 is divided into six box regions with the same size (12 arcsec × 10 arcsec each) based on the photon count rate between 3.3 and 7.5 keV as illustrated in Fig. 1. The adjacent line between regions 1, 2, 3 and regions 4, 5, 6 is along the major axis of the stellar disc of M82. The excellent angular resolution of Chandra can help to resolve bright point sources, which are the key contamination for studies of the diffuse emission. The point sources are detected using the tool wavdetect in CIAO with an encircled psf fraction of 90 per cent and a size parameter ellisigma of 3. Because the nominal pointing direction is different for different observations, the source detection has been done separately. As a demonstration, Fig. 1 shows the excluded point sources marked with ellipses for ObsID 10542. The typical radii are around 1.5 arcsec–2 arcsec. For the central two bright sources, their radii are enlarged by a factor of 2 to minimize their contamination.

For an extended source like M82, it is generally hard to find emission-free regions to do the background subtraction. We use the blank-sky data sets produced by the ACIS calibration team to estimate the background, which is extracted from the same CCD region for the given box.

3 ANALYSIS RESULTS

3.1 Diffuse emission

The background-subtracted spectrum, combined from all eight observations for each region, is plotted in Fig. 2. The Fe 6.4 and 6.7 keV lines are clearly seen in most regions. We find the nuclear spectra of M82 within 0.5–7.5 keV can be fitted with two thermal collisional-ionization-equilibrium (CIE) models with temperatures around 0.65 and 5–6 keV, respectively. The contribution of the low-temperature component is about 5 per cent around 3–4 keV and negligible for higher energies. Thus, for the purpose of the study of the Fe 6.4 and 6.7 keV lines, we limit the fitting energy range to 3.3–7.5 keV and apply only one thermal CIE model (VAPEC; Foster et al. 2012) plus a Gaussian line to fit the spectrum. As the Fe lines are the only strong lines in the fitting range, we only fit the Fe abundance in the VAPEC model, and the abundances of other elements are fixed to solar values (Lodders 2003). The Gaussian line is centred at 6.4 keV and its linewidth is set to a minimum of 10−6 keV, as it cannot be reliably measured due to the limited instrument resolution. To avoid the contamination of the emission lines of Ar XVII, the energy range between 3.8 and 4.0 keV is also ignored. The data are binned to have a minimum count of 25. The spectral analysis is done with the ISIS package (Houck & Denicola 2000), which calls the XSPEC models (Arnaud 1996).

The fitting results are plotted in Fig. 2 and listed in Table 2. From Fig. 2, we see that the CIE model plus a Gaussian line generally provides a reasonable fit to the observed spectra. The fitted temperatures are around 5–6 keV, except for region 6, which may be contaminated by the brightest point source of M82. The fitted Fe abundances are around 0.4–0.6 times solar value. To measure the intensity of Fe 6.7 keV line, we refit the spectra using a power-law model plus two Gaussian lines centred at 6.4 and 6.7 keV, respectively. The fitting results are also listed in Table 2. The fitted power-law indices are around 2. The goodness of the fit for the power-law model is similar to that for the CIE model. The 6.7 keV line is generally stronger than the 6.4 keV line.

In the fitting above, we have neglected the contribution from the unresolved X-ray point sources. Grimm, Gilfanov & Sunyaev (2003) found that the differential luminosity function of the X-ray point sources in star-forming galaxies follows the form of \( N(L_{\text{xy}}) = 3.3 L_{\text{xy}}^{-1.6} \). SFR, where \( L_{\text{xy}} \) is the 2–10 keV X-ray luminosity in units of \( 10^{38} \) erg s−1 and SFR is the star formation rate measured in units of \( M_\odot \) yr−1. The luminosity of the faintest source in the analysed regions is about \( 4 \times 10^{37} \) erg s−1 in 3.3–7.5 keV, which corresponds to \( 10^{38} \) erg s−1 in 2–10 keV for a power-law model with a photon index of 1.8. The adopted SFR of M82 in Grimm et al. (2003) is 3.6 \( M_\odot \) yr−1 based on the Hz flux of the entire galaxy. Assuming that half of the X-ray point sources are located at the analysed regions (a fraction estimated from the detected point sources), for unresolved sources between \( 5 \times 10^{37} \) erg s−1 (the lower limit of the Fe K lines in the nuclear region of M82

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Figure 2. Background-subtracted spectra of six box regions combined for all eight observations. The fitting results of the CIE model plus a Gaussian line centred at 6.4 keV are plotted as solid histograms. The fitted Fe 6.4 keV line is indicated as dotted line separately. $\chi$ is the difference between data and model divided by the error.

