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An Intense Iron Line Emission from NGC 1068

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Abstract

X-rays above the energy of 2 keV were observed from a type-2 Seyfert galaxy, NGC 1068. An intense iron line of about 1.3-keV equivalent width was clearly observed for the first time. The continuum emission can be described either by a power law of photon index of about 1.5 or by a thermal bremsstrahlung at a temperature higher than 27 keV, both models including an additional soft X-ray component. Low-energy absorption was found to be small with a value $N_{\rm H}$ of less than $10^{22}\,{\rm H\,cm^{-2}}$. The source intensity was very faint at about $5\times10^{-12}\,{\rm erg\,cm^{-2}\,s^{-1}}$ in the 2–10-keV energy band which corresponds to $3\times10^{41}\,{\rm erg\,s^{-1}}$ assuming a distance of 22 Mpc. The large iron-line equivalent width is most likely due to reprocessing by thin gas around the central engine in the case when the direct X-ray beam from the central engine is entirely blocked from our line of sight. With this model, we estimate that the luminosity of "hidden" central engine is as large as 10^{43}–$10^{44}\,{\rm erg\,s^{-1}}$.

Key words: Active galactic nuclei; NGC 1068; Type-2 Seyfert galaxies.

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1. Introduction

Active galactic nuclei (AGN) have been one of the most exciting objects in X-ray astronomy. Among many classes of AGNs, type-1 Seyfert galaxies have been studied relatively well because of their high flux. The spectrum of type-1 Seyferts is generally described by a single power-law with a mean photon index of about 1.7 (e.g., Mushotzky et al. 1980). Temporal variability on a time scale of days is common among type-1 Seyfert galaxies, and even shorter time scales less than 1000 s have been reported by several authors (Tennant et al. 1981; Lawrence et al. 1985; Pounds et al. 1986; McHardy and Czerny 1987).

On the other hand, X-ray observations of type-2 Seyfert galaxies are very sparse. In the soft X-ray band, the Einstein Observatory detected faint X-ray flux from several type-2 Seyfert galaxies and found that the mean intensity is one or two orders of magnitude smaller than that of a type-1 Seyfert (Kriss et al. 1980). Due to this faintness, X-ray observations in the band above 2 keV have been limited. Significant improvement has become available with the Ginga satellite. The sensitivity of the Large Area proportional Counter (LAC) on board Ginga is several times higher than that of previous satellites in the hard (>2 keV) X-ray band. Indeed, X-ray flux has been detected from the type-2 Seyfert galaxies NGC 1068 and Mkn 348 (Warwick et al. 1989). In this paper, we report the definite detection of an iron line from NGC 1068 and discuss the emission mechanism of this type-2 Seyfert galaxy.

2. Observation and Results

The observation was made with the Large Area proportional Counter (LAC) on board the Ginga satellite from 31 July to 2 August in 1987. The LAC has a total effective area of 4000 cm^2 with an energy range of 2–37 keV. The overall energy resolution of the LAC is 18% (FWHM) at 6 keV. The observation was made in a mode (MPC1) providing 48 energy channels for each of the 8 detectors with a bit-rate of either 2 kbit s^{-1} or 0.5 kbit s^{-1}. More details of the instruments are given by Makino and the ASTRO-C team (1987) and Turner et al. (1989).

Since the X-ray flux from NGC 1068 was nearly at the detection limit of the LAC, the background subtraction and data qualification had to be done very carefully. The X-ray data observed during the ground-contact orbits were excluded because radio activity due to the South Atlantic Anomaly made the background higher than that during the other orbits. The data at a low geomagnetic cutoff rigidity (<10 GV) region was also excluded. This results in about 36000 s of on-source data. In order to subtract the background accurately, we used background data taken when the satellite was in a similar orbital condition to the on-source observation, and selected the data so as to give the same SUD rate (count rate above 37 keV) as that of the on-source data within an accuracy of a few percent. Details of the background subtraction procedure and its accuracy are given in Turner et al. (1989) and Hayashida et al. (1989). In order to minimize the statistical errors, we collected background data of 3×10^5 s from many places of source-free, off-plane ($|b|>20°$) sky. The background data used here were taken between 23 July and 3 August in 1987. Therefore, the long-term effects in the

