

A GEOMETRIC DETERMINATION OF THE DISTANCE TO THE GALACTIC CENTER¹

F. EISENHAEUER,² R. SCHÖDEL,² R. GENZEL,^{2,3} T. OTT,² M. TECZA,² R. ABUTER,² A. ECKART,⁴ AND T. ALEXANDER⁵

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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 that 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 the 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 $R_0 = 7.94 \pm 0.42$ 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: galaxies: distances and redshifts — Galaxy: center — Galaxy: fundamental parameters — Galaxy: structure

On-line material: color figures

1. INTRODUCTION

The distance to the Galactic center (R_0) is a fundamental parameter for determining the structure of the Milky Way. Through its impact on the calibration 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_0 . At that time, the only primary (geometric) distance indicator to the Galactic center came from the “expanding cluster parallax” method applied to the H₂O masers in Sgr B2. Reid et al. (1988a, 1988b) determined values of 7.1 and 6.5 kpc for the distances to the masers in Sgr B2N and Sgr B2M, respectively, with a combined statistical and systematic (1 σ) uncertainty of ± 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., the Eddington luminosity of X-ray sources and Galaxy structure models). From all these measurements, Reid inferred a best overall estimate of 8.0 kpc, with a combined uncertainty of ± 0.5 kpc. In the time since 1993, Genzel et al. (2000) reported a primary (statistical parallax) distance, $R_0 = 8.0 \pm 0.9$ 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 (± 0.7 kpc) from RR Lyrae and δ Scuti stars. Feast & Whitelock (1997) used Cepheids and a Galactic rotation model, updated for the new *Hipparcos* local distance scale, to obtain $R_0 = 8.5 \pm 0.5$ kpc. Paczyński &

Stanek (1998) and Stanek & Garnavich (1998) combined measurements of red clump stars with the *Hipparcos* scale to obtain $R_0 = 8.2$ kpc, with a claimed combined statistical and systematic uncertainty of ± 0.21 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 Sgr A* 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_0 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 Sgr A* with an orbital period of about 15 years. Ghez et al. (2003a) 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 (Ghez et al. 2003a) star whose line-of-sight velocity can be inferred in a straightforward manner from its H I Br γ absorption. With additional line-of-sight velocity and proper-motion data, it now is feasible to make a precision estimate of all orbital parameters, including the distance to S2/Sgr A*.

2. OBSERVATIONS

2.1. NAOS/CONICA Adaptive Optics Imaging

We observed the Galactic center with the Nasmyth Adaptive Optics System (NAOS) and the near-infrared camera and spectrometer CONICA (the combination being called NACO; Lenzen et al. 1998; Rousset et al. 1998) near-infrared, adaptive optics imager at the VLT on 2003 March 17/18 (2003.21), May 8/9 (2003.35), and June 14/15 (2003.45). We observed through the *H*-band (1.65 μm) and *K*-band (2.2 μm) filters and used the infrared wave-front sensor to correct in the *K* band on the

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

² Max-Planck-Institut für extraterrestrische Physik (MPE), Giessenbachstrasse Postfach 1312, D-85741 Garching, Germany; eisenhau@mpe.mpg.de, rainer@mpe.mpg.de, genzel@mpe.mpg.de, ott@mpe.mpg.de, tecza@mpe.mpg.de, rabuter@mpe.mpg.de.

³ Also at Department of Physics, University of California at Berkeley, 366 LeConte Hall, Berkeley, CA 94720-7300.

⁴ I. Physikalisches Institut der Universität Köln, Zulpicher Strasse 77, D-50937, Cologne, Germany; eckart@ph1.uni-koeln.de.

⁵ Faculty of Physics, Weizmann Institute of Science, P.O. Box 26, 76100 Rehovot, Israel; tal@wicc.weizmann.ac.il.