3.2 Point sources

We extract the spectra from all individual point sources detected in the nuclear region of M82 and find two sources showing the Fe 6.7 keV line, but none showing the Fe 6.4 keV line. One source only appears in the 2010 exposures (ObsID 10545 and 11800) and because its statistics is too low to provide a reliable analysis, it is discarded here. The other one is indicated by the letter ‘A’ in Fig. 1. It is spatially correlated with the radio source 44.0+59.6 detected by Huang et al. (1994) and is possibly a supernova remnant (SNR) or a superbubble produced by several SNRs.

The spectrum of source A is plotted in Fig. 3, for which a background extracted from the dashed panda region illustrated in Fig. 1 is subtracted. We also fit the spectrum of source A with a CIE model. The fitting result is listed at the bottom row of Table 2. The fitted temperature is 5.8 keV, similar to that measured in the diffuse regions. It corresponds to a shock velocity about 2000 km s$^{-1}$ (e.g. Vink 2012). The flux of source A between 2 and 8 keV is...
Table 2. Spectral fitting results.

| Region | $kT$ (keV) | $Z_{Fe}$ | Norm | $\chi^2_{\nu}$ | $\Gamma$ | Norm | $\chi^2_{\nu}$ | $\chi^2_{\nu}$ |
|--------|------------|---------|------|----------------|--------|------|----------------|----------------|
| 1      | 5.2 ± 2.0  | 0.40 ± 0.15 | 2.9 ± 0.3 | 4.2 ± 2.0 | 0.85 | 2.2 ± 0.2 | 1.5 ± 0.4 | 4.0 ± 0.4 | 6.7 ± 2.5 | 0.85 |
| 2      | 6.3 ± 1.1  | 0.57 ± 0.14 | 4.6 ± 0.4 | 6.4 ± 2.6 | 0.75 | 2.0 ± 0.2 | 2.0 ± 0.5 | 6.0 ± 0.7 | 13.5 ± 3.4 | 0.77 |
| 3      | 6.4 ± 1.3  | 0.37 ± 0.13 | 3.4 ± 0.3 | 3.4 ± 2.2 | 0.82 | 2.0 ± 0.2 | 1.5 ± 0.4 | 3.1 ± 2.2 | 7.1 ± 2.7 | 0.80 |
| 4      | 4.1 ± 0.9  | 0.52 ± 0.18 | 2.0 ± 0.3 | 0.10 ± 0.4 | 1.18 | 2.5 ± 0.2 | 1.7 ± 0.6 | 0.3 ± 0.7 | 7.2 ± 2.4 | 1.09 |
| 5      | 5.4 ± 0.8  | 0.53 ± 0.13 | 4.4 ± 0.3 | 4.8 ± 2.3 | 1.01 | 2.2 ± 0.2 | 2.3 ± 0.6 | 4.6 ± 2.3 | 12.7 ± 3.3 | 0.97 |
| 6      | 10.4 ± 1.7 | 0.50 ± 0.33 | 2.1 ± 0.2 | 2.4 ± 2.0 | 0.93 | 1.8 ± 0.2 | 0.7 ± 0.2 | 2.3 ± 1.9 | 3.0 ± 2.2 | 0.97 |
| A      | 5.8 ± 2.0  | 1.72 ± 0.65 | 0.9 ± 0.1 | –     | 1.08 | –     | –     | –     | –     | –    |

Note. $kT$ is in units of keV; the Fe abundance $Z_{Fe}$ is relative to the solar value; the line intensity is in units of $10^{-7}$ photons cm$^{-2}$ s$^{-1}$; $\chi^2_{\nu}$ = 1.09 is the photon index of the power-law model.

1.4 × 10$^{38}$ erg s$^{-1}$. The fitted Fe abundance is 1.7 times solar value, which is about three times that of the diffuse regions. Its implications are discussed in Section 4.

3.3 Imaging analysis

To further illustrate the spatial distribution of the Fe 6.4 and 6.7 keV lines, we plot the flux map of photons within 6.25–6.55 keV and 6.55–6.85 keV in Fig. 4. We see that both emissions have diffuse morphology and similar spatial extent. The 6.55–6.85 keV map is slightly more extended along the minor axis of the disc than the 6.25–6.55 keV map. It is also clear that the two maps do not exactly follow each other and some regions with high 6.25–6.55 keV flux show less 6.55–6.85 keV flux.

4 DISCUSSION AND CONCLUSION

We conduct a spatial study of the Fe 6.4 and 6.7 keV lines in the nuclear region of M82. The Fe 6.4 keV line is clearly detected with the deep data sets. The emission of both lines have similar spatial extent, but their morphology do not exactly follow each other. The total luminosity of the Fe 6.7 keV line is about 1 × 10$^{38}$ erg s$^{-1}$, which is consistent with the value measured by Strickland & Heckman (2007). The total luminosity of the Fe 6.4 keV line is about 4 × 10$^{37}$ erg s$^{-1}$.

