A Geometric Determination of the Distance to the Galactic Center

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ABSTRACT

We report new astrometric and spectroscopic observations of the star S2 orbiting the massive black hole in the Galactic Center, which were taken at the ESO VLT with the adaptive optics assisted, near-IR camera NAOS/CONICA and the near-IR integral field spectrometer SPIFFI. We use these data to determine all orbital parameters of the star with high precision, including the Sun-Galactic Center distance, which is a key parameter for calibrating stellar standard candles and an important rung in the extragalactic distance ladder. Our deduced value of $R_0 = 8.0 \pm 0.4$ kpc is the most accurate primary distance measurement to the center of the Milky Way and has minimal systematic uncertainties of astrophysical origin. It is in excellent agreement with other recent determinations of $R_0$.

Subject headings: Galaxy: center - Galaxy: fundamental parameters - Galaxy: structure - galaxies: distances and redshifts

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1 based on observations obtained at the Very Large Telescope (VLT) of the European Southern Observatory, Chile
1. Introduction

The distance between the Sun and the Galactic Center ($R_o$) is a fundamental parameter for determining the structure of the Milky Way. Through its impact on the calibration of the basic parameters of standard candles, such as RR Lyrae stars, Cepheids and giants, the Galactic Center distance also holds an important role in establishing the extragalactic distance scale. Ten years ago Reid (1993) summarized the state of our knowledge on $R_o$. At that time the only primary (geometric) distance indicator to the Galactic Center came from the ‘expanding cluster parallax’ method applied to the H$_2$O masers in SgrB2, believed to lie within $\sim$0.3 kpc of the Galactic Center (Güsten & Downes 1980). Reid et al. (1988a, b) determined values of 7.1 and 6.5 kpc for the distances to the masers in SgrB2(N) and SgrB2(M), respectively, with a combined statistical and systematic (1$\sigma$) uncertainty of $\pm$1.5 kpc. In addition there existed a number of secondary (standard candle) determinations, based on RR-Lyrae stars, Cepheids, globular clusters and giants, as well as a number of tertiary indicators, derived from theoretical constraints (e.g. Eddington luminosity of X-ray sources, Galaxy structure models). From all these measurements Reid inferred a best overall estimate of 8.0 kpc, with a combined uncertainty of $\pm$0.5 kpc. In the time since 1993 Genzel et al. (2000) reported a primary (statistical parallax) distance, $R_o=8.0\pm0.9$ kpc (statistical error bar), based on a statistical comparison of proper motions and line-of-sight velocities of stars in the central 0.5 pc of the Galaxy. Carney et al. (1995) and McNamara et al. (2000) found secondary distances of 7.8 and 7.9 kpc ($\pm0.7$ kpc) from RR Lyrae and $\delta$-Scuti stars. Feast & Whitelock (1997) used Cepheids and a Galactic rotation model, updated for the new Hipparcos local distance scale, to obtain $R_o=8.5\pm0.5$ kpc. Paczynski & Stanek (1998) and Stanek & Garnavich (1998) combined measurements of red clump stars with the Hipparcos scale to obtain $R_o=8.2$ kpc, with a claimed combined statistical and systematic uncertainty of $\pm0.21$ kpc.

We report here the first primary distance measurement to the Galactic Center with an uncertainty of only 5%. This determination has become possible through the advent of precision measurements of proper motions and line-of-sight velocities of the star S2. This star is orbiting the massive black hole and compact radio source SgrA* that is located precisely at the center of the Milky Way. As discussed by Salim & Gould (1999), the classical ‘orbiting binary’ technique can then be applied to obtain an accurate determination of $R_o$ that is essentially free of systematic uncertainties in the astrophysical modeling. The essence of the method is that the star’s line-of-sight motion is measured via the Doppler shift of its spectral features in terms of an absolute velocity, whereas its proper motion is measured in terms of an angular velocity. The orbital solution ties the angular and absolute velocities, thereby yielding the distance to the binary. Schödel et al. (2002) found that S2 is on a highly elliptical Kepler orbit around SgrA*, with an orbital period of about 15 years and
a peri-center distance of about 17 light hours. Ghez et al. (2003) confirmed and improved the Schödel et al. (2002) results and reported the first spectroscopic identification and line-of-sight velocity measurement of S2. S2 appears to be a 15-20 $M_\odot$ main sequence O8-B0 star whose line-of-sight velocity can be inferred in a straightforward manner from the HI Brγ absorption in the star’s K-band (2.2μm) spectrum. With additional line-of-sight velocity and proper motion data it has now becomes feasible to make a precision estimate of all orbital parameters, including the distance to S2/SgrA*.

