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MICRO-ARCSEC ASTROMETRY OF THE MILKY WAY AND BEYOND

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RESUMEN

Recientemente, hemos logrado obtener, mediante el VLBA, paralajes y movimientos propios con precisiones que se acercan al micro segundo de arco. Se ha medido el movimiento propio aparente de Sgr A* con una gran precisión, lo cual acota los valores posibles de Θ_0/R_0 y ofrece la posibilidad de una nueva definición dinámica del centro de nuestra Galaxia. El movimiento intrínseco de Sgr A* en la dirección perpendicular al plano galáctico es extremadamente pequeño (~ 1 km s^{-1}), y comparable al que se esperaría para un hoyo negro masivo. Este hecho, además de las observaciones en el infrarrojo de órbitas estelares, constituye evidencia contundente a favor de la existencia de un hoyo negro supermasivo. Por otra parte, hemos medido las paralajes trigonométricas y los movimientos propios de una docena de regiones de formación de estrellas masivas (HMSFRs). En general, las distancias cinemáticas son mayores que las que medimos, lo que sugiere que los parámetros galácticos adoptados por la UAI requieren revisión. Los valores que obtenemos con nuestros datos para el Movimiento Solar coinciden con los obtenidos por el Hipparcos, pero al parecer las HMSFRs rotan más lentamente que la Galaxia. Finalmente, se ha usado la extraordinaria capacidad astrométrica del VLBA para medir movimientos propios extragalácticos y para construir mapas de los máseres en los discos de acreción de AGNs distantes, lo cual proporcionará una estimación directa de H_0.

ABSTRACT

Recently we have been able to achieve parallaxes and proper motions with accuracies approaching micro-arcseconds using the VLBA. The apparent proper motion of Sgr A* has been measured with extremely high accuracy, strongly constraining Θ_0/R_0 and potentially offering a new dynamical definition of the Galactic plane. The intrinsic motion of Sgr A* perpendicular to the Galactic plane is extremely small (~ 1 km s^{-1}) and comparable to that expected for a supermassive black hole. When coupled with IR observations of stellar orbits, this provides overwhelming evidence for the existence of supermassive black holes. We have measured trigonometric parallaxes and proper motions for about a dozen high-mass star forming regions (HMSFRs). Generally, kinematic distances exceed the true distances, suggesting that the IAU Galactic parameters, R_0 and Θ_0, may need modification. Values of the Solar Motion from our data agree with those obtained from Hipparcos data, but HMSFRs appear to be rotating slower than the Galaxy. Finally, the extraordinary astrometric capabilities of the VLBA have been used to measure extragalactic proper motions and to map masers in distant AGN accretion disks, which will yield direct estimates of H_0.

Key Words: astrometry — Galaxy: structure — stars: formation

1. Sgr A* MUST BE A SUPERMASSIVE BLACK HOLE

For more than a decade, we have used the VLBA to measure the proper motion of Sgr A*, the compact radio source at the center of the Galaxy. The apparent motion we measure, relative to extragalactic sources, is dominated by the effects of the orbit of the Sun about the Galactic center. It takes the Sun about 225 Myr to complete its orbit, and yet with positional accuracies <0.1 mas, the VLBA can detect this motion in less than 1 month!

Based on VLBA observations spanning 8 years, Reid & Brunthaler (2004) showed that the intrinsic motion of Sgr A* perpendicular to the Galactic plane is extraordinarily small: -0.4 ± 0.9 km s^{-1}. Preliminary analysis of data taken in 2007, shown in Figure 1, extends the time span to 11 years and should reduce the uncertainty in Sgr A*'s motion below ± 0.7 km s^{-1}.

Were Sgr A* an X-ray binary involving, for example, a neutron star or a stellar-mass black hole, it would be moving at $>10^3$ km s^{-1}, as IR observations of stars close to the position of Sgr A* show. However, a supermassive black hole (SMBH) at the Galactic center should move very slowly, ~ 0.3 km s^{-1}, owing to small random perturbations from the $\sim 10^6$ stars within Sgr A*'s sphere of influence (Reid & Brunthaler 2004).

