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Interstellar scintillation of the water masers of NGC 3079

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Green Bank Telescope observations of the 22 GHz H_2O megamasers in the circumnuclear disk of NGC 3079 revealed rapid variability in the maser lines, with rms variations of typically 10% on timescales of ~ 20 minutes. These variations are most readily explained as weak interstellar scintillation. From the scintillation parameters, we estimate an intrinsic size of the mostly saturated maser features of ~ 12 microarcseconds, which is consistent with models assuming a thick, clumpy accretion disk.

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1. Introduction

Extragalactic radio sources smaller than $\sim$ 50 microarcseconds (μas) in angular size are subject to interstellar scintillation (ISS) at centimetre wavelengths, due to scattering of the radio waves in the turbulent, ionized interstellar medium (ISM) of our Galaxy (e.g. [1]). Observations of ISS can in principle be used to deduce the structure of the radio source on these μas angular scales, as well as properties of the scattering medium responsible for the scintillation (e.g. [2, 3]).

NGC 3079 is a well-studied, almost edge-on spiral galaxy at approximately 16 Mpc [4]. It shows either Seyfert 2 or LINER activity, and there is strong evidence from X-ray data that it contains an active galactic nucleus (AGN) (e.g. [5, 6] and references therein). NGC 3079 also contains one of the most luminous 22 GHz H_2O megamasers known to date (e.g. [7, 8]). Like those of NGC 4258, the H_2O maser emission of NGC 3079 has been interpreted as originating in a circumnuclear disk (e.g. [9 – 11, 6]), although the exact disk models proposed differ between authors. Kondratko et al. [6] recently produced the first map of the full extent of the 22 GHz H_2O maser emission of NGC 3079, between $V_{\mathrm{LSR}} \approx 880$ and 1400 km s^{-1}, contained within a region $\sim$ 30 mas in angular extent. The authors propose a model where the accretion disk of NGC 3079 is thick, clumpy, flaring and undergoing star-formation.

Observations with the Green Bank Telescope (GBT) in April 2006 were aimed at measuring the H_2O maser Zeeman splitting due to the magnetic field in the disk. The observations and analysis are described in detail in [12], and summarised briefly in section 2 below. No circular polarization was detected, giving an upper limit of 11 mG for the toroidal magnetic field at a distance of $\sim$ 0.64 pc from the central black hole. This is the tightest upper limit for the magnetic field around a black hole to date. In addition to the measurement of Zeeman splitting, the sensitive GBT observations have allowed us to study the short-term variability of the masers. Previously, line flux variability of several tens of per cent on timescales of minutes has been observed for 22 GHz H_2O megamasers of the Circinus galaxy [13, 14]. As the timescale of intrinsic maser variations are at least an order of magnitude larger, the Circinus maser variability is most likely due to diffractive interstellar scintillation [15]. In the present paper we discuss the observations and interpretation of short timescale variability of the NGC 3079 H_2O megamasers.

2. Observations and results

Observations of the H_2O megamasers in NGC 3079 were carried out at the NRAO GBT[1] between April 10 and April 19 2006. The GBT spectrometer was used with a bandwidth of 200 MHz and 16,384 spectral channels. This resulted in a channel spacing of 0.164 km s^{-1} and a total velocity coverage of 2700 km s^{-1} which was centered on $V_{\mathrm{LSR}} = 1116$ km s^{-1}. The method of observing and baseline correction is described in [12]. The total observing time was 30.2 hr, of which 20.9 hr were spend on source. Once every $\sim$ 1.2 hr point and focus observations were done on J0958+655. This source was also used as a flux density calibrator. Over the full observation run, the gain does not change by more than 10%, while the variation over several hours in the flux

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[1] The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

