SCINTILLATION IN THE CIRCINUS GALAXY H2O MEGAMASERS

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ABSTRACT

We present observations of the 22 GHz water vapor megamasers in the Circinus galaxy made with the Tidbinbilla 70 m telescope. These observations confirm the rapid variability seen earlier by Greenhill et al. We show that this rapid variability can be explained by interstellar scintillation, based on what is now known of the interstellar scintillation seen in a significant number of flat-spectrum active galactic nuclei. The observed variability cannot be fully described by a simple model of either weak or diffractive scintillation.

Key words: galaxies: active — galaxies: individual (Circinus) — galaxies: Seyfert — ISM: molecules — masers

1. INTRODUCTION

Water vapor megamaser emission was first detected from the Circinus galaxy by Gardner & Whiteoak (1982), making it the second closest Seyfert galaxy, after NGC 4945, to host water vapor megamaser emission. Recent VLBI observations show that the emission arises in a thin warped disk with a clumpy, wide-angle outflow subtending an angle of ∼80 mas, which corresponds to a linear region of ∼2 pc at a distance of 4.2 Mpc. The nucleus of the galaxy hosts a 1.7 ± 0.3 × 106 M☉ black hole, which is also a powerful X-ray source (Greenhill et al. 2003).

Greenhill et al. (1997) observed very rapid variations in several of the strong maser lines, with timescales as short as a few minutes in one line. They discussed both intrinsic variability and diffractive interstellar scintillation (DISS) as potential mechanisms and concluded that both were possible, although favoring DISS. Both mechanisms placed limits on the physical conditions in the masers, with intrinsic variations requiring short gain paths of 1–10 AU and DISS requiring angular sizes of at most 1.75 mas (≤7 AU at a distance of 4.2 Mpc). The implied brightness temperatures are in excess of 1016 K. Similar conclusions were reached by Maloney (2002).

Over the last 5 years, unequivocal evidence has accumulated that weak interstellar scintillation (WISS) is the principal mechanism responsible for the intraday variability (IDV) observed at centimeter wavelengths in many compact, flat-spectrum active galactic nuclei (AGNs; e.g., Jauncey et al. 2003 and references therein). In the light of these recent developments, we show here that the very rapid variability seen in Circinus is also well described by interstellar scintillation (ISS).

2. OBSERVATIONS

We present data from three epochs, one observation made with the Parkes 64 m telescope on day 289 of (DOY 289 of) 1995 and two observations made in 1996 with the Tidbinbilla 70 m telescope. The Parkes observation has been previously analyzed and published by Greenhill et al. (1997). The details of the observation and data reduction are not reproduced here.

The Tidbinbilla 70 m observations were made at high elevations in left circular polarization on 1996 March 4 and March 28 (DOYs 124 and 148) using a 20 MHz bandpass with 1024 spectral channels, giving a channel spacing of 19.5 KHz or 0.26 km s⁻¹. The bandpass was centered on 537 km s⁻¹ with a velocity range of 402–672 km s⁻¹ on DOY 124 and centered on 355 km s⁻¹ with a velocity range of 220–490 km s⁻¹ on DOY 148 (heliocentric frame of reference). Circinus was observed in position-switching mode with groups of eight 45 s integrations on- and off-source. The total duration of the observations was 2.8 hr on DOY 124 and 1.9 hr on DOY 148.

The data on both days were calibrated assuming a constant 150 Jy system temperature, so there may be small, slow trends due to atmospheric effects and slow changes in gain with elevation. The weather on both occasions was fine, and the measured gain-elevation curve shows that such effects are both slow and small. In addition, there is no significant correlation between the observed variations of different maser features, which indicates that our calibration is adequate. The measured rms noise level in a spectral channel in a 45 s integration was 0.11 and 0.17 Jy on DOYs 124 and 148, respectively. The average spectrum is shown in Figure 1.