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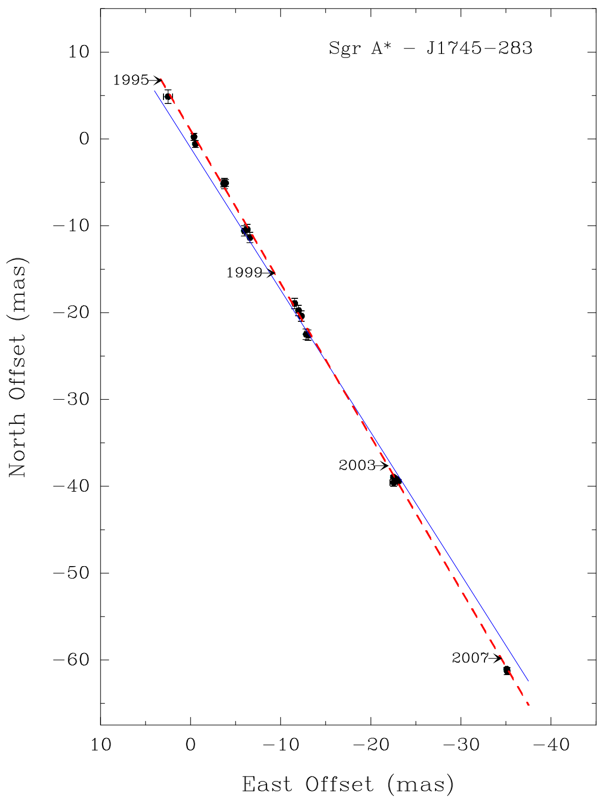

Fig. 1. The position of Sgr A* relative to an extragalactic source, J1745-283, from Reid & Brunthaler (in prep.). Fiducial dates along the path of motion are indicated. The ≈ 6 mas y^{-1} apparent motion is caused by the Sun's Galactic orbit. The *red dashed line* is the best fit proper motion and the *blue solid line* is the orientation of the IAU Galactic plane. The different slopes of these lines is caused by the ≈ 7 km s^{-1} motion of the Sun toward the north Galactic pole, implying that Sgr A* is motionless to within about ≈ 1 km s^{-1} in this direction.

Schödel et al. (2002) and Ghez et al. (2005) have demonstrated, via infrared observations of stars in elliptical orbits about the position of Sgr A*, that there is an unseen mass of $\sim 4 \times 10^6$ $M_\odot$ within 10 mas of the position of Sgr A*. These observations, coupled with our upper limit for the intrinsic motion of Sgr A*, yield a lower limit for Sgr A*'s mass of $\sim 4 \times 10^5$ $M_\odot$. If one combines this mass limit with upper limits of ≈ 0.5 AU for the intrinsic (non-scatter broadened) size of Sgr A* (see Bower et al. (2004) and references therein), one calculates a mass density $> 7 \times 10^{21}$ $M_\odot$ pc^{-3}. This lower limit is within only about two orders of magnitude of a SMBH within its inner-most stable orbit for a Schwarzschild black hole. Thus, the combination of IR and VLBA data provides overwhelming evidence that Sgr A* is a SMBH.

Because Sgr A* should anchor the dynamical center of the Galaxy, we suggest that its apparent motion can provide a dynamical definition of the plane of the Galaxy. Currently the IAU defines the Galactic plane based on the orientation of 21-cm wavelength HI emission and, arbitrarily, places the Sun at zero Galactic latitude. The Sun is now known to be ~ 10 pc above the IAU plane and this definition places Sgr A* ≈ 6 pc below the plane. A better definition of the Galactic plane could come from the direction of the apparent proper motion of Sgr A* (corrected for the small, well-measured, peculiar motion of the Sun perpendicular to the plane), with Sgr A*'s position defining the origin of Galactic longitude and latitude. Interestingly, as the Sun orbits the Galactic center, the position of Sgr A* changes by about 6 mas y^{-1} and, thus, the zero of Galactic longitude needs to be time dependent.

