A Chandra observation of the H$_2$O megamaser IC 2560

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ABSTRACT
A short Chandra ACIS-S observation of the Seyfert 2 galaxy IC 2560, which hosts a luminous nuclear water megamaser, shows: 1) the X-ray emission is extended; 2) the X-ray spectrum shows emission features in the soft ($E < 2$ keV) X-ray band; this is the major component of the extended emission; and 3) a very strong (EW $\sim$ 3.6 keV) iron K$\alpha$ line at 6.4 keV on a flat continuum. This last feature clearly indicates that the X-ray source is hidden behind Compton-thick obscuration, so that the intrinsic hard X-ray luminosity must be much higher than the observed, probably close to $\sim 3 \times 10^{42}$ erg s$^{-1}$. We briefly discuss the implications for powering of the maser emission and the central source.

Key words: Galaxies: individual: IC 2560 — X-rays: galaxies — masers

1 INTRODUCTION
IC 2560 is a relatively nearby ($D = 26$ Mpc) barred spiral galaxy, classified as a Seyfert 2 (Fairall 1986; Kewley et al 2001). It is notable for exhibiting luminous H$_2$O maser emission from its nucleus (Braatz, Wilson, & Henkel 1996). This maser emission resembles that from the archetypal water megamaser source NGC 4258 in that high-velocity emission is seen up to $\Delta V \approx 400$ km s$^{-1}$ away from the systemic velocity, the systemic emission is much stronger than the high-velocity emission, and centripetal acceleration of systemic velocity features has been reported (Ishihara et al. 2001). The high-velocity emission has not yet been imaged; if the data are interpreted in the framework of a Keplerian disk, as in NGC 4258, the implied central mass is $M_c \approx 2.8 \times 10^6 M_\odot$. Ishihara et al. also analyzed an ASCA observation of IC 2560 and concluded that it possesses a fairly heavily obscured ($N_H \sim 3 \times 10^{23}$ cm$^{-2}$) but low luminosity ($L_{2-10keV} \sim 10^{41}$ erg s$^{-1}$) X-ray source.

In this paper we report on a short Chandra observation of IC 2560, which reveals spatially extended soft X-ray emission and a substantially different nature to the hard X-ray source than was inferred by Ishihara et al. (2001) from the ASCA data. Throughout we assume the distance to the galaxy to be 26 Mpc, giving an angular scale of 120 pc arcsec$^{-1}$.

2 OBSERVATION AND DATA REDUCTION
IC 2560 was observed with Chandra X-ray Observatory (hereafter Chandra, Weisskopf et al 2000) on 2000 October 29-30, using the Advanced CCD Imaging Spectrometer (ACIS). The galaxy was positioned on the back-illuminated CCD, ACIS-S3 detector. The focal plane temperature was $-120^\circ$ during this observation. The data reduction was carried out using the Chandra Interactive Analysis of Observations (CIAO) version 2.2 package and calibration files in the calibration database (CALDB) version 2.10. The S3 detector has been inspected for background flares using a source-free region in the 2.5–7 keV band. The detector background appears to be stable during this observation: the background light curve shows that all the data points are within 30 per cent of the mean value. Since the X-ray source of interest is barely extended beyond the point spread function (see Section 3.1), little impact from such moderate background flares is expected on the spectral data of the source. Therefore no background flare rejection has been applied and the resulting good exposure time is 9.8 ks. The mean count rate of the source, corrected for the background, is $3.2 \times 10^{-2}$ ct s$^{-1}$, sufficiently low that the data are unaffected by pile-up. An aspect offset, which was present in the original event file, has been corrected using the latest 2002-May-02 alignment file; the observed X-ray emission peaks at the position R.A. = $10^h16^m18.7^s$, Dec. = $-32^\circ33'49.6''$ (J2000), about 0.2 arcsec away from the nuclear position in NED and well within the absolute astrometric uncertainty ($\sim 0.6$ arcsec).

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1 NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Tech-
Figure 1. The Chandra ACIS-S3 image of IC2560 in the 0.4–7 keV band. The contours are drawn at seven logarithmic intervals from 2 per cent to 80 per cent of the X-ray peak at the nucleus position. Low surface brightness extension appears to be present in the NE-SW direction. The sky coordinates are of J2000. The angular scale is \(\approx 120 \text{ pc arcsec}^{-1}\).

Figure 2. The radial surface brightness profiles of the 0.4–7 keV emission from IC 2560 (filled circles with solid line histogram) and of a point spread function computed at 1 keV (dotted-line histogram). The data for IC 2560 has been corrected for background and the two profiles are normalized by the peak brightnesses, respectively. One pixel corresponds to \(\approx 0.5 \text{ arcsec or 60 pc}\).

