THE IONIZATION FRACTION IN THE OBSCURING "TORUS" OF AN ACTIVE GALACTIC NUCLEUS

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ABSTRACT

The LINER galaxy NGC 2639 contains a water vapor megamaser, suggesting the presence of a nuclear accretion disk or torus viewed close to edge-on. This galaxy is thus a good candidate for revealing absorption by the torus of any compact nuclear continuum emission. In this paper, we report VLBA radio maps at three frequencies and an ASCA X-ray spectrum obtained to search for free-free and photoelectric absorptions, respectively. The radio observations reveal a compact (<0.2 pc) nuclear source with a spectrum that turns over sharply near 5 GHz. This turnover may reflect either synchrotron self-absorption or free-free absorption. The galaxy is detected by ASCA with an observed luminosity of $1.4 \times 10^{41}$ ergs s$^{-1}$ in the 0.6–10 keV band. The X-ray spectrum shows emission in excess of a power-law model at energies greater than 4 keV; we interpret this excess as compact, nuclear, hard X-ray emission with the lower energies photoelectrically absorbed by an equivalent hydrogen column of $\sim 5 \times 10^{23}$ cm$^{-2}$. If we assume that the turnover in the radio spectrum is caused by free-free absorption and that both the free-free and photoelectric absorptions are produced by the same gaseous component, the ratio $\int n_e^2 dl/\int n_H dl$ may be determined. If the masing molecular gas is responsible for both absorptions, the required ionization fraction is $\gtrsim 1.3 \times 10^{-5}$, which is comparable to the theoretical upper limit derived by Neufeld, Maloney, and Conger for X-ray heated molecular gas. The two values may be reconciled if the molecular gas is very dense: $n_{{\text{H}_2}} \gtrsim 10^9$ cm$^{-3}$. The measured ionization fraction is also consistent with the idea that both absorptions occur in a hot ($\sim 6000$ K), weakly ionized (ionization fraction a few times $10^{-5}$) atomic region that may coexist with the warm molecular gas. If this is the case, the absorbing gas is $\sim 1$ pc from the nucleus. We rule out the possibility that both absorptions occur in a fully ionized gas near $10^4$ K. If our line of sight passes through more than one phase, the atomic gas probably dominates the free-free absorption, while the molecular gas may dominate the photoelectric absorption.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: individual (NGC 2639) — galaxies: nuclei — galaxies: Seyfert — radio continuum: galaxies

1. INTRODUCTION

Over the last decade, it has become clear that many, perhaps all, active galactic nuclei, are surrounded by dusty accretion disks or tori on the pc or sub- pc scale (e.g., Antonucci 1993). When viewed equatorially, these tori hide emission from the central regions, and they are believed to be responsible for the observational difference between broad-line objects (Seyfert 1 galaxies, broad-line radio galaxies, and quasars), in which the torus is viewed near pole-on, and narrow-line objects (Seyfert 2 galaxies and narrow-line radio galaxies), in which the torus is viewed near edge-on. This model is supported by a wide range of observational results on narrow-line objects—polarized broad lines (e.g., Tran 1995), reddened nuclei at optical...
wavelengths (Mulchaey, Wilson, & Tsvetanov 1996), broad infrared recombination lines (e.g., Goodrich, Veilleux, & Hill 1994), large gas columns to the nuclei as inferred from photoelectric absorption of soft X-rays (e.g., Turner et al. 1997), and bicones of ionized gas aligned with the radio ejecta (e.g., Wilson & Tsvetanov 1994).

The obscuring material, which appears to take the form of gas clouds in a geometrically thick torus or a warped, thin disk, is illuminated by the central UV and X-ray continuum source. Calculations of the physical and chemical properties of the gas have been made by Krolik & Lepp (1989) and Neufeld, Maloney, & Conger (1994, hereafter NMC). The UV and soft X-rays are expected to be absorbed in thin layers at the surface of the clouds, but hard X-rays may penetrate and heat the interiors. This X-ray heated gas may possess a two-phase structure, in which an atomic phase at \( T \approx 5000-8000 \) K coexists with a molecular phase at \( T \approx 600-2500 \) K (e.g., NMC). The ionization fraction is expected to be \( \leq 10^{-5} \) in the molecular region and a few times \( 10^{-2} \) in the atomic region, but the exact values are sensitive to the X-ray flux and gas density and to details of the chemical and physical processes in the gas. Clearly, an observational determination of the ionization fraction would be of value and is the goal of the present paper.

