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A reflection-dominated X-ray spectrum discovered by *ASCA* in the Circinus galaxy

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ABSTRACT

We report the first pointed X-ray observation, made by *ASCA*, of the nearby Seyfert 2 galaxy in Circinus. The spectrum consists of a very prominent (EW $\sim$2 keV) fluorescent 6.4-keV iron line, a very flat continuum (photon spectral index less than 1) and other lines, including one at $\sim$7 keV that is probably due, at least in part, to iron Kβ fluorescent emission. The spectrum is consistent with Compton scattering and fluorescent emission from cold matter illuminated by an obscured active nucleus.

Key words: line: formation – line: identification – galaxies: individual: Circinus – galaxies: Seyfert – X-rays: galaxies.

1 INTRODUCTION

The Circinus galaxy (A1409 – 65, hereinafter simply Circinus) is a nearby ($\sim$4 Mpc) Sb–Sd spiral galaxy at low Galactic latitude ($b = -3\overset{\circ}{.}8$), but in a region of relatively low Galactic extinction ($A_V \sim 1.5$: Freeman et al. 1977).

There are many indications of intense activity in this galaxy: a luminous water maser (Gardner & Whiteoak 1982) and IR nucleus (Moorwood & Glass 1984), intense and polarized radio emission (Elmouttie et al. 1995) and a spectacular [O III] ionization cone (Marconi et al. 1994), which suggests the presence of an obscured active nucleus. This is further confirmed by the IR/optical spectrum, which is rich in narrow coronal emission lines, probably owing to photoionization from a hidden Seyfert nucleus (Oliva et al. 1994). All these pieces of evidence argue in favour of Circinus being one of the nearest Seyfert 2 galaxies.

In X-rays, the only observation of Circinus reported in the literature is that of the *ROSAT* All Sky Survey (RASS: Brinkmann, Siebert & Boller 1994), which measured a (corrected for absorption) 0.1–2.4 keV flux of about 10^{-11} erg cm^{-2} s^{-1}. This relatively high flux suggested that, in order to assess better the nature of the nuclear activity in this galaxy, one could obtain a spectrum of good signal-to-noise ratio up to 10 keV with the *ASCA* satellite (Tanaka, Inoue & Holt 1994).

2 OBSERVATION AND DATA REDUCTION

The galaxy was observed in the 2-CCD mode on 1995 August 14/15. (*ASCA* consists of four detectors: two CCDs, SIS0 and SIS1, and two GSPCs. As we are particularly interested in the spectral details, in the following we will concentrate on the analysis of the data obtained with the two CCDs.) The data reduction was performed using the standard procedures. The effective exposure time, after data selection, was about 25 (30) ks for SIS1 (SIS0). The count rate is about 0.15 count s^{-1} per CCD, corresponding to a flux of about 10^{-11} erg cm^{-2} s^{-1} in the 2–10 keV band (luminosity $\sim 2\times10^{40}$ erg s^{-1}). There is no evidence for variability along the observation. The image is consistent with the source being point-like.

The spectral analysis was performed using the XSPEC package. Grossly speaking, the spectra of the four instruments are all consistent. There are slight differences between the spectra obtained from the two SIS detectors, probably owing to calibration problems (see below). Unless explicitly stated, in the following we shall refer to SIS1,

Table 1. All lines, if not explicitly stated, refer to Kα transitions. Line energies are in the source rest frame (redshift corrections are smaller than statistical uncertainties), and have been taken from Dyson (1990, neutral atoms) and House (1969, ionized lines).