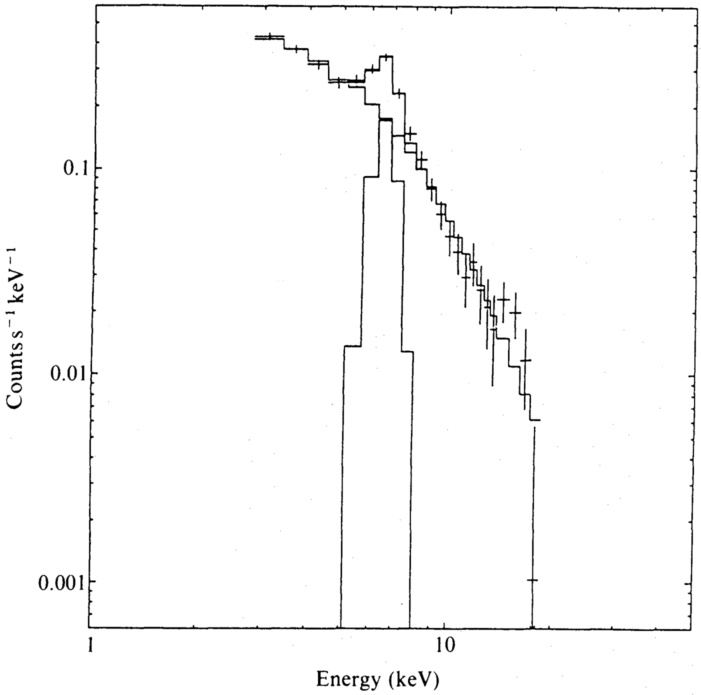

Fig. 1. X-ray spectrum of NGC 1068 together with the best-fit power-law continuum and iron emission line.

instrumental background should be small. The X-ray spectrum from the first layer (top layer) of the LAC obtained in this way is given in figure 1. Note an intense emission line at about 6.5 keV. The X-ray count rate in the energy band 2–10 keV was 2.3 counts s^{-1} which is about 10% of the detector background in the same energy range. Since the ambiguity in determining the detector background is only a few percent (Hayashida et al. 1989), the excess of 2.3 counts s^{-1} in the top layer is not due to the background. The X-ray efficiency of the second layer (mid layer) of the LAC in the 2–6-keV energy band is less than a few percent (Turner et al. 1989) and the excess count rate of the mid layer in the 2–6-keV band was only 0.1 counts s^{-1} with no spurious spectral structure. This fact also gives us confidence that the background was properly subtracted.

Since the X-ray flux above the background level was found mainly in the 2–10-keV band and since the particle induced background of the top layer is lower than that of the mid layer in this energy band (Turner et al. 1989; Hayashida et al. 1989), we used the data from the top layer only. Most X-rays below about 10 keV should be absorbed in the top layer and the inclusion of the mid layer data degrades the quality of the data.

The largest ambiguity in the observed count rate is due to the fluctuation of the cosmic diffuse X-ray background (CDXB) in the LAC field of view. The $\log N$-$\log S$ relation taken from Piccinotti et al. (1982) gives the 1σ fluctuation level in the LAC field of view as about 0.5 counts s^{-1} in the 2–10-keV band. The CDXB observations by Ginga of various sky positions support this value (Hayashida et al. 1989). Therefore, the quoted intensity may have a systematic 1σ error of 0.5 counts s^{-1}. The continuum

Table 1. Best-fit parameters of power-law and thermal bremsstrahlung models.

Flux (2–10 keV) (10^{-12} erg s^{-1} cm^{-2})	Index temperature	Iron energy (keV)	Equivalent width (keV)	N_H (10^{22} atoms)	N_{Fe} (10^{22} atoms)
		Power-law model			
4.9	1.50	6.55	1.3	<1	<4
±0.5	±0.05	±0.1	±0.1	...	...
		Thermal bremsstrahlung model			
4.9	>27	6.55	1.3	<1	<4
±0.5	...	±0.1	±0.1	...	...

The errors quoted here are 90% statistical confidence level. The errors due to the fluctuation of CDXB are given in the text.

spectral shape is also biased by the fluctuation of the CDXB.