The ionization fraction may be estimated, in principle, by comparing the emission measure, \( \int n_e^2 dl \) (from measurements of free-free absorption of the nuclear radio emission) with the total equivalent hydrogen column, \( \int n_H dl \) (from measurements of photoelectric absorption of nuclear X-rays), both through the disk or torus. To provide maximum path length for these absorptions, the disk needs to be oriented close to edge-on. Studies of \( \text{H}_2 \) megamaser emission from the nucleus of NGC 4258 reveal that the maser emission arises in a thin Keplerian accretion disk, which is viewed very close to edge-on (Watson & Wallin 1994; Miyoshi et al. 1995). More recent VLBI mapping of other \( \text{H}_2 \) megamasers shows that, in almost all cases, the maser emission traces a line on the sky with kinematics consistent with an edge-on, rotating disk (Greenhill & Gwinn 1997; Greenhill, Moran, & Herrnstein 1997; Trotter et al. 1998). Thus galaxies with detected \( \text{H}_2 \) megamaser emission provide the best opportunity for measuring the ionization fraction of the circumnuclear disk or torus.

NGC 2639 has a LINER-type nucleus (e.g., Ho, Filippenko, & Sargent 1993) and \( \text{H}_2 \) megamaser emission (Braatz, Wilson, & Henkel 1994). Although a VLBA map of the maser emission is not yet available, the systemic maser emission has been found to drift redward at a similar rate to that seen in NGC 4258 (Wilson, Braatz, & Henkel 1995). In NGC 4258, this redward drift is known to result from the centripetal acceleration of clumps of masing gas on the near side of the edge-on accretion disk, as the gas passes in front of the nuclear radio source (Herrnstein et al. 1997). By analogy with NGC 4258, it may be argued that the redward drift in NGC 2639 arises in the same way and that it too contains an accretion disk viewed very close to edge-on. We therefore chose NGC 2639 for a search for absorption by the putative disk.

Throughout this paper, we adopt a velocity of NGC 2639 with respect to the microwave background radiation of \( V_{\text{lsr}} = 3434 \) km s\(^{-1}\) (de Vaucouleurs et al. 1991) and a Hubble constant of 75 km s\(^{-1}\) Mpc\(^{-1}\), giving a distance of 45.8 Mpc and a scale of 222 pc arcsec\(^{-1}\).

2. Observations

2.1. VLBA Radio Observations

NGC 2639 was observed as part of our survey of Seyfert galaxies on 1996 May 31 using the ten antennas of the VLBA\(^2\) at 1.7, 5.0, and 15 GHz. Baseline lengths were from 130 to 5000 km, and NGC 2639 was observed for 57 minutes at 1.7 GHz, 48 minutes at 5.0 GHz, and 46 minutes at 15 GHz. We recorded left circular polarization with 32 MHz bandwidth and 2 bit sampling. Calibration and imaging were done with the AIPS software, using standard methods. The flux density scale was calibrated using standard VLBA antenna gains and measurements of \( T_{\text{sys}} \) made every 1–2 minutes.

We phase-referenced to the nearby source J0832+4913 (2\(^\circ\)1 away, adopted J2000 position R.A. = 08h32m23s21671, decl. = 49\(^\circ\)13\'21\"0388 ± 0.5 mas [Eubanks 1995, private communication]), with cycle times of 9 minutes at 1.7 and 5.0 GHz, and 2 minutes at 15 GHz. After phase-referencing, the data were imaged, deconvolved, and self-calibrated, with convergence achieved after two iterations of phase-only self calibration. This yielded high-resolution images (from untapered \( u-v \) data) with FWHM beam sizes of 6.4 \( \times \) 4.6 mas in p.a. 159\(^\circ\) at 1.7 GHz, 2.0 \( \times \) 1.7 mas in p.a. 169\(^\circ\) at 5 GHz, and 1.2 \( \times \) 0.75 mas in p.a. 105\(^\circ\) at 15 GHz. The rms noise on these images is \( n = 0.14, 0.35, \) and 0.26 mJy (beam area\(^{-1}\)) at 1.7, 5.0, and 15 GHz, respectively, which is similar to the expected thermal noise at 1.7 and 15 GHz, but somewhat higher than the expected value [0.15 mJy (beam area\(^{-1}\))] at 5.0 GHz. For measuring accurate spectral indices, we tapered the array at 5 and 15 GHz to produce approximately the same beamwidth as for the untapered 1.7 GHz array, using spacings from 0.5, 1.2, and 4.2–40 M\(\lambda\) at 1.7, 5, and 15 GHz, respectively. A restoring beam of 6.4 \( \times \) 4.6 mas (FWHM) was then used at all three frequencies. The rms noise levels in the tapered images were 0.69 mJy (beam area\(^{-1}\)) at 5 GHz and 0.77 mJy (beam area\(^{-1}\)) at 15 GHz.

