X-ray fluorescent lines from the Compton-thick AGN in M51

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ABSTRACT

The cold disk/torus gas surrounding active galactic nuclei (AGN) emits fluorescent lines when irradiated by hard X-ray photons. The fluorescent lines of elements other than Fe and Ni are rarely detected due to their relative faintness. We report the detection of Kα lines of neutral Si, S, Ar, Ca, Cr, and Mn, along with the prominent Fe Kα, Fe Kβ, and Ni Kα lines, from the deep Chandra observation of the low-luminosity Compton-thick AGN in M51. The Si Kα line at 1.74 keV is detected at ~ 3σ, the other fluorescent lines have a significance between 2 and 2.5 σ, while the Cr line has a significance of ~ 1.5σ. These faint fluorescent lines are made observable due to the heavy obscuration of the intrinsic spectrum of M51, which is revealed by NuSTAR observation above 10 keV. The hard X-ray continuum of M51 from Chandra and NuSTAR can be fitted with a power-law spectrum with an index of 1.8, reprocessed by a torus with an equatorial column density of $N_H \sim 7 \times 10^{24}$ cm$^{-2}$ and an inclination angle of 74 degrees. This confirms the Compton-thick nature of the nucleus of M51. The relative element abundances inferred from the fluxes of the fluorescent lines are similar to their solar values, except for Mn, which is about 10 times overabundant. It indicates that Mn is likely enhanced by the nuclear spallation of Fe.

Key words: atomic processes – galaxies: Seyfert – galaxies: individual: M51 (NGC 5194) – X-rays: galaxies

1 INTRODUCTION

The majority of nearby active galactic nuclei (AGN) are obscured by large amounts of cold gas and dust (e.g. Comastri 2004). For Compton thick AGN with absorption column densities larger than $1.5 \times 10^{24}$ cm$^{-2}$ (the inverse of the Thomson cross-section), the continuum below 10 keV is heavily suppressed, and Compton scattering of high energy photons produces a spectral bump around 20 – 30 keV. The cold gas emits fluorescent lines when irradiated by the central AGN. The most prominent line is the Fe Kα line at 6.4 keV, due to its high abundance and high fluorescence yield. The Fe 6.4 keV line is found to be a ubiquitous feature of AGN (e.g. Shu et al. 2010, and reference therein). Since the continuum is heavily suppressed for Compton-thick AGN, their Fe 6.4 keV line will be more noticeable. Indeed, the Fe 6.4 keV lines with equivalent width (EW) as large as a few keV have been reported (e.g. Levenson et al. 2002).

For those AGN with noticeable Fe Kα lines, the fluorescent lines from elements other than Fe should also be detectable. The fluorescent lines of other elements are generally thought to be observationally irrelevant, due to their small yields. Nevertheless, the yields of other elements are not as small as unobservable. For example, the yield of neutral Si Kα is 0.042, larger than 10% of that of the neutral Fe Kα. The fluxes of the fluorescent lines are determined by the chemical abundances, the distribution of the obscuring material, as well as the illuminating intrinsic spectrum of AGN. If detected, the non-Fe fluorescent lines can be used to measure the abundances of the cold gas. A possible example is the ASCA observation of NGC 6552 that shows Kα lines of seven neutral species, which were used to constrain the abundances of the cold gas (Fukazawa et al. 1994, Reynolds et al. 1994).

In this letter we report the detection of fluorescent lines of neutral Si, S, Ar, Ca, Cr, and Mn, along with the prominent Fe Kα, Fe Kβ, and Ni Kα lines, from the deep Chandra spectrum of the nucleus of M51 (NGC 5194). Known as the Whirlpool galaxy, M51 is classified as a LINER/Seyfert II galaxy (e.g. Staubert 1982, Ho et al. 1997). Its face-on inclination and close distance (7.1 Mpc, Takáts & Vinkó 2001) allow detailed studies of the nuclear activity (see e.g. Liu & Mac 2015, and references therein). While the X-ray luminosity of the nucleus of M51 in 2 – 10 keV band is as low as $\sim 10^{39}$ erg s$^{-1}$, the EW of the Fe 6.4 keV line is $\sim 4$ keV, the largest one ever reported (e.g. Terashima & Wilson 2001, Levenson et al. 2002). Such a large EW implies a column density larger than $3 \times 10^{24}$ cm$^{-2}$ as shown by Monte-Carlo simulations of Compton-thick torus (Ikeda et al. 2009, Murphy & Yaqoob 2009).

