The intrinsic line width of the Fe Kα line of AGN

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ABSTRACT

X-ray fluorescent lines are unique features of the reflection spectrum of the cold torus when irradiated by the central AGN. Their intrinsic line widths can be used to probe the line-emitting region. The line widths of the Fe Kα line measured from the first order Chandra High Energy Grating (HEG) spectra are 3–5 times larger than those measured with the Si Kα line for Circinus, Mrk 3, and NGC 1068. Because the observed Si Kα and Fe Kα lines are not necessarily coming from the same physical region, it is uncertain whether the line widths of the Fe Kα line are over-estimated or not. We measured the intrinsic line widths of the Fe Kα line of several nearby bright AGN using the second and third order Chandra HEG spectra, whose spectral resolutions are better than the first order data. We found the measured widths are all smaller than those from the first order data. The results clearly show that the widths of the Fe Kα line measured from the first order HEG data are over-estimated. It indicates that the Fe Kα lines of the studied sources are originating from regions around the cold dusty torus.

Key words: atomic processes – galaxies: Seyfert – galaxies: individual: (Circinus, Mrk 3, NGC 1068, NGC 3783, NGC 4151, NGC 4388, NGC 4507) – X-rays: galaxies

1 INTRODUCTION

The cold dusty gas around active galactic nuclei (AGN) obscures and reprocesses the intrinsic radiation of AGN and is the key ingredient of understanding different types of AGN (e.g. Antonucci 1993). The obscuring gas emits fluorescent lines when irradiated by the central AGN. The most prominent one is the Fe Kα line at 6.4 keV, which is found to be ubiquitous in all types of AGN (e.g. Nandra & Pounds 1994; Shu et al. 2010; Fukazawa et al. 2011). As a result, the fluorescent Fe Kα line can be used to probe the properties of the obscuring gas. For example, the stability of the Fe Kα line of most AGN indicates that the obscuring gas should be outside the broad line region (BLR) (e.g. Bianchi 2012). The exact emitting region of the fluorescent line can be inferred from the intrinsic width of the Fe Kα line (e.g. Shu et al., 2011, and reference therein).

The measurement of the intrinsic line width, however, is limited by the spectral resolution of currently available instruments. The first order data of Chandra High Energy Transmission Grating Spectrometer (HETGS, Canizares et al. 2005) provide a spectral resolution of 0.012 Å (full width half maximum, FWHM) with its High Energy Grating (HEG), which at 6.4 keV corresponds to ~1860 km s⁻¹, very close to the measured mean FWHM of the Fe Kα line (2000 km s⁻¹) by Shu et al. (2011).

Because the HEG spectral resolution is higher at lower energies, the measurement of the line width can be improved by using other low-energy fluorescent lines. In a recent paper (Liu 2016), we measured the FWHM of the Si Kα line (at 1.74 keV) for Circinus, Mrk 3, and NGC 1068, which are 570 ± 240, 730 ± 320, and 320 ± 280 km s⁻¹, respectively. These values are 3–5 times smaller than those measured from the Fe Kα line previously, and the estimated line-emitting regions are outside the dust sublimation radii of these AGN. It indicates that the intrinsic widths of the Fe Kα line are likely to be over-estimated. Nevertheless, because the Si Kα line is much more sensitive to absorption than the Fe Kα line, the Si Kα line may not come from the same physical region as the Fe Kα line. This makes the estimation of the emitting region of the Fe Kα line still uncertain.

In principle, the uncertainty of the Fe Kα emitting region can be solved by spectroscopic observations with resolution higher than the first order HEG data. We noted that the second and third order Chandra HEG data have a resolution approximately 2 and 3 times better than the first order data, but with a less effective area (Canizares et al. 2005). We checked the second and third order Chandra HEG data of Circinus, Mrk 3, and NGC 1068, and found that indeed, the higher order HEG data provide more stringent constraints on the intrinsic widths of the Fe Kα line than the first order data. In this letter we present these measurements. Besides Circinus, Mrk 3, and NGC 1068, we also include NGC 3783, NGC 4151, NGC 4388, and NGC 4515, the higher order HEG data of which are deep enough to provide a meaningful measurement of the intrinsic width of the Fe Kα line. The errors quoted are for 90% confidence level.

