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DISCOVERY OF A SUBPARSEC JET 4000 RADII AWAY FROM THE CENTRAL SCHWARZSCHILD ENGINE OF NGC 4258

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ABSTRACT

We report the VLBI detection of compact continuum emission associated with the maser disk in NGC 4258. The strongest emission is located about 0.5 mas (0.015 pc) north of the dynamical center of the disk. It has an average flux density of about 3 mJy and varies by ∼100% on timescales of weeks. We postulate that we have detected nonthermal synchrotron emission in the base of the northern jet, which is seen on parsec-to-kiloparsec scales in radio to X-ray emission. We also report a detection of emission from the southern jet which may be attenuated by thermal absorption in a layer of ionized gas above the molecular disk. The average flux density of the maser emission in the systemic velocity range is correlated with the flux density of the northern continuum emission. Together with the geometry of the disk, these data suggest that the masers amplify the southern continuum emission and that the southern and northern jet emission are correlated in strength. We discuss the results in the context of jet emission models and properties of other compact radio continuum sources.

Subject headings: accretion, accretion disks — galaxies: individual (NGC 4258) — galaxies: jets — galaxies: nuclei — galaxies: Seyfert — masers

1. INTRODUCTION

VLBI observations of the H_2O maser in the weakly active Seyfert 2 galaxy NGC 4258 reveal an extremely thin, approximately edge-on disk in nearly perfect Keplerian rotation (Miyoshi et al. 1995; Moran et al. 1995). Maser features at the systemic velocity of the galaxy (the systemic features) appear to lie along the inner edge of the near side of the disk, about 0.1 pc from the dynamical center of the system (for a distance of 6.4 Mpc). High-velocity maser features on either side of the systemic features extend from 0.13 to 0.26 pc from the dynamical center. These features possess negligible LOS accelerations (Greenhill et al. 1995) and appear to be confined to the diameter defined by the intersection of the disk with the plane of the sky (the midline). The Keplerian rotation curve exhibited by the high-velocity masers requires a central binding mass of 3.5×10^7 $M_{\odot}$. The disk is slightly warped (Herrnstein et al. 1995), and significant portions of the disk may be directly illuminated by the central X-ray source.

On larger scales, NGC 4258 possesses symmetric jets extending to kpc scales and radiating via radio synchrotron, Hα, and X-ray emission (Cecil, Wilson, & Tully 1992; Cecil, Wilson, & DePree 1995). These jets appear to be composed of several twisted strands. VLA continuum observations indicate that at the 70 pc scale the jets are well aligned with the rotation axis of the subparsec masing disk (Cecil, Morse, & Veilleux 1995). A highly absorbed X-ray source with 2–10 keV luminosity of 4×10^{40} ergs s^{-1} was detected with *ASCA* (Makishima et al. 1994). VLA observations reveal a compact radio source within $0\farcs1$ of the maser emission possessing a 2 cm flux density of ∼3 mJy and a spectral index $\alpha(F_\nu \propto \nu^\alpha)$ of ∼0.4 (Turner & Ho 1994).

Although compact nuclear radio emission has been studied with VLBI in many active galactic nuclei (AGNs), NGC 4258 is an exceptional laboratory for two reasons. Firstly, the mass of the central object and the fundamental length scale defined by the Schwarzschild radius ($R_{\rm S}$) are known with precision. And secondly, the H_2O maser emission provides a local reference frame in which the relative position of the central mass and the continuum emission at 22 GHz can be measured with submilliarcsecond precision. VLBI imaging of the central regions of AGNs usually is limited by a need to make assumptions about the precise location of the center of mass of the system. The maser emission in NGC 4258 obviates the need for such assumptions. We discuss VLBI and VLA observations of 22 GHz continuum emission in NGC 4258; the maser results will be reported separately.

2. VLBA OBSERVATIONS AND RESULTS

We observed the masers in NGC 4258 with the Very Long Baseline Array (VLBA) plus the phased VLA of the NRAO[1] on 1994 April 19, 1995 January 8, 1995 May 29, and 1996 February 22. The observations ranged in duration from 8 to 15 hours. Frequency coverage consisted of four, 8 MHz bands of 512 channels each, with a channel spacing of 0.2 km s^{-1}. Receiver tuning limitations at the VLA made it impossible to simultaneously cover the full 150 MHz of maser emission. Thus, the red- and blueshifted maser emission were observed on alternate scans, while the systemic emission was observed throughout. This

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allowed a strong systemic maser feature to be used as a phase reference.