A bright hard X-ray excess above 10 keV had been reported from the BeppoSAX observation of M51 (Fukazawa et al. 2001), and an absorption column density $\sim 10^{24}$ cm$^{-2}$ was inferred. The lack of spatial information of BeppoSAX, however, makes the inference uncertain. Indeed, as shown in §2, the NuSTAR observation of M51 detects at least three sources within its field of view (FOV).
We include the NuSTAR data of the nucleus of M51 to constrain the continuum above 10 keV.

2 OBSERVATIONAL DATA

The half-arcsec spatial resolution of Chandra makes it possible to resolve the point sources in the nuclear region of M51. This helps to reduce the contamination of other sources to the nucleus of M51. We use twelve Chandra archival observations with ObsID numbers of 13812, 13813, 13814, 13815, 13816, 15496, 15553, 1622, 354, 3932, 12562, and 12668, all of which were taken with ACIS-S. The datasets are analyzed with CIAO (version 4.6) following standard procedures. After removing the flare periods, the total effective exposure time is about 800 ks, and the total count number is about 12,000 for the nucleus. All datasets are aligned to each other using the CIAO tools of wcs_match and wcs_update. As an illustration, the counts image of M51 within 2 – 7.5 keV band merged from all datasets is plotted in the left panel of Figure 1. It is dominated by an off-nuclear ULX. While the nucleus is relatively faint within 2 – 7.5 keV band, its striking 6.4 keV line (as shown in Figure 2) indicates the hidden AGN. The extended emission can be clearly seen in Figure 1, which has been studied previously (e.g. Houck & Denicola 2000). The combined spectrum is plotted in Figure 2, which is binned to a minimum signal-to-noise (S/N) ratio of 4.5 below 6.8 keV and 3 above that to enhance the visibility of emission lines of low counts. We see that the spectrum has a significant soft component below 2 keV, which is likely due to the shock-heated gas by the radio jet (Terashima & Wilson 2001). While above 2 keV, the most prominent feature are the emission lines at 6.4 and 7 keV, which are the Kα and Kβ lines of neutral-like Fe. In addition, there are also many emission spikes between 2 and 6 keV.

We first try to fit the Chandra spectrum of M51 with a thermal model (Vpec, Foster et al. 2012), representing the soft component, plus an absorbed powerlaw model for the hard component. We include two Gaussians to represent the Fe Kα and Kβ lines of neutral-like Fe. In addition, there are also many emission spikes between 2 and 6 keV.

We combine them using the ISIS function combine_dsets, for which the model is calculated for each dataset, and the datasets and models are summed separately before computing the χ².

M51 was observed with NuSTAR for a short exposure of 18.5 ks on Oct. 2012. The data is reduced using NUSTARDAS software and the effective exposure is about 15 ks after cleaning. In the right panel of Figure 1, we show the NuSTAR image of M51 combining the two focal plane modules of FPMA and FPMB. Besides the nucleus, there are two other sources detected by NuSTAR (indicated as black crosses in Figure 1), which correspond to sources 69 (upper one) and 82 (lower-left one) as in Terashima & Wilson (2004).

3 RESULTS

The spectrum of the nucleus of M51 is extracted from a 2′′ radius for each Chandra observation with a background spectrum extracted from a source-free region. We compared the spectra of different observations and found no apparent variation. Thus we combine them using the ISIS function combine_dsets, for which the model is calculated for each dataset, and the datasets and models are summed separately before computing the χ². The combined spectrum is plotted in Figure 2, which is binned to a minimum signal-to-noise (S/N) ratio of 4.5 below 6.8 keV and 3 above that to enhance the visibility of emission lines of low counts. We see that the spectrum has a significant soft component below 2 keV, which is likely due to the shock-heated gas by the radio jet. While above 2 keV, the most prominent feature are the emission lines at 6.4 and 7 keV, which are the Kα and Kβ lines of neutral-like Fe. In addition, there are also many emission spikes between 2 and 6 keV.