Line	SIS0			SIS1			Closest line(s)	Neutral
	E (keV)	σ (keV)	EW (keV)	E (keV)	σ (keV)	EW (keV)	(keV)	(keV)
A	–	–	–	$0.80^{+0.03}_{-0.02}$	$0.00^{+0.04}_{-0.00}$	$0.05^{+0.07}_{-0.04}$	0.85 (Ne II)	0.85 (Ne)
B	$1.33^{+0.02}_{-0.03}$	$0.00^{+0.04}_{-0.00}$	$0.03^{+0.02}_{-0.02}$	$1.34^{+0.03}_{-0.02}$	$0.00^{+0.08}_{-0.00}$	$0.09^{+0.03}_{-0.04}$	1.33 (Mg X) 1.34 (Mg XI)	1.25 (Mg)
C	$1.84^{+0.03}_{-0.03}$	$0.07^{+0.05}_{-0.02}$	$0.13^{+0.06}_{-0.04}$	$1.84^{+0.04}_{-0.03}$	$0.08^{+0.04}_{-0.03}$	$0.19^{+0.05}_{-0.06}$	1.84 (Si XII)	1.74 (Si)
D	$2.35^{+0.05}_{-0.04}$	$0.05^{+0.13}_{-0.05}$	$0.12^{+0.07}_{-0.05}$	$2.43^{+0.07}_{-0.05}$	$0.15^{+0.10}_{-0.06}$	$0.33^{+0.09}_{-0.12}$	2.39 (S XII) 2.41 (S XIII)	2.31 (S)
E	$6.33^{+0.02}_{-0.02}$	$0.12^{+0.02}_{-0.01}$	$1.75^{+0.18}_{-0.17}$	$6.37^{+0.02}_{-0.01}$	$0.10^{+0.02}_{-0.02}$	$2.31^{+0.12}_{-0.26}$	6.40 (Fe II)	6.40 (Fe)
F	$6.95^{+0.12}_{-0.10}$	$0.15^{+0.22}_{-0.05}$	$0.36^{+0.15}_{-0.14}$	$6.99^{+0.10}_{-0.08}$	$0.13^{+0.18}_{-0.08}$	$0.52^{+0.20}_{-0.26}$	6.97 (Fe XXVI)	7.06 (Fe Kβ)

which appears to be better calibrated, at least at the iron line energy, giving a line energy consistent with the expected value of 6.39 keV (after correction for the system velocity of Circinus: Freeman et al. 1977), while SIS0 gives a slightly lower energy (see Table 1).

Another source is present in the field of view of the detectors, at RA$=14^h12^m39^s$, Dec.$=-65°23'30''$ (2000; uncertainty of about 0.5 arcmin), about 5 arcmin away from Circinus, with a count rate about three times smaller. Its spectrum is well fitted either by a power law with $\Gamma=2.25\pm0.18$ (hereinafter all errors correspond to the 90 per cent confidence level for one interesting parameter) and $N_H=8.1(\pm1.4)\times10^{21}$ cm^{-2} ($\chi^2_r=0.98$, 62 d.o.f.), or by a thermal bremsstrahlung with $kT=3.9^{+0.9}_{-0.7}$ keV and $N_H=5.8(\pm1.0)\times10^{21}$ cm^{-2} ($\chi^2_r=1.05$, 62 d.o.f.). No source is visible in the RASS at that position, and an inspection of archive optical plates of this crowded region has not revealed any obvious optical counterpart. Neither finding is surprising, given the large line-of-sight absorption; the measured column density (of the order of or even greater than the Galactic one) argues in favour of an extragalactic source. An optical follow-up to secure identification is planned.

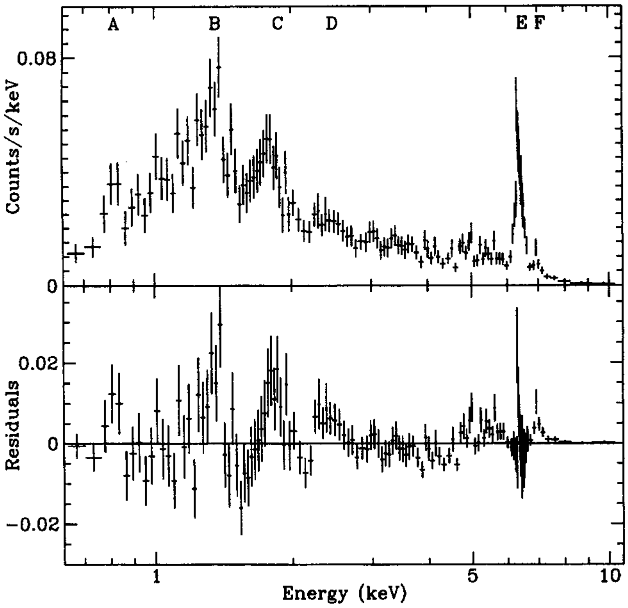

Figure 1. Upper panel: the SIS1 spectrum of Circinus. All of the detected lines are labelled (see Table 1). Lower panel: residuals when the spectrum is fitted with a simple absorbed power law and a Gaussian iron Kα line.