Calibration and imaging were accomplished using standard spectral-line VLBI techniques. Residual delays and fringe rates due to uncertainties in station clocks were estimated and corrected by observations of 4C 39.25, 1308+326, or 3C 345 at 16 minute intervals. Station and source positions and earth orientation parameters were taken from the US Naval Observatory database (Eubanks 1996, private communication). The overall clock calibration was accurate to about 1 ns, and the associated phase errors contribute negligibly to the error budget. Errors in the astrometric position of the reference maser feature result in systematic errors in the positions of emission at other frequencies. These errors scale linearly with frequency offset from the reference feature, and, for emission at the frequencies of the high-velocity features, are about 3.4 μas per mas error in the reference feature position. Analysis of fringe rates for the reference feature establishes its position to better than 10 mas (Herrnstein 1996), and the resulting systematic errors are less than 35 μas. The naturally weighted synthesized beam for the VLBA plus VLA at 22 GHz is about 1 mas, and sensitivity considerations precluded the use of uniform weighting. The continuum detections are all between 5 and 10 σ, and thus the relative positional uncertainties of the continuum source are signal-to-noise limited and between 50 and 100 μas.

Amplitude calibration for the VLBA antennas relied on system temperature measurements and tabulated values for antenna system equivalent flux densities. Phased VLA amplitude calibration was accomplished with antenna temperature measurements for sources of known flux density. Absolute amplitude calibration is accurate to $\sim$10%, and uncertainties in continuum flux are dominated by map noise, which averaged about 0.4 mJy beam^{-1}.

Continuum maps were generated by averaging in frequency after delay and fringe rate calibration, and by excluding the bands with systemic maser emission, which would otherwise completely dominate any continuum emission near the center of the disk. The high-velocity masers are more than 5 beamwidths from the disk center and are readily distinguishable from any central continuum emission. Continuum emission was detected in the first, third, and fourth VLBA epochs, with an average peak flux density of about 3 mJy and significant variability. Figure 1 was generated by combining data from all four VLBA epochs after re-referencing to the systemic maser feature at 509 km s^{-1} (LSR). The continuum emission shows a clear north-south extension that is approximately aligned with the rotation axis of the maser disk. The emission appears to be concentrated into a northern and a southern source, with the northern emission being at least 3 times stronger than the southern in each epoch. The northern emission is unresolved, indicating a linear scale of less than 10^4 R_S (0.03 pc) and a brightness temperature of at least 10^7 K.

Figure 1 also shows the centroid position of the northern feature at each epoch, as well as the systemic maser positions and the location of the dynamical center of the maser disk. The northern continuum emission ranges from 0.4 to 1.0 mas (0.012–0.03 pc; 4×10^3–1×10^4 R_S) north of the dynamical center, and the southern emission appears to be 2–3 times further south of the center. The position of the dynamical center was estimated using a global χ^2 minimization algorithm on the maser data. A detailed error analysis incorporating statistical noise, ambiguities in distinguishing between local and global minima, and improper modeling of the warp indicates that the total uncertainty in the

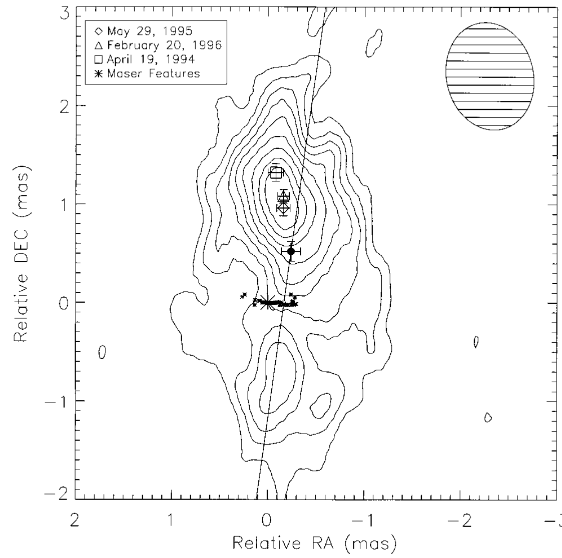

FIG. 1.—Systemic maser and continuum positions in NGC 4258, as measured with the VLBA. The continuum contours are the result of co-adding images from all four VLBA epochs. The vertical line is the projection of the maser disk rotation axis on the plane of the sky. The rms noise in the map is 0.14 mJy beam^{-1}, and the contouring is in 1 σ steps from 4 σ. The large asterisk marks the reference maser feature at 509 km s^{-1}, and the filled circle is the center of the molecular disk. Note that the high-velocity features are displaced 4–8 mas in R.A. from the disk center and are not shown here.