We fit the Chandra spectrum of M51 with a thermal model (Vpec, Foster et al. 2012), representing the soft component, plus an absorbed powerlaw model for the hard component. We include two Gaussians to represent the Fe Kα and Kβ lines. The fitted result is plotted in Figure 2. The fitted temperature of the thermal component is about 0.7 keV, a little higher than the value reported by Terashima & Wilson (2001). The fitted powerlaw index is about -0.3, implying a heavily reprocessed continuum. In the residual panel of Figure 2, there are many remaining spikes, such as the ones around 1.7 keV, 2.3 keV, 5.9 keV, and 7.5 keV. We find they are exactly corresponding to the Kα emission lines of neutral Si, S, Mn, and Ni. Therefore, they are most likely due to the fluorescent lines of neutral species as the Fe 6.4 keV line. To measure the observed line fluxes, it is better to use a

| Line | Energy(keV) | Flux | Yα | Zα/ZFe | Δχ²icted | Sig.² |
|------|-------------|------|-----|--------|----------|------|
| Si Kα | 1.74 | 1.9 ± 0.8 | 0.042 | 0.8 ± 0.3 | 16.0 | 99.9% |
| S Kα | 2.31 | 1.3 ± 0.7 | 0.078 | 0.6 ± 0.3 | 8.3 | 97.4% |
| Ar Kα | 2.96 | 0.8 ± 0.5 | 0.112 | 0.9 ± 0.6 | 6.2 | 97.0% |
| Ca Kα | 3.69 | 0.9 ± 0.5 | 0.124 | 1.3 ± 0.7 | 8.7 | 97.5% |
| Cr Kα | 5.41 | 0.7 ± 0.6 | 0.25 | 2.2 ± 1.9 | 2.4 | 85.8% |
| Mn Kα | 5.89 | 1.8 ± 0.9 | 0.278 | 9.8 ± 4.9 | 8.8 | 97.7% |
| Fe Kα | 6.40 ± 0.01 | 38.0 ± 3.3 | 0.304 | 1 | – | – |
| Ni Kα | 7.26 ± 0.04 | 4.4 ± 2.2 | 0.37 | 2.2 ± 1.1 | 10.2 | 98.3% |
| Fe Kβ | 7.03 ± 0.02 | 7.8 ± 2.2 | – | – | – | – |
| Fe XXV Kα | 6.7 | 1.8 ± 1.3 | – | – | 5.3 | 96.5% |

Note: The abundances of Vpec are relative to their solar values. All the line energies are fixed at expected values, except for Fe Kα, Fe Kβ, and Ni Kα, which are fitted. The line flux is in units of 10⁻³⁸ photons cm⁻² s⁻¹. The yield Yα is taken from Kaastra & Mewe (1993). The errors quoted are for 90% confidence level. The upper limit of the equatorial column density is beyond the valid range of MYTorus model of 10²¹ cm⁻². ∆χ²predicted is the improvement of χ² by adding the line. *The significance is estimated based on Monte-Carlo simulations.
scattered continuum rather than a powerlaw. For this purpose, we adopt the MYTorus model [Murphy & Yaqoob 2009; Yaqoob 2012], which is based on Monte-Carlo simulations of a toroidal geometry. The MYTorus model is specified by the incident power-law continuum, the equatorial column density, and the inclination angle. It provides separable components of transmitted continuum, scattered continuum, and the Fe Kα and Kβ fluorescent lines for a solar abundance [Anders & Grevesse 1989]. Fluorescent lines from other elements are not included. Thus we replace the powerlaw model with the MYTorus continuum, which includes the transmitted and scattered components. We then add Gaussian lines centred at the energies of the Kα lines of neutral elements, including Si, S, Ar, Ca, Cr, Mn, and Ni. We also add a Gaussian line at 6.7 keV, which seems to be a faint Fe XXV Kα line.