2. Observations

2.1. NAOS/CONICA adaptive optics imaging

We observed the Galactic Center on Yepun (UT4 of the VLT) with the NAOS/CONICA (NACO, Lenzén et al. 1998, Rousset et al. 1998) near-infrared, adaptive optics imager on March 17/18 2003 (2003.21) and May 8/9 2003 (2003.35). We observed through the H-band (1.65μm) filter and used the infrared wavefront sensor to correct in K-band on the bright supergiant IRS7, located ~5.6” north of S2/SgrA*. In both runs the seeing was ≤0.5”, resulting in H-band Strehl ratios between 0.3 and 0.5. After producing final maps with the shift-and-add technique, we deconvolved the images with a linear Wiener filter and a Lucy-Richardson algorithm. We extracted stellar positions from the deconvolved images with the program STARFINDER (Diolaiti et al. 1995). We also applied this technique to all 2002 NACO Galactic Center imaging data described by Schödel et al. (2003), thereby improving slightly their results. All positions prior to 2002 are from the observations with the SHARP instrument on the ESO 3.5m NTT, as reported by Schödel et al. (2003). Our positional errors are a combination of fit errors and errors in placing S2 in a common infrared astrometric frame, resulting in overall errors for NACO of 1-3 mas (1σ) in 2003 and 3-7 mas in 2002 (when the performance of the then new NACO instrument was still not optimized), and 6-10 mas for the 1992-2001 SHARP/NTT measurements. In addition, there is a ±10 mas absolute uncertainty between the infrared and radio astrometric frames (Reid et al. 2003a). Figure 1 is a plot of the positions of S2 between 1992 and 2003.

2.2. SPIFFI integral field spectroscopy

On April 8/9 2003 (2003.27) we observed the Galactic Center on Kueyen (UT2 of the VLT) with the new MPE integral field spectrometer SPIFFI (Thatte et al. 1998, Eisenhauer et al. 2000). Briefly, SPIFFI uses a reflective image slicer and a grating spectrometer to
simultaneously obtain spectra with 1024 spectral elements for a contiguous 32×32 pixel, two dimensional field on the sky. In very good seeing conditions (0.4”-0.5” in the optical) we observed with a pixel scale of 0.1”, resulting in a 2µm FWHM of 0.25”-0.3”. The FWHM spectral resolution was 85 km/s, sampled at 34 km/s. We dithered about two dozen exposures of 1 minute integration time each to construct a mosaicked data cube of the central ~8”. Data reduction used the new SPIFFI analysis pipeline, as well as IRAF tools. We determined the wavelength calibration from arc lamps and OH sky emission lines, resulting in an accuracy of ±7 km/s. The effective integration time toward the central part of the mosaic near SgrA* was about 15 minutes. We used both the flat spectrum star IRS16CC and the ATRAN atmospheric code to correct for atmospheric absorption. We then extracted spectra toward S2 and several 'off' positions nearby in apertures of about 0.2” in diameter. We analyzed the direct as well as the off-subtracted spectra. Off-subtraction is important for removing the extended nebular Brγ emission from the SgrA West mini-spiral. For our spring 2003 data, direct and off-subtracted spectra were identical near the star’s Brγ absorption line at \( v_{LSR} = -1545\pm25 \) km/s, far off the nebular contamination. The direct SPIFFI spectrum is shown in the left inset of Figure 2.