The spectral fitting was carried out using two simple models: (a) a power-law and (b) a thermal bremsstrahlung model, both with an emission line and low-energy absorption. The Gaunt factor for the bremsstrahlung model is taken from Matteson (1971). Significant excess above these models at energies below 3 keV was found. This suggests the presence of a soft component in the spectrum of NGC 1068 as previously reported by Monier and Halpern (1987) and by Elvis and Lawrence (1988). The excess was only seen in the lowest 2 energy channels. Therefore, it is not realistic to determine the spectral shape and intensity of the soft component using our data alone. We excluded these 2 channels, therefore, and obtained satisfactory fits in the energy range above 3 keV. We checked the effect of the soft component by including a power-law spectrum of $\alpha_E=3.5$ (Elvis and Lawrence 1988) and found that the best-fit power index for the hard component decreased to 1.3 instead of 1.5 given by a single component power-law model. However, the other best-fit parameters did not change within their statistical errors. For further discussion, we therefore use the best-fit parameters for single-component models. These values are given in table 1. The photon index (power-law model) and temperature (thermal bremsstrahlung) are 1.5 ± 0.1 and higher than 27 keV (90% confidence level), respectively. For the other spectral parameters, both models give values consistent with each other. The iron line energy and the equivalent width are about 6.55 ± 0.1 and 1.3 ± 0.1 keV (90% error), respectively. The low-energy absorption was found to be less than 10^{22} H atoms cm^{-2}. The upper limit is determined by the thickness of the beryllium window of the LAC. No apparent iron K-edge structure was found. The 90% upper limit of N_{Fe} is 1.6×10^{18} Fe atoms cm^{-2} equivalent to 4×10^{22} H atoms cm^{-2} of N_H value assuming the cosmic abundance.

Next, we estimate errors for these spectral parameters by including the fluctuation of the CDXB. The 90% error for the equivalent width is given as +0.7, −0.3 keV and the 90% upper limit of N_{Fe} values is estimated to be equivalent to 7×10^{22} H atoms cm^{-2} assuming cosmic abundance. The total luminosity from NGC 1068 in the

2–10-keV energy band is estimated to be $(3\pm1)\times10^{41}$ ergs s^{-1} assuming the distance to be 22 Mpc (Weedman 1977). This luminosity is one or two orders of magnitude smaller than the typical type 1 Seyfert galaxy (e.g., Kriss et al. 1980).

The error of the line energy due to the background fluctuation is found to be within the statistical errors, because no significant structure near the line energy was observed in the fluctuating component. The photon index of 1.5 is not much different from that of the CDXB [$\alpha=1.4$, see, e.g., Marshall et al. (1980)]. The spectral shape of the fluctuating component of the CDXB was not much different from that of the mean spectrum of the CDXB. Therefore, even if we take into account the fluctuation of the CDXB, the real power index of NGC 1068 should still be about 1.5.

In order to estimate the error caused by the fluctuation of the CDXB more accurately, we need to measure spectral index of the fluctuating component exactly, which is beyond the scope of the present paper. Since the accurate error is not essential for the following discussion, we will not examine it in further detail.

3. Discussion

Several models are proposed for the relationship between type-2 Seyfert galaxies and type-1 Seyferts. The discovery of X-ray emission from many NELGs (Narrow Emission Line Galaxies) provided us with a possible link between type-1 and -2 Seyfert galaxies. One attractive model is that the type-2 Seyfert essentially has the same structure as the type-1 Seyfert and that the only difference in the type-2 Seyfert is that the central engine and the broad line region are obscured by dense matter, possibly by the accretion torus. In fact, Antonucci and Miller (1985) discovered broad lines in the polarized optical emission line from NGC 1068. Since the polarization should be due to the scattering effect of surrounding gas, this observation provides us with a picture for the structure of NGC 1068, that is, the broad-line region is obscured and only the scattered X-rays are visible. Further support was given by the recent discovery of hard X-ray emission from this source with EXOSAT (Elvis and Lawrence 1988). They claimed that the hard X-ray is attributable to the Thomson scattering of the ionized gas around the central engine because the spectral shape of the hard X-rays was same as that of type-1 Seyfert galaxies. Although the detection of iron line emission is essential to confirm this model, they could report only marginal evidence of iron line emission.

We report here definite evidence of the iron line emission. We cannot place the origin of this iron line in hot thermal plasma, because the observed iron energy of 6.55 keV $\pm$0.1 keV is inconsistent with the plasma temperature higher than 27 keV determined by fitting the continuum emission. Furthermore, the equivalent width is larger than that expected from a thin hot plasma of cosmic abundance. Thus the scattering model of a power-law continuum spectrum seems more realistic. The equivalent width of the iron line of 1.3 (+0.7, −0.3) keV is consistent with the predicted value from the scattering by a spherically distributed gas of cosmic abundance. [For example, see Inoue (1985), but Krolik and Kallman (1987) give a smaller equivalent width.] The energy of the iron line of 6.55 ± 0.1 keV gives the constraint that the ionization state of iron in the scattering gas should be between neon-like and lithium-like. Apart from the absolute value of the equivalent width, the observed iron line features are consistent with the theoretical estimation based on the scattering X-ray model of Krolik and Kallman (1987). Since the fluorescence yield depends on the ionization states of iron and iron can be overabundant at the galactic center, the difference of the equivalent width between the predicted (about 0.5 keV) and the observed (about 1.3 keV) may not be serious.