To further constrain the continuum model of MYTorus, we include the NuSTAR spectrum of M51 into the fitting, which is extracted from a circle region of 75″ radius as indicated in Figure 1. The background spectrum is extracted from a source-free region. The spectra of FPMA and FPMB are combined using ISIS function combine_dasets. Because NuSTAR has a half-power diameter of 58″, its spectrum of the nucleus of M51 is contaminated by neighbouring sources. The dominate one is the ULX as indicated in the left panel of Figure 1, the Chandra spectrum (2–7 keV) of which can be well fitted with an absorbed powerlaw with a photon index of 1.85 and a column density of $6.5 \times 10^{22}$ cm$^{-2}$. We also extract a spectrum from a circle region of 60″ radius excluding the nucleus and the ULX, which can be fitted with a powerlaw with an index of 2.4 without absorption. The region of 60″ radius includes most of the extended emission and point sources that contaminate the NuSTAR spectrum. Therefore, besides the model for the nucleus of Chandra data, we also assign these two powerlaw models with
fixed parameters to the NuSTAR data. The instrument normalization between Chandra and NuSTAR is fixed. The fitting results are listed in Table 1 and plotted in Figure 3 for the Chandra data. We see that the model provides a reasonable fit to the observed spectrum. The improvement of $\chi^2$ with the addition of each line is also listed in Table 1. There is a residual spike around 4.02 keV, which could be due to the fluorescent lines of Ca Kβ (4.01 keV), Sc Kα (4.09 keV), and/or Ca XXI Lyα line (4.11 keV). If it is the Ca Kβ line, the measured Ca Kα/Ca Kβ ratio ($\sim 1.5$) would be too small compared with the expected value of 10 (Kaastra & Mewe 1993). Since it is relatively weak ($\Delta \chi^2 \sim 4$ adding two parameters) and offset from the expected fluorescent energies, we neglected it here. The residuals below 2 keV are likely due to the simple model of one thermal component. The fitted equatorial column density of the MYTorus model is $7 \times 10^{24}$ cm$^{-2}$, close to the up-limit of the valid column density of MYTorus. It confirms the Compton-thick nature of the nucleus of M51. The fitted intrinsic powerlaw index is 1.8, typical of unobscured AGN. The model luminosity within $2 - 10$ keV is $6.7 \times 10^{38}$ erg s$^{-1}$, while the intrinsic luminosity corrected for the absorption is $4 \times 10^{39}$ erg s$^{-1}$. The best fitted EW of the Fe Kα and Fe Kβ lines are 4.1 and 1.2 keV, respectively.

To estimate the significance of the detection of each line, we use the Monte-Carlo method following Markowitz et al. (2006), we generate 1000 fake spectra using the exposures and responses of the Chandra observations for a null hypothesis model including Vpec, a continuum, and only the Fe Kα and Kβ lines. For simplicity, we adopt the powerlaw continuum model in Figure 2, instead of the continuum model of MYTorus, both of which are similar in $2 - 8$ keV band. We then calculate the improvement of $\chi^2$ over the null hypothesis model by adding an energy line around the energy of each detected line (within a range of ±0.1 keV). The cumulative distribution of the $\Delta \chi^2$ is created for each line. We find the distributions are similar for different lines except the one of Ni line for $\Delta \chi^2 < 5$. Therefore we adopt an $\Delta \chi^2$ distribution averaged over all lines, which is plotted in Figure 4. The estimated significance of the detection of each line is listed in the last column of Table 1. We see that the Si line is detected at $\sim 3\sigma$, and the other fluorescent lines have a significance between 2 and 2.5, while the Cr line has a significance of $\sim 1.5\sigma$.

The unfolded spectrum for NuSTAR data is plotted in Figure 5. There are totally about 1200 photons in the NuSTAR spectra and only the 3 – 50 keV energy range is used due to the low S/N of the data above 50 keV. We see that below $\sim 10$ keV the spectrum is dominated by the ULX indicated in Figure 1, while above that the nucleus dominates. Because the exposure of the NuSTAR observation is short, there are no many photons above 20 keV and the intrinsic spectrum is not well constrained. Further deep NuSTAR observations will help to determine the intrinsic spectrum.