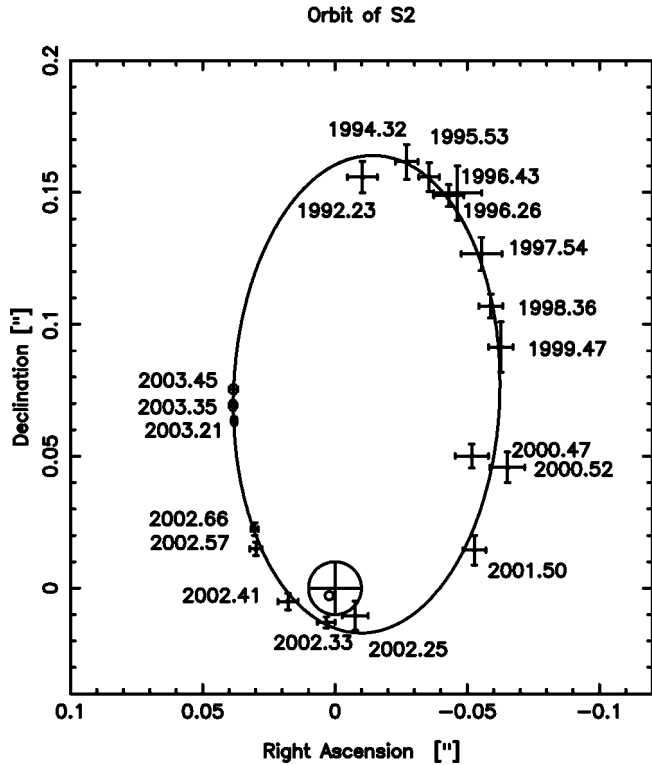


FIG. 1.—Position measurements of S2 in the infrared astrometric frame. Crosses (denoting 1σ error bars) with dates mark the different position measurements of S2, taken with the MPE speckle camera SHARP on the NTT (between 1992 and 2001) and with NACO on the VLT (in 2002 and 2003). The continuous curve 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 milliarcseconds at the position of the compact radio source, which is marked by a large circled cross. The size of the cross denotes the ± 10 mas positional uncertainty of the infrared relative to the radio astrometric reference frame. [See the electronic edition of the *Journal* for a color version of this figure.]

bright supergiant IRS 7, located $\sim 5''.6$ north of S2/Sgr A*. In all runs, the seeing was $\leq 0''.5$, resulting in Strehl ratios between 0.3 and 0.5 in the H band and up to 0.7 in the K band. After producing final maps with the shift-and-add technique, we deconvolved the images with a linear Wiener filter and a Lucy-Richardson algorithm. The point-spread function was measured from typically 10 stars within the field of view. We extracted stellar positions from the deconvolved images with the program STARFINDER (Diolaiti et al. 2000). We also applied this technique to all 2002 NACO Galactic center imaging data described by Schödel et al. (2003), thereby slightly improving their results. All positions prior to 2002 are from the observations with the SHARP (System for High Angular Resolution Pictures) instrument on the New Technology Telescope (NTT), as reported by Schödel et al. (2003). The coordinates from all epochs have been transformed to a common astrometric reference frame via nine (SHARP) and 20 (NACO) stars with well-known positions and proper motions. The positions of these stars have been measured for every epoch relative to typically 50–200 stars of the stellar cluster surrounding the central black hole (T. Ott et al. 2003, in preparation). The average error in the velocity components of our nine astrometric reference stars is approximately 26 km s^{-1} (T. Ott et al. 2003, in preparation). The uncertainty in the relative motion of our reference frame with respect to the stellar cluster is given by the error in the average velocity of those nine stars and is 11.7 km s^{-1} . Our

