PREVALENCE OF HIGH-X-RAY OBSCURING COLUMNS AMONG AGNs THAT HOST H$_2$O MASERS

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ABSTRACT

Of 104 AGNs known to exhibit H$_2$O maser emission, X-ray data that enable estimation of column densities, or lower limits, are available for 42. Contributing to this, we report analysis of new and archival X-ray data for eight galaxies and collation of values for three more. Masers are indicative of large columns of cold gas, and in five of the eight new cases, maser spectra point toward origins in accretion disks viewed close to edge-on (a.k.a. “disk maser” systems). In these, we detect hard continuum and Fe K$\alpha$ emission with equivalent widths on the order of 1 keV, which is consistent with Compton reflection, fluorescence by cold material, and obscuring columns $\gtrsim 10^{24}$ cm$^{-2}$. Reviewing the full sample of 42, 95% exhibit $N_{\text{H}} > 10^{23}$ cm$^{-2}$ and 60% exhibit $N_{\text{H}} > 10^{24}$ cm$^{-2}$. Half of these are now recognized to be disk masers (up from 13); in this subsample, which is likely to be more homogeneous vis-à-vis the origin of maser emission, 76% exhibit $N_{\text{H}} > 10^{24}$ cm$^{-2}$. The probability of a common parent distribution of columns for disk masers and other AGN masers is $\lesssim 3\%$. Because ground-based surveys of AGNs to detect new disk masers are relatively unbiased with respect to X-ray brightness and comparatively inexpensive, they may also be efficient guides for the sensitive pointed X-ray observations required to identify Compton-thick objects outside of shallow surveys.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: nuclei — masers — radio lines: ISM — X-rays: galaxies

1. INTRODUCTION

Extragalactic H$_2$O maser emission at 22 GHz is known in 104 active galactic nuclei (AGNs) (Zhang et al. 2006; Kondratko 2007; Braatz & Gugliucci 2008; J. A. Braatz et al. 2008, in preparation). In early analyses, the majority of the nuclei for which pointed X-ray observations exist are Compton thick or nearly so, with columns ($N_{\text{H}}$) $\gtrsim 10^{24}$ cm$^{-2}$ (Madejski et al. 2006; Zhang et al. 2006; Greenhill 2007). Zhang et al. (2006) consider all maser-host galaxies, where the emission is associated with either nuclear activity or star formation. In a subsample of 26 with apparent maser luminosity $> 10^6 L_\odot$ (a.k.a. “megamasers”), 85% exhibited $N_{\text{H}} > 10^{23}$ cm$^{-2}$ and 50% exceeded $10^{24}$ cm$^{-2}$. Madejski et al. (2006) focus on a probably more homogeneous subsample for which maser spectra suggest the emission specifically traces rotating, highly inclined disk structures close to the central engines. (We refer to these as “disk masers.”) Seven of nine nuclei with disk masers were Compton thick.

It is plausible that AGNs which host masers are characterized by high $N_{\text{H}}$ in general, because large reservoirs of molecular gas along the line of sight are required to produce substantial maser amplification (Elitzur 1982). Among disk masers, prevalence of high $N_{\text{H}}$ may be anticipated because the emission is believed to arise in inclined disk structures. We have analyzed new, archival, and published X-ray data for maser AGNs and examine the statistics of the updated sample, now about one-third larger than that of Zhang et al. (2006). Masers show promise as signposts of Compton-thick AGNs that are readily detected from the ground. In § 2, we describe new spectral analyses and estimation of $N_{\text{H}}$. We discuss selection effects in the full sample and inferences about maser AGNs in § 3.

2. DATA ANALYSIS

We observed seven maser-host AGNs using the XMM-Newton observatory. In addition, we identified unpublished observations of five disk-maser hosts in the XMM and Chandra archives (12 targets total). All data were reduced using standard tasks in SAS and CIAO. XMM observations of NGC 6323 and NGC 6264 were lost due to flaring; NGC 3735 and NGC 2639 were lost due to high background. Table 1 lists the final sample.

XMM EPIC PN spectra were extracted from 30" circles centered on the brightest pixels within 2" of the target coordinates (comparable to the 1.5" astrometric accuracy). Background spectra were extracted from 80" circles, centered off-source, as far from the readout nodes as the targets. We did not use EPIC MOS data due to smaller effective area above 2 keV. Chandra ACIS target spectra were extracted from 6" circles, while the backgrounds were obtained from annuli centered on the targets, with radii of 15" and 30". The spectra were grouped with 10 counts bin$^{-1}$ and analyzed using XSPEC11.