The flux-density measurements have uncertainties due to flux-scale calibration, thermal noise, and deconvolution errors. The flux scale has a nominal uncertainty of 5% at each frequency (uncertainties quoted throughout this paper are rms). Deconvolution effects were estimated approximately by experimenting with different depths of cleaning and sizes of the clean boxes. The test was performed on NGC 1068, which was observed during the same run and in the same way as NGC 2639. A grid of nine different sets of reasonable parameters produced a distribution of total flux densities that had a standard deviation of 6.8%, and we adopt this estimate as the error induced by deconvolution. Resolution effects should be minimal in the measurement of spectral indices, because we have matched the beamwidths at all frequencies and because the source is only slightly resolved. Combining all the above effects in quadrature, the uncertainty on the flux-density measurements is \([0.08S]^2 + n^2]\(^{1/2}\) mJy, where \( S \) is the flux density and \( n \) is the noise given above for each frequency.

2.2. ASCA X-Ray Observations

NGC 2639 was observed by ASCA (Tanaka, Inoue, & Holt 1994) on 1997 April 16. ASCA carries two pairs of

\(^{2}\) The VLBA is part of the National Radio Astronomy Observatory, a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.
removal of times intervals for the SIS and GIS were determined following and hot and flickering pixels were removed. Good time (SIS; hereafter S0 and S1) and the gas-imaging spectrometers known as the solid-state imaging spectrometers (SIS; hereafter S0 and S1) and the gas-imaging spectrometers (GIS; hereafter G2 and G3). The SIS data were obtained in 1 CCD mode, converted to BRIGHT mode, and hot and flickering pixels were removed. Good time intervals for the SIS and GIS were determined following Weaver et al. (1994), with additional SIS screening to remove times ≤ 60 s after South Atlantic Anomaly passages and transitions from satellite day to satellite night.

Data were extracted from within circular regions centered on the source with radii 2.3 and 5.3 in the SIS and GIS, respectively (larger source regions for the SIS do not improve the signal). The SIS background was obtained from an annular ring of width ~ 1.5 on the source chip, while the GIS background was obtained from circular regions in the source field chosen to avoid a nearby serendipitous X-ray source. NGC 2639 has a total ASCA count rate of 0.01–0.02 counts s⁻¹ depending on the detector, 70% to 81% of which is made up of background counts. Subtracting this background yields maximum count rates of 0.01 and 0.006 counts s⁻¹ (keV)⁻¹ for S0 and G3, respectively. We measure smaller count rates in S1 and G2, in which NGC 2639 is positioned about 8' from the optical axis. The effects of vignetting cause the galaxy to be indistinguishable from the background in these detectors above ~ 3 keV. In S0 and G3, NGC 2639 is ~ 5' from the optical axis and thus less affected by vignetting. Therefore we consider only data from S0 and G3 in our spectral fits.

For a weak source like NGC 2639, incorrect background subtraction can cause spurious results. Therefore we have examined background taken from blank-sky fields in addition to background taken from near the source (described above). The choice of background makes little difference for S0 but has a significant effect on the data from G3. We therefore performed two sets of spectral fits with the different G3 backgrounds. The qualitative features of the spectrum do not depend on which background is used, and the errors quoted (§ 3.2 and Table 2) include the uncertainty in the background.

