DETERMINATION OF THE DISTANCE TO THE GALACTIC CENTRE

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Abstract: This paper summarises an investigation into the wide ranging methods employed to determine the distance to the Galactic centre, R_o. Remote methods commonly use luminosity reference objects such as RR Lyraes and red clump stars. Ruler methods involve annual parallax or line-of-sight velocity. Examples of all the methods are described and their limitations discussed. The main uncertainties with remote methods arise from calibration, extinction and group eccentricity. The main uncertainties with ruler methods arise from object location error and unknowns in relation to Galactic rotation. A total of 63 determinations were studied, from which six remote method and six ruler method determinations are identified for refining the value of R_o. Both categories are found to give the same mean value of R_o = 7.9 ± 0.3 kpc. High-precision astrometry of objects within the Galactic nucleus provides the most potential for improvement in accuracy of the determination of R_o.

Keywords: Galaxy, Galactic centre, distance determination, parallax, astrometry, Sgr A*

1. Introduction

Much less is known about the overall structure of our Galaxy than those of other galaxies. We are tied to our location in the Galactic disc, giving us a highly disadvantageous viewing point (Figure 1). Remarkably, given its relative proximity on the cosmological scale, the distance from the Sun to the Galactic centre, R_o, is imprecisely known, yet it provides the essential baseline upon which the calculated absolute values of Galactic properties depend.

A major problem, historically, has been the optical invisibility of the Galactic centre, due to the extreme visual extinction from dust in the disc. Optical observations make use of breaks in the obscuration around the Galactic centre, in particular Baade's window.

The generally accepted value of R_o in the 1960s was 10 kpc. In the 1980s this was reduced to 8.5 kpc. A subsequent comprehensive review determined R_o = 8.0 ± 0.5 kpc (Reid 1993). Observations at infrared and radio wavelengths, which suffer much less extinction, have become the principle source of information. The main tools employed are photometry, astrometry, spectroscopy and, most importantly, ingenuity.
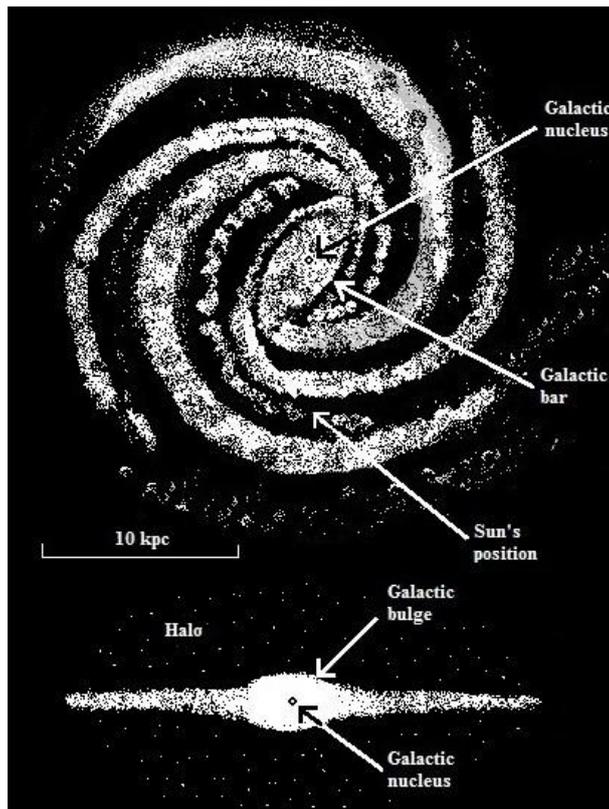
Figure 1: Sketch of our Galaxy, showing the disc and our view from within

[This sketch is illustrative only and represents the view in optical and near-infrared light. The scale, the spiral arm system and the bar structure are not known definitively. The disc rotates clockwise in this perspective.]

There are two main categories of distance determination methods. For remote methods the reference quantity, such as luminosity, is at the location of the object. For ruler methods the reference quantity, which is a length, is at the location of the observer. All methods have their limitations. The investigation, which is summarised here, describes the methods, assesses them with regard to their uncertainties, and uses them to derive the value of R_o.

2. Remote Methods

The most common remote method is where the intrinsic luminosity of objects is employed. These are called luminosity reference objects (LROs). In Galactic studies, the LROs most generally used are non-cataclysmic stars of particular classes, which are identified by reference to their spectra or their light curves. The intrinsic luminosity, in terms of the absolute magnitude of the object, is determined from correlation with observed characteristics, such as the period of variation or position on a colour-magnitude diagram.