3 RESULTS

The spectrum of Circinus is shown in the upper panel of Fig. 1. A prominent line at about 6.4 keV, corresponding to fluorescence from neutral iron, is the most remarkable feature. Also remarkable are a very flat spectrum and several other features.

We first fitted the spectrum with a simple absorbed power law plus a Gaussian line to model the 6.4-keV line. The best-fitting parameters are $N_H=1.0(\pm0.6)\times10^{21}$ cm^{-2}, $\Gamma=0.93\pm0.11$, and for the line an energy of 6.38 ± 0.02 keV, $\sigma=0.12\pm0.02$ and an equivalent width (EW) of 3.7 ± 0.4 keV. The column density is lower than expected on the basis of the Galactic optical extinction ($\sim3\times10^{21}$ cm^{-2}: Savage & Mathis 1979), and the spectral index is probably the lowest ever observed in an active galaxy. The fit is statistically unacceptable ($\chi^2_r=1.89$ for 120 d.o.f.), mainly owing to the presence of other line emission features (see the lower panel of Fig. 1). When these features are included in the fitting model, the quality of the fit improves dramatically, the χ^2_r becoming 1.23 (105 d.o.f.). However, the column density and the spectral index are even lower than in the previous fit ($N_H\leq5\times10^{20}$ cm^{-2} and $\Gamma=0.67^{+0.11}_{-0.06}$).

For these reasons, and prompted also by the large equivalent width of the iron line [which is of the order expected for a pure Compton reflection continuum: see e.g. Matt, Perola & Piro (1991), Ghisellini, Haardt & Matt (1994) and Reynolds et al. (1994)], we fitted the continuum with a power law plus a Compton reflection component from neutral matter. This model has just one more free parameter, namely the relative normalization r of the reflected component ($r=1$ for 2π illuminated matter and a spectrum averaged over the emitting angle, provided that the illuminating radiation is isotropic and visible). The improvement in the fit is significant at the 99.9 per cent level ($\chi_r^2=1.1$ for 104 d.o.f.), and more reasonable values are obtained for the column density and spectral index: $N_H=2.3(\pm 0.9)\times 10^{21}$ cm^{-2}, $\Gamma=1.6^{+0.5}_{-0.4}$, while r is equal to 41^{+57}_{-23}. Similar results have been obtained from SIS0: $N_H=3.2^{+0.5}_{-0.8}\times 10^{21}$ cm^{-2}, $\Gamma=2.40^{+0.35}_{-0.59}$ and $r=148^{+168}_{-90}$ ($\chi_r^2=1$, 147 d.o.f.). In Table 1 the best-fitting parameters of the various line features are given for both instruments.

The large value of r means that above 2 or 3 keV the reflected component is the most important one, being dominant at the iron line energy (as expected from the iron line EW). This component could arise from the illumination of the inner surface of the molecular torus by an otherwise invisible nucleus (e.g. Smith, Done & Pounds 1993; Ghisellini et al. 1994; Matt, Brandt & Fabian 1996; if the nucleus were directly visible, r should be of order unity). The matter obscuring the nucleus, probably the torus itself, should be Compton-thick (i.e. its column density should be at least $\sim 10^{24}$ cm^{-2}) in order for the nucleus to remain invisible up to 10 keV. The X-ray luminosity of the hidden nucleus is estimated to be $\sim 4\times 10^{41}/(\Omega/2\pi)$ erg s^{-1}, Ω being the solid angle subtended to the nucleus by the visible part of the reflecting matter. The bolometric (FIR) luminosity of the Circinus galaxy is $\sim 4\times 10^{43}$ erg s^{-1} (Moorwood & Glass 1984; Ghosh et al. 1992); this suggests that $\Omega/2\pi$ is of the order of a few per cent.