3. RESULTS

3.1. Radio Structure and Spectrum

Radio fluxes of the nuclear source and beam sizes are given in Table 1, while the radio spectrum is shown in Figure 1. Our 5 GHz flux of 47 ± 4 mJy is higher than both a previous VLBI measurement of 27 ± 4 mJy (Hummel et al. 1982, made between 1980 June and 1981 April) and the peak brightness of 23.4 ± 0.9 mJy beam⁻¹ in a VLA map (Ulvestad & Wilson 1989, made on 1985 February 3–4), indicating the source is variable. The source is unresolved at 1.7 and 5.0 GHz, but extended at 15 GHz. The peak flux density in our highest resolution 15 GHz map is 33.8 mJy (beam area)⁻¹, significantly lower than the total flux of 45 ± 4 mJy. The FWHM deconvolved source size is 0.70 × 0.15 mas (0.16 × 0.03 pc) with major axis in p.a. 111°. For comparison, VLA observations reveal an incompletely resolved triple source with overall length 1.4 (310 pc) in p.a. 105° (Ulvestad & Wilson 1989). The agreement between the p.a.'s of the sub-pc scale and the hundreds of pc scale radio emission strongly suggests that the extension

| Parameter | Frequency (GHz) |
|-----------|----------------|
|           | 1.7 | 5.0 | 15.3 |
| Flux Density (mJy) | 6.9 ± 0.6 | 47 ± 4 | 40 ± 3 |
| Beam Size (mas) | 6.4 ± 4.6 | 2.0 ± 1.7 | 1.2 ± 0.75 |

Note.—J2000 position of peak radio flux: R.A. = 08°43'38''07788, decl. = 50°12'20''0044 ± 0.9 mas (absolute position uncertainty).

### TABLE 1

| Flux Densities, Beam Sizes (FWHM), and Position from VLBA Observations |
|--------------------------|----------------|----------------|
| Parameter | Frequency (GHz) |
|-----------|----------------|
|           | 1.7 | 5.0 | 15.3 |
| Flux Density (mJy) | 6.9 ± 0.6 | 47 ± 4 | 40 ± 3 |
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Models of the X-Ray Spectrum

| Model | Γ⁺ | Nₑ(soft) (10⁻²³ cm⁻²) | Nₑ(hard) (10⁻²³ cm⁻²) | χ²/dof (SB⁺) | χ²/dof (BB⁺) |
|-------|-----|-----------------------|-----------------------|---------------|---------------|
| A     | 1.8 (1.4–2.4)⁺ | 0 (0–0.19)⁺ | ... | 56.5/45 | 55.3/45 |
| B⁺    | 2.4 (1.9–2.8)⁺ | 0.03⁺ | 42 (19–98)⁺ | 44.2/44 | 45.6/44 |
| C     | 1.9⁺ | 0.03⁺ | 53 (22–130)⁺ | 47.7/45 | 48.5/45 |
| D⁺    | 1.9⁺ | 0.03⁺ | ... | 46.7/45 | 42.0/45 |

Note.—The 0.6–10 keV and 2–10 keV observed (absorbed) fluxes are ~ 6 × 10⁻¹³ and ~ 4 × 10⁻¹³ erg cm⁻² s⁻¹, respectively. The 0.6–10 keV and 2–10 keV intrinsic (unabsorbed) fluxes are ~ 4 × 10⁻¹² and ~ 2 × 10⁻¹² ergs cm⁻² s⁻¹, respectively.

⁻⁺ Models are as follows: (A) uniformly absorbed power law; (B) power-law source partially covered by Nₑ(hard) and fully covered by Nₑ(soft); (C) like model B, but with Γ fixed at 1.9; and (D) power law plus Gaussian (intended to represent Fe Kα emission) with Galactic absorption only.

α Photon index.

β SB and BB represent fits with the G3 background taken from the source and blank-sky fields, respectively.

The values given represent the 90% confidence ranges for the two free parameters Γ and Nₑ in models A and B and the 90% confidence range for the single free parameter Nₑ in model C. Errors on Γ and Nₑ include the uncertainty in the G3 background.

Cloud covering factor is 0.93 (90% confidence range is 0.83–0.98).

Galactic hydrogen column density toward NGC 2639.

Fixed parameter.

The energy and equivalent width of the Gaussian are 5.5 (90% confidence range is 5.0–5.7) keV and ~ 3 keV, respectively. The line width is fixed at σ = 0.01 keV.
found with the VLBA observations represents the inner part of the jet presumed to fuel the VLA-observed structure. The spectrum of the nuclear source (Fig. 1) is flat between 5 and 15 GHz ($\alpha_{5-15} = 0.04 \pm 0.08$ and $S \propto \nu^{-0.5}$) and turns over sharply below 5 GHz ($\alpha_{1-5} = -1.8 \pm 0.1$). We now discuss various interpretations of the emission mechanism of the nuclear radio source and the cause of the low-frequency turnover.

