THE DISTANCE TO THE GALACTIC CENTER: R_o

MARK J. REID
Harvard-Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, Massachusetts 02138

ABSTRACT. Great progress has been made toward measuring the size of the Milky Way. There are now several methods that employ independent calibrations to estimate the distance to the center of the Galaxy, R_o, and these methods have been applied to many types of astronomical objects. R_o estimates generally have been decreasing over the last 15 years. At this time a reasonable "best value" estimate for R_o is 7.7 ± 0.7 kpc.

1. Introduction

In 1918 Harlow Shapley published a landmark paper on the distribution of globular clusters in the Milky Way. He found that globular clusters were most concentrated at a distance of $\approx$ 13 kpc toward Sagittarius at $\ell^I = 325°$. Shapley correctly suggested that the Galactic Center resided near the center of this distribution and not at the apparent maximum of the stellar distribution (which later was understood to be strongly affected by absorption). This work was the first major step leading to the currently adopted value for R_o, the distance to the Galactic Center, of 8.5 kpc (Kerr and Lynden-Bell 1986).

Why do we care about R_o? A change in the value of $R_o$has widespread impact on astrophysics. The following is a brief list of items that would be affected by changing R_o:

1) all kinematic distances;
2) the mass of the Galaxy and the Galactic Center;
3) the luminosity of most stars and some X-ray sources that appear super-Eddington for large R_o values;
4) extragalactic distances by
    a) recalibrating the absolute magnitudes of RR Lyrae variables, globular clusters, Cepheids, OB stars and Mira variables, and
    b) moving spiral galaxies closer to or further from the Sun to match Milky Way size (e.g., de Vaucouleurs 1983);

M. Morris (ed.), The Center of the Galaxy, 37–46.

5) the "dark matter" in the Local Group by affecting the Andromeda infall speed if Θ_o is also adjusted (Trimble 1986).

In Section 2 of this review we discuss estimates of R_o from papers published since 1974. This section includes a new method of directly measuring R_o from H_2O maser proper motions. In Section 3 we combine estimates of R_o to give a "best value," taking into account statistical as well as systematic uncertainties. Finally, in Section 4 we mention some examples of observations now being conducted, or possible in the near future, that will greatly improve our estimate of R_o.

2. Review of the Determinations of R_o

2.1 DIRECT MEASUREMENT

We define a direct measurement of R_o as a distance measured without a "standard candle" calibration or galactic rotation model to a source at or very near the Galactic Center. Presently this has been done only for the H_2O maser source in Sgr B2(N).

2.1.1 *H_2O proper motions in Sgr B2*

Interstellar masers occur in the envelopes of newly formed massive stars. H_2O molecules are a trace constituent of these envelopes, and population inversion of the molecular energy levels followed by coherent de-excitation causes the appearance of masing "spots" of emission $\sim 10^{13}$ cm in size with brightness temperatures as high as 10^{15} K. Because of the small sizes and high brightnesses of interstellar maser spots, they are amenable to precise astrometric measurements that allow their proper motions to be determined. VLBI techniques have achieved a relative positional accuracy of ~ 10 micro-arcsec (μas) across fields of size ~ 3 arcsec. This is sufficient to determine proper motions and estimate distances throughout the Galaxy.

Proper motion studies of the Sgr B2(N) water masers in the galactic center region (Reid *et al.* 1988) indicate that the H_2O maser spots are expanding, presumably in an energetic stellar wind from a newly formed O-type star. The maser spots are observed to move along straight lines on the sky. The three measured motions (two dimensions of proper motion and the radial motion from Doppler shifts) are modelled as a uniformly expanding spherical source, and a least-squares fit to the data yields an estimate of the distance to the source of 7.1 ± 1.5 kpc. Sgr B2(N) is almost certainly within 0.3 kpc of the Galactic Center (see discussion in Reid *et al.* 1988) and, thus, the Sgr B2(N) distance can be directly used as an estimate of R_o.

2.2 SECONDARY MEASUREMENTS

Secondary measurements use “standard candle” distances to objects whose distributions are assumed to be symmetrical about the Galactic Center.