Figure 3. The ACIS-S spectrum of IC2560. The solid histogram shows the best-fitting model consisting of a broken power-law and a gaussian line for Fe K, modified only by Galactic absorption. Note the residuals in the soft X-ray range (see also Fig. 4).

3 RESULTS

3.1 Extended X-ray emission

X-ray emission from IC2560 is found to be extended in the Chandra image. Fig. 1 shows the 0.4–7 keV band ACIS-S3 image of IC2560. The image suggests that there is a faint extension to the SW up to 6 arcsec (\(\sim 720 \text{ pc}\)), and possibly to the NE up to 5 arcsec (\(\sim 600 \text{ pc}\)), although the significance of these features is low (\(\sim 2\sigma\)). The azimuthally-averaged radial surface brightness profile of the image in Fig. 1 is shown in Fig. 2. To investigate the extension of the X-ray core, a point spread function (PSF) is computed and plotted in Fig. 2 for a comparison. The PSF was computed for the same position on the detector as that of IC2560 in this observation, and the energy, at which the PSF was constructed, was assumed to be 1 keV, as much of the detected counts are distributed around that energy (see the energy spectrum in Fig. 3). A simple comparison with the PSF indicates that the core region of IC2560 is extended with a significance of larger than 3\(\sigma\) and at least by 80 pc in radius. The hard band (3–7 keV) image shows a possible elongation in the SE–NW direction, but with only 58 counts detected in the energy range, the reality of this feature is highly uncertain.

3.2 Spectrum

Fig. 3 shows the Chandra ACIS-S spectrum extracted from a circular region with radius of 2.5 arcsec centred on the X-ray peak. A very strong Fe Kα line at 6.4 keV is clearly seen on a faint, flat continuum. A steep rise of soft X-ray emission is seen below 2 keV, which appears to be the major component of the extended emission. When the 0.4–7 keV data are fitted by a broken power-law modified only...
by Galactic absorption (\(N_H = 6.5 \times 10^{20} \text{cm}^{-2}\), Dickey & Lockman 1990) plus a gaussian for the Fe K line (Fig. 3), a spectral break is found at \(E_{br} = 2.0^{+0.5}_{-0.4} \text{keV}\) with photon indices of \(\Gamma = 2.8^{+0.2}_{-0.2}\) and \(\Gamma = 5.5^{+0.2}_{-0.2}\) below and above the break energy, respectively (the quoted errors throughout are 90 per cent confidence limits for one parameter of interest). The line centroid of the Fe K emission is 6.41 ± 0.03 keV when corrected for the galaxy’s redshift. The line is not spectrally resolved: the upper limit to the dispersion of a gaussian is 150 eV. Besides the Fe K line, the residuals of the above fit suggest the presence of soft X-ray emission features, the origin of which is discussed later. The fluxes as observed are \(5.7 \times 10^{-14} \text{erg cm}^{-2} \text{s}^{-1}\) in the 0.5–2 keV band, and \(3.6 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1}\) in the 2–10 keV band. The 0.5–2 keV luminosity corrected for Galactic absorption is \(5.0 \times 10^{39} \text{erg s}^{-1}\). The observed 2–10 keV luminosity is \(2.7 \times 10^{40} \text{erg s}^{-1}\), of which half is contributed by the iron K line.

The flat hard continuum is consistent with a cold reflection spectrum (e.g., Iwasawa, Fabian & Matt 1997 for an example seen in NGC1068). A spectrum of reflection alone from an optically thick cold slab (e.g., computed using pexrav by Magdziarz & Zdziarski 1995 in XSPEC, assuming the incident source to have a power-law spectrum with \(\Gamma = 2\)) is in good agreement with the continuum shape above 3 keV. The Fe K line flux is \((1.32 \pm 0.55) \times 10^{-5} \text{ph s}^{-1} \text{cm}^{-2}\), and its equivalent width with respect to the reflection continuum is extremely large, 3.6 ± 1.5 keV.