The brightness temperatures, $T_b$, of the nuclear source are $>1.5 \times 10^{10}$ K, $>9.8 \times 10^9$ K, and $>2.9 \times 10^9$ K at 1.7, 5.0, and 15 GHz, respectively. For comparison, the brightness temperature of the source S1 in NGC 1068, which is believed to coincide with the nucleus and may be thermal in origin, is of order a few times $10^5$ K to a few times $10^6$ K at 8.4 GHz (Gallimore, Baum, & O'Dea 1997; Roy et al. 1998). The high brightness temperature of the source in NGC 2639 makes a thermal origin unlikely.

The three processes that could, in principle, be responsible for the low-frequency turnover are synchrotron self-absorption, Razin-Tsytovich suppression and free-free absorption, and we discuss each in turn. We can ascribe an effective temperature $T_e$ to electrons of a given energy through the equation $3kT_e = \gamma e mc^2$ or $T_e = 2.0 \times 10^9 \gamma e$ K, where $\gamma$ is the relativistic gamma factor of the radiating electrons, $m_e$ is the electron mass, $c$ is the speed of light, and $k$ is Boltzmann’s constant (e.g., Longair 1981). For a synchrotron self-absorbed source, $T_e = T_b$. The brightness temperature measurements are only lower limits and are obviously consistent with a synchrotron self-absorption interpretation. The source is, however, resolved in one dimension at 15 GHz. If we adopt a 15 GHz size of $0.16 \times 0.03$ pc (where the minor axis extent is taken to be equal to its upper limit) and assume the size is the same at 5 GHz (where the spectrum begins to turn over), then $T_e$ (5 GHz) $\approx 2.9 \times 10^{10}$ K, which allows the possibility of synchrotron self-absorption. The mean magnetic field strength would be $\sim 0.5$ G (using eq. [1] of Kellermann & Pauliny-Toth 1981), which is similar to the equipartition value of $\sim 0.3$ G (calculated assuming that the total energy in cosmic rays is twice that in electrons, the radio source is optically thin at 15 GHz, the electron energy spectrum extends from radiated frequencies 10 MHz to 100 GHz with index $\gamma = 2.5$ [$N(E) \propto E^{-\gamma}$], and the source is ellipsoidal in shape with axes $0.16 \times 0.03 \times 0.03$ pc). We should, however, bear in mind that the resolved flux at 15 GHz is only $\approx 25\%$ of the total flux, so most of the observed emission may come from unresolved regions with higher brightness and weaker magnetic fields.

Razin-Tsytovich suppression occurs at frequencies below $\approx 20n_e/B_1$, where $n_e$ is the thermal electron density (in cm$^{-3}$) within the synchrotron-emitting region, and $B_1$ is the perpendicular component of the magnetic field (in gauss). Comparison with the equation for free-free absorption (see below) shows that the Razin-Tsytovich cutoff frequency will lie above the free-free absorption frequency only if $B_1 \leq 4 \times 10^{-5}L^{-1/2}$ G, where $L$ is the dimension of the absorbing region in pc (e.g., Moffet 1975). We can take the measured maximum extent of the source at 15 GHz, 0.16 pc, as an upper limit for $L$, so for Razin-Tsytovich suppression to occur at a higher frequency than free-free absorption, the magnetic field would need to be $B_1 \leq 1 \times 10^{-4}$ G, which is more than 3 orders of magnitude below equipartition. We conclude that Razin-Tsytovich suppression is an implausible explanation for the low-frequency turnover in NGC 2639.