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Table 1. The line widths of the Fe Kα line measured from the second and third order Chandra HEG data and the first order data

| Name        | $\sigma(\pm 2, \pm 3)$ eV | $\sigma(\pm 1)$ eV | $\text{FWHM}(\pm 2, \pm 3)$ km s$^{-1}$ | $\text{FWHM}(\text{Si K}\alpha)$ km s$^{-1}$ |
|-------------|---------------------------|-------------------|----------------------------------------|----------------------------------------|
| Circinus    | 6.2 ± 1.4                 | 9.8 ± 0.9         | 680 ± 150                              | 570 ± 240                              |
| NGC 4151    | 11.4 ± 6.9                | 18.6 ± 2.9        | 1260 ± 760                             | 610 ± 240                              |
| NGC 3783    | 11.3 ± 5.2                | 14.9 ± 3.0        | 1250 ± 570                             | -                                      |
| Mrk 3       | 4.9 ± 0.3                 | 19.0 ± 3.9        | 540 ± 570                              | 730 ± 320                              |
| NGC 1068    | 7.1 ± 0.9                 | 18.0 ± 4.1        | 780 ± 570                              | 320 ± 280                              |
| NGC 4388    | 10.0 ± 0.9                | 13.0 ± 7.5        | 1100 ± 570                             | -                                      |
| NGC 4507    | 11.9 ± 0.9                | 14.6 ± 7.0        | 1310 ± 570                             | -                                      |

Note: For Circinus, NGC 4151, and NGC 3783, the second and third order Chandra HEG data are deep enough to allow the $\chi^2$ statistic, while for other sources, the Cash statistic is used. The $\chi^2$ statistic is used for the first order data of all sources. The FWHM of the Si Kα line is quoted from Liu (2011), except for that of NGC 4151, which is measured in this paper, while for NGC 3783, NGC 4388 and NGC 4507, the Si Kα line is too weak to provide meaningful constraints.

2 OBSERVATIONAL DATA

Because the Chandra HEG effective areas of the second and third order are about 15 times less than that of the first order (Canizares et al. 2005), only for nearby bright sources with deep exposures, the higher order HEG data can be used to measure the intrinsic width of the Fe Kα line. We searched Chandra Transmission Grating Data Archive and Catalog (TGCat, Huenemoerder et al. 2011), and found that besides Circinus, Mrk 3, and NGC 1068, the second and third order HEG data of NGC 3783, NGC 4151, NGC 4388, and NGC 4151 are also usable. Among them, NGC 3783 and NGC 4151 are classified as type 1.5 AGN, while the others are type 2 AGN. All the spectra are extracted from a region with a 2 arcsec half-width in the cross-dispersion direction. The instrumental responses are extracted using TGCat software with the calibration database (CALDB) 4.6.8. The HEG data from ±2 and ±3 orders are combined together. The continua around the Fe Kα line of NGC 4151 of different observations show variations with a factor of 5, and only the low-state observations are used. The continuum variations of NGC 3783 between different observations are within a factor of 2, and to improve the signal-to-noise (S/N) ratio, all the observations of NGC 3783 are used. For all the other sources, no apparent continuum variations are noted. Some higher order HEG spectra of stellar-mass black holes have been published in Miller et al. (2015, 2016).

3 RESULTS

For Circinus, NGC 4151, and NGC 3783, the second and third order Chandra HEG spectra are deep enough to allow a robust measurement of the width of the Fe Kα line. Their spectra are plotted in Figure 1, which are rebinned with a minimum S/N ratio of 4. For comparison, the corresponding first order HEG spectra (reduced by a factor of 15) are over-plotted in Figure 1. As can be seen, the second and third order HEG spectra are narrower than the first order spectra, and can provide better constraints on the width of the Fe Kα line. It also shows that the Fe Kα line is dominated by the neutral Fe atoms, and the contribution from low-ionized Fe$^+$ ions (located around 6.42 keV, Kastra & Mushwe 1993) is negligible.

The neutral Fe Kα line is composed of a doublet, Kα1 at 6.404 keV, and Kα2 at 6.391 keV, with a flux ratio of 2:1 (Bearder 1967).