Characteristic timescales for variability, T_char, were calculated from the normalized autocorrelation function (ACF) of the light curves for both the Parkes and Tidbinbilla data using the discrete ACF (Edelson & Krolik 1988). Following Rickett et al. (2002), we measure the lag at which the ACF falls to 0.5 as the estimate of T_char. The velocities of the Parkes data have been recalculated, as it appears that these were previously in reference to the local standard of rest (LSR) despite being labeled as heliocentric in Greenhill et al. (1997).

There are some difficulties in calculating the ACF of the data due to the regular observing gaps. This is because the number of points for a lag interval decreases as the lag time approaches...
3. RESULTS AND DISCUSSION

Table 1 summarizes the measured properties of the well-observed lines in the data. The velocity and FWHM of the lines are taken from the fitted Gaussian profiles, as is the mean flux density ($\langle S \rangle$) and the standard deviation of the variability ($\sigma$).

The modulation index, $\mu$, was calculated by $\sigma / \langle S \rangle$. The characteristic timescale, as defined above, is included together with the estimated depth of the ACF at its first minimum. The listed errors were calculated using the estimation error formula of Appendix A of Rickett et al. (2002). The extremely large errors are due to the short observing time and illustrate the need for longer observations.

The light curves presented in Figures 2 and 3, as well as the original Parkes light curves (Greenhill et al. 1997), clearly show the rapid variability in the stronger lines. It is apparent that there

![Light curves of the three strongest lines observed on DOY 124 of 1996 from Tidbinbilla. A range of timescales is apparent in the data, with short-timescale, low-amplitude variations superposed on a much larger, slower trend in the 558 km s$^{-1}$ line. The strongest line, at 564 km s$^{-1}$, is observed to more than halve its flux density in less than 10 minutes. This is the largest proportional change observed in this set of observations.](image)

![Average spectrum of the Circinus megamasers, made using the Tidbinbilla telescope. The two observations made on DOYs 124 and 148, of the red- and blueshifted emission, respectively, have been amalgamated. The velocity range covered by both observations is between 402 and 490 km s$^{-1}$. The regular sampling pattern, with equal integration times on- and off-source, and losses due to calibration and slewing overheads means that there are no data for some lags. Using the discrete correlation function, we excluded those lags that were computed using less than a third of the available data.](image)
is no significant cross-correlation in the Tidbinbilla data between the variations at the different line frequencies, showing that the variations cannot be due to systematic effects, mispointings, or atmospheric effects, for example. Moreover, different lines show quite different timescales, with the 295 km s\(^{-1}\) line on DOY 148 showing much slower variations than the 257 km s\(^{-1}\) line. There is, however, some evidence for rapid, low-amplitude variations superposed on the slow variations in the 295 km s\(^{-1}\) line.

There are two strong lines present in both the Parkes and Tidbinbilla observations (i.e., the 295 and 557 km s\(^{-1}\) lines). In both cases, they are much weaker in the Tidbinbilla observations, having roughly halved their flux densities. The modulation indices, timescales, and FWHM (full width at half-maximum of the fitted Gaussian profile) of the masers have also changed. In the DOY 124 observations of the 557 km s\(^{-1}\) line, it has narrowed considerably and has a slightly faster timescale, whereas the modulation index is very similar. For the 295 km s\(^{-1}\) line, its FWHM is unchanged, whereas the modulation index has doubled and the timescale has significantly increased. A prediction of ISS theory is that the characteristic timescale of variability should change throughout the year as the motion of the Earth around the Sun changes the relative speed of the interstellar medium (ISM) across the line of sight (Macquart & Jauncey 2002). This should then cause the variability of both lines to speed up or slow down. The observed timescale changes in which one line slows down dramatically and the other speeds up tells us that source structure is affecting the scintillation and may be evolving on timescales of a few months. The observed line narrowing in the 557 km s\(^{-1}\) line is indicative of this, and previous observations have indicated that the average lifetime of an individual maser feature is \(\sim 1\) yr.