2. GALACTIC ASTROMETRY

Based on techniques developed for the Sgr A* astrometry, an international team, including A. Brunthaler, K. Menten, L. Moscadelli, M. Reid, Y. Xu, B. Zhang and X.-W. Zheng has initiated a major program on the VLBA designed to map the spiral structure of the Milky Way. We plan to accomplish this task by measuring trigonometric parallaxes and proper motions to sources of maser emission.

Our first observations involved 12 GHz methanol masers toward the high-mass star forming region W3OH; it resulted in a parallax of 0.512 mas with an uncertainty of only 0.01 mas (Xu et al. 2006). Building on the success of these observations, we set out to measure parallaxes for about a dozen maser sources, mostly methanol masers. This phase of our program has recently been completed, and we have preliminary parallaxes shown in Figure 2. Many of the sources appear to lie close to spiral arms proposed years ago by Georgelin & Georgelin (1976). Some of the nearby sources appear to lie between the Carina-Sagittarius and Perseus arms and probably are part of a Local (Orion) spur. We are in the process of obtaining many more parallaxes in order to map the spiral structure of the Milky Way.

In Figure 2, we plot the kinematic distances of these sources. Xu et al. (2006) found that the Perseus arm source, W3OH, has a distance that is only half that suggested by its kinematic distance (based on its LSR velocity and a model of Galactic rotation). We are able to confirm that two more sources in the Perseus arm, S252 and NGC 7538, share a similarly large kinematic distance anomaly.

Almost all sources have kinematic distances greater than their true (trigonometric parallax) dis-

