Session I

Resolved stars in the Milky Way

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The distance to the Galactic Center

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Abstract. One of the Milky Way's fundamental parameters is the distance of the Sun from the Galactic Center, R_0. This article reviews the various ways of estimating R_0, placing special emphasis on methods that have become possible recently. In particular, we focus on the geometric distance estimate made possible thanks to observations of individual stellar orbits around the massive black hole at the center of the Galaxy. The specific issues of concern there are the degeneracies with other parameters, most importantly the mass of the black hole and the definition of the reference frame. The current uncertainty is nevertheless only a few percent, with error bars shrinking every year.

Keywords. Galaxy: center, Galaxy: fundamental parameters

1. Introduction

There are three basic reasons why the distance to the Galactic Center, R_0, is of interest:

- R_0 is one of the Milky Way's fundamental parameters and its value is tightly interconnected with measurements of the structure of the Galaxy.
- R_0 is a 'large' distance that allows for geometric methods using resolved objects, and it thus becomes of interest in the context of the cosmic distance ladder.
- R_0 sets a physical size scale to the uniquely accessible astrophysical system around the Milky Way's central supermassive black hole.

Following Genzel *et al.* (2010) and Reid (1993), there are three different types of methods to determine R_0:

(*a*) Direct methods. These are methods that are direct in the sense that they do not rely on the calibration of a secondary relation. Examples are parallax measurements, the stellar orbits around the massive black hole (MBH), or a statistical cluster parallax.

(*b*) Indirect methods. These are methods that are based on a relation which needs to be calibrated in advance, typically a relation between an absolute luminosity and some other, well-measurable parameter. Examples include RR Lyrae stars and Cepheids with their respective period–luminosity relations, as well as the red clump in the Hertzsprung–Russell diagram.

(*c*) Model-based methods. These are methods which yield a galaxy model, where R_0 is just one parameter. Often these are kinematic models. They can be obtained, for example, from VLBI measurements of star-forming regions containing masers. Other examples are the spatial distribution of certain object types that can be traced throughout the Milky Way's disk.

The following sections briefly review the three types of methods. This summarizes and updates the review on R_0 by Genzel *et al.* (2010).

2. Direct methods

The MBH in the Galactic Center is, within the uncertainties, at rest at the dynamical center of the Milky Way (Reid & Brunthaler 2004; Reid 2008). Hence, determining the distance to the MBH is a way to measure R_0.

2.1. *Parallax*

Since $R_0 \approx 8$ kpc, the expected parallax value is around 125 μas. Therefore, a direct parallax measurement requires accurate astrometry. The radiative counterpart to the MBH, Sgr A*, is a prominent radio source and, hence, VLBI would be a promising approach. Unfortunately, the source is scatter-broadened and thus not well-suited for VLBI observation. However, the massive star-forming region Sgr B2 contains H_2O masers, for which a trigonometric parallax can be obtained. Sgr B2 is known to be close to Sgr A* (Reid *et al.* 1988), and its kinematics places it ≈ 130 pc in front of the Galactic Center (Reid *et al.* 2009). The latter paper reports, for the first time, such a challenging parallax measurement. The value obtained corresponds to $R_0 = 7.9 \pm 0.8$ kpc.

2.2. *Stellar orbits*

Stellar orbits offer another elegant way of determining a geometric distance to the Galactic Center. Individual stars have been found to orbit the MBH on short-period Keplerian orbits (Schödel *et al.* 2002; Ghez *et al.* 2005; Gillessen *et al.* 2009a), such that the combination of astrometry (i.e. proper motions in mas yr^{-1}) and radial velocities (in km s^{-1}) allows for a direct distance estimate (Salim & Gould 1999; Eisenhauer *et al.* 2003, 2005). This method has improved significantly during the last decade due to the advent of adaptive optics on 8 m-class telescopes. Routinely, astrometry with an accuracy of 300 μas (Fritz *et al.* 2010) and Doppler velocities with an accuracy of ≈ 20 km s^{-1} are achieved. This yields impressively well-measured Keplerian orbits for more than 30 stars. Outstanding are the data for the star S2 on a 16 year orbit around Sgr A* (see Fig. 1). In practice, R_0 is one of the fit parameters in the search for an orbital solution. Recent papers have reported $R_0 = 8.4 \pm 0.4$ kpc (Ghez *et al.* 2008), $R_0 = 8.33 \pm 0.35$ kpc (Gillessen *et al.* 2009a), and $R_0 = 7.7 \pm 0.4$ kpc (Morris *et al.* 2012).