2.2.1 *Globular Clusters*

Table 1. Globular Clusters

REFERENCE	R_o (kpc)	CALIBRATION	COMMENTS
Harris 1976,1980	8.5 ± 1.6	M_V(HB)=0.6	using means, Z_{lim}
de Vaucouleurs & Buta 1978	7.0	M_V(RR)=0.86	Harris's method
Frenk & White 1982	6.2 ± 0.9	M_V(HB)=0.6	low metallicity
	9.1 ± 1.4	M_V(HB)=0.6	high metallicity
	7.2 ± 1.1	M_V(HB)=1.1	” ”
Sasaki & Ishizawa 1978	9.2 ± 1.3	M_V(RR)=0.6	cone of avoidance
Surdin 1980	10.1 ± 0.7	M_V(RR)=0.6	metallicity distrib.

2.2.1.1 CENTROID OF DISTRIBUTION: This technique assumes that globular clusters are symmetrically distributed about the Galactic Center. Therefore, if one plots the number of clusters versus distance from the Sun (toward the Galactic Center), the peak should occur near the distance of the Galactic Center. Table 1 lists some recent estimates of R_o from globular clusters. There is considerable controversy over the question of the absolute magnitude of the horizontal branch, M_V(HB), as a function of cluster metallicity. M_V(HB) differences of up to 0.5 mag, or a factor of about 25%, are involved. Also extinction is a problem at low galactic Z's (i.e., distance from the galactic plane) and for distant clusters at moderate Z's. Finally, there is disagreement on biases introduced in the statistical procedures used to estimate R_o from the distributions. Note, for example, that the estimates of R_o by Harris (1976, 1980) and Frenk and White (1982) are based on essentially the same data set.

2.2.1.2 CONE OF AVOIDANCE: Wright and Innanen (1972) noted that the density of globular clusters diminishes in a cone with a ~ 15° opening angle whose axis is aligned with the galactic rotation axis. Sasaki and Ishizawa (1978) suggest that tidal interactions with the galactic center region will preferentially disrupt clusters located along the galactic rotation axis. They claim that $R_o = 9.2 \pm 1.3$ kpc maximizes the cone angle and that this procedure indicates the distance of the Galactic Center. This distance seems to be based upon M_V(RR)=0.6 with no note of the metallicity of clusters used.

2.2.1.3 METALLICITY DISTRIBUTION: The metallicity of globular clusters decreases with distance, R, from the Galactic Center. Surdin (1980) points out that if the globular cluster distribution is axially symmetric about the galactic rotation axis, then R_o can be estimated by adjusting its value until the cluster metallicity is *uncorrelated* with galactocentric azimuth. He points out that metallicity estimates are not strongly affected by extinction corrections, thus avoiding this source of systematic error. Surdin estimates a value of $R_o = 10.1 \pm 0.7$ kpc, averaging catalog distances based on M_V(RR)=0.6 for all metallicities and a metallicity dependent M_V. The quoted statistical error seems to be considerably underestimated, since it is estimated from the scatter in a plot of the correlation coefficient (of metallicity with galactocentric azimuth) versus R_o. Because the same data set is used for each point in that plot, the points are correlated, leading to an underestimate of the variation in R_o that would arise were an ensemble of globular cluster data sets available.

2.2.2 *RR Lyrae Variables*

Individual RR Lyrae variables can be seen across the Galaxy and toward the Galactic Center through fortuitous "windows" of low extinction such as Baade's Window. Thus, R_o can be estimated by finding the distance toward the Galactic Center of the peak of the distribution of RR Lyrae variables (similar to the method used for globular clusters). Table 2 summarizes recent RR Lyrae results.

Table 2. RR Lyrae Variables

REFERENCE	R_o (kpc)	CALIBRATION	COMMENTS
Oort & Plaut 1975	8.7 ± 0.6	M_{pg}=0.7	
Clube & Dawe 1980	7.0 ± 1.0	M_V(RR)=1.0	
Blanco & Blanco 1985	8.0 ± 0.7	M_V(RR)=0.6	all metallicities
	6.9 ± 0.6	M_V(RR)=f($[\frac{Fe}{H}]$)	
Walker & Mack 1986	8.1 ± 0.4	M_V(RR)=0.6	

In large part M_V(HB) is tied to M_V(RR) and hence globular cluster distances are *correlated* with those of RR Lyrae variables. As for globular clusters, M_V(RR) as a function of metallicity is not well known. Also, extinction is significant and variable across these windows. Finally, crowding of stellar images in these very densely populated fields can lead to inaccurate measures of apparent magnitude.