The nature of the power-law component (hereinafter the 'soft' component), dominating below ~ 2 keV, is more difficult to assess. In the fit procedure, the two components are formally linked, because the shape of the reflection component depends on that of the illuminating radiation, which has been assumed, in order to reduce the number of free parameters, to be equal to that of the soft component. The soft component could be the nuclear radiation reflected by ionized matter, as suggested by the (poorly constrained) spectral index which is typical for active galactic nuclei (AGN). Alternatively, it could be completely unrelated to the reflection component, and come from a starburst region and/or a hot plasma. The extended circumnuclear starburst visible in Hα images (Marconi et al. 1994), which accounts for at least half of the FIR luminosity, is a plausible candidate; the X-ray luminosity of the soft component ($\sim 10^{40}$ erg s^{-1}) is high but not impossible for integrated emission of massive X-ray binaries. It is worth noticing that the RASS image of the source appears extended, even if the total number of source counts (31) is far too small to permit any firm conclusion. Moreover, the measured absorption is consistent with the Galactic one, while excess absorption towards the nucleus of Circinus is known (Oliva et al. 1994; Marconi et al. 1994), also suggesting extended emission. X-ray observations of good spatial resolution are needed.

We now discuss, in some detail, all the detected lines.

3.1 The fluorescent 6.4-keV iron line

The energy of the line constrains the iron to be neutral or very weakly ionized. Its EW is consistent with that expected for a pure reflection continuum, if elemental abundances are equal to the solar values (e.g. Matt et al. 1991). The σ for a Gaussian line is ~ 0.1 keV. The fit with the line forced to be narrow is significantly worse (the χ_r^2 going from 1.1 with 104 d.o.f. to 1.33 with 105 d.o.f.), and symmetric wings in the residuals are clear. A fit with two lines, one broad and the other narrow, results in a zero-intensity narrow component. If the measured width of the line were intrinsic, it would correspond to a velocity of several thousand km s^{-1}, typical of that of the broad-line region. However, it is more likely that the broadening is an instrumental effect. With respect to the satellite PV phase, at the time of our observation the energy resolution of the CCDs had significantly degraded, to a value corresponding to $\sigma\sim 0.1$ keV at the iron Kα line energy (Mukai, private communication; *ASCA* news at the World Wide Web High Energy AStrophysics ARChive site, updated on 1996 April 12), entirely consistent with the measured value. A re-evaluation of this issue should await the updated response matrices.

If the iron line originates in Compton-thick matter, as indicated by its EW, a Compton shoulder with an intensity about one-tenth that in the line core is expected (e.g. Matt et al. 1991), but the data do not require it. The 90 per cent upper limit is about 10 per cent of the line intensity. We therefore cannot reach any firm conclusion about its existence. The absence of the Compton shoulder would imply that the matter is only slightly Compton-thick.

3.2 Other lines

Looking at Table 1 it can be seen that lines B–F are all statistically significant, even if at least part of line D could be due to an instrumental effect (namely the gold M-edge at 2.31 keV). Line A is only marginally significant in SIS1, and absent altogether in SIS0. Lines A–D and line F are discussed separately.

Reflection from neutral matter should produce, besides the iron 6.4-keV line, other fluorescent lines from lighter elements. The most prominent are those due to Ne, Mg, Si and S, the EWs of which, with respect to the reflection continuum, are 0.45, 0.18, 0.25 and 0.22 keV respectively (Reynolds et al. 1994, and private communication). There is little doubt that features A–D should be identified with lines from these elements. However, after dilution by the soft component is considered, the expected EWs reduce to about 10–20 eV for the Ne and Mg lines, and 50–70 eV for the Si and S lines, significantly lower than observed (see Table 1). An explanation could be that the abundance of these elements is significantly larger than solar; this is in contrast, however, to the iron line intensity being consistent with the solar abundance. Besides, observations of high-excitation (coronal) lines of Si, S and Fe at optical and IR wavelengths indicate that the Si/Fe and S/Fe abundances are close to solar (Oliva et al. 1994). Alternatively, the lines could be due to fluorescence and/or recombination and/or resonant scattering from ionized matter. The best-fitting energies would favour this hypothesis. The lines could be associated with the soft continuum component. A simple, single-temperature optically thin plasma model, however, does not provide a satisfactory fit, indicating a more complex scenario.

