PROPER MOTION OF THE COMPACT, NONTHERMAL RADIO SOURCE IN THE GALACTIC CENTER, SAGITTARIUS A*  

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ABSTRACT  
Proper motions and radial velocities of luminous infrared stars in the Galactic center have provided strong evidence for a dark mass of $2.5 \times 10^6 \, M_\odot$ in the central 0.05 pc of the Galaxy. The leading hypothesis for this mass is a black hole. High angular resolution measurements at radio wavelengths find a compact radio source, Sagittarius (Sgr) A*, that is either the faint glow from a small amount of material accreting onto the hole with low radiative efficiency or a miniature active galactic nucleus (AGN) core-jet system. This paper provides a full report on the first program that has measured the apparent proper motion of Sgr A* with respect to background extragalactic reference frame. Our current result is  
\[
\begin{align*}
\mu_{l, e} &= [-6.18 \pm 0.19] \, \text{mas yr}^{-1} \\
\mu_{b, e} &= [-0.65 \pm 0.17] \, \text{mas yr}^{-1}.
\end{align*}
\]

The observations were obtained with the NRAO Very Large Array at 4.9 GHz over 16 yr. The proper motion of Sgr A* provides an estimate of its mass based on equipartition of kinetic energy between the hole and the surrounding stars. The measured motion is largest in galactic longitude. This component of the motion is consistent with the secular parallax that results from the rotation of the solar system about the center, which is a global measure of the difference between Oort's constants ($A-B$), with no additional peculiar motion of Sgr A*. The current uncertainty in Oort's galactic rotation constants limits the use of this component of the proper motion for a mass inference. In latitude, we find a small, and weakly significant, peculiar motion of Sgr A*, $-19 \pm 7 \, \text{km s}^{-1}$ after correction for the motion of the solar system with respect to the local standard of rest. We consider sources of peculiar motion of Sgr A* ranging from unstable radio wave propagation through intervening turbulent plasma to the effects of asymmetric masses in the center. These fail to account for a significant peculiar motion. One can appeal to an $m=1$ dynamical instability that numerical simulations have revealed. However, the measurement of a latitude peculiar proper motion of comparable magnitude and error but with opposite sign in the companion paper by Reid leads us to conclude at the present time that our errors may be underestimated and that the actual peculiar motion might therefore be closer to zero. Improvement of these measurements with further observations and resolving the differences between independent experiments will provide the accuracies of a few km s$^{-1}$ in both coordinates that will provide both a black hole mass estimate and a definitive determination of Oort's galactic rotation constants on a global Galactic scale.

Subject headings: astrometry — Galaxy: center — ISM: individual (Sagittarius A*) — radio continuum: ISM

1. INTRODUCTION

The compact, nonthermal radio source, Sagittarius (Sgr) A*, was discovered by Balick & Brown (1974) while looking for compact H II regions in the center of the Galaxy. The nature of Sgr A* and its role in the center of our Galaxy have been a matter of speculation over the past 25 years. Until recently, theoretical and observational arguments were advanced that the Galactic center contains a $10^6 \, M_\odot$ black hole that might be identified with Sgr A* (Lynden-Bell & Rees 1971; Genzel, Hollenbach, & Townes 1994). However, emission across the electromagnetic spectrum definitively identified with, or even possibly identified with, Sgr A* contains no more than $10^{36}$ solar luminosities (Beckert et al. 1996; Serabyn et al. 1997), which does not necessarily demand a supermassive object. Angular size measurements of Sgr A* have yet to reveal definitively the nature of this object owing to the blurring effects of interstellar scattering in the dense, turbulent plasma near the Galactic center (Lo et al. 1985; Backer 1988; Jauncey et al. 1989; Frail et al. 1994; Rogers et al. 1994; Bower & Backer 1998; Lo et al. 1998). From the highest frequency VLBI observations we infer an upper limit to the size of 1 AU at 86 GHz (Rogers et al. 1994). Recent summaries of the variability of the radio emission (Zhao et al. 1992; Gwinn et al. 1991; Backer 1994; Wright & Backer 1993; Tsuboi, Miyazaki, & Tsutsui 1999) and limits on its linear and circular polarization (J.-H. Zhao 1992, private communication; Bower & Backer 1999) also do not give us a definitive handle on the intrinsic nature of this object—is it a stellar mass object or supermassive black hole?

Over the past 5 years, our understanding of both the presence of dark matter in the center and the nature of Sgr A* has improved dramatically. Large proper motions of luminous infrared stars within 0.1 pc of Sgr A* have now
been detected and lead to a good estimate of the central dark mass of $2.5 \times 10^6 M_\odot$ (Eckart & Genzel 1997; Genzel et al. 1997; Ghez et al. 1998). However, models for the full Sgr A* electromagnetic flux spectrum based on low radiative efficiency accretion of wind-driven matter from nearby stars onto a black hole are not yet consistent with a mass of a few million solar masses given nominal estimates of the mass accretion rate (Melia 1992, 1994; Falcke et al. 1993; Falcke & Melia 1997; Narayan, Yi, & Mahadevan 1995; Narayan et al. 1998; Mahadevan 1998).

Shortly after the discovery of Sgr A*, we began an astrometry program to determine its proper motion relative to extragalactic reference sources, active galactic nuclei (AGNs) and quasars, with the NRAO\textsuperscript{1} Green Bank interferometer (Backer & Sramek 1982, hereafter BS82). If Sgr A* were “just” a stellar mass object, then it would be buzzing around in the central gravitational potential well in equipartition with the other stars and gas clouds in the center. Transverse velocity components of at least $100-200$ km s\(^{-1}\) would be expected (Sellgren et al. 1990). Alternatively, if Sgr A* were indeed a supermassive black hole, then it might very well be at rest in the center. Different formation scenarios for such an object as well as considerations of galactic dynamics predict different residual motions of a black hole with respect to the Galactic center.