Based on the possible emission line features, the soft excess emission could be thermal emission (i.e., collisionally ionized plasma) arising from a nuclear starburst. A fit with a thermal emission spectrum (computed by mekal in XSPEC based on the model calculations of R. Mewe and J. Kaastra with updated Fe L calculations by D.A. Liedahl; Mewe Greunenschidl & van den Oord 1985; Kaastra 1992; Liedahl, Osterheld & Goldstein 1995) gives a temperature of \(kT = 0.63^{+0.11}_{-0.14} \text{keV}\) and 0.03±0.03 solar metallicity. Since the implied metallicity from the fit is much too low to be realistic, this single temperature thermal emission model may not be appropriate. It is unclear whether there is a nuclear starburst in IC2560 capable of producing the thermal emission. Although a number of HII regions distributed along spiral arms have been imaged with Hα+[NII] (Tsvetanov & Petrosian 1995), these HII regions are located 20 arcsec or more away from the nucleus where the X-ray emission is observed, and none of them are detected in the Chandra image. The optical light from the nucleus is dominated by Seyfert 2 emission. The 1.6 μm luminosity of the unresolved nucleus, \(2.3 \times 10^{48} \text{erg s}^{-1}\), as measured with the Near-Infrared Camera and Multiobject Spectrometer (NICMOS) on Hubble Space Telescope (Quillen et al 2001), is as low as typically seen in the non-Seyfert control sample, suggesting that the near infrared emission from the nucleus of IC2560 is largely due to a stellar cluster. Since the near-infrared to soft X-ray luminosity ratio is more than an order of magnitude too low to match those of starburst galaxies, a nuclear starburst does not appear to be powerful enough to produce the observed soft X-rays. An alternative source for the soft X-ray emission is extended photoionized gas. A few suggestive features in the energy range between 0.5–1.4 keV (Fig. 4) could be due to recombination lines and radiative recombination continua from highly ionized N, O, Ne, Fe (L-shell emission) and Mg. The steep rise of soft X-ray emission towards lower energies could be dominated by these and other emission features, which are not resolved at the spectral resolution of a CCD, and a scattered nuclear continuum may not necessarily be present. Higher resolution spectroscopy is required to test this hypothesis.

We analyzed the ASCA data of IC2560, available from the public archive, and confirmed the presence of a strong iron K line with \(EW = 2.2 \pm 0.8 \text{keV}\) at an energy of 6.4 keV in the spectrum. Prior to our Chandra observation, two contrary claims have been reported for the ASCA data: Risaliti, Maiolino & Salvati (1999) found an enormous iron line with \(EW = 6.3^{+2.6}_{-3.0} \text{keV}\) at \(6.56^{+0.25}_{-0.17} \text{keV}\), suggesting a Compton-thick source, while Ishihara et al (2001) interpret the hard X-ray emission as an absorbed power-law with \(N_H \sim 3 \times 10^{23} \text{cm}^{-2}\) without noting the iron line. Our Chandra data support the interpretation of Risaliti et al (1999), although our ASCA results do not agree exactly.

4 DISCUSSION

4.1 The true luminosity of the hidden active nucleus

The hard X-ray spectrum dominated by an iron K line indicates the absence of direct continuum emission from a central source in the Chandra band, meaning that we are seeing only reflected light from a hidden nucleus. The absorption column density must be larger than \(N_H \sim 1 \times 10^{24} \text{cm}^{-2}\), i.e., the X-ray source is Compton-thick. How much of the intrinsic luminosity emitted by the hidden nucleus is seen

\[\text{Flux}\ (	ext{erg cm}^{-2} \text{s}^{-1}) = \frac{10^{-4}}{2 \times 10^{-4}} \times \text{Energy (keV)} \]

Figure 4. The low energy part of the spectrum of IC2560. The data have been corrected for the detector efficiency and the energy scale has been corrected for the galaxy’s redshift (\(z = 0.00975\)).
in reflection depends on the obscuration/reflection geometry. Reflection from cold material, as inferred from the iron line energy and the flat hard X-ray continuum, is not an efficient process, since photoelectric absorption within the reflector suppresses reflected light significantly, in particular at low energies. With the observed continuum luminosity of $1.3 \times 10^{40} \text{ erg s}^{-1}$ in the 2–10 keV band, the minimum incident luminosity to yield the reflection is about $2.6 \times 10^{41} \text{ erg s}^{-1}$. However, in a realistic toroidal geometry in which the incident source is hidden from our direct view, the true value will be much larger.

We estimate the upper limit to the 2–10 keV luminosity to be $\sim 3 \times 10^{42} \text{ erg s}^{-1}$, 10 per cent of the infrared (bolometric) luminosity, $L_{\text{bol}} \sim 3 \times 10^{43} \text{ erg s}^{-1}$ (obtained from the Infra-Red Astronomical Satellite (IRAS) measurements using the formula given in Sanders & Mirabel (1996)), assuming the typical 2-10 keV X-ray to bolometric luminosity ratio for Seyfert galaxies (e.g., Mushotzky, Done & Pounds 1993). The AGN luminosity is likely to be close to the above upper limit, given the warm IRAS colour ($S_{\text{12}}/S_{\text{25}} = 3.4$) and the AGN-dominated nuclear optical spectrum, suggesting that the infrared emission is predominantly powered by a hidden active nucleus.