To estimate the Fe abundance, we replace the two Gaussian lines of Fe Kα and Fe Kβ with the component of Fe fluorescent lines of MYTorus model and allow its normalization to vary. We find that the normalization of the line component of MYTorus is about 2 times that of the continuum component. Nevertheless, it does not necessarily mean Fe is overabundant. Gohil & Ballantyne (2015) showed that the EW of the Fe Kα line could be enhanced by dust due to the reduction of the reflected continuum intensity caused by the smaller backscattering opacity of dust. This dust effect needs to be investigated to obtain the Fe abundance.

4 DISCUSSION

The Compton-thick nature of the nucleus of M51 is confirmed by the NuSTAR observation of hard X-ray emission above 10 keV. The fitted equatorial column density of MYTorus model is $7 \times 10^{24}$ cm$^{-2}$. This value is consistent with the detection of strong HCN emission at the nucleus of M51, which suggests the presence of compact dense molecular gas (Matsumita et al. 2015). A gas disk/torus with a density of $\sim 10^6$ cm$^{-3}$ and a pc-scale size can provide the fitted column density.

We detected the faint fluorescent lines of neutral Si, S, Ar, Ca, Cr, and Mn, along with the prominent Fe Kα, Fe Kβ, and Ni Kα lines, from the deep Chandra observation of M51. These lines can be used to measure their abundances. As the reprocessing matter is Compton-thick, detailed radiative calculations, such as those by Murphy & Yaqoob (2009), are needed to obtain accurate results. Nevertheless, the relative abundance can be roughly estimated as follows.
The observed fluorescent lines are most likely due to the scattering from a surface layer of unit optical depth that is not heavily absorbed by the torus itself. The fluorescence flux of certain element x can be expressed as follows (e.g. George & Fabian 1991):

$$F_x \propto Y_x \int E_x \frac{AE^{-\tau}}{\sigma_{\text{Fe}}(E)} dE,$$

where $Y_x$ is the fluorescence yield, $AE^{-\tau}$ is the incident photon spectrum, $Z_x$ is the abundance relative to solar value, and $\sigma_{\alpha}$ and $\sigma_{\tau}$ are the absorption cross-sections of the K-shell electron of element x and of all elements, respectively. $Z_{\text{Fe}}/Z_x$ expresses the probability that a photon is absorbed by the K-shell electron of element x. For $Z_{\text{Fe}} > 1$, Fe dominates the opacity above the binding energy of Fe and $\sigma_{\tau}$ is sensitive to $Z_{\text{Fe}}$. This dependence is neglected for the rough estimate here. We also neglect the difference of the absorption of produced fluorescent photons.

The estimated abundances relative to Fe are listed in Table 1. The S, C, Ar, and Fe have an abundance pattern similar to that of the Sun. While for the trace element of Mn, its abundance is about 10 times overabundant. This enhancement of Mn is likely due to nuclear spallation of Fe caused by cosmic rays from the nucleus (Skibo 1997; Turner & Miller 2010). In principle, it is possible that the soft Vpec component is due to the jet-heated gas, which originally is part of the disk/torus gas emitting fluorescent lines. In this case, the abundances of the Vpec model should be similar to those estimated from the fluorescent lines. The relative abundance of S, C, Ar, and Fe to Ca is about 1.5 for the Vpec model, a little higher than those estimated from the fluorescent lines. This is expected since lower energy photons have a larger probability of being absorbed than higher energy photons. Nevertheless, the details of the absorption depend on the distribution of the obscuring material and further modelling is needed for rigorous comparison. These results show that the non-Fe fluorescent lines can be a valuable probe of the obscuring matter of AGN and the physical processes they related to.

As noted in §1, the EW of the Fe 6.4 keV line of M51 is as large as 4 keV. This large EW of the Fe line is due to the suppression of the illuminating intrinsic spectrum, which also makes it possible to detect non-Fe fluorescent lines much fainter than the Fe line. In fact, M51 is the only one with an EW of the Fe line larger than 2.5 keV in Levenson et al. (2002). It would be difficult to detect non-Fe fluorescent lines for samples with lower EW of the Fe line. A search with other Compton-thick samples with an EW of the Fe line $\sim 1 - 2$ keV is undertaking.

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