We model the observed spectra with two Gaussian lines plus a linear continuum. The two Gaussian lines are centered at 6.404 and 6.391 keV with their redshifts and widths fixed with each other, and the intensity of the Kα2 line is set to be half of the Kα1 line. The fitting region is between 6 and 6.6 keV. The fitted results are plotted in Figure 1 and listed in Table 1. For comparison, the line widths obtained from the first order HEG data using the same model are also listed in Table 1. Note that the widths of the first order HEG data presented here are a little smaller than those reported by Shu et al. (2010, 2011), because they used one Gaussian line to model the Fe Kα line.
The intrinsic line width of the Fe Kα line of AGN

Kα doublet. For Circinus, the one with the best data, the line width measured from the second and third order spectra is about 2/3 of that from the first order spectra. The corresponding FWHM velocity is similar to that obtained from the Si Kα line in Liu (2016). For NGC 4151 and NGC 3783, the line widths of the second and third order spectra are also about 2/3 of those from the first order spectra.

The second and third order Chandra HEG spectra of all the other sources are plotted in Figure 2. Because their signals are not as good as the above three sources, their spectra are rebinned with a minimum S/N ratio of 1.5, and the Cash statistic is used. The same doublet model is adopted. The fitted results are plotted in Figure 2 and listed in Table 1. As expected, the errors of the measured line widths are larger, compared with those of Circinus, NGC 4151, and NGC 3783. Nevertheless, all the line widths of the second and third order spectra are smaller than those of the first order spectra. The corresponding FWHM velocities of the Fe Kα line of Mrk 3 and NGC 1068 are consistent with those obtained from the Si Kα line in Liu (2016).

4 CONCLUSION AND DISCUSSION

X-ray fluorescent lines are unique features of the reflection spectrum emitted by the torus when irradiated by the central AGN. The intrinsic line widths of the X-ray fluorescent lines can be used to probe the location of the line-emitting region. The line widths of the Fe Kα line measured from the first order Chandra HEG spectra are 3 – 5 times larger than those measured with the Si Kα line for Circinus, Mrk 3, and NGC 1068. Nevertheless, because the observed Si Kα and Fe Kα lines are not necessarily coming from the same physical region, it is still uncertain whether the line widths of the Fe Kα line are over-estimated or not.

In this letter we measured the line width of the Fe Kα line using the second and third order Chandra HEG spectra of several nearby bright AGN. For Circinus, NGC 4151, and NGC 3783, which have deep enough signals, the measured line widths are about 2/3 of those measured from the first order HEG spectra. While for Mrk 3, NGC 1068, NGC 4388, and NGC 4507, the measured line widths are also smaller than those measured from the first order HEG spectra. The results clearly show that the line widths of the Fe Kα line measured from the first order HEG spectra are over-estimated.

In principle, the first order and higher order HEG data should provide consistent results on the line widths. However, when the intrinsic line width is too narrow to be resolved by the first order data, we do not expect the same results, since there are observational noises and the instrument responses are not ideal. To validate our measurements, we simulated 100 HEG observations of the Fe Kα line using Marx (Davis et al. 2012) for the two Gaussian model of Circinus with an intrinsic width of 5 eV (corresponding to the velocity of that measured from the Si Kα line width), and the exposure time is set to be the same as that of the real observations. We note that Marx is used to generate the Chandra HEG RMF calibration products, and contains all known effects about the instrumental line profile (D. Huembemoerder, private communication). We then fitted the simulated HEG spectra with the same two Gaussian model. We found that 90% of the fitted Fe Kα widths from

http://space.mit.edu/cxc/marx
the first order spectra are within 8.2 ± 1.1 eV. On the other hand, 90% of the fitted widths from the second and third order spectra are within 6.1 ± 1.4 eV. Considering that the first order spectra are contaminated by the Compton shoulder, which is less important for the higher order spectra of better resolution, the simulation results are fully consistent with our measured results.

We note that except for Circinus, NGC 4151, and NGC 3783, the Fe Kα lines of all the other sources are not well resolved, and the measurements presented here are only upper limits of the true widths. Deeper data with similar or higher spectral resolution are needed to obtain the true widths.

For the current measurements, the FWHM velocities of the Fe Kα line are around 1000 km/s, similar to those of narrow emission lines. If assuming a virialized orbit, the Fe Kα line-emitting regions are close to the dust sublimation radii, as inferred from the widths of Si Kα line in Liu (2016). It indicates that the Fe Kα lines of the studied sources are originating from regions around the cold dusty torus.

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