

MASERS AND THE COSMIC DISTANCE SCALE

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ABSTRACT. Studies of H₂O masers have demonstrated the power of VLBI techniques to measure relative positions with sufficient accuracy ($\sim 10 \mu\text{as}$) to determine proper motions and to estimate distances to maser sources throughout the Galaxy. The distance to four H₂O masers have been determined, and the distance to the center of the Galaxy has been determined to be 7.1 ± 1.5 kpc from observations of the H₂O masers in Sgr-B2. Proper motion distances for other H₂O masers, and possibly for OH masers, may allow the determination of the fundamental parameters describing the size (R_o) and rotation rate (Θ_o) of the Galaxy with accuracies of better than 10%. Finally, the measurement of the proper motions of H₂O masers in nearby galaxies (< 10 Mpc) is feasible and offers the possibility of direct calibration of the extragalactic distance scale.

1. INTRODUCTION

The combination of proper motion data and information about motion along the line-of-sight can be used to determine the distance to a source, as well as to understand the dynamics of the emitting material. The proper motion of a component, $\dot{\theta}_{app}$, is given by

$$\dot{\theta}_{app} = \frac{1}{d} \left(\frac{v \sin \theta}{1 - \beta \cos \theta} \right), \quad (1a)$$

or in the nonrelativistic limit by

$$\dot{\theta}_{app} = \frac{v \sin \theta}{d}, \quad (1b)$$

where v is the speed of the emitting material moving at an angle θ to the line-of-sight, $\beta = v/c$, c is the speed of light, and d is the distance to the source. Line-of-sight velocities can be determined indirectly from intensity information, provided bulk relativistic motions are involved, via the equation

$$I_{app}(\nu_{app}) = \frac{D^3}{169} I_{em}(\nu_{em}), \quad (2a)$$

where $D = \sqrt{1 - \beta^2} / (1 - \beta \cos \theta)$, or directly from Doppler (or radial) velocities, v_R , of spectral lines via

$$v_R \approx v \cos \theta \quad , \quad (2b)$$

in the nonrelativistic limit.

Equations (1) and (2) relate measurable quantities to three physical parameters: the distance to the source (d) and the speed (v) and direction (θ) of the emitting material. VLBI observations of quasars and active galactic nuclei are often interpreted in the context of equations (1a) and (2a), and, assuming d from the source redshift, one can, in principle, determine the “jet” flow speed and direction. Alternatively, for molecular maser sources, equations (1b) and (2b) are appropriate. If proper motions and Doppler velocities are measured for a number of maser spots in one source, one can solve for the parameters by modelling the source dynamics or by assuming an isotropy constraint (e.g., $\langle \sin^2 \theta \rangle = \langle \cos^2 \theta \rangle$) as for a statistical parallax). Both techniques have been used to determine distances to H₂O maser sources.

2. MEASURED DISTANCES TO H₂O MASERS

Maser emission occurs in the envelopes of newly formed massive stars (interstellar masers) and evolved Red Giant stars (stellar masers). H₂O and OH molecules are trace constituent of these envelopes, and population inversion of the molecular energy levels leads to the appearance of “spots” of emission $\sim 10^{13}$ cm in size with brightness temperatures as high as 10^{15} K. Because of the small size and high brightness of interstellar maser spots, they can be used to make precise astrometric measurements that allow proper motions to be determined. With VLBI techniques, relative positions across fields of $\sim 3''$ can be measured with an accuracy of ~ 10 microarcsec (μ as). This accuracy is sufficient to determine proper motions and estimate distances throughout the Galaxy.

Genzel *et al.* (1981a) measured proper motions of H₂O maser spots in the Orion–KL source, and found that the spots are expanding about a central point near the massive young star IRc2. Using the two dimensions of spatial information (i.e., relative positions), and the three dimensions of velocity information (i.e., radial and proper motions) available for the maser spots, they constructed a three dimensional kinematic model of the source. The distance of the entire source, which is needed to relate the angular (proper) motions to true velocities, was then estimated by least-squares fitting techniques to be 480 ± 80 pc, in accord with optical luminosity distances of associated O-stars.

Genzel *et al.* (1981b) and Schneps *et al.* (1981) measured proper motions of H₂O masers in W51(M) and W51(N), respectively. The motions in these sources appeared largely random, and the technique of statistical parallax was employed to determine distances to the sources. Distance estimates are given by the ratio of the dispersion in Doppler velocities to the dispersion in (each dimension) of the proper motions. The distance to the W51 sources was estimated to be 7 ± 1.5 kpc. This value is consistent with the far kinematic distance to the W51 region.

Recently completed studies of the water masers in the galactic center region, Sgr-B2 (Reid *et al.* 1988), indicate a phenomenon similar to the Orion case. The H₂O maser spectrum of Sgr-B2(North) is composed of ~ 100 maser spots with an LSR velocity range from 15 to 115 km s⁻¹. Spectral-line VLBI maps made from observations between 1980.9 to 1982.5 clearly show up to 50 spots stronger than

1 Jy at each epoch. With four telescopes spanning the United States, a synthesized beam of 2.4×0.4 milliarcseconds (mas) is obtained.