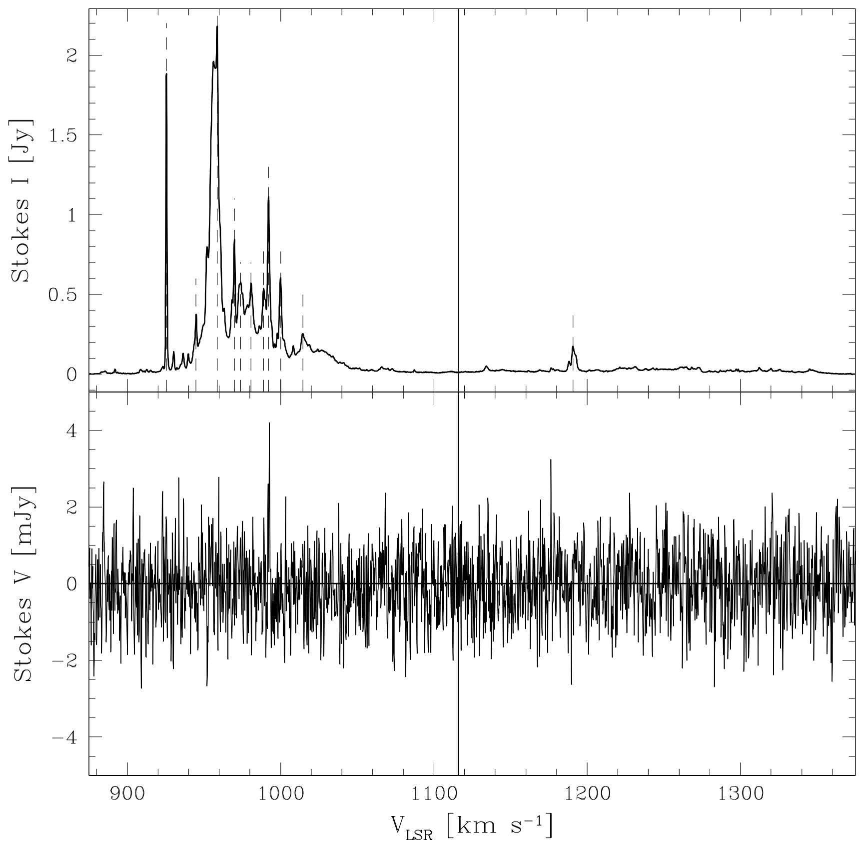

Figure 1: Average total intensity (I, top) and circular polarization (V, bottom) spectrum of the NGC 3079 H_2O megamasers. The solid vertical line at $V_{\rm LSR} = 1116$ km s^{-1}indicates the systemic velocity. The dashed vertical lines indicate the maser features for which the variability parameters are given in Table 1.

density of J0958+655 is $< 5\%$. However, the gain corrections using J0958+655 were only determined every ~ 1.2 hr after correcting the telescope pointing. Accumulated pointing uncertainties and elevation effects can cause a global gain variation of up to $\sim 10-25\%$ between two consecutive observing blocks. Such large variations occur only six times during the whole observing run, and these occasions were found to have no significant effect on our determination of the variability characteristics presented in Section 2.1 below.

Figure 1 shows the average spectrum in total intensity (Stokes I) and circular polarization (Stokes V). No significant circular polarization is detected. These are the most sensitive observations of the H_2O megamasers of NGC 3079 to date. Although the peak flux has varied by up to 50%, the overall shape of the total intensity spectrum is strikingly similar to the earlier spectrum from 2003 seen in Figure 3 of [6]. The only major difference is the appearance of a strong, somewhat isolated blue-shifted feature at $V_{\rm LSR} = 925.5$ km s^{-1}.

2.1 Variability characteristics of the NGC 3079 H_2O megamasers

In contrast with the other maser features, the blue-shifted feature at $V_{\rm LSR} = 925.5$ km s^{-1}showed a steady decline in flux density of ~ 64 mJy/day. A recent spectrum taken with the Effelsberg Telescope shows that the feature was very weak in April 2007. There are several possible mechanisms that can explain such gradual, time-variable behaviour [16]. One possibility is a time-variable maser pump. The H_2O megamasers could be powered by X-ray emission from the AGN, as discussed by [17]. Variations in the AGN would then result in variations in the H_2O maser flux density. However, although the location of the $V_{\rm LSR} = 925.5$ km s^{-1}with respect to the other maser features is unknown, one would expect correlated flux density variation in at least some of the other masers lines. Another more likely explanation is that the variability is caused by the amplification of background emission from another maser feature. As the disk of NGC 3079 is thought to be strongly inhomogeneous, the maser emission is narrowly beamed along the line-of-sight by the overlap of masing regions with similar Doppler velocities. As discussed in [6], chance alignments of masing regions will then result in variability on timescales of severals days or longer.