Even though the method seems rather clean, it turns out that the mass, M, of the MBH, its velocity, and R_0 are significantly correlated parameters. For a purely astrometric data set $M \propto R_0^3$, for a data set only consisting of radial velocities, M does not depend on R_0. The combined data for S2 yields roughly $M \propto R_0^2$. For a single star, one has up to 13 parameters (six orbital elements, the position and velocity of the MBH, and the mass of the MBH). Using multiple stars helps breaking the degeneracies (Gillessen *et al.* 2009a), but in the data set at hand, S2 dominates. Using a multiple fit for the five stars S1, S2, S8, S12, and S13, and the latest *VLT*-based data yields $R_0 = 8.2 \pm 0.34$ kpc. The only moderate improvement compared to Gillessen *et al.* (2009a) is owing to the fact that the measurement is dominated by systematic errors.

2.3. *Cluster parallax*

Sgr A* is surrounded by a dense stellar cluster. Assuming that it is a uniform, isotropic, phase-mixed system (in addition to its rotation in the Galactic plane; Trippe *et al.* 2008), allows for a cluster parallax determination. The velocity dispersion in Galactic latitude must equal the dispersion in the radial velocity. Eisenhauer *et al.* (2003) used that property and found $R_0 = 7.2 \pm 0.9$ kpc. From $\sigma_b = 2.53 \pm 0.07$ mas yr^{-1} and $\sigma_r = 102 \pm 3$ km s^{-1}, Trippe *et al.* (2008) derived $R_0 = 8.07 \pm 0.35$ kpc.

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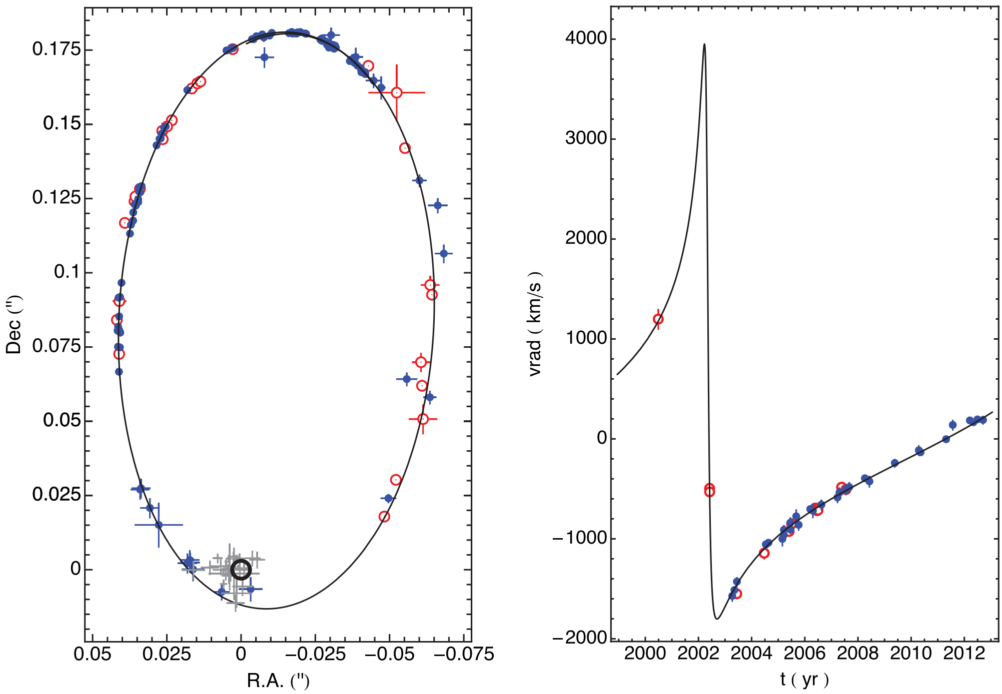

Figure 1. The orbit of the star S2 around Sgr A*, measured from 1992 to 2012. (left) The measured positions of S2 show a Keplerian ellipse. Blue data are from the *NTT* (1992–2001) and *VLT* (2002–2012); red data are from *Keck* (Ghez *et al.* 2008). The black line is the best–fitting orbit, using the same combination scheme as in Gillessen *et al.* (2009b). (right) The corresponding radial-velocity data and fit.