### 4.2 Large EW of Fe K line

The equivalent width for the iron Kα line, in excess of 3 keV, is one of the largest measured among the reflection-dominated Seyfert 2 galaxies (see Matt et al 2001 and Levenson et al 2002 for recent compilations). Iron overabundance (2–3 solar) could be a possible reason (Ballantyne, Fabian & Ross 2002), but even with solar metallicity, an optically thick torus can produce a very large EW. In models assuming obscuring matter in a toroidal form, the Fe K line EW depends on the optical depth and geometry of the torus (Leahy & Creighton 1993; Ghisellini, Haardt & Matt 1994; Krolik, Madau & Zycki 1994; Levenson et al 2002). All these models indicate that, in order to produce an EW as large as 3.6 keV, a torus needs to have a column density $N_H \geq 3 \times 10^{24} \text{ cm}^{-2}$ (or Thomson optical depth, $\tau_T \geq 2$) and a small half-opening angle, $\theta \leq 20^\circ$, and to be viewed nearly edge-on.

The required column density is consistent with the lack of transmitted primary source emission in the Chandra spectrum, from which the lower limit of the line of sight absorption column density, $N_H \geq 1 \times 10^{24} \text{ cm}^{-2}$, has been derived (Section 4.1). The requirement of a small opening angle means that the X-ray absorbing matter should be located close to the central source. The inner radius of the water maser disk was inferred to be 0.07 pc (Ishihara et al 2001), but the accretion disk could extend inwards, with the inner part of the disk too cold to induce masing (Neufeld & Maloney 1995, hereafter NM95). Perhaps this dense ($n > 10^{10} \text{ cm}^{-3}$) inner part of the accretion disk may be the region where the X-ray absorption primarily occurs. However, in this case, the water maser-omitting part of the disk must be warped in order to see the X-ray flux directly, otherwise the X-rays from the central source will not impinge on the disk.

### 4.3 Water maser disk and accretion flow

If the geometry of the maser emission in IC 2560 is similar to that in NGC 4258, which has not yet been determined by imaging, then we can use the X-ray emission and the kinematic data to place constraints on fueling of the central massive black hole. The observed velocities of maser emission in IC 2560 imply that the outer disk radius is at $R_{\text{out}} \approx 0.26 \text{ pc}$. Assuming that the maser emission is powered by the X-ray flux from the central source (Neufeld, Maloney & Conger 1994; NM95), as appears likely for the majority of H$_2$O megamasers (see Maloney 2002 for a recent review), we can identify the outer radius of the disk with the location of the molecular to atomic phase transition (see equation 4 of NM95). For a hard X-ray luminosity of $L_{2–10} = 10^{42} L_{\odot} \text{ erg s}^{-1}$ and black hole mass $M_\bullet = 10^8 M_\odot$, the ratio of the mass accretion rate to the viscosity parameter $\alpha$ is then

$$\frac{M}{\alpha} \approx 6.2 \times 10^{-3} \left(\frac{R_{\text{out}}}{0.26 \text{ pc}}\right)^{1.23} L_{2-10}^{0.53} M_\odot^{-0.77} M_\odot \text{ yr}^{-1} \quad (1)$$

which, for the inferred mass of the central black hole $M_\bullet \approx 2.8 \times 10^8 M_\odot$, is $M/\alpha \approx 2.8 \times 10^{-3} M_\odot \text{ yr}^{-1}$. Assuming that the bolometric luminosity is approximately ten times the 2–10 keV X-ray luminosity, the product of $\alpha$ and the radiative efficiency factor $\epsilon$ is then $\epsilon \alpha \sim 0.06$, similar to the value inferred for NGC 4258 (NM95). (In making this estimate we have assumed that flow through the disk is steady over the accretion timescale from the disk outer edge, and that the disk sees the true X-ray luminosity.) Although the fractional Eddington luminosity ($\sim 0.03$) and mass accretion rate are much higher than in NGC 4258, the efficiency of radiation appears to be similar. We also note that the Compton-thick obscuration of the hard X-ray source is consistent with the accretion disk itself acting as the obscurer, as in NGC 4258, given the larger derived value of $M/\alpha$.

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