In addition to the long-term variability seen in the feature at $V_{\rm LSR} = 925.5$ km s^{-1}, the maser features of NGC 3079 also vary on timescales of tens of minutes. There is no significant correlation in the variability of the different maser lines, indicating that the observed variability is not due to calibration errors. Figure 2 shows the light curves of the two brightest maser lines observed on April 17-18 2006. To characterise the variability of the NGC 3079 maser lines, we have determined the discrete autocorrelation function (DACF) following [18]. Following [3], we define the characteristic timescale for variability, $T_{\rm char}$, as the time-lag where the DACF falls to 0.5. We further determine the depth of the first DACF minimum and the modulation index $\mu = \sigma/\langle S \rangle$. Here $\langle S \rangle$ is the mean peak flux density of the maser line and σ the rms of the variability. The variability parameters are given in Table 1 along with the local standard of rest (LSR) velocity, $V_{\rm LSR}$, and the full-width half-maximum (Δv). The velocity and Δv are determined from fitting Gaussian profiles to the maser spectrum. However, many of the maser features are heavily blended, increasing the uncertainties in the velocity and Δv determinations.

3. Interstellar scintillation

Short timescale variability of masers can be caused by gain variation along the maser amplification path. The characteristic timescale of such variability is $\sim L/c$, where L is the maser length. The clumpy masing disk model of [6] predicts clump sizes between 0.001 and 0.006 pc. Taking these sizes as limits on L, this implies a variability timescale of this type of $\sim 10^5$ s, two orders of magnitude longer than the variability timescale detected here. Here we show that not only are the observed rapid variations of the maser features of NGC 3079 readily explained as interstellar scintillation, but that scintillation of these compact sources is indeed expected.

Unlike Circinus which is viewed through the Galactic plane, NGC 3079 is at Galactic latitude $b = +48.36^\circ$. The NE2001 Galactic electron density model [19] predicts a transition frequency of $\nu_0 = 8.8$ GHz between strong and weak scattering along this line-of-sight. Although the model uncertainties of NE2001 are significant at high latitude and for individual lines-of-sight, NGC 3079 is expected to be in the weak scattering regime at 22.2 GHz.

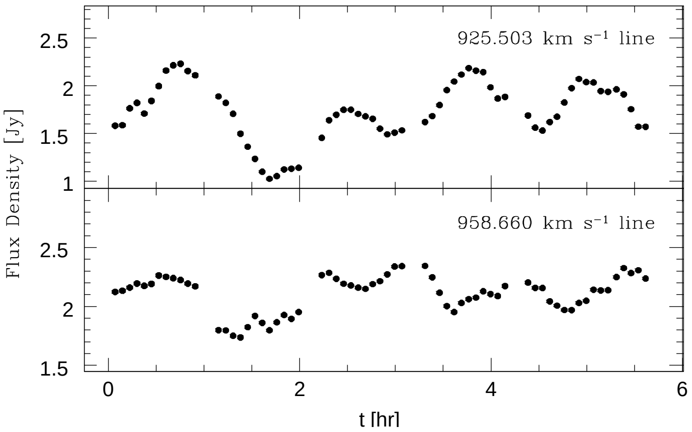

Figure 2: Light curves of the two strongest blueshifted H_2O maser lines of NGC 3079 observed on April 17-18 2006. Data points are plotted for every 4 minute observing scan. The light curve of the maser feature at 925.503 km s^{-1}has been corrected for the observed linear flux density decrease described in Section 2.1.