3. Indirect methods

Indirect methods rely on a secondary calibration step, namely an independent way to determine an absolute magnitude, which can be compared to an apparent magnitude. Before the wide-spread use of infrared detectors, extinction was a major systematic uncertainty affecting methods using apparent magnitudes.

3.1. *Variable stars*

For several classes of variable stars, empirical period–luminosity relations can be found.

(*a*) RR Lyrae stars are abundant throughout the Galaxy and have an absolute magnitude of around $M \approx 0.75$ mag. This value needs to be calibrated in advance, which is a complex problem on its own: for example, for an accurate calibration one needs to take into account the effects of metallicity. Baade (1951) presented the first estimate of R_0 from RR Lyrae stars, observing stars in a low-extinction window (later nicknamed 'Baade's Window,' after him) at optical wavelengths. He obtained $R_0 = 8.7$ kpc, using $M = 0$ mag. The first infrared-based study was that of Fernley *et al.* (1987), who concluded that $R_0 = 8.0 \pm 0.65$ kpc. More recently, Dambis (2009) identified dynamically six subpopulations of RR Lyrae stars and obtained $R_0 = 7.58 \pm 0.40$ kpc. Majaess (2010) used RR Lyrae stars from the OGLE fields, getting $R_0 = 8.1 \pm 0.6$ kpc while clearly stating the systematic problems: the determination of R_0 is "hindered by countless effects that include an ambiguous extinction law, a bias for smaller values of R_0 because of a preferential sampling of variable stars toward the near side of the bulge owing to extinction, and an uncertainty in characterizing how a mean distance to the group of variable stars relates to R_0."

(*b*) Cepheids are, on average, brighter than RR Lyrae stars. However, they are much less frequent. Their period–luminosity relation is, in most cases, calibrated in the Large Magellanic Cloud. Groenewegen *et al.* (2008) used infrared observations containing 49 Cepheids in the Galactic bulge to derive $R_0 = 7.94 \pm 0.45$ kpc. More recently, Matsunaga *et al.* (2011) even detected three Cepheids in the nuclear bulge within 200 pc from Sgr A*. These authors concluded that $R_0 = 7.9 \pm 0.36$ kpc.

(*c*) Mira stars are intrinsically redder than RR Lyraes or Cepheids and therefore extinction is less of an issue. However, the absolute magnitudes of Mira stars are harder to calibrate. Groenewegen & Blommaert (2005) used 2691 Miras in the OGLE fields and found $R_0 = 8.8 \pm 0.7$ kpc. From a sample of 143 Miras that were more strongly concentrated towards the Galactic Center, Matsunaga *et al.* (2009) found $R_0 = 8.24 \pm 0.43$ kpc.

3.2. *Globular clusters*

Using Cepheids, one can determine the individual distances to the globular clusters in the Milky Way. Assuming symmetry of the entire system, this yields a value of R_0. This way, Shapley (1918) used 69 clusters and derived the first ever estimate of R_0, 13 kpc. Bica *et al.* (2006) applied the same method, using up-to-date data and calibrations for 116 clusters. Their value of $R_0 = 7.2 \pm 0.3$ kpc seems a bit short, perhaps because some clusters behind the Galactic Center are missing from the sample, and source confusion might bias apparent magnitudes of the stars used to determine the individual cluster distances.