2.2.3 *Red Giants and Miras*

Bright stars, other than RR Lyrae variables, also can be seen through interstellar windows. For example, Mira variables (Glass and Feast 1982) are a particularly attractive class of stars for estimating R_o, since they are luminous and can be observed with moderate sized telescopes. Also, they are bright at infrared wavelengths where the effects of extinction are greatly reduced. Table 3 gives recent estimates of R_o from red giant stars.

Table 3. Red Giants

REFERENCE	R_o (kpc)	CALIBRATION	COMMENTS
van den Bergh & Herbst 1974	9.2 ± 2.2	M_V(RR)=0.5	Red Giants
Glass & Feast 1982	8.8	M_{bol}(P=0)=0.76	Miras; LMC calib
	7.9	M_{bol}(P=0)=0.54	gal. calib

The calibration of the red giant data of van den Bergh and Herbst (1974) is tied to RR Lyrae variables, and hence does not give a truly independent estimate of R_o from that of RR Lyrae variables or globular clusters. The zero-point, M_{bol}(P=0), in the period-luminosity calibration of the Miras differs by 0.22 mag depending on whether one adopts a galactic calibration or one based on the Large Magellanic Cloud distance (determined from Cepheid variables).

2.3 INDIRECT MEASUREMENTS

Indirect determinations of R_o combine observations with either a model of the Galaxy or some other theoretical constraints. For example, one approach is to assume a fixed (e.g., Eddington) luminosity and determine distances from observed fluxes for a class of objects.

2.3.1 *Rotation Models of the Galaxy: using A or* Θ_o

Table 4. Cepheids, OB stars, HII regions, etc.

REFERENCE	R_o (kpc)	ASSUMPTIONS	COMMENTS
Cruz-Gonzalez 1974	8.9± 0.5	A=15 km/s/kpc	stars<25 pc distant
Bologna & Feast 1974	9.0	A=16.8 km/s/kpc	OB stars
Crampton *et al.* 1976	8	A=16.8 km/s/kpc	OB stars/solar circle
Byl & Ovenden 1978	10.4± 0.5		mostly OB stars
Caldwell & Coulson 1987	7.8± 0.7		Cepheids
Quiroga 1980	8.4		HI vs OB stars
Brand 1986	8.0± 0.5	Θ_o=220 km/s	HII regions
Rohlfs *et al.* 1986	7.9± 0.7		HII regions
Herman *et al.* 1985	8.1± 1.1	Θ_o=220 km/s	OH/IR stars
Backer & Sramek 1986	8.5± 1.0	Θ_o=220 km/s	Sgr A*motion
Caldwell & Ostriker 1981	8.2		Modelling
Toomre 1972; Rybicki *et al.* 1974	8	A–B=25 km/s/kpc	"

Stars and atomic and ionized clouds that partake in the galactic rotation and have estimated distances can, in the context of a model of the Galaxy, be used to estimate R_o. For example, radial velocity measurements for a sample of stars can be used with a kinematic model for the Galaxy to derive kinematic distances. These distances can be compared with luminosity distances and brought in to agreement by adjusting R_o (since kinematic distances scale directly with R_o). There are a great variety of objects and analysis techniques in the literature. Table 4 summarizes some of the recent results; consult the original papers for discussions of the distance calibrations for the various objects. (Note the result of Herman *et al.* (1985) has been rescaled for Θ_o=220 km/s.)

Thackeray (1972) and Crampton *et al.* (1976) point out that there is a sizeable difference in the kinematic properties and, hence, R_o values inferred from stars in the northern and southern portions of the Galaxy. Northern stars tend to yield R_o values about 3 to 4 kpc smaller than southern stars. Byl and Ovenden (1978) claim to reconcile some of this difference by accounting for noncircular motions associated with spiral structures. It is important to remember that most of these methods are sensitive to local deviations from noncircular motions and/or to sizeable extinction corrections.