Our observations from the solar system of an object in the Galactic center relative to the extragalactic sky are sensitive, of course, to the secular parallax resulting mainly from the rotation of the Galaxy with a small additional contribution from the solar motion with respect to the local standard of rest. The expected motion is approximately $6$ mas yr\(^{-1}\), using current values of galactic constants (Kerr & Lynden-Bell 1986). If we remove this large secular parallax from the apparent motion, the residual, peculiar motion with respect to the Galactic barycenter can be used to estimate the mass of Sgr A* using an equipartition or other dynamical argument. The uncertainty in the secular parallax correction is largest in the longitude direction. Therefore, the peculiar motion of Sgr A* in Galactic latitude is most important for assessment of the mass of the parent body of Sgr A*. Alternatively, if we assume both that Sgr A* is attached rigidly to a several million solar mass black hole and that this object defines the inertial reference frame for the Galaxy, then the apparent motion can be used to define Galactic constants.

The intensity distribution of Sgr A* is broadened by multipath propagation (diffraction) in the intervening thermal plasma, the density of which is perturbed on small length scales. The detection of similar broadening of OH masers near Sgr A* by Frail et al. (1994) suggests strongly that this plasma is located in the central $140$ pc of the Galaxy. The apparent diameter of Sgr A* is $1.4$ mas $\lambda^{2.0}$, where $\lambda$ is the wavelength in centimeters. Past and present proper-motion measurements have an error much smaller than this size; therefore, we have a particular concern about the temporal stability of diffractive and refractive propagation effects.

Our Green Bank experiment (1976–1981) detected a proper motion in Galactic longitude that was consistent with the expected secular parallax and therefore with negligible peculiar motion or refractive effects (BS82). However, the errors were too large to place a meaningful limit on the mass of Sgr A*. They did establish that Sgr A* was Galactic and not a chance superposition of an extragalactic background source.

In 1981 we began a new Sgr A* proper-motion experiment with the NRAO Very Large Array (VLA; see Napier, Thompson, & Ekers 1983). The number of antennas, the two-dimensional distribution of antennas in a Y configuration, the excellent site for phase stability, and the sensitive receivers provided considerable new capability. Reports of the progress of this experiment have been provided in a series of conference reports (Backer & Sramek 1987; Backer 1994, 1996). This paper provides a full report of 8 epochs of VLA observations between 1982 and 1998. The observations are described in § 2, and our procedures for the determination of the apparent proper motion of Sgr A* are explained in § 3. In § 4 we discuss the current best estimate for Galactic constants that lead to the $\sim 6$ mas yr\(^{-1}\) secular parallax in Galactic latitude that dominates the measured motion. The possibility of refractive wander of the position of Sgr A* is then explored and limited by recent dual frequency data. The third topic in § 4 concerns interpretation of the peculiar motion that remains after subtraction of the estimated secular parallax. A summary of the paper is given in § 5.

2. OBSERVATIONS AND DATA REDUCTION

In 1981, we searched the literature for candidate reference sources closer to Sgr A* than those used in the Green Bank experiment reported previously (BS82). The Westerbork planetary nebula searches (Wouterloot & Dekker 1979; Isaacman 1981) provided the most sensitive and highest angular resolution images for location of background quasars or other compactextragalactic sources. We further undertook a blind search at the VLA by making snapshot images at 5 GHz of about 50 fields, the solid angles of which were determined by a combination of primary and delay beams. The Westerbork candidates were also observed. These efforts led to the identification of three reference sources with sufficiently strong fluxes ($>25$ mJy) and compact structure ($<1''$). Sources W56 (B1737−294) and W109 (B1745−291) were from the Westerbork surveys, and source GC441 (B1737−294) was the first source cataloged in our 44th blind search beam. Figure 1 provides a map of the sky surrounding Sgr A* with the relative locations of the three reference sources. While these sources are not “identified” as quasars or AGNs, their brightness temperature lower limits and spectra are such that we can confidently assume that they were extragalactic. The three sources yield an estimated source density of three per 4 deg$^2$ at an average 5 GHz flux density of $75$ mJy. This is consistent with source counts of extragalactic sources (Condon 1984). A test of this primary extragalactic assumption is presented in a later section. Table 1 provides the assumed source positions for our primary calibration sources, Sgr A*, and the three reference sources. The initial positions and Besselian 1950 reference frame were assumed for all measurements. In our analysis, relative offsets between the three reference sources from their assumed positions were determined. These offsets and the improved positions for all three reference sources are included in Table 1.

There remains a bias in the reference source positions with respect to our primary phase calibrator, B1748−253,
as will be evident when we introduce Figure 2. Furthermore, our assumed position for B1748−253 at the start of our observations is not accurate, as evidenced by hourly observations of the astrometric standard B1741−038. Table 2 presents J2000 FK5 positions of all sources. The positions of Sgr A* and the three reference sources were kindly provided by G. Bower during his polarization study (Bower et al. 1999). These were referenced to B1748−253 assuming our original coordinates. The four positions were then corrected for the errors in the original B1748−253 coordinates as determined by that listed in the current VLA manual and that determined in our data via the B1741−038 observations. Our estimate of the 1σ absolute accuracy is 5 mas.

From 1982 to 1998, a sequence of eight observations at 4.885 GHz were conducted using the VLA in its 36 km (A) configuration. In more recent epochs, a second band was recorded at 4.835 GHz, but these data were typically not analyzed owing to the dominance of atmospheric errors that are very strongly correlated between the two bands. In the last three epochs, a portion of the standard observing schedule was devoted to observations at 8.435 and 8.485 GHz. Typically 3 days of observations were obtained each epoch. In the text below, we refer to the two bands by their center frequencies of 4.9 and 8.4 GHz.