To investigate the possibility that free-free absorption by ionized gas along the line of sight to the radio source is responsible for the low-frequency cutoff, we assume the observed spectrum may be described by

$$S(\nu) = a\nu^{-\delta}e^{-\tau(\nu)},$$

with

$$\tau(\nu) = 8.235 \times 10^{-2}T_e^{-1.35}\nu^{-2.1}\int n_e^2\,dl,$$

where $a$ is a constant, $\tau(\nu)$ is the optical depth to free-free absorption, $T_e$ (K) and $n_e$ (cm$^{-3}$) are the electron temperature and density of the absorbing gas, $\nu$ is the frequency (GHz), and $l$ is the path length in pc (e.g., Mezger & Henderson 1967). The three observed flux densities may be used to solve for the three unknowns ($a$, $\delta$, and $\tau$) in equation (1), given the known dependence of $\tau$ on $\nu$ in equation (2). The result for the spectral index and optical depth is $\delta = 0.25$ and $\tau(5\text{ GHz}) = 0.25$. The value of $\alpha$ should not be taken too seriously (a flux measurement at a higher frequency is needed to tie down the optically thin part of the spectrum), but $\tau$ is well defined by the observed spectrum. The spectrum from this model is shown by the line in Figure 1. The derived value of $\tau(\nu)$ implies

$$\int n_e^2\,dl = 2.3 \times 10^7T_e^{-1.35}\text{ cm}^{-6}\text{ pc},$$

where $T_e = T/d$ K. We discuss the nature of the absorbing gas in §4.

3.2. X-Ray Spectrum

We first modeled the X-ray spectrum as a single, uniformly absorbed power law, but we found the fit to be poor (model A, Table 2), with the data showing an excess over the model above 4 keV. This excess emission is independent of the choice of G3 background and probably represents a heavily absorbed, hard component. A model (model B) comprising a single power-law spectrum absorbed by an
intrinsic medium covering 93% of the source (i.e., “partial covering”) and the Galactic column density \(N_H = 3 \times 10^{20} \text{ cm}^{-2}\) covering the whole source provides an excellent description of the data (again, independent of the choice of G3 background). The part of the X-ray source covered by only the Galactic column could be scattered or intrinsically extended X-ray emission. The best estimate of the photon index is \(\Gamma = 2.4 \pm 0.4\). Constraining the power-law index of the photon spectrum to \(\Gamma = 1.9\) (close to the “canonical” value for Seyfert galaxies) does not significantly worsen the fit (model C). We also tried a model that consists of a power law absorbed by the Galactic column plus a Gaussian function to represent the Fe Kα emission often seen in active galaxies (model D). Such a model describes the high-energy excess as well as models B and C; however, the line energy is much too low to be Fe Kα emission at the redshift of NGC 2639 (Table 2).

Both models B and C require an intrinsic column density \(\int n_H \, dl = (4-5) \times 10^{25} \text{ cm}^{-2}\), although columns half to almost three times as large are acceptable at the 90% confidence level (Table 2). The observed S0 and G3 spectra and model B folded through the instrumental response are shown in Figure 2.

4. THE IONIZATION FRACTION

A number of assumptions must be made in calculating the ionization fraction. First, we assume that the low-frequency turnover in the radio spectrum results from free-free absorption. There is now strong evidence that the VLBI-scale radio sources in several Seyfert galaxies suffer free-free absorption at GHz frequencies (Halkides, Ulvestad, & Roy 1998; Roy et al. 1998; Ulvestad et al. 1998), and our spectrum of NGC 2639 is consistent with this process (synchrotron self-absorption is, however, a viable alternative: see § 3.1). Second, the lines of sight to the hard X-ray source and the compact radio source must be the same. While the resolution of the VLBA is high and the radio source is compact (<0.2 pc), coincidence of the two sight lines is not guaranteed. For example, if some of the radio emission originates from a compact jet, it may be spatially separated from the presumed nuclear hard X-ray source.

Third, we assume that the same gas is responsible for both free-free and photoelectric absorptions. This is not necessarily so, even if the two lines of sight coincide: it is possible that the photoelectric absorption is dominated by weakly ionized atomic or molecular gas that is dense or far from the central ionizing source, while the free-free absorption may result from highly ionized gas of low density or close to this source. The apparent ionization fraction would then represent a suitably weighted average along the line of sight and is not necessarily representative of this parameter in a particular gaseous component. Later in this section (§ 4.4), we explore the consequences of abandoning this third assumption.