2.3.2 *Eddington Luminosity Limit*

Ebisuzaki *et al.* (1984) estimate the luminosity of a sample of X-ray bursters. Assuming that the emission is associated with a 1.4 $M_\odot$ compact object (e.g., a contact binary containing a neutron star) and that the emission is at the Eddington limit, they derive "luminosity distances" for the sample. The distribution for 27 bursters peaks toward the Galactic Center at a distance of 6 ± 2 kpc. This can be taken as an estimate of (or an upper limit to) R_o, provided the emission is at (or below) the Eddington limit.

Cyg X3 is a contact binary containing one and possibly two compact objects. It is a strong, periodic X-ray and radio source. HI (21 cm wavelength) studies (Dickey 1983) indicate that all galactic HI emission lines are seen in absorption against its continuum radio emission, implying a kinematic distance of at least $1.16R_o$. If the (X-ray) emission from Cyg X3 is sub-Eddington from a 1.4 $M_\odot$ object, then Molnar (1985) finds a "luminosity distance" limit of 9.0 kpc, suggesting $R_o \lesssim 7.7$ kpc. (We adopt this value as a distance estimate, even though strictly speaking it is an upper limit.)

The critical assumptions used to estimate (or limit) R_o from the X-ray bursters and Cyg X3 are that the emissions are at (or below) the Eddington limit and that the compact objects ultimately responsible for the emissions have typical neutron star masses of 1.4 $M_\odot$. While the former assumption seems reasonable, Molnar *et al.* (1988) give evidence that, at least for Cyg X3, a more massive object (probably a black hole) is involved.

3. A "Best Value" for R_o

It is not possible to combine all existing estimates of R_o to form a "best value" in a statistically rigorous manner. This would require knowledge of the variance-covariance matrix for the set of R_o estimates. Unfortunately, we do not have reliable values of the uncertainty for each estimate because *systematic* sources of error are poorly known and often not even discussed. In addition to not knowing the variances, we have only a qualitative understanding of the *covariances* among the different R_o estimates. For example, a change in the RR Lyrae absolute magnitudes directly affects the calibration of absolute magnitudes for globular clusters and to some extent for other stars such as red giants and Cepheids. Thus, the covariances among different methods of determining R_o are substantial.

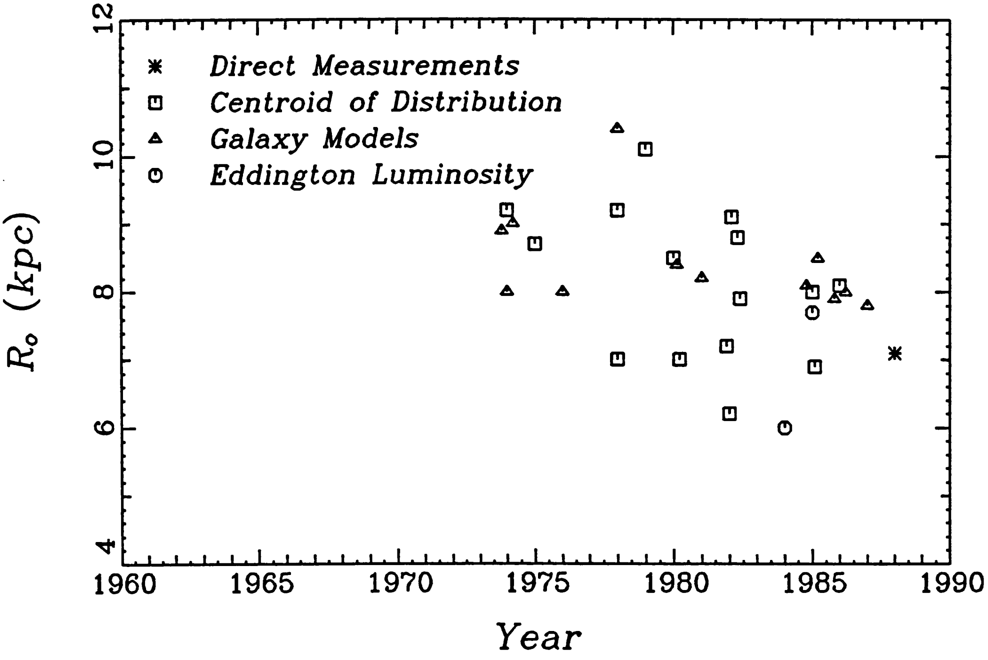

Figure 1. Estimates of the distance to the Galactic Center versus publication date since 1974.