Each day’s observations were divided into hour-long blocks. During each block we first observed the three nearby reference sources, then Sgr A*, then two reference sources, then Sgr A*, then two reference sources, etc., with a final observation of the three reference sources. At every hour, our phase calibration source B1748−253 and a standard VLA calibration source B1741−038 were observed. Table 3 gives a detailed UT schedule for a block to show typical integration times and spacings. Identical local sidereal time (LST) stop times were used to schedule all observations. Sgr A* was observed every 10 minutes in these blocks. During epochs 6 through 8 we allocated one LST block to 8.4 GHz observations. Given that our analysis had shown that the dominant errors in phase referencing were temporal rather than angular, we revised the schedule for the 8.4 GHz observations by looking at only one reference source between Sgr A* scans and therefore returning to Sgr A* every 6 minutes.

Table 4 provides a journal of the observations with epoch number, sequential day index within the epoch, calendar date, Julian Date, and a code to indicate which band was observed during which block (C for 4.9 GHz and X for 8.4 GHz).
Fig. 2.—First difference positions (hourly phase calibration by B1748—253) in right ascension and declination for our three reference sources (open symbols: triangle = GC 441; inverted triangle = W56; square = W109) and for Sgr A* (solid circle) for three epochs. The solid line represents the eighth-order temporal polynomial fit to the reference source data. Abscissa axes provide the epoch keys: 22 = epoch 2, day 2; 31 = epoch 3, day 1 (a "bad" day on the Plains of St. Augustin); and 81 = epoch 8, day 1 (a "spectacular" day).

### Table 3

| Source    | Start    | Stop     |
|-----------|----------|----------|
| 1741—038  | 09:47:00 | 09:49:20 |
| 1748—253  | 09:51:30 | 09:53:20 |
| GC 441    | 09:54:50 | 09:57:50 |
| W56       | 09:58:20 | 10:01:20 |
| W109      | 10:01:50 | 10:04:50 |
| SGRACN    | 10:05:30 | 10:07:50 |
| GC 441    | 10:08:30 | 10:11:20 |
| W56       | 10:11:50 | 10:14:50 |
| SGRACN    | 10:15:30 | 10:17:50 |
| W109      | 10:18:30 | 10:21:50 |
| GC 441    | 10:21:50 | 10:24:40 |
| SGRACN    | 10:25:20 | 10:27:40 |
| W56       | 10:28:20 | 10:31:10 |
| W109      | 10:31:40 | 10:34:40 |
| SGRACN    | 10:35:20 | 10:37:40 |
| GC 441    | 10:38:20 | 10:41:10 |
| W56       | 10:41:40 | 10:44:40 |
| W109      | 10:45:10 | 10:48:10 |
| 1748—253  | 10:48:50 | 10:52:10 |
| 1741—038  | 10:59:20 | 11:02:10 |

GHz). LST blocks at 15, 16, 17, 18, and 19 hr were originally used with all observations at 4.9 GHz. In later epochs we observed at 8.4 GHz during the 18 hr block and dropped the 15 hr block. For recovery of the files containing these observations, we include in Table 4 the information needed to access the archive tapes at NRAO in Socorro, New Mexico.

Calibration proceeded along standard lines for the VLA. The flux densities for 3C 286 were established with the SETJY task. Then the CALIB task was run to determine the gains for 3C 286 using recommended UV restrictions. Next CALIB was run on secondary flux standards: B1748—253, B1741—038, 3C 48, and NRAO 530. The flux densities of these sources were determined using the GETJY task. The program source, Sgr A* and the three reference sources, were then calibrated in flux and phase using a two-point interpolation of the B1748—253 data via the CLCAL task. These calibration steps are described using the current AIPS program names while the earliest epochs of data were processed using predecessor versions of the software. The hourly calibration to B1748—253 removed instrumental phases and part of the atmospheric phase. While this helps in subsequent data analysis, the effects of this phase calibration are accurately removed by the reference source.
compared to the plane-wave assumption in this model. We expect, however, that the effects of these higher-order terms will be similarly encoded in the differential refraction angles for the set of sources.

Our first program reads a scan of phases and associated antenna locations and then fits them to a plane wave model to produce the instantaneous refraction angle, $\Delta s(t_j)$, with an iteration algorithm. Sidereal time is calculated from the recorded TAI values, and current coordinates of the sources were rotated from the B1950.0 positions (Table 1). On the first iteration, only phase data from baselines with projected lengths between 150 and 200 k$\lambda$ are used. The minimum excludes baselines for which large-scale structure will confuse the phase. The maximum prevents use of data that may have a 2$\pi$ lobe ambiguity. Phases that exceed 90° are excluded owing to a possible lobe ambiguity. On the next iteration, the first estimate is used and the maximum baseline is extended to include the full array. One final pass is done to ensure that the maximum amount of data is used. Each $\Delta s(t_j)$ solution has its internal error estimated from the variations of the phases. Much of the phase variation is not independent from baseline to baseline, so this internal error estimate will underestimate the uncertainty. The error will, however, reflect the phase scatter and so is useful as a relative weight in further analysis.

Figure 2 displays three sets of these differential refraction angles for one day each in epochs 2, 3, and 8. The data from epochs 2 and 8 show the best differential phase stability. In general, the four sources, Sgr A* and the three reference objects, meander back and forth with an amplitude of 0.1 on a timescale of one-half hr. The data from epoch 3 (1983 September 2) display the worst differential phase stability in the entire experiment.