The maser spots in Sgr-B2(North) were slightly resolved and the location of peak brightness was estimated by fitting an elliptical Gaussian model. Formally, the center of a Gaussian brightness distribution can be estimated with a one-sigma precision given by $\sigma_\theta \approx 0.5\theta_{app}/SNR$, where θ_{app} is the apparent size (FWHM) of the maser spot (dominated by the synthesized beam) and SNR is the peak signal-to-noise ratio for the spot in the map. Plots of position versus time for features at the same line-of-sight velocity were made. These plots indicated that the maser spots typically appeared to move in straight lines on the sky to within a factor of two of the expected (theoretical) position uncertainties.

The dominant motion of the maser spots in Sgr-B2(North) appeared to be expansion. A least-squares fit of a uniformly expanding spherical source resulted in an estimate of the distance to the source of 7.1 ± 1.5 kpc. The estimated expansion velocity is about 45 km s^{-1} and the velocity residuals were about 15 km s^{-1} . These residuals are much greater than the measurement errors, suggesting that the source contains "turbulent" motions of about 15 km s^{-1} .

Sgr-B2 is almost certainly within 0.3 kpc of the galactic center. Thus, the Sgr-B2 distance estimate can be used directly as an estimate of R_o , the distance between the Sun and the galactic center. The H_2O maser distance estimate of 7.1 kpc to the center of the Galaxy is significantly lower than the previous standard value of 10 kpc and in better agreement with the newly revised IAU value of 8.5 kpc (Kerr and Lynden-Bell 1986).

A decrease in the value of R_o has widespread impact on astrophysics. The following is a brief list of items that would be affected by reducing R_o :

- 1) decrease all kinematic distances;
- 2) reduce the mass of the Galaxy and of the galactic center;
- 3) decrease some extragalactic distances (i.e., increase H_0) by a) favoring recent revisions of the absolute magnitudes of RR Lyrae variables (Frenk and White 1982), which in turn affects distances in the Local Cluster, and b) bringing spiral galaxies closer to match Milky Way size (e.g., DeVaucouleurs 1983);
- 4) decrease the luminous mass in the Milky Way and increase the "dark matter" in the Local Group (see Trimble 1986); and
- 5) reduce the total luminosity of X-ray bursts, some of which appear super-Eddington for $R_o = 10$ kpc (see Ebisuzaki *et al.* 1984).

3. FUTURE PROSPECTS FOR GALACTIC DISTANCE MEASUREMENTS

Analysis of existing data as well as future observations hold the promise of greatly increasing the accuracy of estimates not only of R_o , but also of the Galactic rotation parameter, Θ_o . If one assumes circular rotation in the Galaxy, then the observed radial velocity, v_R , and absolute source proper motion, μ_ℓ , are given by

$$v_R = R_o \sin \ell \left(\frac{\Theta}{R} - \frac{\Theta_o}{R_o} \right), \quad (3)$$

and

$$\mu_\ell = \frac{\Theta}{d} \left[\left(\frac{R_o}{R} - 1 \right) \cos \ell - \frac{d}{R} \right], \quad (4)$$

where R and Θ are the distance and rotation speed of the source with respect to the galactic center, d is the distance of the source from the Sun, and ℓ is the galactic longitude of the source. After some algebraic manipulation (and with the assumption of a flat rotation curve), one can use measurements of d , v_R , and μ_ℓ to give estimates of R_0 and Θ_0 as follows:

$$R_0 = \frac{\rho^2 - d^2}{2(\rho - d \cos \ell)} \quad (5)$$

and

$$\Theta_0 = -\frac{v_R}{\sin \ell} \left[\frac{\rho^2 - 2\rho d \cos \ell + d^2}{2\rho(\rho - d \cos \ell)} \right] \quad (6)$$

where

$$\rho = R_0 - R = \left(\frac{\cos \ell}{d} - \frac{\mu_\ell \sin \ell}{v_R} \right)^{-1} \quad (7)$$

From these equations one can see that, in general, measurement of the absolute proper motion as well as the source distance are needed to determine R_0 and Θ_0 with data from a single source. A proper motion experiment to measure the motion of a source against the extragalactic background, such as that of Backer and Sramek (1982) for Sgr A*, is possible using H₂O and/or OH masers. Analysis of equations (5) and (6), however, indicates that only sources near the solar circle (and not too close to the Sun) or sources near the galactic center can be used if deviations from circular motions ($\sim 10 \text{ km s}^{-1}$) and errors in distances ($\approx 10\%$) are not to affect the estimates of R_0 and Θ_0 too seriously.