3.3. *Red clump stars*

The red clump is an overdensity in the Hertzsprung–Russell diagram, consisting of giants whose absolute luminosity is relatively independent of other parameters (metallicity or age). Hence, one can use the feature as a standard candle for a stellar system. Paczyński & Stanek (1998) used Baade's low-extinction window and derived $R_0 = 8.4 \pm 0.4$ kpc. Using the Galactic bulge and infrared observations, Babusiaux & Gilmore (2005) and Nishiyama *et al.* (2006) found $R_0 = 7.7 \pm 0.15$ kpc and $R_0 = 7.52 \pm 0.36$ kpc, respectively. From observations of the nuclear cluster in the central few parsecs and an updated extinction law in the infrared, Fritz *et al.* (2011) measured $R_0 = 7.94 \pm 0.65$ kpc.

4. Model-based methods

Here, R_0 is determined as one of the parameters for a more comprehensive model, for example of the Milky Way's disk. Such a model can either be purely based on structure or also include kinematics.

4.1. *Stellar sources in the disk*

(*a*) H_2O maser sources in massive star-forming regions are very well suited for constructing models of the Milky Way, since they can be observed at radio wavelengths throughout the disk. For many, one can actually determine all six phase-space variables and, hence, a kinematic model can be derived. In its most basic form, such a model assumes a rotation curve given by $\Theta(R) = \Theta_0 + \mathrm{d}\Theta/\mathrm{d}R\,(R - R_0)$, where Θ_0 is the rotation speed at the solar radius. The parameter that is measured best in this model is Θ_0/R_0, but both numbers can be derived individually. Using one high-mass star-forming region, W49, Gwinn *et al.* (1992) estimated $R_0 = 8.1 \pm 1.1$ kpc. Reid *et al.* (2009) improved this method by including 18 star-forming regions and obtained $R_0 = 8.4 \pm 0.62$ kpc.

Currently, a large VLBA project is underway to map many more of such regions (see Reid, this volume).

(*b*) Cepheids have also been used to derive the structure of the Milky Way. Joy (1939) used 156 stars and derived $R_0 = 10$ kpc. Metzger *et al.* (1988) repeated this with modern data, including radial velocities for eight Cepheids that are located such that they are well-suited to constrain R_0. These authors obtained $R_0 = 7.66 \pm 0.32$ kpc.

4.2. *Gas in the disk*

Van den Hulst *et al.* (1954) derived the structure of the Milky Way by measuring the 21 cm hydrogen line and obtained $R_0 = 8.26$ kpc. Rybicki *et al.* (1974) concluded that $R_0 = 9.0$ kpc from a similar analysis. A rotation curve for the HI disk has also been obtained by Honma & Sofue (1996), from which these authors obtained $R_0 = 7.6$ kpc. Interestingly, in none of these studies an error estimate is given.

4.3. *Bulge model*

Vanhollebeke *et al.* (2009) used a photometric model of the Galactic bulge, as proposed by Binney *et al.* (1997), including several stellar populations and varying metallicity distributions. The best fit to OGLE and 2MASS data is obtained for $R_0 = 8.7 \pm 0.5$ kpc.

5. Summary

In Fig. 2 we compile published R_0 measurements from the last 20 years. The scatter in the values has decreased somewhat in that period, but apparently an uncertainty of ≈ 0.4 kpc remains. The IAU-recommended value of 8.5 kpc appears to be too large. On the other hand, R_0 does not appear to be much less than 8 kpc. We do not attempt to give another best combined estimate here, but point the reader to Genzel *et al.* (2010), where we argued that the most likely value is between 8.15 and 8.25 kpc, with an uncertainty of 0.35 kpc.

6. Outlook

In which ways will our knowledge of R_0 improve in the coming years?

• Clearly, direct parallax measurements to Sgr B2 will improve in the future, even if simply based on current instrumentation. This is because they are dominated by statistical uncertainties.

• The increasing number of star-forming regions measured with VLBI will soon yield a Galaxy model which will probably have the smallest statistical error in R_0 for the next few years.

• The stellar-orbits method will give a boost to our knowledge of R_0 when another close pericenter passage can be observed astrometrically and spectroscopically. At the latest, this should happen in 2018, when S2 is closest to Sgr A* again. The statistical error in R_0 will then be reduced to ≈ 40 pc and will probably be smaller than for the other methods.