One can readily see in Figure 2 that the position of Sgr A* drifts away from the cluster of reference sources over the

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**TABLE 4**

**JOURNAL OF OBSERVATIONS**

| Epoch | Day | Date    | JD     | Band | VLA Tape | Files | Code |
|-------|-----|---------|--------|------|----------|-------|------|
| 1...... 1 | 1981 Mar 04 | 2,444,667.5 | CCCCC | XL81003 | 33, 34 | BACK |
| 1...... 2 | 1981 Mar 05 | 2,444,668.5 | CCCCC | XL81003 | 36, 37 | BACK |
| 2...... 1 | 1982 Apr 25 | 2,445,084.5 | CCCCC | XH82007 | 45, 46 | BACK |
| 2...... 2 | 1982 Apr 26 | 2,445,085.5 | CCCCC | XH82007 | 48, 49 | BACK |
| 2...... 3 | 1982 Apr 27 | 2,445,086.5 | CCCCC | XH82008 | 3, 4 | BACK |
| 3...... 1 | 1983 Sep 02 | 2,445,579.5 | CCCCC | XH83016 | 24, 25, 26 | AB248 |
| 3...... 2 | 1983 Sep 09 | 2,445,586.5 | CCCCC | XH83017 | 7, 8 | AB248 |
| 3...... 3 | 1983 Sep 16 | 2,445,593.5 | CCCCC | XH83017 | 40, 41 | AB248 |
| 4...... 1 | 1985 Jan 05 | 2,446,070.5 | CCCCC | XH85001 | 18, 19 | AB248 |
| 4...... 2 | 1985 Jan 19 | 2,446,084.5 | CCCCC | XH85003 | 7, 8, 9 | AB248 |
| 4...... 3 | 1985 Jan 29 | 2,446,094.5 | CCCCC | XH85004 | 25, 26 | AB248 |
| 5...... 1 | 1986 Apr 17 | 2,446,537.5 | CCCCC | XH86011 | 9, 10, 11 | AB388 |
| 5...... 2 | 1986 Apr 29 | 2,446,549.5 | CCCCC | XH86012 | 24, 25, 26 | AB388 |
| 5...... 3 | 1986 May 29 | 2,446,579.5 | CCCCC | XH86016 | 3, 4, 5 | AB388 |
| 6...... 1 | 1989 Jan 28 | 2,447,554.5 | CCCCC | XH89003 | 14 | AB520 |
| 6...... 2 | 1989 Feb 02 | 2,447,559.5 | CCCCC | XH89004 | 10 | AB520 |
| 6...... 3 | 1989 Feb 04 | 2,447,561.5 | CCCCC | XH89004 | 13, 14 | AB520 |
| 7...... 1 | 1994 Apr 02 | 2,449,444.5 | CXCX | XH94024 | 8,9 | AB708 |
| 7...... 2 | 1994 Apr 21 | 2,449,463.5 | CXCX | XH94028 | 7,8 | AB708 |
| 7...... 3 | 1994 Apr 26 | 2,449,468.5 | CXCX | XH94029 | 3 | AB708 |
| 8...... 1 | 1998 Apr 10 | 2,450,913.5 | CXCX | XH98038 | 7 | AB857 |
| 8...... 2 | 1998 Apr 18 | 2,450,921.5 | CXCX | XH98040 | 9, 10 | AB857 |
| 8...... 3 | 1998 Apr 24 | 2,450,927.5 | CXCX | XH98042 | 2 | AB857 |
16 yr span of the data in both right ascension (R.A.) and declination (decl.), which corresponds to an apparent motion toward negative galactic longitude. This drift is caused mainly by the inexorable rotation of the solar system around the center of the Galaxy.

In our next analysis step, we interpolatethe differential refraction angles of the reference source observations to the times and position of the Sgr A* observations. Figure 2 demonstrates that temporal variations dominate. If we were to start the program over, we would choose to switch sources even more rapidly. We separately analyze the data within each of the 1 hr blocks of the schedule. Position offsets are removed from the reference sources as we have used constant source position models for all observations, while we determined improved positions in later years. All reference source data in a given block, typically 12 observations, are fitted to an eighth-order polynomial in time. This polynomial is then evaluated at the times of all sources and removed. Then a simple two-point calibration is done between the data of all reference sources for each Sgr A* observation. Examples of these polynomials are shown in Figure 2.

These two analysis steps can be represented as follows:

First the \( \chi^2 \) sums are defined that allow solution for the right ascension \( (\alpha) \) and declination \( (\delta) \) polynomial coefficients:

\[
\chi^2 = \sum \delta [\Delta x(t_i) - \sum a_i (t_j - \langle t \rangle)^i]^2 \tag{1a}
\]

\[
\chi^2 = \sum \delta [\Delta \delta(t_i) - \sum d_i (t_j - \langle t \rangle)^i]^2 \tag{1b}
\]

Then the polynomial coefficient estimates \( (a_k, d_k) \) are used to remove this effect from all sources:

\[
\Delta x(t_i) = \Delta x_i - \sum a_i (t_j - \langle t \rangle)^i \tag{2a}
\]

\[
\Delta \delta(t_i) = \Delta \delta_i - \sum d_i (t_j - \langle t \rangle)^i \tag{2b}
\]

Finally the primed reference source data are interpolated in time, combined with weights to effect an interpolation in angle, and subtracted from the primed Sgr A* data:

\[
\Delta x'_i(t_j) = \Delta x'_i(t_j) - \sum w_i \left[ \Delta x'_i(t_j+) \left( \frac{t_j - t_{j-}}{t_{j+} - t_{j-}} \right) + \Delta x'_i(t_j-) \left( \frac{t_{j+} - t_j}{t_{j+} - t_{j-}} \right) \right] \tag{3}
\]

These optimal weights were chosen such that the mean weighted reference position was equal to that of Sgr A*:

\[
\Delta x_{\text{w}} = 0.288, \quad \Delta \delta_{\text{w}} = 0.288, \quad \Delta \alpha_{\text{w}} = 0.424 \text{ (GC 441, W56, and W109, respectively. One can estimate these weights by inspection of Figure 2, which has the right ascension of W56 nearly equal to that of Sgr A* and the declination of W109 nearly that of Sgr A*, and the right ascension offset of GC441 nearly double and opposite that of W109 and the declination of GC441 nearly equal and opposite that of W56. The errors are propagated from the internal errors carried along with the various steps outlined above. In the best conditions, these errors do indicate the agreement of the data. The errors also display when the data is less good, but as stated earlier, the magnitude of the errors may underestimate the expected data agreement owing to correlation of phase errors between baselines.