### 3.1 Weak Scintillation

The quasisinusoidal variations of the light curves in Figures 2 and 3, plus those in Figure 2 of Greenhill et al. (1997), are remarkably similar in amplitude and timescale to the variations seen at 4.8 and 8.4 GHz in the extragalactic radio sources PKS 0405–385 (Kedziora-Chudczer et al. 1997), PKS 1257–326 (Bignall et al. 2003), and J1819+3845 (Dennett-Thorpe & de Bruyn 2000). Weak interstellar scintillation has been demonstrated as the principal cause of these rapid variations in each of these sources, PKS 0405–385 (Rickett et al. 2002), PKS 1257–326 (Bignall et al. 2003), and J1819+3845 (Dennett-Thorpe & de Bruyn 2003), so it follows that WISS should also be considered as potentially responsible for the variability of the lines in Circinus.

These three “fast” AGN scintillators exhibit such rapid variability because they undergo weak scattering and have been found to be behind nearby scattering screens. The evidence for weak scattering is well established; the flux density variations are very broadband and are highly correlated at 5 and 8 GHz, and each of these sources shows much slower variations at 1.4 and 2.4 GHz in the strong-scattering regime.

Another strong similarity between the well-established AGN weak scintillation and the rapid variations in the Circinus masers is the presence of a deep first minimum in the ACF. This is clearly illustrated in Figure 4, which is the ACF of the strongest line in the DOY 124 observations. In the case of PKS 0405–385, the deep first minimum has been shown to indicate scattering in an anisotropic ISM (Rickett et al. 2002).

The evidence for nearby screens for the fast scintillators is also compelling. The linear size of the first Fresnel zone is proportional to \((D/\nu)^{0.5}\), and hence the corresponding timescale for traversing this zone is proportional to \((D/\nu)^0 V_{\text{ISM}}\), where \(D\) is the screen distance, \(V_{\text{ISM}}\) is the speed of the ISM, and \(\nu\) is the frequency. Thus, for the measured values of \(V_{\text{ISM}}\) for these sources, \(\sim 30\) km s\(^{-1}\), and for the observed frequencies of \(~5–8\) GHz where weak scattering predominates in AGNs, screen distances of \(~15–30\) pc are implied for PKS 0405–385 (Rickett et al. 2002), PKS 1257–326 (Bignall et al. 2003), and J1819+3845 (Dennett-Thorpe & de Bruyn 2002).

For Circinus, and following Walker (1998),

\[
T_{\text{char}} = (1.2 \times 10^6)(V_{\text{ISM}})^{-1}(D/\nu)^{0.5},
\]

where \(T_{\text{char}}\) is the characteristic timescale of the observed quasisinusoidal variations (in seconds). Substituting \(T_{\text{char}} = 700\) s, typical of the timescales in Table 1, \(V_{\text{ISM}} = 50\) km s\(^{-1}\) (Rickett et al. 1995) yields a screen distance, \(D\), of 20 pc. If the screen is
moving at the $\sim 30$ km s$^{-1}$ of the LSR and the values determined for the fast scintillators, then the screen distance is reduced to 7 pc. These screen distance estimates are remarkably similar to those found for the three fast AGN scintillators. At 22 GHz, the angular size of the first Fresnel zone is 12 $\mu$as for a screen distance of 20 pc. This is much larger than the expected size of the individual maser features. Galactic masers observed using VLBI subtend milliarcsecond sizes at kiloparsec distances, which implies microarcsecond sizes at megaparsec distances, since the physical sizes are likely to be comparable. The Tidbinbilla observations show that all of the lines that have a sufficient signal-to-noise ratio appear to exhibit rapid variations, as might be expected from the large angular size of the first Fresnel zone. This, in turn, allows an estimate of the transverse extent of the scattering screen. The overall angular scale of the maser emission from the galaxy is $\sim 80$ mas (Greenhill et al. 2003), which at 20 pc projects to a linear size of $2.4 \times 10^8$ km. If all of the disk and outflow lines scintillate rapidly, then this represents a lower limit to the size of the nearby scattering screen. Circinus is the only source that has such close multiple scintillating components, so this is the first time that such a size estimate can be derived.