2.3. NACO long slit spectroscopy

We took K-band grism spectroscopy of S2 with NACO on Yepun on May 8/9 2003 (2003.35). As for the H-band imaging, the optical seeing was ~0.4”-0.5” and we used the infrared wavefront sensor on IRS7. We chose the 86 mas slit, resulting in 210 km/s resolution sampled at 69 km/s per pixel. The spatial pixel scale was 27 mas and we placed the slit at position angle 78° through S2. We integrated for about 5 minutes per readout and nodded the slit by ±5”. We accumulated 30 minutes of on-source integration. Data analysis employed standard IRAF longslit tools. We calibrated on arc lamps, resulting in a velocity accuracy of ±10 km/s. We corrected for atmospheric absorption by dividing the Galactic Center spectra by an early type star observed at the same airmass. The inferred LSR velocity of the Brγ absorption of S2 was -1512±35 km/s. Again, no correction for nebular emission was necessary. The nodded NACO spectrum in a 0.086” ×0.1” aperture is shown in the right inset of Figure 2.
3. Results

3.1. Geometric Distance Estimate to the star S2

For the analysis of our measurements we fitted the positional and line-of-sight velocity data to a Kepler orbit, including the Galactic Center distance as an additional fit parameter. In principle the dynamical problem of two masses orbiting each other requires the determination of 14 parameters: 6 phase space coordinates for each mass, plus the values of the two masses (see Salim & Gould 1999). At the present level of accuracy, four of these 14 parameters can be safely neglected: the mass of the star (since $m_{S2}/M_{SgrA*} \sim 5 \times 10^{-6}$) and the three velocity components of SgrA*. Radio interferometry of SgrA* with respect to background quasars has established that after subtraction of the motions of Earth and Sun around the Galactic Center the proper motion of SgrA* is $\leq 20$ km/s in the plane of the Galaxy and $\leq 8$ km/s toward the Galactic Pole (Backer & Sramek 1999, Reid et al. 1999, Reid et al. 2003b). This implies $v_{SgrA*} \sim v_{S2}$. Likewise the uncertainty in the local standard of rest velocity ($\leq 10$ km/s) can also be neglected at the present level of analysis (see Salim & Gould 1999). In the actual orbital fitting we solve for the geometric parameters of the orbit (Table 1), as well as the time of peri-center passage. The central mass is a dependent variable that is calculated from the semi-major axis and period, using Kepler’s 3rd law. Our measurement constraints consist of the 18 ($x^2$) S2 positions between 1992 and 2003 and 4 line-of-sight velocities: 2 from Ghez et al. (2003), 1 from SPIFFI and 1 from NACO. This leaves us to fit 10 parameters with 40 data points, resulting in an over-constrained problem with 30 degrees of freedom. For fitting the orbit of S2, we expanded our existing IDL program codes for Keplerian orbits (see Schödel et al. 2003) to take into account the additional information provided by line-of-sight velocity measurements. The errors of the orbital parameters are based on an analysis of the covariance matrix. The uncertainty in $R_o$ is most strongly correlated with the semi-major axis $a$, the inclination $i$, and the time of peri-center approach $T_{peri}$, all of which are well determined in our model. Table 1 is a list of the fitted parameters of the S2 orbit, the mass and location of the central object and the distance to the Galactic Center. Figures 1 and 3 show the best-fit orbital and line-of-sight velocity curves derived from the fit parameters in Table 1, superposed on our data. The accuracy of the orbital parameters in Table 1 is 3 to 6 times better than those in Schödel et al. (2002), and 1.3 to 2 times better than those in Ghez et al. (2003).
3.2. Statistical Parallax to the Central Star Cluster