Our next step is to combine the position offsets for Sgr A* for each block on each day using the internally propagated errors as weighting factors. The poor quality of the low elevation data in the 15 hr LST block leads us to ignore this data for all days. Only on a few occasions does its quality match that of the higher elevation data. The results of this block averaging for the 4.9 GHz data are displayed in Figure 3 along with a weighted least squares fit for a proper motion, which is

\[
\mu_{x,*} = -2.70 \pm 0.15 \text{ mas yr}^{-1} \tag{4a}
\]

\[
\mu_{b,*} = -5.60 \pm 0.20 \text{ mas yr}^{-1} \tag{4b}
\]

This fit is presented in Figure 4 along with the results of six other fits to subsets of the data. In three subsets, we selected one of the 3 days in each epoch. In the other three subsets, we selected one of the three hour-angle blocks that are available for all epochs. These provide a measure of the effects of the troposphere and other errors on our measurement and serve as our primary estimator of uncertainty in the measured proper motion. We also explored the chance possibility that the reference sources themselves might be Galactic by setting the weight of each reference source to zero in separate runs. The results are all contained in the error polygon shown in Figure 4, which is used to estimate the errors quoted above. We conclude then that the reference sources are indeed extragalactic and not chance compact objects in the center themselves.

The three-epoch, 8.4 GHz data also provided a proper-motion fit that is presented in Figure 4. The result is consistent with the 4.9 GHz result quoted above, although the errors are larger. Again, we used the data on independent days to provide three independent fits to assess errors. The phase analysis discussed here has been done primarily on computers at Berkeley with migration from VAX to \( \mu \text{VAX} \) to SUN.

Use of the B1950 coordinate frame is not ideal for precision astrometry owing to improved precession constants

![Figure 3](image-url)
Fig. 4.—Proper-motion estimates. Circle (solid and open) points are based on eight epochs (16 yr) of 5 GHz data. The solid circle is from a weighted fit to all data. The open circles are from subsets of the data: each of 3 hour-long blocks and each of 3 days for 5 GHz. The crosses are from three epochs (9 yr) of 8.4 GHz data. The circled cross is from a weighted fit to all data. The plain crosses are from each of 3 days. The spread in these subset points provides our best estimate of the errors quoted in the text for these two measurements. The solid square points give the expected proper-

and its incorporation of E-terms of aberration into the cal-

brator source positions. However, our differential technique

suppresses errors in the reference frame and calculation of

apparent coordinates for use in observation time modeling

of the fringe phase. We have inspected the effects of the

B1950 system by precessing source positions at and near

Sgr A* from 1950 to various epochs in the range of 1981 to

1998 with old precession and nutation values and then to

2000 using the new values as specified for FK4 to FK5

catalog conversions by Seidelman (1992; § 3.5). We find that a

false proper motion of

\[
\delta \mu_x = -0.0 \text{ mas yr}^{-1}
\]

is induced. This small motion is similar for our three refer-

ence sources and therefore has negligible effect on our mea-

surements. The size of the effect is significantly larger in

other parts of the sky.

4. INTERPRETATION

4.1. Secular Parallax for Object at Rest in the

Galactic Center

The expected motion for an object at rest in the Galactic

barycenter, its secular parallax, is given in Galactic coordi-


de 

ates by

\[
[\mu_l, \mu_b]_\odot = [\mu_l, \mu_b]_{GR} + [\mu_l, \mu_b]_\odot
\]

\[
\quad = -[(A - B), 0] - [V_\odot/R_\odot, W_\odot/R_\odot],
\]

where \( A \) and \( B \) are Oort’s constants expressed in angular

terms, \( V_\odot \) and \( W_\odot \) give the solar motion with respect to the

local standard of rest in directions of \( l = 90^\circ \) and \( b = 90^\circ \),

respectively, and \( R_\odot \) is the distance to the Galactic center.

The 1984 IAU adopted value for \( (A - B) \) is 26.4 ± 1.9 km

s\(^{-1}\) kpc\(^{-1}\) (Kerr & Lynden-Bell 1986). More recent deter-

minations are consistent with this value: Hanson (1987)

uses the Lick northern sky proper-motion data to obtain

25.2 ± 1.9 km s\(^{-1}\) kpc\(^{-1}\); Feast & Whitelock’s (1997) use of a

Hipparcos study of Cepheid stars yields 27.2 ± 1.0 km s\(^{-1}\)

kpc\(^{-1}\); Olling & Merrifield (1998) use a more complete

model of the Galactic mass field to determine 25.2 ± 1.9 km

s\(^{-1}\) kpc\(^{-1}\); and Feast, Pont, & Whitelock (1998) analyze

Cepheid period-luminosity zero point from radial velocities

and Hipparcos proper motions and revise their previous

result to 27.23 ± 0.86 km s\(^{-1}\) kpc\(^{-1}\). As the 1984 IAU value of

\( (A - B) \) remains in the midst of these new estimates, we

will use this in further calculations.

\[
[\mu_l, \mu_b]_{GR} = [-5.57 \pm 0.42, 0.0] \text{ mas yr}^{-1}.
\]

The solar motion has been determined by Dehnen & Binney
(1998) using Hipparcos results: \((U_\odot, V_\odot, W_\odot) = (11.0 \pm 0.4,

5.3 \pm 0.6, 7.0 \pm 0.4) \text{ km s}^{-1}\). The apparent proper motion

toward solar motion with respect to the local standard of rest

using \( R_\odot = 8.5 \text{ kpc} \) is

\[
[\mu_l, \mu_b]_\odot = [-0.13 \pm 0.02, -0.17 \pm 0.01] \text{ mas yr}^{-1}.
\]

The total secular parallax is

\[
[\mu_l, \mu_b]_\odot = [-5.70 \pm 0.42, -0.17 \pm 0.01] \text{ mas yr}^{-1}.
\]

The solar motion contributes negligible additional uncer-

tainty to the secular parallax.

4.2. Apparent Peculiar Motion of Sgr A*

We project the observed proper motion, equation (4),

from equatorial coordinates to Galactic coordinates and

remove the expected secular parallax for an object at rest in

the Galactic barycenter, equation (9), to obtain the peculiar

motion. The north celestial pole (NCP), north Galactic pole

(NGP), and Galactic center (GC) form a spherical triangle.