For this to be weak scattering requires a transition frequency ($v_0$) of somewhat less than 22 GHz. The mean modulation index is 0.19, so following Walker’s (1998) equation (6) and assuming quite reasonably that the maser features are unresolved on a 12 $\mu$as scale yields a transition frequency of 7 GHz, little higher than the $\sim 3$–5 GHz found for the AGN, albeit at higher Galactic latitudes. We are really only looking here at the scattering that is taking place at the nearby screen. Circinus lies at a low Galactic latitude of $-3.8^\circ$, and so the radiation is passing through a dense and turbulent region of the Galaxy. Models of the Galactic electron distribution such as Cordes & Lazio’s NE2001 model$^2$ (Cordes & Lazio 2003) predicts a transition frequency of 56 GHz for the line of sight to Circinus, placing the 22 GHz water maser radiation in the strong-scattering regime. In addition, since this takes the entire path length through the Galactic plane into account, the screens are likely to be at a distance of hundreds or thousands of parsecs. We address the possibility of diffractive scintillation in the next section, but these distant screens are also likely to cause refractive scintillation. This has a characteristic timescale of several hours and a relatively large modulation index given by $\mu = \xi^{-1/3}$, where $\xi$ is the scattering strength (Walker 1998). For the predicted transition frequency of 56 GHz, this results in a modulation index of $\sim 0.6$.

There is a clear observational bias present in our data toward detecting rapid variations on a timescale of minutes to hours but missing those variations with timescales of many hours. Both our data and the well-sampled part of the data of Greenhill et al. (1997) span no more than 3–4 hr. However, both the 1995 Parkes and the 1996 Tidbinbilla data show evidence of longer term variations with timescales of at least several hours. It would appear highly likely, if WISS is the mechanism responsible for these variations, that longer duration observations would uncover longer timescales of hours to days, which would be caused by scattering at a more distant screen(s). This would be the first time that scattering from multiple screens has been observed.

Using a local screen, we can explain many of the observed characteristics of the variability in the Circinus megamasers. However, one problem is that we do not see all the lines varying on a single timescale, which is expected for weak scattering. The large size of the first Fresnel zone means that source structure is unlikely to be responsible for the range of observed timescales unless both the source and scintillation pattern are highly anisotropic. Axial ratios of 6 or more have been suggested for scintillating sources such as PKS 0405–385 and J1819+3845, and VLBI images of Galactic masers often show elongated structures (Imai et al. 2002). Another possibility is that refractive scattering at some distant screen has broadened the image of the maser sources to a size comparable to that of the first Fresnel zone of the local scattering screen. Anisotropic structures will create distinctive patterns in the annual cycle.

It would appear that the rapid variability observed in the maser lines in the Circinus galaxy is indeed consistent with weak interstellar scintillation on the basis of the striking similarities with the variations observed in the other three fast AGN scintillators. Like the fast AGN scintillators, rapid variations imply the presence of a nearby scattering screen, and the presence of such a nearby screen is now more readily acceptable given those already found. These screens for the three AGNs and Circinus are spread widely across the sky and suggest the possible presence not so much of a “local bubble” (Bhat et al. 1998) as the remains of a burst bubble.

3.2. Diffractive Scintillation

Because of the rapidity of the intensity variations in Circinus, Greenhill et al. (1997) and Maloney (2002) both suggested diffractive interstellar scintillation (DISS) in the turbulent ISM rather than the weak scattering in a very nearby screen that we have considered above. With DISS it is feasible to produce such short timescales for the maser lines at 22 GHz using a distant screen. The diffractive timescale is given by $t_{\text{diff}} = t_p/\xi$, and for a scattering strength of 5 (as predicted by the NE2001 model [Cordes & Lazio 2003]) and a screen at 1 kpc, the corresponding diffractive timescale is $\sim 1000$ s.