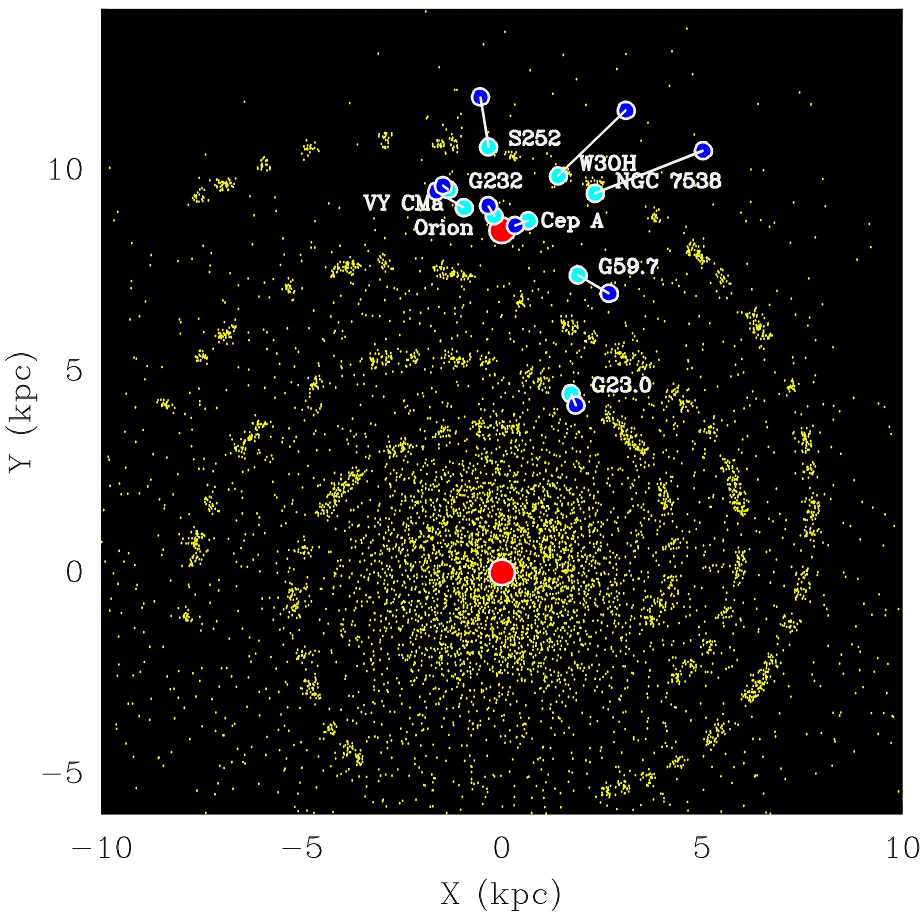

Fig. 2. Plots of distances to high-mass star forming regions based on trigonometric parallaxes (*light cyan circles*). Plotted for comparison are kinematic distances (*dark blue circles*), assuming $R_0 = 8.5$ kpc and a flat rotation curve with $\Theta_0 = 220$ km s^{-1}. For almost all sources, kinematic distances are larger than the trigonometric parallaxes. The data are shown superposed on a schematic model of the Milky Way with spiral arms from Taylor & Cordes (1993). For reference, the Sun (0,8) and Sgr A* (0,0) kpc are plotted (*large red circles*).

tances. Decreasing R_0 and/or increasing Θ_0 would reduce the kinematic distances. We note that the proper motion of Sgr A* by Reid & Brunthaler (2004), when corrected for the well determined Solar Motion, implies Θ_0/R_0=29.45 ± 0.15 km s^{-1} kpc^{-1}. Thus, for example, if R_0=8.0 kpc (Reid 1993), then Θ_0=236 km s^{-1}. Were we to use these Galactic parameters, most kinematic distances would decrease by $\approx 12\%$.

The proper motions obtained from our data, combined with parallaxes and LSR velocities, yield the full space motion of the masers. Typically we achieve velocity component uncertainties of ~ 1 km s^{-1} in only one year of observation. Since methanol masers generally have small internal motions (about ± 3 km s^{-1}), their space motions largely reflect those of their associated high-mass stars (and hence of its star forming region in general). The space motions of our masers typically indicate small components out of the plane of the Galaxy, as expected for high-mass star forming regions. However, the in-plane components of the space velocities are complex and quite interesting.

If we transform to a coordinate system that rotates with the Galaxy, we can plot peculiar (non-circular) motions of our star forming regions (see Figure 3). We find that nearly all sources show large peculiar motions, and most run counter to Galactic rotation. A possible explanation is that the Galactic rotation model, using IAU standard parameters for R_0 and Θ_0, is wrong. However, while decreasing R_0 and increasing Θ_0, can reduce the peculiar motions a bit, significant reduction of the peculiar motions can only come by changing the Solar Motion corrections or adding a new parameter for the Galactic orbits of star forming regions.