Velocity (km s^{-1})	Δv (km s^{-1})	$\langle S \rangle$ (Jy)	σ_S (Jy)	μ	$T_{\rm char}$ (hr)	Depth of First Minimum
925.503 ± 0.003[a]	0.81 ± 0.01	1.913	0.255	0.133	0.26 ± 0.03	−0.41 ± 0.08
944.92 ± 0.02	0.77 ± 0.09	0.378	0.042	0.110	0.34 ± 0.04	−0.30 ± 0.09
958.660 ± 0.006	0.89 ± 0.02	2.195	0.197	0.090	0.27 ± 0.04	−0.03 ± 0.06
969.84 ± 0.01	1.05 ± 0.03	0.847	0.089	0.105	0.27 ± 0.05	−0.32 ± 0.10
973.53 ± 0.04[b]	3.4 ± 0.2	0.584	0.050	0.086	0.40 ± 0.10	−0.13 ± 0.09
980.89 ± 0.03	1.45 ± 0.14	0.576	0.047	0.081	0.44 ± 0.07	−0.21 ± 0.09
988.93 ± 0.04[b]	1.4 ± 0.2	0.539	0.045	0.090	0.31 ± 0.05	−0.13 ± 0.09
992.16 ± 0.01	1.30 ± 0.06	1.122	0.097	0.087	0.34 ± 0.03	0.09 ± 0.07
999.89 ± 0.01	1.34 ± 0.06	0.612	0.083	0.136	0.35 ± 0.03	−0.28 ± 0.08
1014.45 ± 0.04[b]	3.3 ± 0.2	0.256	0.025	0.096	0.38 ± 0.10	−0.08 ± 0.15
1190.65 ± 0.03	1.48 ± 0.05	0.177	0.025	0.139	0.37 ± 0.05	−0.27 ± 0.18

[a] For the variability analysis the linear flux density decrease has been removed.

[b] Heavily blended feature.

Table 1: Variability parameters of the NGC 3079 H_2O maser lines.

Using equation 6 from [20] for the frequency dependence of modulation index for weak scintillation of a point source, we find from our observations, with typical modulation index $\mu = 0.1$, that the implied transition frequency between weak and strong scintillation is $\nu_0 = 4.4$ GHz. The transition frequency would be higher if the maser size invalidates the point source approximation. If the source angular diameter θ_S is larger than the angular size of the first Fresnel zone $\theta_F = \sqrt{c/(2\pi\nu z)}$ at the distance z of the equivalent scattering screen, then the modulation index is decreased. At 22.2 GHz, $\theta_F = 59(z/1\mathrm{pc})^{-1/2}$ μas. We have shown in [12] that the H_2O masers of

NGC 3079 are mostly saturated. Assuming saturation, cylindrical masers are beamed by a factor of ~ 3 [21]. As the clump sizes in the maser disk are estimated in [6] to be between 0.001 and 0.006 pc, this yields for the beamed masers, at 16 Mpc, an angular size between 4 and 25 μas. As several maser features are only partly saturated, the beaming is more pronounced, and the angular sizes are even smaller. Thus, taking a typical maser size of $\theta_S = 10$ μas, the scattering screen would need to be at $z \sim 150$ pc to satisfy $\theta_S/\theta_F \approx 2.3$ if the transition frequency is indeed close to the NE2001 model $\nu_0 = 8.8$ GHz, for example.

It is interesting to note that our calibration source J0958+655 (B0954+658), at an angular separation of 9.9° from NGC 3079, showed the prototypical extreme scattering event in 1980-81 [22], which was suggested as being possibly associated with the edge of Galactic Loop III at a distance of 145 pc [23]. This source is also a known intra-day variable (IDV) [24], but at 22 GHz it is not variable enough on short timescales to affect our calibration of the NGC 3079 spectrum. Based on CO observations towards J0958+655, Fuhrmann et al. [25] suggested that an ionized shell or envelope at the edge of a high-latitude molecular cloud may be responsible for the scintillation of the source. The detected CO may be part of the Ursa Major cloud complex at a distance of ~ 100 pc.