However, there are several problems in applying diffractive scintillation to the Circinus megamasers. First, as noted by Greenhill et al. and Maloney, the observed $\sim 700$ s timescale observed at 22 GHz implied a timescale that was significantly shorter than found in pulsars at comparable Galactic latitudes at lower frequencies. The diffractive timescale varies with frequency as $(v/v_0)^{1.2}$, which means that the diffractive timescale at 1 GHz is a factor of 40 less than at 22 GHz (Walker 1998). The predicted timescale is therefore on the order of 20 s, which is comparable to some of the most rapidly scintillating pulsars (Cordes 1986).

However, Circinus is extragalactic, whereas most pulsars are within the Galaxy and as such experience less scattering. In addition, the combination of steep pulsar spectra, narrow diffractive bandwidths, and intrinsic pulse variations makes it extremely difficult or impossible to observe very short timescale intensity variability in most pulsars. Intrinsic pulse variations have very large modulation indices (Kramer et al. 2003 reports a modulation index of 1.21 for intrinsic variations at 1.4 GHz in the pulsar B1133+16), and the variations in the pulses are uncorrelated. Looking for ISS involves averaging over a large number of pulses and then examining the variability of the averaged data. The averaging time has to be in excess of 100 pulses to remove the effect of this intrinsic variability, and hence timescales on the order of 10 s or less cannot be easily measured directly. Estimating the strength of the scattering could be attempted by measuring dynamic spectra of the two high–dispersion measure (DM) pulsars (see below) close to the line of sight to the Circinus galaxy.

$^2$ Available at http://rsd-www.nrl.navy.mil/7213/lazio/ne_model/.
In modeling the variability of the Circinus megamasers as due to diffractive scintillation, we note that the masers have a modulation index of \( \mu = 0.20 \), rather than unity, as would be expected for diffractive scintillation. This implies that the source has structure on scales greater than the diffractive limit. This extended structure acts as a spatial filter, reducing both the speed and amplitude of the variations.

In quenched diffractive scintillation, the modulation index is reduced to \( \mu = \theta_S/\theta_{\text{diff}} \), and the timescale is increased by a factor of \( \theta_S/\theta_{\text{diff}} \) so that the dominant length scale is now the linear size of the source as projected onto the scattering screen. Using this model, the observed timescale of a maser feature would be proportional to its angular size. Taking the most rapidly varying feature with its 700 s timescale and modulation index of 0.20, we can apply plausible estimates of source size and ISM velocity to investigate the screen. Using an ISM speed of 50 km s\(^{-1}\) and a source size of 1 \( \mu \)as, we obtain a screen distance of \( \sim 230 \) pc, with a scattering strength of 18 and a transition frequency of 120 GHz. Decreasing the assumed angular size of the masers increases both the implied screen distance and the scattering strength. For a 0.25 \( \mu \)as maser (which corresponds to a linear size of \( \sim 1 \) AU at Circinus), the implied screen distance is \( \sim 1 \) kpc with a scattering strength of \( \sim 40 \) and a transition frequency of \( \sim 200 \) GHz. Although this is extremely high and well above that predicted by the NE2001 model for the line of sight to Circinus, it is characteristic of lines of sight at lower Galactic latitudes. We have inspected the Australia Telescope National Facility (ATNF) pulsar database,\(^3\) and it is worth noting that the two pulsars closest to Circinus both have quite high DMs, \( \sim 250 \) pc cm\(^{-3}\), which is higher than that of other pulsars at comparable Galactic latitudes. We have used the ATNF pulsar database to produce a DM map of the Galactic plane near to the line of sight to Circinus (Fig. 5), which shows that the line of sight to Circinus is associated with high DMs. This suggests that either the pulsars in this region are more distant than some of the other, less scattered pulsars or that there is some enhanced scattering occurring along that line of sight, or perhaps both. At present, none of the pulsars used in the DM map have had their distances measured independently. H\(\alpha\) images of the same region show strong emission nearby, which is suggestive that enhanced scattering may be present.