fitted disk center is about 100 μas (Herrnstein 1996). Hence, the northern offsets of the continuum emission are significant at the 4, 4, and 7 σ level for each of the three detections. We note that forcing the disk center to be coincident with the northern continuum emission results in a global reduced χ^2 of >20, as compared to $\sim$1.5 when the fitted disk center is unconstrained. We conclude that *the continuum emission is offset significantly from the dynamical center of the molecular disk and speculate that the emission may arise in the base of the symmetric jets seen on kiloparsec scales.*

In two of the three detections we were able to image the continuum source independently in two different continuum bands separated by 1600 km s^{-1} (1224 to 1493 km s^{-1} and -530 to -347 km s^{-1}), and the emission was present in both bands with consistent positions and flux densities. This confirms the broadband nature of the emission. Maps of the continuum were also made after extracting all of the channels known to contain red- or blueshifted maser emission prior to averaging the bands in frequency. This did not significantly affect estimates for the strength or position of the continuum emission, indicating that it is not an artifact of the high velocity masers. Finally, continuum maps were made from the bands containing systemic maser features to search for emission well displaced from the disk center. No evidence for such continuum emission was present at the 1.5 mJy level (4 σ) in the 52 mas field of view.

3. VLA OBSERVATIONS AND RESULTS

NGC 4258 was observed five times with the VLA at 22 GHz between 1995 November and 1996 February, with tracks ranging from 15 minutes to 3 hr. The weather was good for all epochs. The array was in the B configuration for the first epoch, the CnB configuration for the second and third epochs, and the C configuration for the final two. 1146+399 was used for phase calibration in all epochs and as a flux calibrator for one of the epochs. 3C 286 was used for flux calibration in the

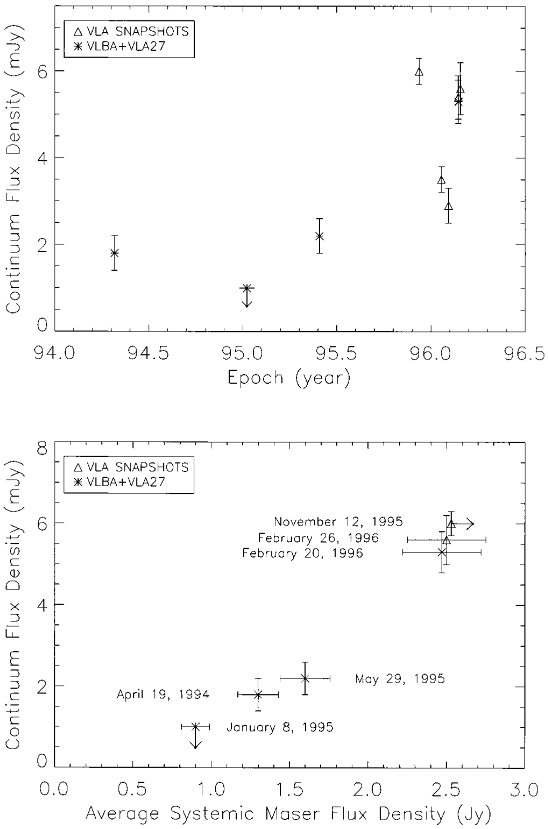

FIG. 2.—*Top*: Continuum flux density as a function of time. *Bottom*: Continuum flux density versus average flux density of systemic masers. The latter was generated by averaging over the central 3 MHz (40 km s^{-1}) of the systemic maser emission. VLA27 refers to the phased VLA. VLBA flux densities measure the northern continuum component only. The VLA measurements include any southern emission as well.

remaining four epochs. Amplitude calibration is accurate to ~5% when 3C 286 is used and to ~10% otherwise. In most cases, uncertainty in the continuum flux density was dominated by thermal noise in the map, which averaged ~0.4 mJy. The continuum emission was unresolved by the 300 mas beam of the B-configuration. The observations were performed at frequencies well outside the range of known water maser emission, ~2500 km s^{-1} from the galaxy's systemic velocity. The top panel of Figure 2 presents both the VLA and the VLBA data. *The continuum emission is time variable by up to 100% over timescales of a few weeks.* The good agreement between the VLBA and VLA observations of 1996 February 22 provides a consistency check for the amplitude calibration of both. In addition it establishes that the VLA observations are not contaminated by additional sources in the comparatively large VLA beam.