In addition to the \( R_0 \) value from the S2 orbit, we also report an update of the statistical parallax distance to the stars in the central 0.5 pc. We used the proper motion and line-of-sight velocity data base of Ott et al. (2003) and complemented these by additional \( \sim 100 \) velocities of early type and late type stars in the central 10" extracted from the new SPIFFI data cube discussed above (Abuter et al. 2003). We now have 106 late type stars and 27 early type stars with all three velocities. For these two sets we can apply the anisotropy independent distance estimator introduced by Genzel et al. (2000),

\[
\left( \frac{R_0}{8 \text{kpc}} \right) = \left( \frac{<p v_z^2>_8}{1/3 <p v_R^2>_8 + 2/3 <p v_T^2>_8} \right)^{0.5} \tag{1}
\]

where \( p \) is the sky projected distance of a star from SgrA*, and \( v_z, v_R \) and \( v_T \) are the line-of-sight, sky projected radial, and sky projected tangential velocities (from proper motions). The symbol \(<>\) denotes the ensemble average for an assumed distance of 8 kpc. Within the radius of influence of the black hole (\( \sim 0.5 \) pc) this estimator gives an equal weight to stars at different distances from SgrA*. Applying this estimator to the 106 late type stars \( (p \leq 10") \) with three velocities yields \( R_0 = 7.1 \pm 0.7 \) kpc. For the 27 early type stars we find \( R_0 = 8.0 \pm 1.6 \) kpc, where the error bars are statistical in both cases. The early and late type stars have very different dynamical properties and thus need to be treated separately (Genzel et al. 2003). We estimate that both values have an additional systematic uncertainty (due to phase space clumping, possible streaming motions etc.) of \( \pm 0.6 \) kpc. The statistical parallax method thus gives \( R_0 = 7.2 \) kpc (with a combined uncertainty of \( \pm 0.9 \) kpc), in good agreement with the more accurate S2 orbit determination.

4. Discussion

The value of \( R_0 \) deduced from the orbit of S2 is \( 8.0 \pm 0.4 \) kpc. Our determination rests on the analysis of a simple dynamic system. The massive black hole candidate SgrA* is located at the very center of the Milky Way. The distance value and its uncertainty come from a global fit to all data that includes all parameter interdependencies through the covariance matrix. Hence we are confident that the deduced errors contain all sources of uncertainty. The derived distance has no sizeable additional systematic uncertainties due to the astrophysical modeling. For instance, deviations of the gravitational potential from that of a point source are small. Schödel et al. (2002, 2003) and Genzel et al. (2003) conclude that any distributed mass with a density distribution similar to that of the central stellar cusp cannot contribute more than a few hundred solar masses within the peri-center distance of S2, or \( 10^{-4} \) of the mass of the central black hole. It is also unlikely that the
central mass is a binary black hole of approximately equal masses, since such binary hole would have to have a separation less than 10 light hours (constrained by the data) and would coalesce by gravitational radiation in a few hundred years. The fractional uncertainty in the value of $R_o$ is under 5%, thus delivering the most accurate, primary Galactic Center distance measurement so far. It is gratifying to see how well our value agrees with all other, primary and secondary distance measurements. This gives confidence in the quality and robustness of the standard candles methods (RR Lyrae stars, Cepheids, red clump stars etc.) that are at the key of the second rung of the extragalactic distance ladder.

Future improvements in the accuracy of $R_o$ from the orbit of S2 alone will be relatively slow. This is because we have already sampled three quarters of the entire orbit, and have also observed the largest swing in the line-of-sight velocity curve. As discussed in Salim & Gould (1999), further significant improvements to the level of under a few percent can be expected from combinations of several orbits, since then the number of degrees of freedom is rapidly increasing (as four fit parameters are common to all orbiting stars).