We discuss now the ionization condition of the scattering gas with following simple assumptions: the gas distribution is spherical with a constant density n (cm^{-3}) and radius r (pc), the X-ray emission from the central engine is isotropic, the elemental abundance is cosmic and the source distance is 22 Mpc; the direct beam from the central engine is completely blocked from our line of sight. The observed X-ray flux (the scattered flux) we derive is $3\times10^{41}\,erg\,s^{-1}$. Since the Thomson scattering cross section is $6.65\times10^{-25}\,cm^2$, the X-ray luminosity of the central engine is given as

$$L_x = 5\times10^{41}(10^{24}/N_H)\,erg\,s^{-1}\,, \tag{1}$$

where $N_H = nr$. Then, the ionization parameter ξ (Kallman and McCray 1982) at a distance of r(pc) is

$$\xi = L_x/nr^2 = 5\times10^{65}/N_H{}^2 r\,erg\,cm\,s^{-1}\,. \tag{2}$$

From the iron-line energy, the ionization state of iron should be between neon-like and lithium-like. This condition is realized if $\log\xi$ is between 2.5 and 3. Then from equation (2), we get following relation:

$$N_H = (1\text{–}2)\times10^{22}(1\,pc/r)^{0.5}\,H\,atoms\,cm^{-2}\,. \tag{3}$$

Since the dimension of the scatttering gas (r) may be of the order of 1 pc (Krolik and Kallman 1987), the N_H value should be about $(1\text{–}2)\times10^{22}$ H atoms cm^{-2}. Although this value does not conflict with the observed N_{Fe} value, it is inconsistent with the N_H obtained from the low-energy absorption. We note here that the EXOSAT observation reported a smaller upper limit to the value of N_H less than 10^{21} H atoms cm^{-2}. This constraint can be relaxed by assuming partially ionized gas. If the oxygen K shell ($\sim$0.6 keV) is fully ionized and the iron L shell ($\sim$1 keV) is not fully ionized, then both the low-energy absorption and the iron-line energy can be reasonably explained. These ionization conditions are realized near $\log\xi = 2.5\text{–}3.0$. In this case, the electron temperature of the scattering gas is about 10^5 to 10^6 K (Kallman and McCray 1982) which is consistent with the optical line width observed in the polarization measurements (Antonucci and Miller 1985). Therefore, the N_H value and the measured luminosity L_x is estimated to be about $(1\text{–}2)\times10^{22}$ H atoms cm^{-2}, and about $(2\text{–}4)\times10^{43}\,erg\,s^{-1}$, respectively. If we assume the covering factor ($\Omega/4\pi$) to be 0.25 (Krolik and Begelman 1986), then the total, intrinsic, luminosity can be as high as $10^{44}\,erg\,s^{-1}$. This luminosity is typical of type-1 Seyfert galaxies (Kriss et al. 1980).

The X-ray luminosity of $3\times10^{41}\,erg\,s^{-1}$ in the 2–10-keV band is same as that observed with the EXOSAT in 1983 and 1985. Therefore, we note that no significant luminosity change over 4 yr in the hard X-ray band has been observed. This fact is in sharp contrast to that of type-1 Seyfert galaxies in which time variability is very common. If the X-ray emission observed here is really the scattered component in a region of gas about 1 pc big, then any intrinsic time variability on time scales less than several years will be smeared out (Elvis and Lawrence 1988).

In conclusion, our observational results strongly support the model of Antonucci and Miller (1985). We interpret our data as follows: The luminosity of the central engine of NGC 1068 is 10^{43}–10^{44} erg s^{-1}. The direct beam from this central engine is completely obscured by a dense gas of accretion torus. Therefore, the observed X-ray flux is due to the scattering (continuum component of the spectrum) and the reprocessing (iron line) by the surrounding optically thin "warm" gas. The observed X-ray flux is only a few percent of the total flux of the central engine.

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