All eight observations are characterized by relatively hard continua above 2 keV. Importantly, this is accompanied in five sources by Fe K$\alpha$ emission with large equivalent widths (EWs), regardless of continuum model (Table 2; Fig. 1). The strong lines probably arise from continuum reprocessing via fluorescence when the central engine is detected only in Compton reflection (e.g., Levenson et al. 2002, 2006). Since signal to noise is relatively low for a majority of targets, we adopted a “minimum” model with a common set of fixed and free parameters. Because of degeneracies, results are best viewed as indicative. We assumed that the continuum is entirely described by reflection (a PEXRAV model) with underlying (incident) photon index fixed to 1.7. Larger values ($\Gamma \sim 2$; e.g., Zdziarski et al. 1996) observed toward type 1 AGNs are also consistent. We modeled the Fe K$\alpha$ lines as Gaussians with fixed 6.4 keV rest-frame energy and $\sigma = 20$ eV intrinsic width. We also
added a MEKAL component to match better emission below 2 keV. Fitted subsolar abundances, when these arose, were probably not an accurate reflection of composition, but rather a consequence of a one-temperature model and omission of photoionization effects. Separate absorption columns were applied to MEKAL and PEXRAV plus line components.

Spectral fitting with even the minimum model shows Fe Kα line emission in Mrk 34, Mrk 1419, and NGC 6926, as well as marginally in NGC 5793 (Table 2; Fig. 1). We compute EWs or directly from the absorbed power law normalizations.

Comparatively high signal-to-noise ratios enabled fitting more complex models to data for NGC 1194 and NGC 1320. For NGC 1194, we were able to fit a photon index, 1.42 -0.48 , consistent with the value employed for other targets. The spectrum also shows excess consistent with Fe Kβ emission. In order to better represent the spectrum below 2 keV, we added a second MEKAL component with fixed 0.08 keV temperature.

The spectrum of NGC 1194 is still richer, exhibiting evidence above 5 keV for direct transmission from the central engine, which we modeled as an absorbed power law with $N_H = 1.06^{+0.24}_{-0.24} \times 10^{24}$ cm$^{-2}$ and $\Gamma = 2.58^{+0.06}_{-0.04}$. The column presumably arises in the reflector. About 70% of the estimated apparent source luminosity (2–10 keV) arises from transmission. Assuming that this component corresponds to emission from the central engine, the unabsorbed luminosity is $4.4 \times 10^{42}$ erg s$^{-1}$, and the inferred $\Omega/2\pi$ for the reflector is on the order 0.1, which is consistent with that inferred for cold gas in, e.g., NGC 1068 (Colbert et al. 2002; Pounds & Vaughan 2006), Mrk 3 (Pounds & Page 2005), NGC 4945 (Done et al. 2003).

The spectrum of NGC 1194 also includes what appear to be Kα lines from Si, S, and Ca (Table 2). The profiles are broadened, which we hypothesize is due to photoionization and blending of emission from different states, as observed in IC 2560 (Madejski et al. 2006). Because our primary intent is characterization of absorption columns, we only note in passing that treatment of photoionization could be done in detail using an XSTAR model (e.g., Bautista & Kallman 2001).

### 3. DISCUSSION

We have combined published estimates and limits on $N_H$ with results of our analyses to obtain a sample of 42 AGNs (out of 104 known maser hosts). The sample includes: (1) 31 AGNs that exhibit megamasers and weaker emission (Zhang et al. 2018).
Fig. 1.—XMM EPIC PN spectra of 8 AGNs that host H$_2$O masers. Each source was fitted with thermal emission model and a Compton reflection component (Table 2). All except VV 340A and ESO 013-G012 exhibit Fe K$_a$ emission at 6.4 keV (rest). Mrk 34, NGC 1320, and NGC 1194 also show Fe K$_b$ at 7.05 keV (rest). NGC 1194 exhibits evidence as well for (1) direct transmission of the central engine power law spectrum, obscured below ~5 keV by a $1.06 \pm 0.36 \times 10^{24}$ cm$^{-2}$ column, and (2) K$_a$ emission from Si, S, and Ca.

Table 3: Column Measurements among Known Maser AGNs

| Sample                  | $>10^{23}$ cm$^{-2}$ | $>10^{24}$ cm$^{-2}$ | Number |
|-------------------------|----------------------|----------------------|--------|
| Disk masers             | 100%                 | 76%                  | 21     |
| All AGN masers          | 95%                  | 60%                  | 42     |
| Megamasers              | 87%                  | 58%                  | 31     |

* In addition to five sources in Table 2, we recognize 16 other reported disk-maser AGNs with accompanying estimates of $N_H$ or limits: NGC 591, NGC 1068, NGC 1386, NGC 2273, NGC 3079, NGC 3393, NGC 4051, NGC 4258, NGC 4388, NGC 4945, NGC 5728, IC 2560, Mrk 1, Mrk 1210, Circinus, and 3C 403.

Fig. 2.—Left: Distribution of $N_H$ in AGNs that host masers and where X-ray data are available. Shaded bars indicate lower limits. Middle: Distribution for disk masers. Based on geometry, disk-maser hosts are plausibly anticipated to constitute a more homogeneous sample with respect to $N_H$. Right: Distribution for maser AGNs that are not identifiable as disk masers at this time.
emission bracketing the systemic velocity. Disks may be oriented close to edge-on, resulting in large columns toward the central engine, while these spectroscopic markers may nonetheless be absent (e.g., high-velocity masers may be beamed away from the observer due to warping; see Miyoshi et al. 1995).