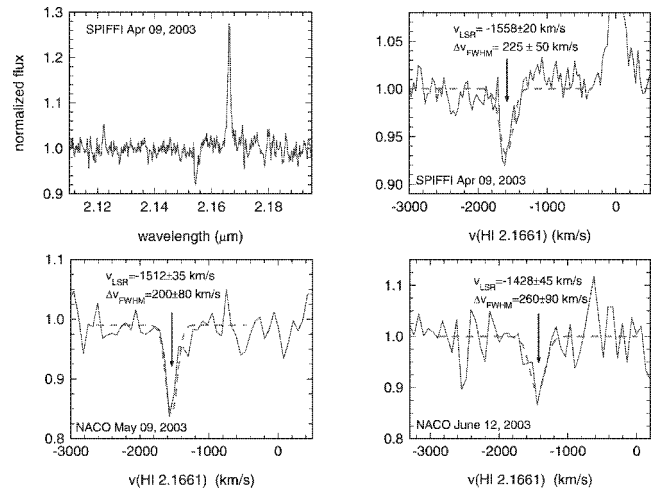


FIG. 2.—H I Br γ absorption spectra of S2, obtained on 2003 April 8/9 with the SPIFFI (upper two panels), on May 8/9 (lower left panel), and on June 11/12 (lower right panel) with NACO at the VLT. The SPIFFI spectrum is sky-subtracted and in a $0''.1 \times 0''.2$ aperture; the NACO spectrum is slit-nodded and in a $0''.086 \times 0''.1$ aperture. These differences account for the fact that the minispiral emission features between -400 and $+400\text{ km s}^{-1}$ 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. [See the electronic edition of the *Journal* for a color version of this figure.]

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, and 6–10 mas for the 1992–2001 SHARP measurements. In addition, there is a ± 10 mas absolute uncertainty between the infrared and radio astrometric frames (Reid et al. 2003b). Figure 1 is a plot of the positions of S2 between 1992 and 2003.

2.2. SPIFFI Integral Field Spectroscopy

On 2003 April 8/9 (2003.27), we observed the Galactic center with the new MPE integral field spectrometer SPIFFI (Spectrometer for Infrared Faint Field Imaging; Thatte et al. 1998; Eisenhauer et al. 2000) at the VLT. Briefly, SPIFFI uses a reflective image slicer and a grating spectrometer to simultaneously obtain spectra for a contiguous 32×32 pixel, two-dimensional field on the sky. In very good seeing conditions, we observed with a pixel scale of $0''.1$, resulting in a $2\text{ }\mu\text{m}$ FWHM of $0''.25$ – $0''.3$. The spectral resolution was 85 km s^{-1} , sampled at 34 km s^{-1} . We dithered about two dozen exposures of 1 minute integration time each to construct a mosaicked data cube of the central $\sim 8''$. We used the new SPIFFI analysis pipeline for data reduction. The accuracy of the wavelength calibration is $\pm 7\text{ km s}^{-1}$. The effective integration time toward the central part of the mosaic near Sgr A* was about 15 minutes. The sky spectrum was extracted from a dark region $590''$ west and $423''$ north of the Galactic center. We used the flat-spectrum star IRS 16CC to correct for atmospheric absorption. We then extracted the spectrum toward S2 from a $0''.1 \times 0''.2$ aperture. The SPIFFI spectrum is shown in the upper two panels of Figure 2. The strong emission line close to zero velocity is the extended nebular Br γ emission from the Sgr A West minispiral. The Br γ absorption line of S2 is at $v_{\text{LSR}} = -1558 \pm 20\text{ km s}^{-1}$, far off the nebular contamination. A significant error in the velocity measurement from flux dilution by other high-

TABLE 1
BEST-FIT KEPLER ORBIT FOR S2

Parameter	Value
Semimajor axis a	$0''.1203 \pm 0''.0027$
Eccentricity e	0.881 ± 0.007
Orbital period P	15.56 ± 0.35 yr
Time of pericenter approach T_{peri}	2002.331 ± 0.012 yr
Inclination i	$-48^\circ.1 \pm 1^\circ.3$
Angle of line of nodes Ω	$45^\circ.0 \pm 1^\circ.6$
Angle of nodes to pericenter ω	$245^\circ.4 \pm 1^\circ.7$
x_0	$0''.0023 \pm 0''.0012$
y_0	$-0''.0031 \pm 0''.0012$
R_0	7.94 ± 0.38 kpc

NOTES.—The uncertainties in the fit parameters include a uniform error scaling to produce a χ^2_{red} of 1. The unscaled errors are larger by a factor of 1.35. All coordinates are given for our infrared astrometric reference frame described in § 2.1, which is tied to the Sgr A* radio source with an accuracy of ± 10 mas. The errors do not include a small possible drift (<12 km s $^{-1}$) of our reference frame relative to Sgr A*. The uncertainty in the distance estimate, including this systematical error, is ± 0.42 kpc.

velocity stars close to S2 can be excluded: The brightest star within the seeing disk around S2 is S14, which is approximately a factor of 4 fainter than S2. The next star with comparable brightness to S2 is S4, which is located at a distance of $0''.24$. Both stars thus cannot contribute significantly to the observed depth of approximately 8% of the Br γ absorption.