Acknowledgements. We are grateful to N.Thatte, C.Iserlohe, J.Schreiber, M.Horrobin, C.Röhrle, S.Huber and S.Weisz whose work on SPIFFI was essential for the Galactic center data taken here. We also thank the Paranal staff and our colleagues from NAOS (D.Rouan, F.Lacombe) and CONICA (R.Lenzen, P.Hartung) for their support. We thank M.Reid for valuable comments on this paper, and B.Schutz for comments on the coalescence time for binary black holes. TA is supported by GIF grant 2044/01, Minerva grant 8484 and a New Faculty grant by Sir H. Djangoly, CBE, London, UK.
REFERENCES

[Reid, M. J. 1993, ARAA, 31, 345]

[Reid, M.J., Menten, K.M., Genzel, R., Ott, T., Schödel, R. & Brunthaler, A. 2003b, Astr Nachr., S1, 3


 & R.K.Tyson, 3353, 704
Table 1. Best Kepler orbit fit to the NACO, SPIFFI and NIRC2 data of S2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>degrees of freedom of fit</td>
<td>30</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>17.22</td>
</tr>
<tr>
<td>$\chi^2_{red}$</td>
<td>0.58</td>
</tr>
<tr>
<td>semi-major axis $a$</td>
<td>$0.1200 \pm 0.0026$ arcsec</td>
</tr>
<tr>
<td>eccentricity $e$</td>
<td>$0.880 \pm 0.006$</td>
</tr>
<tr>
<td>orbital period $P$</td>
<td>$15.559 \pm 0.337$ yr</td>
</tr>
<tr>
<td>time of peri-center approach $T_{peri}$</td>
<td>$2002.329 \pm 0.011$ yr</td>
</tr>
<tr>
<td>inclination $i$</td>
<td>$-47.9 \pm 1.3$ deg</td>
</tr>
<tr>
<td>angle of line of nodes $\Omega$</td>
<td>$45.3 \pm 1.5$ deg</td>
</tr>
<tr>
<td>angle of nodes to peri-center $\omega$</td>
<td>$245.1 \pm 1.6$ deg</td>
</tr>
<tr>
<td>$x_0$</td>
<td>$0.0022 \pm 0.0012$ arcsec</td>
</tr>
<tr>
<td>$y_0$</td>
<td>$-0.0032 \pm 0.0011$ arcsec</td>
</tr>
<tr>
<td>$R_0$</td>
<td>$7.99 \pm 0.38$ kpc</td>
</tr>
<tr>
<td>$M_0$</td>
<td>$3.65 \pm 0.25 \times 10^6$ $M_{\odot}$ \textsuperscript{a}</td>
</tr>
</tbody>
</table>

\textsuperscript{a} $M_0$ is not a fit parameter but equals $4\pi^2a^3/(GP^2)$ (3\textsuperscript{rd} Kepler law).
Fig. 1.— Position measurements of S2 in the infrared astrometric frame. Crosses (denoting $1\sigma$ error bars) with dates mark the different position measurements of S2, taken with the MPE speckle camera SHARP on the 3.5m ESO NTT (between 1992 and 2001), and with NACO on the VLT (in 2002 and 2003). The continuous curve shows the best-fit Kepler orbit from Table 1, whose focus is marked as a small error circle. The focus of the ellipse is within a few mas at the position of the compact radio source, which is marked by a large circled cross. The size of the cross denotes the $\pm 10$ mas positional uncertainty of the infrared relative to the radio astrometric reference frame.
Fig. 2.— HI Brγ absorption spectra of S2, obtained on April 8/9 2003 with the SPIFFI integral field spectrometer on Kueyen (left inset), and on May 8/9 2003 with the NACO grism on Yepun (right inset). The SPIFFI spectrum is not off-subtracted and in a 0.2” × 0.2” aperture, while the NACO spectrum is sky-nodded and in a 0.086” × 0.1” aperture. These differences account for the fact that the mini-spiral emission features between -400 and +400 km/s LSR are visible in the SPIFFI data but not in the NACO spectrum. Likewise, dilution of the S2 flux by other nearby sources in the larger SPIFFI beam plausibly accounts for the shallower absorption relative to NACO.
Fig. 3.— Line-of-sight velocity as a function of time for the best-fit model of Table 1 (continuous curve), along with the $1\sigma$ uncertainties (dotted). Filled circles (with $1\sigma$ error bars) denote the Keck and VLT line-of-sight velocities of S2 in 2002 and 2003.