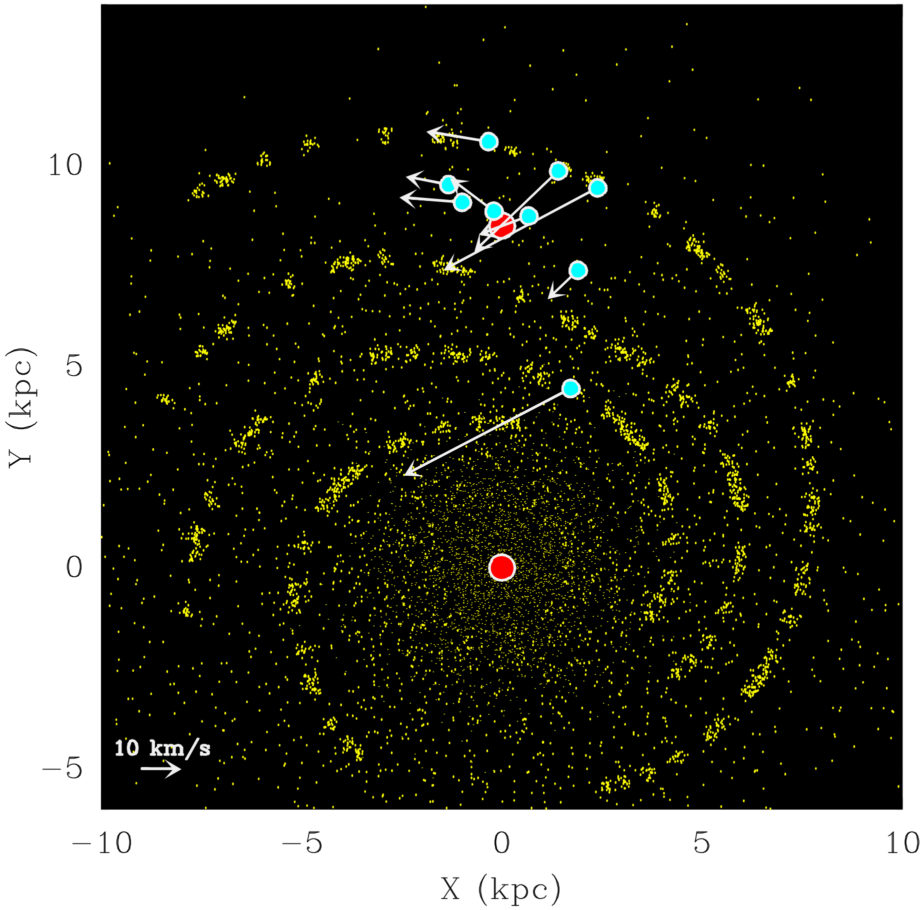

Fig. 3. Peculiar motions of HMSFRs after transforming to a reference frame that rotates with the Galaxy, assuming R_0=8.5 kpc and a flat rotation curve with Θ_0=220 km s^{-1}. We also assume Solar Motion parameters from Dehnen & Binney (1998). Note the strong trend counter to Galactic rotation in the peculiar motions.

In Figure 4 we reproduce the Hipparcos data presented by Dehnen & Binney (1998) and used by them to determine the Solar Motion. We also plot the Solar Motion components that would be required to remove the large systematic residuals for our HMSFR parallaxes and proper motions. The components of the Solar Motion in the direction of the Galactic center (U) and toward the north Galactic pole (W) are simple to measure and there is good agreement between the Hipparcos and VLBA results. Further confirmation of the W component of Solar Motion comes from the proper motion of Sgr A*. However, our VLBA results appear to require that the V component of Solar Motion (in the direction of Galactic rotation) is ≈ 18 km s^{-1}. This result is not very sensitive to the values adopted for R_0 and Θ_0. Our V greatly exceeds the Hipparcos value of ≈ 5 km s^{-1}, obtained by extrapolating the "asymmetrical drift" to zero stellar dispersion (ie, the dynamical Solar Motion; see Dehnen & Binney (1998) for a more complete discussion).

There is no reason to doubt the Hipparcos Solar Motion, which is very well measured from many tens of thousands of stars in the solar neighborhood. The discrepancy between the measurements suggests that HMSFRs as a group rotate ≈ 13 km s^{-1} slower than the Galaxy spins. A possible explanation for this finding is that HMSFRs are born near apocenter in slightly elliptical Galactic orbits, perhaps owing to the effects of spiral density wave shocks. Such shocks could compress gas clouds, induce star formation, and remove angular momentum from gas clouds originally in circular Galactic orbits.

3. EXTRAGALACTIC PROPER MOTIONS

With our present astrometric accuracy we can measure parallaxes to sources across the Galaxy. However, even with near micro-arcsecond position