The equatorial coordinates of the NGP and the GC are

12h49m and +27°24’ and 17h42m24’ and −28°55’, respec-

tively (B1950; Blaauw et al. 1960). The spherical angle

NGP-NGP-GC is then 73:37, and the side of the triangle

opposite NGP-GC-NCP has length 62:60. NGP-NCP-GC

is the negative of the position angle \(^2\) of the positive Galactic

latitude axis (\( b \)) and by law of sines is −58°29’. The position

angle of the positive longitude axis (\( l \)) is then +31°71.’

Errors in determination of the Galactic pole and center are

of order 7’ (Blaauw et al. 1960) and hence of little conse-

quence to these calculations. Redetermination of the prin-

cipal plane of the Galaxy via Population II stars seen by

IRAS (Habing 1988) would be an interesting stellar mass

check on the early H I gaseous disk determination. The

resultant observed proper motion of Sgr A* in Galactic

coordinates is

\[
\mu_{l,*} = [-6.18 \pm 0.19] \text{ mas yr}^{-1}
\]

\[
\mu_{b,*} = [-0.65 \pm 0.17] \text{ mas yr}^{-1}.
\]

\(^2\) Position angles are measured north toward east, counterclockwise on

the sky.
The observed peculiar motion of Sgr A* is then obtained by subtracting the expected secular parallax, equation (9), from the measurements:

\[
\Delta \mu_\ell,*, = [-0.48 \pm 0.46] \text{ mas yr}^{-1}
\]

\[
\Delta \mu_\phi,*, = [-0.48 \pm 0.17] \text{ mas yr}^{-1}.
\]

The errors have been combined in quadrature. At a distance of 8.5 kpc, the peculiar velocity of Sgr A* is

\[
v_\ell,*, = [-19 \pm 19] \text{ km s}^{-1}.
\]

\[
v_\phi,*, = [-19 \pm 7] \text{ km s}^{-1}.
\]

The timescale for the scattered image to sample an independent portion of the turbulent screen is given by the ratio of the linear size of the image to the velocity of the screen relative to the line of sight. If we take this transverse velocity to be 100 km s\(^{-1}\), which is characteristic of the rotating molecular disk, then independent samples of any refractive beam wander (or source size change) will occur on time intervals of 20 (7) yr, respectively. Over the somewhat shorter 16 yr interval of our 4.9 GHz measurements, we might see just a linear change of the position if our above conclusion that refraction was not important was wrong.

A separate test of refractive effects is to look at the differential proper motion from refractive wander is 0.25y mas yr\(^{-1}\), where \(g(t)\) is the fractional shift of the centroid of the scattering disk from its long-term average. Statistically, the amplitude of this false motion would be frequency independent as the timescale shortens with frequency just in proportion to the apparent size. During any short time interval, the refractive motion will differ over an octave of frequency, so we could expect that the effects at our two radio frequencies would differ.

4.3. Radio Wave Propagation Effects

VLBI observations show that the apparent angular diameter of Sgr A* depends strongly on frequency, 1.4 mas \(\lambda^{+2.0}\), which is consistent with angular broadening by scattering in the intervening plasma (Lo et al. 1981, 1985; Backer 1988; Jauncey et al. 1989; Lo et al. 1993; Alberdi al. 1993; Yusef-Zadeh al. 1994; Backer 1994; Rogers et al. 1994; Bower & Backer 1998; Lo et al. 1998). The scattering interpretation is strengthened by the demonstration that OH masers within 0.1 of Sgr A* are similarly broadened (van Langevelde et al. 1992; Frail et al. 1994). A simple interpretation is that the diffuse thermal plasma in the central 140 pc (diameter in longitude) is sufficiently turbulent to produce the observed scattering. This gas may be that seen in the northern hemisphere where VLBI baseline coverage is poor, several experiments have shown convincingly that the scatter-broadened image is elliptical with a ratio of axes of about 2:1 at position angle (P.A.) \(\sim 80^\circ\). The strong ellipticity in scattering most likely indicates that the scattering gas is threaded by a relatively uniform magnetic field, the pressure of which dominates the thermal and turbulent pressures of the plasma. The thin “threads” of synchrotron emission detected in the Galactic center provide ample evidence for strong and uniform magnetic fields (Yusef-Zadeh, Morris, & Chance 1984). The field is not uniform over scales of 50 pc as the OH maser elongations are not aligned.

Our concern here is not so much with the scattering itself but, rather, with the stability of the scattering. Consider a scattering screen located a distance \(fD\) from Sgr A* with the observer at \(D\). The screen broadens a plane wave by an angle \(\Theta_s\). The observed source size is then \(\theta_0 = f\Theta_s\), which leads to a decorrelation in the visibility domain on baselines of length \(b_0 = \lambda/(2\pi\Theta_s)\). This decorrelation arises from phase differences through the screen on length scales of \(b_0\).

For 4.9 (8.4) GHz this is 240f (400f) km. The identification of the scattering with a 140 pc halo around the Galactic center suggests \(f \approx 0.01\) and therefore decorrelation on extremely small scales, 2.4 (4.0) km. These length scales are most likely smaller than the inner scale of the density fluctuations spectrum that is set by plasma wave dissipation processes. When phase decorrelation occurs on scales much smaller than that of the density fluctuations owing to many-radian phase wrapping, the expected dependence of scattering diameter on wavelength is exactly \(\lambda^{+2.0}\), which is consistent with current observations. In this regime, we also do not expect image wander from large-scale refractive effects, and any changes in the angular broadening will occur on long timescales set by \(\theta_0/v_1\), where \(v_1\) is the transverse motion of the line of sight through the perturbing plasma. We proceed to inspect the evidence for stable propagation through the intervening medium.