However, a distant scattering screen implies a long scintillation timescale. At 22.2 GHz, the variability timescale for a point source is $t_F = 8100\ V_{\rm ISM}^{-1} z^{1/2}$, with $V_{\rm ISM}$ being the transverse speed of the scattering screen with respect to the source in km s^{-1}. For $\theta_S > \theta_F$, the characteristic variability timescale $T_{\rm char} = t_F(\theta_S/\theta_F)$. Thus for a screen at $z = 150$ pc and $\theta_S/\theta_F = 2.3$, $T_{\rm char} = 2.3\ 10^5\ V_{\rm ISM}^{-1}$ s. To reconcile this with the typical observed timescale of 1200 s requires $V_{\rm ISM} \approx 190$ km s^{-1}, which is much larger than the expected value of $V_{\rm ISM} \approx 40$ km s^{-1}corresponding to the velocity of the Earth with respect to the LSR in the direction of NGC 3079 at the date of the observation.

Alternatively, the observed rapid variations and lower transition frequency compared to the NE2001 model prediction could result from scattering in a nearby screen, as has been determined for the handful of extremely rapid "intra-hour" scintillating quasars [26, 3, 27]. Although there are some exceptions, the maser lines in Table 1 have a tendency to display the smallest $T_{\rm char}$ and largest μ for those lines with the lowest $\Delta\nu$, which are thus thought to be only partially saturated. This would be consistent with the corresponding maser features being the smallest due to the increased maser beaming. We thus expect $\theta_S \lesssim \theta_F$ for the partially saturated sources and expect θ_S to be slightly larger than θ_F for the fully saturated sources. Taking $T_{\rm char} \approx 1000$ s from partially saturated masers to be t_F, we find that the velocity and the screen distance have to satisfy $z^{1/2} = 0.12\ V_{\rm ISM}$. For $V_{\rm ISM} \approx 40$ km s^{-1} for a screen moving with the local standard of rest, this indicates $z \approx 25$ pc. This in turn gives $\theta_S \approx \theta_F = 12$ μas, thus the maser feature sizes expected from the scintillation are consistent with those estimated from the saturation level and the clump sizes from [6].

There is a slight tendency for masers with larger μ to show deeper first minima in the DACF. This is also consistent with the sources with lowest μ, thought to be fully saturated, having $\theta_S > \theta_F$. [3] showed that anisotropic scattering in a thin screen produces a deep first minimum or "negative overshoot" in the ACF, and as the source becomes more extended, this "negative overshoot" is suppressed. A deep first minimum in the DACF is also seen for the intra-hour variable quasars and for the H_2O masers in Circinus [14], suggesting that anisotropic scattering in discrete "screens" is a widespread phenonemon.

There is some indication of nearby scattering along other lines-of-sight close to NGC 3079 from the MASIV VLA Survey [28]. The MASIV Survey found that, while a large fraction of all compact, flat-spectrum extragalactic sources vary with modulation indices typically in the range 0.01 to 0.1 at 5 GHz in a 72 hour period, only a tiny fraction ($<1\%$) have characteristic timescales of a few hours or less. J0949+5819, the closest MASIV source to NGC 3079 at an angular separation of 3.2°, showed variations with $\mu = 0.15$ on a timescale of less than a few hours in 2002 January. This is likely to be due to scattering in a nearby screen within a few tens of parsec of the Sun. J0949+5819 was the most extreme variable observed in the first epoch of the MASIV Survey apart from the already known intra-hour variable J1819+3845 [26]. Of the nine MASIV sources within 10° of NGC 3079, five sources showed significant variability in at least three out of four observed epochs (J.E.J. Lovell et al., in preparation), namely J0949+5819, J0946+5020, J0929+5013, J0958+4725, and our calibration source J0958+655. The fraction of IDV sources in the region of sky around NGC 3079 is large, but not exceptionally so compared with the overall statistics of ISS in compact AGN found in the MASIV Survey. However, it is notable that the variations in J0929+5013 were also unusually rapid with a characteristic timescale less than a few hours. Such rapid variability is extremely rare; only a handful of sources in the entire MASIV Survey sample have such short characteristic timescales. The presence of several rapid variables in the region of sky near NCG 3079 is suggestive of these sources being scattered by related structure in the very local Galactic interstellar medium.

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