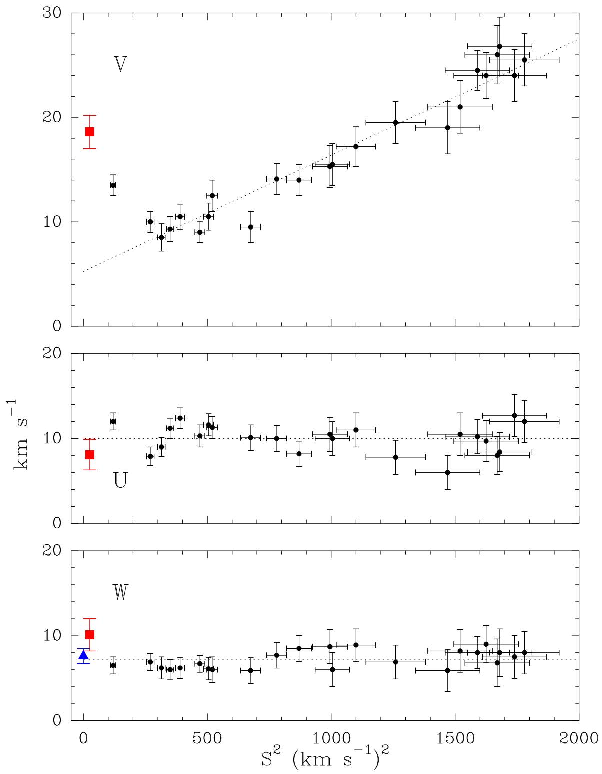

Fig. 4. Plots of the three components of Solar Motion (U toward the Galactic center, V in the direction of Galactic rotation; W toward the north Galactic pole) as a function of the velocity dispersion of groups of stars. *Black points* are from Hipparcos data by Dehnen & Binney (1998); *red squares* are from our parallaxes and proper motions; the *blue triangle* is from the proper motion of Sgr A*. The well-known "asymmetrical drift" (*dotted line)*, seen in Hipparcos data in the *top* plot (V), when extrapolated to zero stellar dispersion defines the dynamical Solar Motion.

measurements, we can't measure parallaxes to other galaxies with reasonable accuracy. However, since proper motion accuracy increases rapidly (as $T^{-3/2}$ for uniform time sampling) with the time spanned between observations, T, we can measure proper motions of other galaxies.

In the 1920s, Adrian van Maanen claimed to have measured the angular rotation of stars in M33. His measurements indicated rotational motions, μ, of order 10 mas y^{-1}, which required a distance given by

$$D \sim 2 \left(\frac{V_{\rm rot}}{100 \text{ km s}^{-1}}\right) \left(\frac{\mu}{10 \text{ mas y}^{-1}}\right)^{-1} \text{ kpc},$$

where $V_{\rm rot}$ is the rotation speed of the nebula. This placed the M33 nebula within the Milky Way and resulted in a great debate with Hubble over the nature of spiral nebulae.

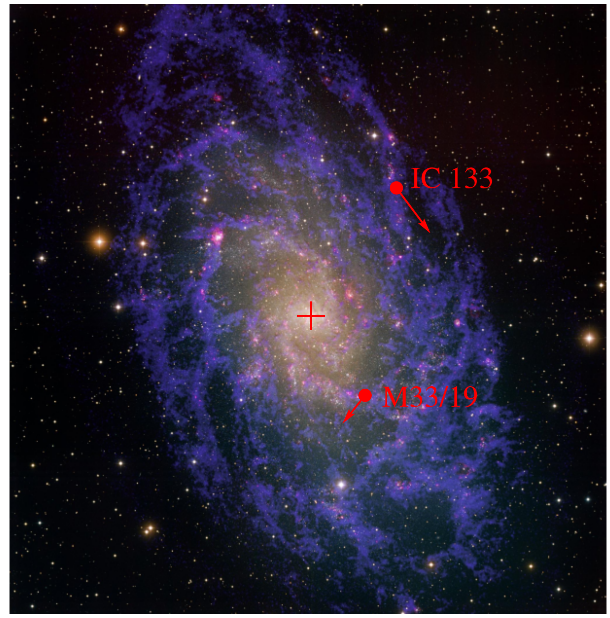

Fig. 5. Combined radio and optical image of M33. The locations and rotational motions of two sites of high-mass star formation containing powerful H_2O maser are indicated.

Recently, a group lead by A. Brunthaler, and including H. Falcke and M. Reid, has succeeded in measuring the internal angular rotation of M33 (the van Maanen experiment), as well as its proper motion with respect to distant sources (Brunthaler et al. 2005). In addition to formally resolving the "van Maanen-Hubble debate", the observed rotation, combined with the spin speed and inclination determined from HI maps, gives a geometric distance to the galaxy.

The proper motion of the M33 with respect to background radio sources (see Figure 5), obtained by removing the rotational component, yields important clues to the history and ultimate fate of M33 as it orbits M31 (Andromeda) and of the distribution of dark matter in M31 and the Milky Way (Loeb et al. 2005).