The relevance of this discussion to our proper-motion measurements is that our epoch accuracy is around 1–2 mas, while the scatter-broadened image is 50 (18) mas (and VLA synthesized beam is 500 (180) mas) at 4.9 (8.4) GHz, respectively. The scattered image size itself is very stable. Lo et al. (1981) determined a size at 8.4 GHz of 17 ± 1 mas in 1974.4 with principal resolution in the east-west direction. Later measurements in 1983.4 had sufficient UV coverage to determine elliptical source parameters: 15.5 ± 0.1 mas with axial ratio of 0.55 ± 0.25 and P.A. of 98° ± 15° (Lo et al. 1985). Recent VLBA observations provide parameters of 18.0 ± 1.5 mas with ratio of 0.55 ± 0.14 and P.A. of 78° ± 6° (Lo et al. 1998). We conclude that the source size has not changed by more than 5%–10% over 23 yr either with random or secular variations. Thus the apparent source image is not expanding or contracting at a rate any larger than 0.07 mas yr\(^{-1}\) at 8.4 GHz.

The timescale for the scattered image to sample an independent portion of the turbulent screen is given by the ratio of the linear size of the image to the velocity of the screen relative to the line of sight. If we take this transverse velocity to be 100 km s\(^{-1}\), which is characteristic of the rotating molecular disk, then independent samples of any refractive beam wander (or source size change) will occur on time intervals of 20 (7) yr, respectively. Over the somewhat shorter 16 yr interval of our 4.9 GHz measurements, we might see just a linear change of the position if our above conclusion that refraction was not important was wrong.

The typical contribution to the proper motion from refractive wander is 0.25y mas yr\(^{-1}\), where \(g(t)\) is the fractional shift of the centroid of the scattering disk from its long-term average. Statistically, the amplitude of this false motion would be frequency independent as the timescale shortens with frequency just in proportion to the apparent size. During any short time interval, the refractive motion will differ over an octave of frequency, so we could expect that the effects at our two radio frequencies would differ.

A separate test of refractive effects is to look at the differential positions at the two frequencies at a single epoch. In our Green Bank experiment (BS882), we found that the differential positions at 2.7 and 8.1 GHz were identical to within \(\sim 0.02\) of the scattering diameter at 2.7 GHz. Note that the reference sources in the Green Bank and VLA experiments differ. In Figure 5 we show the differential Sgr A* positions from three days of observations in epoch 8 at 4.9 and 8.4 GHz. There is a systematic offset of \(\sim 5\) mas in right ascension that is 0.1 times the scattering diameter at 5 GHz. Source structure can be one source of difference, although 5 mas is a large value for this effect. Without further high-resolution imaging and monitoring we cannot determine the source or the stability of this offset. A similar offset is seen in the epoch 7 data, although the errors are somewhat larger. We conclude that even if refractive wander is present, \(q\) is no more than 0.1 and the apparent motion it might contribute is less than our current errors.
4.4. Dynamical Effects on the Central Black Hole

A black hole in the center of the Galaxy will have a statistical motion with respect to the Galactic barycenter owing to the influence of the uneven momentum distribution of objects surrounding it. Consider the motion induced by the transit, or orbit, of a perturbing mass ($m_2$) such as a nearby star or a passing molecular cloud. The effect of $m_2$ on the mass enclosed ($m_1(r)$), and therefore Sgr A*, is given by the acceleration $Gm_2/r^2$ acting for a time given by $r$ divided by the circular velocity at $r$, $r/v_c(r)$. The circular velocity at $r$ is given by $[Gm_1(r)/r]^2$. The resulting motion of the barycenter (toward $m_2$) is then

$$\Delta v_{\text{BC}} = \frac{\sqrt{Gm_2}}{\sqrt{rm_1(r)}}.$$

Figure 6 shows the mass and radial distance of a number of asymmetric masses in the center of the Galaxy. In general, these appear to grow as $r^{-1.5}$, which is shown in Figure 6. The asymmetric masses range from the nearest solar mass star, the orbital period of which is long with respect to our measurement interval to the star formation complex, Sgr B2. Inside of about 1 pc, $m_1$ is constant as shown by the IR stellar motions (Eckart & Genzel 1997; Ghez et al. 1998), and $\Delta v_{\text{BC}}$ will be proportional to $r$ as one considers various contributions to the barycentric motion. The resultant motions, however, are small—less than 1 km s$^{-1}$. In the range 1–100 pc, the enclosed luminous mass grows as $r^{1.2}$ based on 2 $\mu$m measurements (see review by Genzel et al. 1994). Mass asymmetries in this range then have an influence on the motion of objects surrounding it. Consider the motion induced owing to the influence of the uneven momentum distribution of objects surrounding it. As one goes to larger and larger radii, the peculiar motion from mass asymmetries will be increasingly dominated by a longitude motion and not a latitude motion, which is the central concern in this paper. We conclude that the influence of mass asymmetries in the Galactic center can be ignored at the present level of accuracy.

The perturbations of a few km s$^{-1}$ that are expected for a central black hole in our Galaxy based on the discussion above can be compared with that expected in other galaxies based on observed asymmetries. The nature of the double nucleus in M31 remains uncertain. The nucleus has probably been identified by the large-velocity dispersion at the location of the P2 nucleus (Statler et al. 1999). The other nucleus, P1, may be a concentration of stars in an eccentric disk (Tremaine 1995). Alternatively, P1 may be a star cluster that will shortly be “absorbed” into the central core by tidal disruption. In either case, the observations indicate that the 7 $\times$ 10$^7$ $M_\odot$ black hole and the surrounding stars will not be at rest in the mass center of M31 at the level of 10 km s$^{-1}$ owing to the influence of the estimated 3 $\times$ 10$^6$ $M_\odot$ stars in P1. This mass asymmetry in M31 is considerably larger than that known for our Galaxy at a comparable radius (Fig. 6).