Our measurements imply \(\int n_e^2 \, dl/\int n_H \, dl = 140 \ T_e^{-1.35} \ cm^{-3}\), with a formal uncertainty of a factor of \(~2\) (dominated by the uncertainty in \(\int n_H \, dl\)). For a uniform absorbing medium, the ionization fraction is then

\[
x_e = n_e/n_H = 1.2 \times 10^{-4} T_e^{0.675} n_{H10}^{-0.5},
\]

where \(n_{H10} = n_H/10^{10} \text{ cm}^{-3}\). The uncertainty in \(\int n_H \, dl\) translates into an uncertainty of \(~1.4\) in \(x_e\). Within the context of a model in which dense gas is heated and photoionized by a nuclear UV and X-ray source, the absorption could occur in a warm, weakly ionized molecular phase, a hot, weakly ionized atomic phase or a hot, highly ionized atomic phase (listed in order of decreasing distance from the ionizing source). We consider these three possibilities in turn.

4.1. Warm Molecular Phase

For water vapor maser emission, we require (e.g., Elitzur, Hollenbach, & McKee 1989) \(n_H \lesssim 10^{16} \text{ cm}^{-3}\) (to avoid collisional quenching) and gas temperatures \(T_e \sim 600 \text{ K}\) for (collisional pumping). Thus, if the observed column of absorbing gas comprises the masing region, equation (4) implies \(x_e \lesssim 1.3 \times 10^{-3}\) (with the equality for \(n_{H10} = 10^{10} \text{ cm}^{-3}\)), assuming \(T_e = T_\gamma\). This lower limit is comparable with the upper limit of \(x_e \lesssim 5\) derived theoretically for X-ray heated molecular gas by NMC. The theoretical, column-averaged ionization fraction may be as high as several times \(10^{-5}\), depending on the X-ray flux, gas column and pressure (P. R. Maloney 1997, private communication). Thus warm molecular gas could potentially provide both the free-free and photoelectric absorptions, but only if the density is high \((n_H \gtrsim 10^9 \text{ cm}^{-3})\).

4.2. Hot, Weakly Ionized, Atomic Phase

If, on the other hand, the absorption occurs in the hot (~6000 K) atomic region in pressure balance with the molecular region (e.g., NMC), equation (4) implies \(x_e \gtrsim 2.7 \times 10^{-4}\), which is consistent with the few times \(~10^{-2}\) expected by NMC. If our line of sight passes through this atomic region, its free-free absorption should dominate the molecular phase (NMC). Demanding NMC's ionization fraction of \(~2 \times 10^{-2}\), our data imply \(n_H \approx 2 \times 10^5 \text{ cm}^{-3}\) in the atomic region and a path length of \(N_H/n_H \sim 1 \text{ pc}\) for the absorbing gas.

The intrinsic 1–100 keV X-ray luminosity of NGC 2639 is \(L_X = 1.5 \times 10^{42} \text{ erg s}^{-1}\) (for \(\Gamma = 1.9\)) or \(1.1 \times 10^{42} \text{ ergs s}^{-1}\) (for \(\Gamma = 2.4\)). The X-ray flux incident on the gas is \(F_X = 10^5 F_5 \text{ erg s}^{-1} \text{ cm}^{-2}\), where \(F_5 = 0.084(L_X/10^{42} \text{ ergs})\)
\( s^{-1} (R/pc)^{-2} \) and \( R \) is the distance from the X-ray source to the illuminated surface of the gas. For the masing molecular gas and the absorbing atomic phase to coexist, NMC's Figure 1 implies \( F_\gamma / (N_{24}^2 P_{14}) \approx 10 \), where \( N_{24} = 10^{24} N_{24} \) cm\(^{-2} \) and \( p/k = 10^4 P_{14} \) K cm\(^{-3} \) (\( p \) is the pressure). Taking \( N_{24} = 0.5 \) (from the X-ray absorption), \( n_H = 2 \times 10^2 \) cm\(^{-3} \) (see above) and \( T = 6000 \) K for the atomic region, we find \( F_\gamma \approx 0.06 \) and \( R \approx 1.2-1.4 \) pc. This size scale corresponds to \( \approx 5-6 \) mas, which will be easily resolvable in planned VLBA observations of the H\(_2\)O megamaser.