• For stellar orbits, there are several systematic effects which one might hope to improve in the coming years: (i) The astrometric accuracy for the current generation of cameras has not yet reached its ultimative limit, which should be around $150\,\mu$as (Fritz *et al.* 2010). Higher Strehl-ratio adaptive-optics systems would, in addition, allow to reach that limit for more and fainter stars. (ii) The definition of the infrared coordinate system will continue to gradually improve. Knowing the position and velocity of the mass can be used as a prior for the orbital fits, thus reducing degeneracies. (iii) The current data

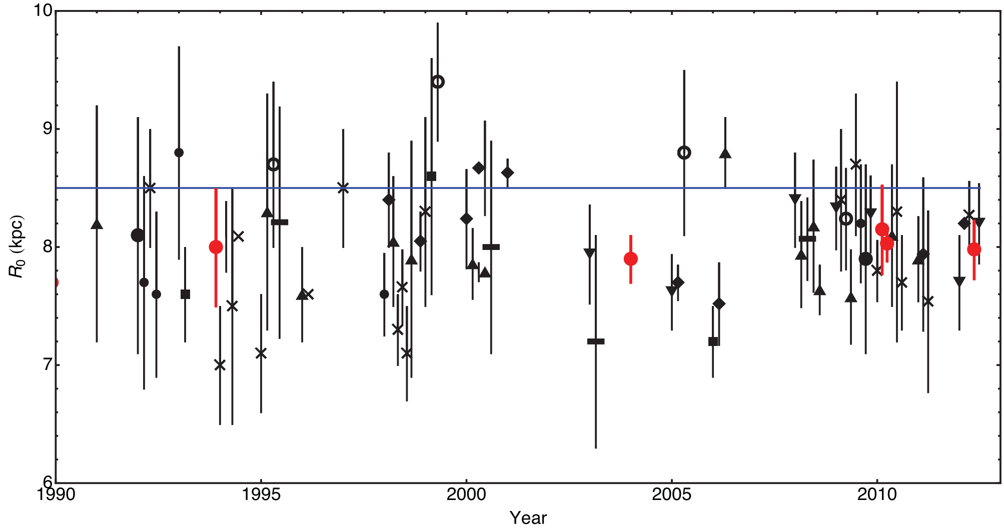

Figure 2. Overview of published R_0 values from 1990 to 2012. Large circles are for H_2O maser-based values, crosses represent other Galactic models. Upward-pointing triangles mark RR Lyrae/Cepheid measurements, downward-pointing traingles are stellar orbit measurements. Diamonds denote red-clump-based data, and rectangles stand for statistical cluster parallaxes. Open circles are for Mira-based values. All other measurements are plotted as small points. The red points are values given in review articles, and the blue line is the current IAU-recommended value of $R_0 = 8.5$ kpc.

sets only contain radial velocities for less than half of the time span covered, and thus continuing the monitoring programs will yield a better balance. (iv) The longer the data set, the better confusion events can be removed from it. This is particularly important for quick pericenter passages of stars on eccentric orbits, where the data determines the orbits best.

• The combination of stellar orbits with other measurements can be useful, if the other data sets have a different scaling between M and R_0 than the orbital data. Two examples in this context are: (i) The orbital roulette technique (Beloborodov & Levin 2004) for the massive, young stars orbiting Sgr A* in a clockwise disk (Paumard *et al.* 2006; Lu *et al.* 2009 Bartko *et al.* 2009) can yield an independent way of estimating the mass, which scales differently with R_0. The idea uses the fact that the orbital phases should be distributed randomly. (ii) If the general relativistic photon ring around Sgr A* can be detected (Bardeen 1973; Falcke *et al.* 2000; Johannsen *et al.* 2012), its apparent size scales $\propto M/R_0$ and can thus also be used to break the degeneracy. This would require an intercontinental array of submillimeter telescopes for interferometric observations (Doeleman *et al.* 2008). For both examples, the expected improvements for measuring R_0 are moderate compared with the more direct methods and their perspectives.

In conclusion, the direct and model-based methods will probably increasingly dominate R_0 estimates. It is, however, not clear whether this in turn will be used to gauge the secondary relations (such as the period–luminosity relations), in which case R_0 would be a direct anchor for the cosmic distance ladder. It will also remain useful to have different methods at hand, allowing for cross checks of the systematics.

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