4. MEASURING H_0

A fundamental problem in contemporary cosmology is the determination of the equation of state (w) of dark energy. Current estimates suggest $w \approx -1$, based on observations of fluctuations in the Cosmic Microwave Background, coupled with data from supernovae, gravitational lensing and galaxy distributions. However, this estimate uses *a priori* assumptions of either a flat universe or a value of the Hubble Constant (H_0). An accurate determination of H_0

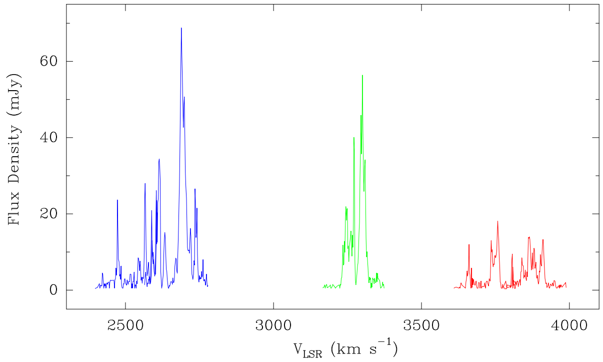

Fig. 6. A spectrum of the H_2O masers toward UGC 3789 from an interferometric map made with VLBA/GBT/Effelsberg data. The spectrum is characteristic of a rotating, edge-on disk (as in NGC 4258): *blue*- and *red*-shifted high-velocity emission complexes that straddle the systemic emission complex (*green*) centered near 3300 km s^{-1}.

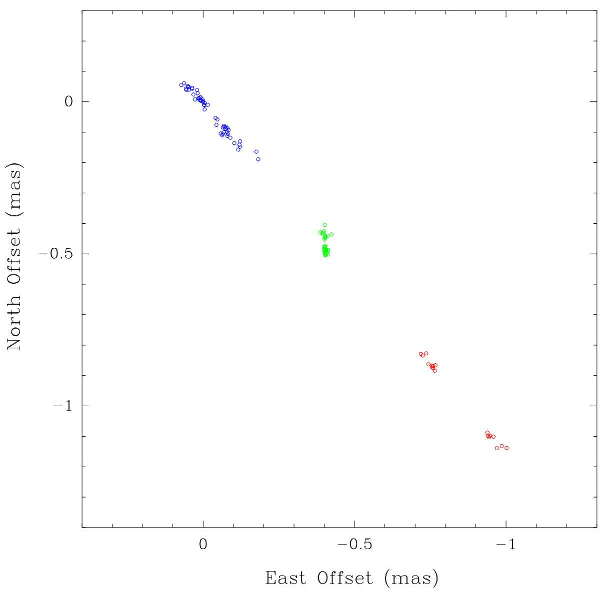

Fig. 7. Map of H_2O masers toward UGC 3789. The *blue*-shifted (*red*-shifted) high-velocity components are offset to the East (West) of the systemic masers (*green*) near $(-0.4, -0.5)$ mas.

could remove the need for the assumption of a flat universe (and indeed check that it really is flat), as well as constrain w.

The Seyfert 2 galaxy NGC 4258 has a nuclear accretion disk, which is traced by VLBI imaging of its H_2O maser emission at sub-pc radii. Possibly the most accurate distance (7.2 ± 0.5 Mpc) to any galaxy has come from modeling H_2O maser observations of this galaxy (Herrnstein et al. 1999). Unfortunately, the recessional velocity of NGC 4258 is small (475 km s^{-1}) and the likelihood of non-Hubble flow motions of ≈ 200 km s^{-1} precludes a direct estimate of H_0. Instead, NGC 4258 provides an extremely valuable anchor for the extragalactic distance scale by allowing re-calibration of the Cepheid PL relation.