4.3. Hot, Fully Ionized, Atomic Phase

Next we investigate the hypothesis that a fully ionized (\( x_e \approx 1 \)) gas at \( 10^4 \) K is responsible for both absorptions. In this case, equation (4) gives \( n_e \approx 140 \) cm\(^{-3} \), and the absorber path length \( l = N_{10} n_H \approx 1 \) kpc. For a Strömgren sphere geometry, the required number of ionizing photons is

\[
N_\star = x_a n_e^2 4 \pi l^3 / 3
\]

(5)

(\( x_a \) is the total hydrogen recombination coefficient in case B), giving \( N_\star = 9.6 \times 10^6 \) photons s\(^{-1} \). This rate of ionizing photons may be compared with \( N_\star = 3.3 \times 10^{53} \) photons s\(^{-1} \) obtained by extrapolating the measured hard X-ray flux down to the Lyman limit with \( \Gamma = 2.4 \), the best estimate of the photon index of the hard X-ray source. This value of \( \Gamma \) is also typical of radio-quiet quasars between the Lyman limit and 1 keV (e.g., Laor et al. 1997); however, the spectra of LINERs in the ionizing UV are poorly known, so our estimate is very uncertain. Nevertheless, given that the required value of \( N_\star \) is more than 3 orders of magnitude larger than this estimated value, we rule out the possibility that both free-free and photoelectric absorptions occur in the fully ionized phase.

4.4. Multiple Phases

Last, we abandon the assumption that the same gas is responsible for both types of absorption and consider the possibility that the free-free absorption occurs in the fully ionized gas at \( 10^4 \) K, while the photoelectric absorption is dominated by another, weakly ionized component. Taking \( N_\star = 3.3 \times 10^{53} \) photons s\(^{-1} \) from the extrapolation of the X-ray spectrum, \( T_{\text{elec}} = 1 \) and combining equations (3) and (5), we have \( n_e \sim 1000 \text{ cm}^{-3} \) and \( l \approx 20 \) pc, suggestive of a large, dense cloud in the narrow-line region. The implied column density through the fully ionized layer is \( N_H \approx 7 \times 10^{22} \text{ cm}^{-2} \), a factor of 7 lower than inferred from the X-ray spectrum, so a weakly ionized column of \( \sim 4 \times 10^{23} \text{ cm}^{-2} \) would also have to be present. The fully ionized gas would produce an H\( \beta \) flux of \( 1.2 \times 10^{-12} \) ergs cm\(^{-2} \) s\(^{-1} \), which is factor of 8 larger than the observed, reddening-corrected H\( \beta \) flux from the nucleus of NGC 2639 (Ho et al. 1993), so most of this gas would have to be obscured at optical wavelengths in this interpretation.

4.5. Synopsis of Absorption Results

In summary, our data are consistent with the absorptions occurring in any of (1) a warm molecular region of density \( \gtrsim 10^3 \text{ cm}^{-3} \) and ionization fraction several times \( 10^{-5} \), (2) a hot atomic region of density \( \sim 10^3 \text{ cm}^{-3} \) and ionization fraction a few times \( 10^{-2} \), which coexists with the masing molecular gas about 1 pc from the nuclear X-ray source, or (3) a combination of atomic and molecular regions, with the hot atomic region dominating the free-free absorption and the molecular region dominating the photoelectric absorption.

5. CONCLUSIONS

We have found that the spectrum of the nuclear radio source in NGC 2639 turns over below \( \sim 5 \) GHz and shown that this effect may result from either synchrotron self-absorption or free-free absorption. If the latter process is responsible, the implied value of \( \int n_e^2 dl \) may be combined with the equivalent hydrogen column, \( \int n_H dl \) (derived from the X-ray spectrum), to provide the ionization fraction of the gas in terms of the electron temperature and hydrogen density, assuming the same gas is responsible for both kinds of absorption. The lower limit to the ionization fraction obtained by assuming the absorptions occur in the masing molecular gas is comparable to the upper limit to the ionization fraction derived theoretically by NMC for warm molecular gas heated by a nuclear hard X-ray source, implying that the molecular gas must be dense (\( \gtrsim 10^3 \text{ cm}^{-3} \)) if it is to provide the free-free absorption. The required ionization fraction is consistent with that expected in the atomic phase at \( 5000-8000 \) K, which may coexist with the molecular component. If our line of sight passes through both phases, the hot atomic phase would likely dominate the free-free absorption, while molecular gas could dominate the photoelectric absorption. We rule out the hypothesis that both types of absorption occur in a fully ionized gas at \( 10^4 \) K. Planned VLBA imaging of the H\(_2\)O megamaser will help distinguish between these various possibilities.

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