One source of the excitation of an eccentric disk in M31 mentioned above is an unstable $m = 1$ normal mode in an axisymmetric disk. Numerical N-body simulations by Miller & Smith (1992) have shown that the core of galaxies will exhibit motions owing to an unstable $m = 1$ normal mode of oscillation. For the parameters of our Galactic center, the black hole and its associated cusp of stars could be moving as fast as 70 km s$^{-1}$ (Miller 1996). The instability is the result of an amplification of the small motions discussed above. The direction of this putative motion is arbitrary if the perturbations are the result of mass asymmetries on scales less than 100 pc. Over these scales, there is as much evidence for order as disorder with respect to the well-defined Galactic plane seen on kiloparsec scales. At
the level of 70 km s\(^{-1}\), we definitely do not see the effect predicted by Miller. We can be unlucky and the motion may be largely radial. If so, we would expect the black hole to be offset in angle from the centroid of stars at larger radii, which could be tested with analysis of the IR stellar distribution.

If there is a massive black hole at the center of the Galaxy, Gould & Ramirez (1998) have shown that our limit on the observed acceleration implies that Sgr A* is either coincident with or closely bound to that black hole. They point out that acceleration has the advantage of not being confused by uncertainty in Oort's constants. If one expresses both the peculiar velocity and the acceleration of Sgr A* in units of the Earth's motion around the Sun, the normalized velocity and acceleration are equal at a distance of 140 AU for a gravitational mass of \(2.5 \times 10^6 M_\odot\). Acceleration measurements, or limits, are therefore relatively more important for distances inside 140 AU if the measurements have comparable precision in Earth units. If Sgr A* is a random object in the gravitational potential that one can establish firmly from the IR proper-motion studies, then its acceleration is expected to be 0.27\(a_g\), where \(a_g\) is the acceleration of the Earth in its orbit around the Sun. Our upper limit of the acceleration allowed using the full 1982 to 1998 data set is 0.3 mas yr\(^{-2}\), or 0.06\(a_g\). This result, although slightly higher than that used by Gould & Ramirez, is still small compared to that of a low-mass object near the massive black hole. By comparison, the precision of our latitude peculiar motion is 7 km s\(^{-1}\), or 0.21\(v_g\). We conclude that if the center harbors a massive black hole, then the radio source Sgr A* must be attached to it. They also discuss the possibility that Sgr A* is in very close orbit around the black hole with an excursion less than our single epoch precision and an orbital period less than our time base. The VLBA result of Reid (1999) and its comparison with the longer duration VLA result here will place further constraints on this extreme scenario.

Gould & Ramirez also use the limit on acceleration to state the low probability of Sgr A* being a random object passing through a dense cluster of weakly interacting dark matter. In their conclusion, they return to this scenario and describe a test using flux density variations caused by Doppler boosting. Such variations would be evident in the daily sampled data discussed by Backer (1994). They note in passing that the equipartition mass of Sgr A* based on the acceleration limit is 250 \(M_\odot\) based on a 10 \(M_\odot\) characteristic mass. The equipartition mass limit for Sgr A* based on the limit on peculiar motion of \(<19\) km s\(^{-1}\) and 10 \(M_\odot\) IR stars moving at 1000 km s\(^{-1}\) is \(>2 \times 10^4 M_\odot\).

Maoz (1998) discusses the dynamical constraints on alternatives to supermassive black holes in galactic nuclei. Critical to his discussion are estimates of the black hole mass and surrounding density in the cusp of stars that form around the black hole. Sgr A*'s diameter upper limit from the 3 mm VLBI measurements of Rogers et al. (1994) is 1 AU. When combined with the mass limit this leads to a lower limit for its density of \(\sim 10^{21} M_\odot\) pc\(^{-3}\). As noted by E. Maoz (1998, private communication), one can argue this point. The radio emission may come from the central body of a cluster or a disk and hence may not delimit the full size of the parent mass. In proceeding we assume that the radio emission encompasses the parent mass as it would in the case of quasi-spherical accretion and core-jet models. The density estimate is such that any form of matter other than a black hole will have a dissipative lifetime less than \(10^8\) yr.

5. Conclusion

Measurements with the NRAO Very Large Array from 1982 to 1998 at 4.8 GHz have provided the first proper motion of the compact radio source in our Galactic center, Sgr A*. The peculiar motion of Sgr A* in the mass center of the Galaxy is obtained after removing an estimate of the secular parallax that results from the solar motion. In latitude, the estimated peculiar motion is \(19 \pm 7\) km s\(^{-1}\). Our ongoing uncertainty about the nature of Sgr A* leads us to use the limit on peculiar motion along with an equipartition argument to place a lower bound on its mass of \(2 \times 10^4 M_\odot\). The inferred mass density of Sgr A* is then \(10^{21} M_\odot\) pc\(^{-3}\) based on a previous estimated 1 AU source diameter at 86 GHz. This is the highest mass density inferred for any Galactic black hole candidate. Mass density is currently the best argument for existence of a black hole when consideration is given to the stability of configurations of dark matter other than a solitary black hole.

The simplest model is that Sgr A* is radiation from the atmosphere of the 2.5 \(\times 10^6 M_\odot\) black hole. Nearly steady inflow and outflow models for the radiative properties of Sgr A* exist. The possibility of a nonzero peculiar motion has led to consideration of the influence of known mass asymmetries in the central region of our Galaxy. We conclude that these would account for no more than a few km s\(^{-1}\) perturbation. Another source of motion may be a \(m = 1\) instability in the central potential. Our estimated peculiar motion is in fact smaller than the estimated size of this effect, although projection factors need to be considered to make a firm statistical statement.

A nonzero proper motion might be attributed to systematic errors in the measurements, time-variable frequency-dependent effects, or variations in the intrinsic structure. At 4.8 GHz, Sgr A* is scattered by angles significantly greater than our relative position measurement accuracy. While one can argue that variable refraction is probably not important, this remains a source of uncertainty for the VLA measurements. Models for the radio emission of Sgr A* suggest an increasing intrinsic source size with decreasing radio frequency. This could lead to additional systematic effects for the VLA measurements. Further measurements at higher radio frequencies are planned to resolve these uncertainties.

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