Zhang et al. (2006) discussed an alternate subsample, selected based on apparent maser luminosity (i.e., megamasers). Within the current sample of 42 AGN with masers, we count 58% (18 of 31) of recognized megamaser hosts are Compton thick (13 from Zhang et al. 2006, plus NGC 1194, NGC 6926, Mrk 1, Mrk 1419, and Mrk 34), matching the incidence among maser AGNs broadly (Table 3). We link the larger incidence of columns >10^{23} cm^{-2} among disk masers to a simple model geometry (edge-on orientation) and contrast this with selection based on maser luminosity, which is nearly always estimated with the convenient but inaccurate assumption of isotropic emission, without knowledge of beam angles and orientation to the line of sight.

Columns \( \gtrsim 10^{23} \text{ cm}^{-2} \) are more common in maser AGNs than in a sample of 22 hard X-ray (14-195 keV) selected, similarly nearby AGNs observed with Swift (Winter et al. 2008), which includes no maser hosts (95% vs. 50%; Table 3). However, for \( N_H > 10^{23} \text{ cm}^{-2} \), incidence rates are similar (60% vs. 50%). For masers in all classes of AGNs, we estimate a statistically similar frequency of Compton-thick columns to that reported by Guainazzi et al. (2005) and Risaliti et al. (1999) among Seyfert 2 objects: 46% (22 of 48) and 65% (22 of 34), respectively. However, this is somewhat below the rate for masers associated with Seyfert 2 nuclei, 74% (20 of 27). The difference is suggestive but comparison of column distributions of maser systems and local type 2 AGNs is complicated by sample incompleteness in luminosity and distance, overlap between the X-ray and maser samples (e.g., 15/45 sources for Risaliti et al. 1999), and uncertainty in X-ray luminosities for obscured AGNs (although aperture and extinction-corrected [O iii] luminosities could be used in place of X-ray estimates; e.g., Meléndez et al. 2008).

Demonstrated correlation between incidence of maser emission and high \( N_H \) may suggest a new strategy for future efforts to identify obscured AGNs. This is of particular interest if such objects are indeed substantial contributors to the hard X-ray background. Heavily obscured AGNs typically have relatively low apparent luminosities and require long integrations (e.g., >100 ks to obtain \( >10^3 \) counts for \( c z = 10^3-10^4 \text{ km s}^{-1} \)). In contrast, maser emission in AGNs as distant as \( c z \approx 10^3 \text{ km s}^{-1} \) can be detected with integrations on the order of 1 ks, using a well-instrumented 100 m–dish antenna. We characterize the relative efficiency of maser and pointed X-ray observations, \( R \), by the ratio of Compton-thick AGNs discoverable in a fixed time by each means, for a sample of optically identified type 2 objects. We obtain \( R \sim 3 \) from \( (10^2 f_M / M_{CT}) / 10^5 X_{CT} \), where \( f_M \) is the maser detection rate (\( \sim 0.03 \); Kondratko et al. 2006), \( M_{CT} \) is the Compton thick fraction of maser AGNs (\( \sim 0.6 \); Table 3), and \( X_{CT} \) is the fraction of type 2 AGNs found to be Compton thick in X-ray studies (\( \sim 0.5 \); e.g., Risaliti et al. 1999).

Deep, wide-field, hard X-ray surveys (e.g., NuSTAR) will extend synergy with maser studies, creating statistically significant X-ray and joint X-ray/radio samples. Nonetheless, there will be practical constraints on survey fields (\( 5^\circ \times 5^\circ \) for NuSTAR), and all-sky radio observations with well-defined completeness criteria could usefully guide pointed follow-up to enrich X-ray samples.

Strengthened correlation between disk-maser emission and large obscuring columns begs the question, is maser gas in disks responsible for obscuration in type 2 objects (Greenhill et al. 2003; Madejski et al. 2006)? On the one hand, obscuration by cold disk gas at radii of 0.2–0.3 pc is inferred in NGC 4258 (Fruscione et al. 2005; Herrnstein et al. 2005), and for Circinus along other lines of sight (Greenhill et al. 2003). On the other hand, time-variable \( N_H \) data indicate obscuration at radii of a few \( \times 0.01 \) pc toward NGC 1365, NGC 4388, and NGC 4151 (Elvis et al. 2004; Risaliti et al. 2007; Puccetti et al. 2007). Direct physical association of maser and obscuring gas volumes still appears to be case-specific. Highly inclined structures that give rise to disk masers probably span a range of radii, at least extending inward with accretion flows. Where these cross the line of sight to the central engine, and how extensively, likely depends on the detailed geometry of each system, requiring case study to establish.

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