For the ~7-keV line, there are two possible identifications: an Fe H-like Lyα line (6.97 keV: Mewe, Groneschild & van der Oord 1985), or a fluorescent iron Kβ line (7.06 keV). An iron Kβ fluorescent line from neutral or low-ionization iron must be there. In fact, for neutral iron the Kβ/Kα ratio is about 1:9 and a Kβ EW of order 200 eV is therefore expected. The observed EW is greater than this value (it is about one-fifth that of the 6.4-keV line), but marginally consistent within the errors. As the best-fitting intensity of the line is greater than expected, and the line is centred at an energy lower than predicted, it is possible that the observed line is actually a blend of iron Kβ from neutral iron and Fe XXVI Kα from highly ionized material. This matter could be illuminated and photoionized by the nuclear radiation. In this case, the line should be dominated by resonant scattering, and the EW should be about 3 keV (with respect to the scattered continuum from the same material), provided that the iron abundance is solar, all iron is in the Fe XXVI form and the matter is optically thin to resonant absorption (Matt et al. 1996). Identifying the soft continuum with scattering from this ionized matter, one can estimate from the best-fitting values the dilution factor, which is about 5–15. The observed EW is therefore consistent with this hypothesis. The ionization level of Fe would imply that the lighter elements are completely ionized: the matter responsible for this line should therefore be different from that producing the low-energy lines even if they were ionized.

4 CONCLUSIONS

We report the first observation above 2 keV of the nearby Seyfert 2 galaxy in Circinus. The spectrum is quite remarkable, with a prominent iron fluorescent line at 6.4 keV (EW about 2 keV) and a very flat continuum (photon index less than 1). Both facts strongly argue in favour of the emission being dominated by reprocessing from cold matter of an otherwise invisible nuclear source.

Other lines are also evident in the spectrum: low-energy lines from Ne, Mg, Si and S, and a ~7-keV line which should be at least in part due to neutral iron Kβ fluorescent emission. The expected intensities of these lines, if emitted by the same material as responsible for the 6.4-keV iron line, are smaller than observed (even if that of the iron Kβ line is marginally consistent). Moreover, their best-fitting energies point to emission from mildly ionized (the Ne to S lines) and highly ionized (the H-like Fe line) matter. The highly ionized matter (provided that the Fe H-like line is real) could be a 'warm mirror' like that responsible, in NGC 1068, for both the scattering and the polarization of the optical broad lines (Antonucci & Miller 1985) and the emission of He- and H-like iron Kα lines (Ueno et al. 1994). Optical spectropolarimetry could be very helpful in this respect. The lines from lighter elements should have a different origin as their ionization is inconsistent with H-like iron. A single-temperature optically thin plasma model is also unable to reproduce the observed spectrum below ~2 keV. A better estimate of both centroid energies and intensities of these lines, which should await improved response matrices, is needed before further investigating their origin.

There are a handful of other Seyfert 2 galaxies with a 6.4-keV iron line having an EW exceeding 1 keV. Interestingly, all of them, like Circinus, are Compton-thick. In NGC 1068 (Ueno et al. 1994) there is clear evidence for both neutral and highly ionized lines, with comparable EWs. Therefore two reflectors, one neutral (probably the obscuring torus), one ionized (the 'warm mirror' discussed above), are at work (Matt et al. 1996). NGC 4945 (e.g. Iwasawa et al. 1993; Done, Madejski & Smith 1996) is more puzzling; the iron line possibly originates in the transmission of the nuclear X-rays through the absorbing material. The source most similar to Circinus is NGC 6552 (Fukazawa et al. 1994; Reynolds et al. 1994), which also can be fitted with an almost pure reflection continuum. It is much fainter than Circinus, and many details (e.g. the Kβ line and the lower energy lines, if due to the same matter) could not have been detected. Circinus is therefore the best example yet of an X-ray reflection-dominated spectrum. Finally, it is worth recalling that Compton reflection-dominated sources have been invoked in the past to explain the shape of the hard X-ray cosmic background (XRB: Fabian et al. 1990). Even if there are now other successful models for the XRB (see Matt 1995 for a recent review), the present result makes the Fabian et al. model a concrete one.

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