4. DISCUSSION

Compact radio emission is observed in the nuclei of virtually all types of galaxies, from quasars to quiescent ellipticals (Kellermann & Owen 1988; Wrobel & Heeschen 1991). The high-brightness temperatures and flat or inverted spectra of these sources suggest that they emit via self-absorbed, nonthermal synchrotron radiation. The majority of compact sources possess a parsec-scale core-jet morphology, in which a bright core is located at one end of a jetlike structure. Superluminal motion is observed between the core and components of the jetlike feature in about half of the compact sources hosted by quasars and AGNs (Vermeulen & Cohen 1994). In the "standard model" for such systems (Blandford & Königl 1979, hereafter BK) the core-jet structure arises in the base of a relativistic bipolar outflow. The core is a stationary feature located in the nozzle of the jet, at the point where the relativistic plasma becomes opaque to its own nonthermal synchrotron emission. The jet features are shocks or other inhomogeneities in the relativistic flow. This model accounts for many of the observed features of superluminal systems. However, one of its more distinguishing characteristics has not been unambiguously confirmed. The BK model requires that *all* detected emission be offset from the central engine of the jet since no emission should be visible below the stationary core, at the point in the jet nozzle where the plasma transitions from optically thick to optically thin. The predicted minimum offset is of order 10 pc at 1 GHz for a jet with a total power of 10^{44} ergs s^{-1} and scales as ν^{-1} and jet power to the 2/3 power (eq. [28] of BK). While there is observational evidence for stationary cores in compact radio structures (Bartel et al. 1986; Junor & Biretta 1995), the relative position of the central engine with respect to the cores is not known in these systems.

NGC 4258 provides a superb laboratory for testing the core-jet standard model because the water masers pinpoint the dynamical center of the system and define the orientation of the jet axis while providing a stable reference frame suitable for μas relative astrometry. In the three continuum detections, the minimum offset of the northern jet emission from the dynamical center of the disk is ~0.4 mas (0.012 pc; Fig. 1). This can be compared with the predicted minimum offset of the stationary core at 22 GHz in the BK model. Observations of scattered optical light in NGC 4258 suggest a nuclear bolometric luminosity of 10^{42-44} ergs s^{-1} (Wilkes et al. 1995). *ASCA* observations show a 2–10 keV luminosity of 4×10^{40} ergs s^{-1} (Makishima et al. 1994). If 10% of the energy of the accreting matter is released as X-rays in such systems, these observations together suggest an accretion disk luminosity of about 10^{42} ergs s^{-1}. The ratio of total jet power to disk power is thought to be of order unity over a very broad range of system energies (Rawlings & Saunders 1991; Falcke, Malkan, & Biermann 1995), and we adopt a value of 10^{42} ergs s^{-1} for the total jet power. The core offset also depends on the jet bulk Lorentz factor (γ_j), the jet opening angle (ϕ), and the angle between the jet and the line of sight (LOS). The last quantity is known from the maser disk to be 82°, and we estimate $\phi = 15°$. This is consistent with the angular displacement of the northern continuum emission from the disk rotation axis (Fig. 1). With these parameters, the BK model predicts a core offset of approximately $2\gamma_j^{-2}$ mas. *The observed minimum offset of the northern continuum emission is consistent with the stationary core offset predicted by the BK model for* $\gamma_j \simeq 2$. The more general requirement that all emission lie beyond the stationary core requires $\gamma_j \gtrsim 2$. Ghisellini et al. (1993) estimate $\gamma_j \simeq 10$ for a sample of 40 superluminal sources, and Falcke et al. (1995) conclude that $3 \lesssim \gamma_j \lesssim 10$ for a sample of 170 radio-loud and radio-weak quasars. Thus this lower limit on γ_j is quite reasonable. In the first VLBA continuum detection (observed more than a year before the other two), the northern offset is approximately twice as large. Following the BK model, it is plausible to associate this emission with shocks in the jet, in which case we might expect this feature to move at approximately the jet bulk velocity. However, we note that numerical simulations (Daly & Marscher 1988; Gómez et al. 1995) demonstrate the potential for standing shocks in the jet downstream from the stationary core.