2.3. NACO Long-Slit Spectroscopy

We took K -band spectroscopy of S2 with NACO at the VLT on 2003 May 8/9 (2003.35) and June 11/12 (2003.45). As for the imaging, the optical seeing was $\sim 0''.4$ – $0''.5$, and we used the infrared wave-front sensor on IRS 7. We chose the 86 mas slit, resulting in 210 km s $^{-1}$ resolution sampled at 69 km s $^{-1}$ pixel $^{-1}$. The spatial pixel scale was 27 mas, and we placed the slit at a position angle of 78° through S2. We integrated for about 5 minutes per readout and nodded the slit by $\pm 5''$. We accumulated 30 minutes of on-source integration. The wavelength calibration is accurate to ± 10 km s $^{-1}$. We corrected for atmospheric absorption by dividing the Galactic center spectra by an early-type star observed at the same air mass. The inferred LSR velocity of the Br γ absorption of S2 was -1512 ± 35 km s $^{-1}$ on 2003 May 8/9 and -1428 ± 45 km s $^{-1}$ on 2003 June 11/12. The nodded NACO spectra in a $0''.086 \times 0''.1$ aperture are shown in the lower panels 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: six phase-space coordinates for each mass plus the values of the two masses (see Salim & Gould 1999). At the present level of accuracy, four parameters can be safely neglected: the mass of the star (since $m_{\text{S2}}/M_{\text{Sgr A}^*} \sim 5 \times 10^{-6}$) and the three velocity components of Sgr A*. Radio interferometry of Sgr A* 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 Sgr A* is ≤ 20 km s $^{-1}$ in the plane of the Galaxy and \leq km s $^{-1}$ toward the Galactic pole (Backer & Sramek 1999; Reid et al. 1999, 2003a). This implies $v_{\text{Sgr A}^*} \sim$

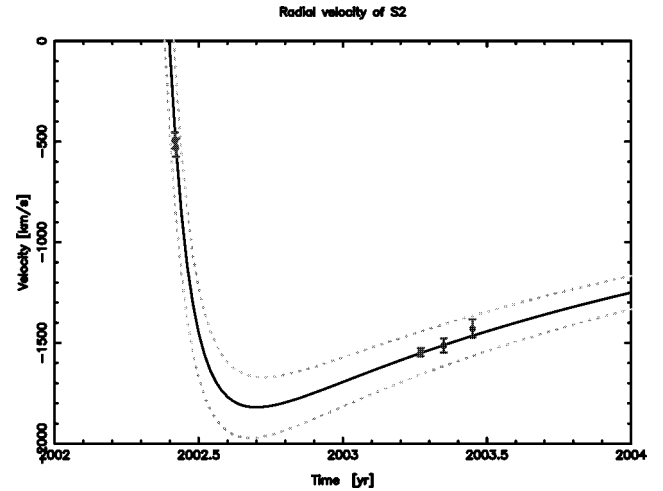


FIG. 3.—Line-of-sight velocity as a function of time for the best-fit model of Table 1 (continuous curve), along with the 1σ uncertainties (dotted curves). The filled circles (with 1σ error bars) denote the Keck and VLT line-of-sight velocities of S2 in 2002 and 2003. [See the electronic edition of the Journal for a color version of this figure.]