Note that for a source on the solar circle, such as W49, the results just derived have relevance for distances estimated from internal motions, even if the absolute proper motion of the source is not measured. Near the solar circle, the terms involving ρ ($= R_0 - R \approx 0$) in equations (5) and (6) can be much smaller than d . This results in an estimate of R_0 dependent only on the measurement of d . In this case, equation (5) becomes

$$R_0 \approx \frac{d}{2 \cos \ell} \quad (8)$$

independent of the measurement of the absolute proper motion μ_ℓ . The formal uncertainty in estimating R_0 , σ_{R_0} , is given by

$$\frac{\sigma_{R_0}}{R_0} \approx \frac{\sigma_d}{d} \quad (9)$$

Unfortunately, an estimate of Θ_0 depends on both μ_ℓ and d , and near the solar circle, equation (6) reduces to

$$\Theta_0 \approx -\frac{d \mu_\ell}{2 \cos \ell} \quad (10)$$

The most luminous maser in the Galaxy, W49, is known to be on the far side of the galactic center (from hydrogen absorption studies). It has a low radial velocity and, therefore, is nearly on the solar circle. Thus, R_0 can be accurately determined from the distance to W49, even assuming a crude value for Θ_0 . For $\ell_{W49} = 43^\circ$ and

$d_{W49} = 12$ kpc, circular rotation (with $R_0 = 8.5$ kpc and $\Theta_0 = 220 \text{ km s}^{-1} \text{ pc}^{-1}$) gives $v_R = 6 \text{ km s}^{-1}$ and $\mu_\ell = -5.4 \text{ mas yr}^{-1}$. By measuring v_R and μ_ℓ exactly and d with an error of 1.2 kpc (10%), R_0 and Θ_0 are estimated with uncertainties of 0.8 kpc and 20 km s^{-1} , respectively. If we add “noise” to the motion of the source in the amount of 10 km s^{-1} to simulate deviations from circular motion or measurement error in μ_ℓ , the uncertainties for R_0 and Θ_0 are increased only slightly to 1.0 kpc and 23 km s^{-1} , respectively.

4. EXTRAGALACTIC DISTANCES

H_2O masers have recently been discovered in about a dozen galaxies. For example, several sites of maser activity are known in M33, a galaxy about 0.7 Mpc from the Sun. The strongest H_2O maser in M33 has a flux density of about 5 Jy. The most distant extragalactic H_2O maser known is in the nucleus of the active galaxy NGC 3079. This maser reaches a peak flux density of about 10 Jy; at the distance of 16 Mpc this maser is emitting $500L_\odot$ in the H_2O line, assuming isotropic emission. Detections of VLBI fringes have been reported from the galaxies NGC 3079 by Haschick *et al.* (1987) and from NGC 4258 by Claussen *et al.* (1987).

Two types of proper motion studies can be done to estimate distances to galaxies: 1) measurement of the internal motions within one source (as done for example for Orion, W51 and Sgr-B2), and 2) measurement of the orbital motion of an entire source around the galaxy. Regarding the first type of study, galactic H_2O maser sources have internal motions with a dispersion of about 30 km s^{-1} . At a distance of 1 Mpc, such motions correspond to transverse angular velocities of $6 \mu\text{as yr}^{-1}$. The second type of proper motion study involves measuring orbital motions due to galactic rotation of H_2O masers with respect to a “reference” source, e.g., an H_2O maser or continuum source located elsewhere in the galaxy (perhaps at the center). In this latter case, the relative velocities are $\sim 300 \text{ km s}^{-1}$ —an order of magnitude greater than internal source motions. If the orbital speed (rotation curve) and inclination of the galaxy are known, then measurement of the proper motion directly yields the galaxy’s distance. A maser located away from the center of a face-on galaxy 1 Mpc from the Sun moves $60 \mu\text{as yr}^{-1}$, a motion that over one year is a significant fraction of the synthesized beam of intercontinental VLBI arrays and comparable to the synthesized beam of proposed space-based VLBI observations.

The most crucial aspect in the measurement of proper motions of H_2O masers is to locate reliably each maser spot at several epochs. Maser spots often cluster together. For example, the strongest maser source in the Milky Way is in W49 ($d \approx 12$ kpc). This source contains about 100 maser spots stronger than 100 Jy, with large numbers of these maser spots separated by less than 0.03 arcsec. At a distance of 1 Mpc, this separation would be about 0.3 mas, comparable to the best resolution obtainable by an Earth-based array. Once two or more maser spots with similar radial velocities fall within the interferometer beam, intensity variations mimic position shifts. This leads to a “confusion” limit. For example, an Earth-based array observing a source like W49 in a galaxy 1 Mpc distant would not be able to determine the proper motions of the clustered spots. The higher angular resolution provided by future space-based VLBI observations may prove crucial in resolving the structure of H_2O maser clusters, thereby removing the “confusion” problem (as well as allowing motions to be determined over a shorter time base).

Even now, measurements of extragalactic proper motions are feasible for known sources with the largest existing radio telescopes and reasonable integration times under good weather conditions. However, we note that no nearby galaxy has yet been searched *completely* for H₂O masers. A major program to find the best candidate galaxies for proper motion studies still needs to be done. Since H₂O proper motions yield a direct estimate of the distance to a source, independent of absolute luminosities and extinctions, they share none of the sources of systematic error usually associated with distance estimates. Thus, obtaining a distance to even one galaxy would provide a crucial check on the calibration of Cepheids and of other distance indicators, and hence could remove significant sources of error in the determination of the Hubble constant.

5. REFERENCES

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