There is considerable evidence suggesting that the core-jet model of compact radio emission is not limited to superluminal sources. Falcke & Biermann (1995, 1996) demonstrated a correlation between UV and radio luminosity spanning 8 orders of magnitude in energy, in systems ranging from galactic sources to quasars. They postulate that in all these systems the radio emission arises in a core-jet structure and that mass and energy conservation between the jet and an accretion disk result in the observed UV/radio correlation. For a disk luminosity of $\sim 10^{42}$ ergs s^{-1} and with $L_{22\,\mathrm{GHz}} \simeq 10^{26}$ ergs s^{-1} Hz^{-1}, NGC 4258 falls along this UV/radio correlation.

If the continuum emission in Figure 1 does arise in the base of a symmetric jet, then the relative faintness of the southern component cannot be due to differential beaming effects because the jets, which seem to be aligned with the spin axis of the maser disk, are tipped 82° to the LOS. The difference in flux density may arise because the southern jet emission must pass through the disk along its LOS, while the northern emission does not. Neufeld & Maloney (1995) argue that X-ray irradiation by the central engine creates a layer of partially and fully ionized atomic gas above the molecular disk. Herrnstein, Greenhill, & Moran (1996) estimate thermal free-free optical depths in this layer of 2–3 at 22 GHz, which can explain the persistent relative faintness of the blueshifted maser features. Assuming the jet is symmetrical, our failure to detect continuum emission 0.4–1.0 mas south of the dynamical center suggests optical depths $\gtrsim 2$ in the inner part of the disk. The continuum emission located 1.5 mas south of the dynamical center passes through the disk at a correspondingly larger radius and may suffer significantly less attenuation. Analogous emission in the north would be dominated by the brighter emission closer to the disk center.

Undetected continuum emission ~ 0.5 mas south of the dynamical center may provide seed radiation that the systemic masers amplify. This may explain why the high-velocity features, which are presumably self-amplified, only achieve flux densities of ~ 0.5 Jy, while the systemic features can reach ~ 10 Jy. Assuming that the ~ 3 mJy seed continuum encounters optical depths of 2 in the disk prior to amplification, a 10 Jy maser requires a gain of about 10^4, or an optical depth of ~ -9. The optical depth in a maser is $-1.3 \times 10^{-10} L \Delta P/\Delta\nu$, where L is the gain path length, ΔP is the differential pump rate per unit volume, $\Delta\nu$ is the line width ($\sim 5 \times 10^4$ Hz), and we have adopted standard values for the Einstein A coefficient (1.9×10^{-9} s^{-1}) and for the decay rate from the maser levels, Γ (1 s^{-1}; see Reid & Moran 1988). For $L = 0.002$ pc, which is approximately the maximum path length through the disk (Moran et al. 1995), a value of $\Delta P \simeq 0.5$ cm^{-3} s^{-1} is required. This can be achieved under expected conditions with a hydrogen density of 10^9 cm^{-3}, which is below the density where maser action is quenched. Thus, the southern continuum appears to be capable of sustaining the brightest systemic masers.

We propose that flares in the systemic masers may arise as clouds drift across peaks in the background southern jet emission. The systemic masers appear to be confined to a narrow annulus 4.0 mas (0.013 pc) from the disk center, and this may be the result of pumping constraints in the disk. The flux density at which an amplifying maser saturates is $12(D_m/0.13\ \mathrm{pc})^2(D/6.4\ \mathrm{Mpc})^{-2}$ Jy, where D_m is the distance between the maser and the continuum emission and D is the distance to the source (Haschick et al. 1990). Hence, the brightest systemic masers are only mildly saturated. In this regime, we expect a correlation between the maser strength and the background continuum flux density. This is supported by Figure 2, which suggests a correlation between the *northern* continuum emission and the average systemic maser flux density. *A plausible conclusion is that the systemic masers are amplifying southern jet emission which is strongly correlated with the observed northern jet emission.*

Lasota et al. (1996) propose that NGC 4258 may be powered by an advection-dominated accretion disk, in which a significant fraction of the gravitational potential energy is accreted through the event horizon of a central black hole. In order to accommodate the observed X-ray luminosity, Lasota et al. require a mass accretion rate of $8 \times 10^{-3}\alpha\ M_\odot$ yr^{-1}, where α is the standard viscosity parameter. The advection flow generates thermal synchrotron emission centered on the black hole, with an approximate 22 GHz strength of 0.5–2.0 mJy and a linear scale of several hundred R_S (R. Mahadevan 1996, private communication). In two of the VLBA epochs, there is jet continuum emission offset less than 1 beamwidth from the dynamical center of the disk, making it somewhat difficult to put a limit on any central emission. However, we find no evidence for any continuum emission from an advection disk at the level of about 1.5 mJy.

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