In Figure 1, we plot R_o versus publication date from the results cited in this review. Based upon this plot, a case could be made for a statistically significant decrease in estimates of R_o with time. In part, this effect is a result of changes in the complex and interrelated distance calibrations for different stars. However, one could also speculate that a significant "bandwagon effect" is operative here. Statistical analyses of (usually incomplete) astronomical data are not straightforward, and current wisdom as to the "correct answer" can affect estimates of R_o. Faced with these problems Kerr and Lynden-Bell (1986) adopted the simplest approach to finding a "best value" for R_o and calculated an *unweighted* average of recent R_o values. We will adopt a different approach, trying to account, in an admittedly crude manner, for statistical and systematic errors, as well as for the covariances among different methods.

Table 5 groups R_o values based upon four methods that have *nearly independent* calibrations. Each of these groups are further subgrouped by the stars or sources used to estimate R_o. Each entry in the table contains an unweighted mean value of R_o for that star or source category (from data given in Tables 1 to 4) and a *statistical* uncertainty that approximately reflects the precision of the technique. The variance-weighted average of R_o for each of the four groups is indicated along with its formal uncertainty.

Table 5. R_o by Methods

METHOD	R_o (kpc)	±	σ_{stat}
Direct Measurement:			
Sgr B2(N) H_2O Proper Motions	7.1	±	1.1
	7.1	±	1.1
Centroid of Distributions:			
Globular Clusters	8.2	±	1.1
RR LyraeVariables	7.7	±	0.7
Red Giants	8.6	±	1.7
	7.9	±	0.6
Galaxy Models:			
Nearby Stars	8.9	±	0.5
OB Stars	9.1	±	1.0
Cepheids	7.8	±	0.7
HI & HII Regions	8.1	±	0.6
OH/IR Stars	8.1	±	1.1
Sgr A^* Proper Motions	8.5	±	1.0
Disk Modelling	8.1	±	1.5
	8.4	±	0.3
Eddington Luminosity:			
X-ray Bursters	6.0	±	1.0
Cyg X3	7.7	±	1.0
	6.9	±	0.7

Table 6 summarizes the results presented in Table 5 by group. In addition to the formal statistical error (σ_{stat}), Table 6 contains an estimate of the *systematic* error (σ_{sys}) likely for the group value. For example, the 1.0 kpc systematic error associated with the R_o estimate from the Centroid of Distributions method (applied to globular clusters, RR Lyrae variables, and red giants) is primarily due to an uncertainty of ≈ 0.3 in the absolute magnitudes of RR Lyrae variables. We combine the statistical and systematic errors in quadrature and calculate a weighted average of the values of R_o for the four groups. This approach yields

$$R_o = 7.7 \pm 0.7 \text{ kpc},$$

(This value for R_o does not contain any estimate of possible bias from a "bandwagon effect" mentioned above.)

Table 6. "Best Value" for R_o

METHOD	$R_o \pm (\sigma^2_{stat} + \sigma^2_{sys})^{\frac{1}{2}}$ (kpc)
Direct Measurement	$7.1 \pm (1.1^2 + 1.0^2)^{\frac{1}{2}}$
Centroid of Distributions	$7.9 \pm (0.6^2 + 1.0^2)^{\frac{1}{2}}$
Galaxy Models	$8.4 \pm (0.3^2 + 1.2^2)^{\frac{1}{2}}$
Eddington Luminosity	$6.9 \pm (0.7^2 + 2.0^2)^{\frac{1}{2}}$
WEIGHTED AVERAGE	7.7 ± 0.7

4. Tomorrow's R_o

The accuracy of R_o estimates will improve as a consequence of several current studies. Preliminary results from H_2O proper motions in a second Sgr B2 maser source and in the W49 source, which is near the solar circle, are very promising. Other work on maser sources involves extending the OH/IR stars method to objects near the Galactic Center (see Cohen *et al.* these proceedings).

The advent of optical telescopes in space (Hipparcos and the Hubble Space Telescope) should lead to improved distance calibrations, for example, through better proper motions and the resolution of individual stars in clusters. Finally, a true (Earth's orbit) trigonometric parallax to Sgr A* is within the reach of the new VLBI arrays being constructed in Australia and the United States.

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