$10^{-2}v_{\text{S2}}$. Likewise, the uncertainty in the local standard of rest velocity (≤ 10 km s $^{-1}$) can also be neglected at the present level of analysis (see Salim & Gould 1999). As outlined in § 2.1, our astrometric reference frame is tied to the stellar cluster surrounding the central black hole. We further assume that the stellar cluster is gravitationally bound to the black hole and that the velocity of the central object, which dominates by far the gravitational potential, is close to zero in this reference frame. Our measurement constraints consist of the 19 ($\times 2$) S2 positions and five line-of-sight velocities: two from Ghez et al. (2003a), one from SPIFFI, and two from NACO. This leaves us to fit 10 parameters with 43 data points, resulting in an overconstrained problem with 33 degrees of freedom. The errors of the orbital parameters are based on an analysis of the covariance matrix. Table 1 is a list of the fitted parameters of the S2 orbit and the distance to the Galactic center. The χ^2_{red} of our orbital fit is 0.55, indicating that we have systematically overestimated our measurement errors. We have thus scaled our errors uniformly to produce a χ^2_{red} of 1. The uncertainties in the fit parameters in Table 1 include the error scaling. The unscaled errors are larger by a factor of 1.35. The best distance estimate for the Galactic center is 7.94 ± 0.38 kpc. The uncertainty in the distance estimate without error scaling is ± 0.52 kpc. The error does not include the systematics from the motion of our reference frame relative to Sgr A* of ± 11.7 km s $^{-1}$. If we allow such an additional motion in the orbital fit, the distance to the Galactic center would change systematically by ± 0.16 kpc. Adding quadratically the errors from the orbital fitting and the relative motion of our reference frame results in a combined error of ± 0.42 kpc. 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 3–6 times better than those in Schödel et al. (2002), 1.3–2 times better than those in Ghez et al. (2003a), and comparable with those in Ghez et al. (2003b). The latter two references also consider the uncertainties in the reference frame velocity, which has been omitted in our orbital fitting. The central mass M_0 is calculated from the semimajor axis a , the distance R_0 , and the period P , using Kepler's third

law. Our best mass estimate, including the uncertainties in the distance, is $(3.59 \pm 0.59) \times 10^6 M_\odot$. For comparison, our best mass estimate for a given distance to Sgr A* is $(3.68 \pm 0.30) \times 10^6 (R_0/8 \text{ kpc})^3 M_\odot$.

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 database of T. Ott et al. (2003, in preparation) and complemented these by an additional ~ 100 velocities of early-type and late-type stars in the central $10''$ extracted from the new SPIFFI data cube discussed above (R. Abuter et al. 2003, in preparation). 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),

$$\left(\frac{R_0}{8 \text{ kpc}}\right) = \left(\frac{\langle p v_z^2 \rangle_8}{1/3 \langle p v_R^2 \rangle_8 + 2/3 \langle p v_T^2 \rangle_8}\right)^{0.5}, \quad (1)$$

where p is the sky-projected distance of a star from Sgr A* and v_z , v_R , and v_T are the line-of-sight, sky-projected radial, and sky-projected tangential velocities (from proper motions), respectively. The symbol $\langle \dots \rangle_8$ denotes the ensemble average for an assumed distance of 8 kpc. 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 ± 0.6 kpc. The statistical parallax method thus gives $R_0 = 7.2$ kpc (with a combined uncertainty of ± 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 7.94 ± 0.42 kpc. Our determination rests on the analysis of a simple dynamic system, and our global fit 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 sizable additional systematic un-

certainties 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 pericenter distance of S2, or 10^{-4} of the mass of the central black hole, and that it is also unlikely that the central mass is a binary black hole of approximately equal masses since such a binary hole would have to have a separation less than 10 lt-hr and would coalesce by gravitational radiation in a few hundred years. The fractional uncertainty in the value of R_0 is about 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 us 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. With the new value for the distance (7.94 ± 0.42 kpc), we can also derive a more accurate value for the rotation velocity of the Galaxy at the solar point, $\Theta_0 = 220.7 \pm 12.7 \text{ km s}^{-1}$, where we combine our distance with the average of the differential rotation parameter of the Galaxy (the difference of Oort constants $A - B$) obtained from Cepheids (Feast & Whitelock 1997) and the proper motion of Sgr A* (Backer & Sramek 1999; Reid et al. 1999). Future improvements in the accuracy of R_0 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).

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