The spectra can be fitted well with a CIE model plus a Gaussian line over the energy range of 3.3–7.5 keV. The fitted temperatures are around 4–6 keV, which are consistent with the scenario of superwinds (Chevalier & Clegg 1985). The fitted Fe abundances are around 0.5 solar value. Strickland & Heckman (2007) calculated the Fe abundance produced by SN ejecta and stellar winds using STARBURST99 and found five times solar abundances. However, the iron may not be well mixed with the hot plasma. The spectrum of the point source A provides an Fe abundance of 1.7 times solar value. Although source A cannot be the population of SNRs that are responsible for the present hot gas, if it represents a typical case, then the iron may be depleted heavily. A mild mass-loading of a factor of 3 will make the Fe abundance of source A in agreement with that of the hot gas.

As discussed by Strickland & Heckman (2007), the inverse Compton spectrum will have a photon index around 1.3 if the electron population is also responsible for the synchrotron radiation. This index is different from our fitting results of the power-law models, which have photon indices around 2. The contribution of a power-law model of index of 1.3 cannot exceed 50 per cent, otherwise it will produce more flux than observed at energies above 7 keV. Adding a power-law model of index of 1.3 to the fit will lower the fitted temperatures. If we require the fitted temperatures to be above 4 keV, the contribution of the inverse Compton emission cannot exceed 30 per cent. This is consistent with the contribution fraction of 25 per cent estimated by Strickland & Heckman (2007). Including both the contributions of unresolved point sources and inverse Compton emission will increase the Fe abundances to 0.7–0.9 solar value, still far below the expected value if there is no depletion of Fe.

We have assumed thermal CIE models when fitting the Fe abundances in Section 3. The ion at the charge state $i$ approaches to ionization equilibrium on a time-scale of $t \sim n_e(C_i + \alpha_i)^{-1}$, where $n_e$ is the electron density, $C_i$ is the collisional ionization rate and $\alpha_i$ is the recombinaton rate out of the charge state $i$ (Liedahl 1999). For a temperature of 6 × 10$^4$ K, $t \sim 1.5 \times 10^{16}$ yr cm$^{-3}$ for the ion of Fe$^{4+}$. The electron density can be estimated from the normalization of the VAPEC model, which is $n_{e,\text{VAPEC}} = \frac{\epsilon_{\text{VAPEC}}}{4\pi D^2} \int n_e n_H dV$, where $D$ (in units of cm) is the distance to M82, $n_e$ and $n_H$ are the electron and hydrogen densities in units of cm$^{-3}$. We adopt a depth of 0.6 kpc, which is the disc spatial extent of the X-ray emitting region of M82. Assuming a filling factor of 1 and $n_{H} = 0.8 n_e$, the electron density $n_e \sim 0.35$ cm$^{-3}$ for the hot gas in the nuclear region of M82. This gives an ionization equilibrium time-scale of 4 × 10$^4$ yr. It is relatively short compared with the typical time-scale (~10$^6$ yr) in the starburst region and the outflow time-scale (~5 × 10$^6$ yr) of the nuclear region of M82. It suggests that non-equilibrium ionization

Figure 3. Background-subtracted spectrum of the point source A (see Fig. 1) that shows the Fe 6.7 keV line. The fitted thermal CIE model is plotted as the solid histogram.
is unlikely to be important for the Fe 6.7 keV line of M82. When applying a non-equilibrium ionization model (VNEI), we find no improvement in the fits, and it provides a little higher temperature (7–8 keV) and a lower Fe abundance.

The Fe 6.4 keV line is the fluorescent line of neutral-like Fe. It has also been observed in another starburst galaxy of NGC 253 (Mitsuishi, Yamasaki & Takei 2011). They attributed the 6.4 keV line to the irradiation of molecular gas by surrounding point sources. A similar mechanism is applicable for M82, the nuclear region of which contains plenty of cold molecular gases (e.g. Weiß et al. 2001).

The luminosity of all nuclear point sources within 7–8 keV is about $5 \times 10^{39}$ erg s$^{-1}$, which is about 15 times the 7–8 keV luminosity of the diffuse emission and 100 times the luminosity of the Fe 6.4 keV line. The H$_2$ column densities in the nuclear region of M82 are measured to be around $5 \times 10^{22}$ cm$^{-2}$ (Weiß et al. 2001). Assuming a solar Fe abundance ($3 \times 10^{-5}$, relative to the number of H$_2$), the absorption optical depth of the neutral Fe is about 0.1 at 7 keV given an absorption cross-section of $4 \times 10^{-20}$ cm$^2$ (Veigele 1973). Taking into account the fluorescence yield of the neutral Fe K line of 0.34 (e.g. Kallman et al. 2004), the observed Fe 6.4 keV line luminosity ($4 \times 10^{37}$ erg s$^{-1}$) is consistent with the irradiation by the hard X-ray photons from nuclear point sources.

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