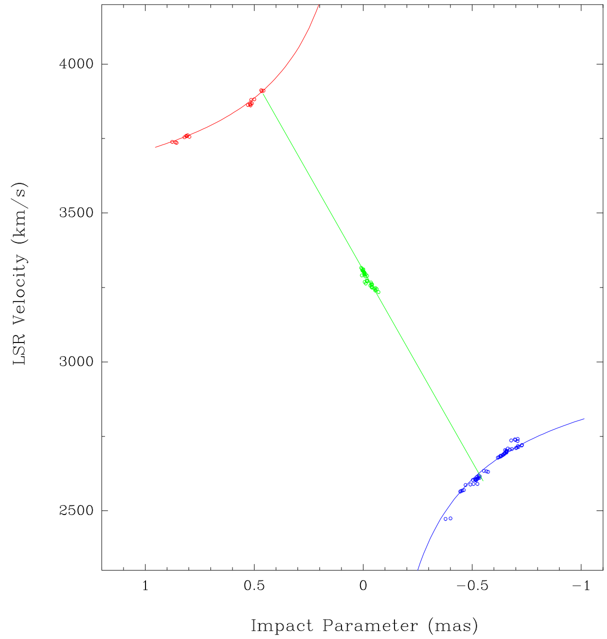

Fig. 8. Position-velocity plot of H_2O masers toward UGC 3789. The *blue*- and *red*-shifted components indicate Keplerian rotation about a $\approx 10^7\ M_\odot$ SMBH and the systemic masers (*green*) show the characteristics of an edge-on disk.

Galaxies like NGC 4258, but more distant and into the "Hubble flow", could allow direct determinations of H_0. The Water Maser Cosmology Project (WMCP) intends to do just this. It is an international collaboration, including J. Braatz, J. Condon, L. Greenhill, C. Henkel, K.-Y. Lo, and M. Reid, and its goal is to measure H_0 directly with an accuracy of better than 3%. The WMCP seeks to find new "NGC 4258-like" water masers with surveys using the GBT and other large radio telescopes. Once candidates are found, the VLBA, along with one or more large aperture telescopes, images the masers. Coupling the VLBA images with spectral monitoring observations provides the data needed to fit a rotating disk model and obtain an accurate distance.

J. Braatz has recently discovered a very promising candidate for distance measurement: UGC 3789, which has a recessional velocity of ~ 3300 km s^{-1} and thus is into the "Hubble flow". The H_2O

masers in UGC 3789 have been imaged with the VLBA/GBT/Effelsberg, and an interferometer spectrum is shown in Figure 6. UGC 3789 displays the characteristics of a sub-pc scale accretion disk surrounding a SMBH: systemic velocity components centered between high-velocity components that are shifted by up to ± 750 km s^{-1}.

In Figure 7, we present a preliminary map of the H_2O masers in UGC 3789 with relative positional accuracies approaching ~ 5 μas. As observed in NGC 4258, the maser spots present a linear pattern in which the blue- and red-shifted high-velocity components straddle the systemic velocity components, indicative of an edge-on disk. The angular extent of the detected spots is ≈ 1.5 mas, which is a factor of ≈ 10 smaller than for NGC 4258, consistent with UGC 3789's much greater distance.

A position-velocity plot, constructed along the position angle of the linear pattern of spots, is shown in Figure 8. The signatures of Keplerian rotation are clearly evident, indicating a rotation speed of ≈ 600 km s^{-1} at an angular radius of ≈ 0.5 mas. This implies a central gravitational source, presumably a SMBH, of 10^7 $(D/50 \text{ Mpc})$ $M_\odot$, where D is the distance.

The distance to an edge-on disk in Keplerian rotation is given by $D = V^2/A\theta$, where V and A are the rotational velocity and centripetal acceleration at an angular radius θ. We measure centripetal accelerations by monitoring the spectrum and directly observing drifts in Doppler shift with time. Our preliminary measurement of A, based on one year's monitoring with the GBT, gives a distance consistent with H_0 near 70 km s^{-1} Mpc^{-1} and an anticipated uncertainty of about $\pm 10\%$. If a more detailed analysis confirms this result, this would give an *entirely independent* value of H_0 with an accuracy comparable to that of the Hubble Key Project (Freedman et al. 2001).

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