Another problem with applying a diffractive scintillation model is that the expected anticorrelation between timescale and modulation index is not apparent in the data. Figure 3 illustrates this well with the very large amplitude flux variation in the 295 km s\(^{-1}\) line occurring on a very long timescale, contrasted with the rapid, lower amplitude variations in the 256 km s\(^{-1}\) line. This may be an effect of source and/or screen anisotropy, which is suggested by the deep first minima of the ACFs, which will produce a range of timescales depending on the relative orientations of the axes of anisotropy and screen velocity.

4. CONCLUSIONS

We have shown that the variability of the Circinus megamasers has continued since its first detection and that it can be explained through ISS. The Circinus megamasers offer a unique opportunity to study both the interstellar scattering medium and the structure of extragalactic megamasers at high angular resolution.

There are several experiments that can be made to confirm that scintillation is the cause of the variability and identify whether it is due to a weakly scattering local screen or a strong...
distant one. Monitoring the variability of the Circinus megamasers will allow us to test for the presence of an annual cycle in its characteristic timescale. The annual cycle is created by the motion of the Earth around the Sun and can be used to measure the peculiar velocity of the scattering material, to estimate the extent and orientation of anisotropies in the medium, and to create a model of the source itself, as has been accomplished for PKS 0405–385 (Rickett et al. 2002), J1819+3845 (Dennett-Thorpe & de Bruyn 2003), and PKS 1257–326 (Bignall et al. 2004). Both of our ISS scenarios expect that the scattering medium will be anisotropic and that source structure is directly involved in the timescale of variability. This means that different maser features may display different annual cycles as a result of their structure. In the case of a local screen, its intrinsic velocity is likely to be comparable to the LSR, producing a clear annual modulation index of at most 50 km s$^{-1}$. A more distant screen may have some significant intrinsic velocity, which will make the annual cycle harder to detect as the difference between the high and low speeds becomes proportionally less. The relative transverse speed of the ISM can also be directly measured by observing the time delay between the scintillation patterns recorded at two widely separated telescopes, as has been done for PKS 0405–385 (Jauncey et al. 2000), PKS 1257–326 (Bignall et al. 2004), and J1819+3845 (Dennett-Thorpe & de Bruyn 2002) using intercontinental baselines. A direct measurement of the ISM velocity is an extremely valuable constraint in producing models of anisotropic structure.

These experiments will not conclusively distinguish between a local or distant screen model. One test would be to investigate longer timescale variability, which is predicted by both models as a result of refractive scintillation at some distant screen. In the local screen scenario, the refractive timescale would be decoupled from that of the rapid variations, whereas in the distant screen both the diffractive and refractive variations would display the same annual cycle. The masers should all be point sources to refractive scintillations, and so the timescale and modulation index is expected to be the same for all the masers. In addition, the pulsars near Circinus provide another probe of the ISM. If characteristic timescales and diffractive bandwidths can be measured from dynamic spectra, then these can be used to make estimates of the screen strength and distance.

We have shown that the presence of variability in the Circinus megamasers can be explained as being due to ISS and have presented two models. At this stage, both require unusual, although not unprecedented, conditions to explain some characteristics of the Circinus megamasers. The local screen model using weak scintillation can explain the observed variability using a local, weakly scattering screen with a distance of at most 20 pc and $v_0 \sim 7$. This is comparable to what has been observed in the most rapidly scintillating AGN sources. The appearance of the light curves is also strongly reminiscent of those seen in scintillating AGNs. However, it does have some problems in explaining the observed range of timescales, since the angular size of the first Fresnel zone vastly exceeds that of any realistic source unless there is also scattering by a more distant screen. In addition, the low Galactic latitude of Circinus and the predictions of models of the Galactic electron distribution suggest that strong scattering and distant screens should be involved. The distant, strongly scattering screen model we have proposed satisfies most of our observations and fits with the predictions of electron density models. However, it predicts an anticorrelation between modulation index and timescale, which we do not observe. Further observations will allow us to refine our models and to resolve some of our present uncertainties.

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