2.1 RR Lyraes

As a by-product of an optical ground-based sky survey, nearly two thousand RR Lyrae stars were detected in the Galactic bulge and catalogued, which Majaess (2010) used to determine R_o. Although, because of the extreme visual extinction, none are at the Galactic centre itself, most are within 4° (Majaess et al. 2010, fig. 1). The value of R_o was taken to be the mean distance of the employed set of RR Lyraes, which was determined to be 8.1 ± 0.6 kpc. As the set is large, the stated uncertainty is mainly systematic, arising from measuring the extinction and determining the absolute magnitude of RR Lyraes. The author points out that extinction causes the RR Lyraes to be preferentially sampled toward the near side of the Galactic bulge (Majaess et al. 2010, fig. 5). The faintest observations were therefore excluded from the employed data set entirely.

Earlier studies using RR Lyraes are based upon smaller samples and mostly use only Baade's window stars. Recalibration of previous observations has been conducted by several authors. This has a considerable effect, demonstrating the uncertainty in the absolute magnitude.

2.2 Miras

An advantage of Mira stars over RR Lyraes is their high near-infrared luminosity, enabling them to be detected much nearer to the Galactic centre. Over a hundred Miras have been identified within the Galactic nucleus, in the near-infrared (Matsunaga 2009). In order to compensate for fainter Miras being undetected on the far side of the Galactic centre, those with the highest extinction were excluded. The value of R_o, calculated from the position of the peak of the resulting distance modulus distribution, is equal to 8.2 ± 0.5 kpc (Matsunaga et al. 2009, fig. 24).

The main source of the stated uncertainty is from the absolute magnitude determination of Miras, which is primarily obtained from observations of the Large Magellanic Cloud (LMC). The authors acknowledge the possibility of Miras being of a different population type in the LMC from those in the Galactic nucleus. Earlier Mira studies are based on fields a few degrees from the Galactic centre.

2.3 Red Clump Stars

Near-infrared observations of red clump stars within one degree of the Galactic centre have been employed (Nishiyama 2006). These giant stars are detected there in vast numbers. After allowing for the crucial effect of extinction, the apparent magnitude distribution thereby obtained shows a well-defined peak, which is taken to correspond to the Galactic centre (Nishiyama 2006, fig. 2). Using the peak apparent magnitude value in conjunction with the absolute magnitude of red clump stars,

derived on the basis of local Galactic observations, yields R_o= 7.8 ± 0.4 kpc. The authors' calculation included a 'population correction', based on a theory that Galactic bulge red clump stars are less luminous, obtaining R_o = 7.5 ± 0.4 kpc. A similar study by Babusiaux & Gilmore (2005) gave R_o = 7.7 ± 0.4 kpc. Earlier studies using red clump stars predominantly use those in Baade's window.

2.4 Other Luminosity Reference Objects

Classical (Type I) Cepheids have been identified in the Galactic centre region, though not in sufficient numbers to determine R_o reliably. Groenewegen et al. (2008) and Majaess et al. (2009) have used Type II Cepheids observed in the Galactic bulge, which are found there in larger numbers. They determined R_o = 8.0 ± 0.6 kpc and R_o = 7.8 ± 0.6 kpc, respectively. Although delta Scuti stars can also be used as LROs (Lind, 2007), they are rather dimmer than RR Lyraes, making their observation more restricted. A study by Pottasch (1990) employed planetary nebulae, observed across a large region within 10° of the Galactic centre. However, the values of R_o varied across a wide range depending upon which calibration was adopted.

2.5 Globular Clusters

Study of the globular cluster distribution, which is throughout the Galactic halo, famously provided the first assessment of R_o (Shapley, 1918). A modern study is by Bica et al. (2006). The distance to the centre of the distribution is taken to be the value of R_o, which was determined to be 7.2 ± 0.3 kpc (Bica et al. 2006, fig. 4). However, there is the likelihood of globular clusters on the far side of the Galaxy from our location being unobserved, which would mean the derived value is an underestimate.

3. Ruler Methods

The classical ruler method in astronomical distance determination is annual parallax, which uses the accurately known astronomical unit as the reference length. Other ruler methods use the Doppler shift of spectral lines as the reference length, to give the line-of-sight velocity.

3.1 Annual Parallax

In order to use annual parallax to determine R_o directly, an angular resolution of the order of ten microarcseconds is required. This is equivalent to discerning a pound coin on the Moon. The Very Long Baseline Array, a radio interferometer, has been used in recent years to measure the annual parallax of Sagittarius B2 (Sgr B2), which is a giant molecular cloud in the Galactic nucleus (see Figure 2). Masers are detected there. These are intense, coherent radiation beams. Their position was

measured relative to an extragalactic reference source over a period of about one year (Reid 2009). The authors determined the annual parallax to be 129 ± 12 microarcseconds, which gives a distance to Sgr B2 of 7.8 ± 0.7 kpc.
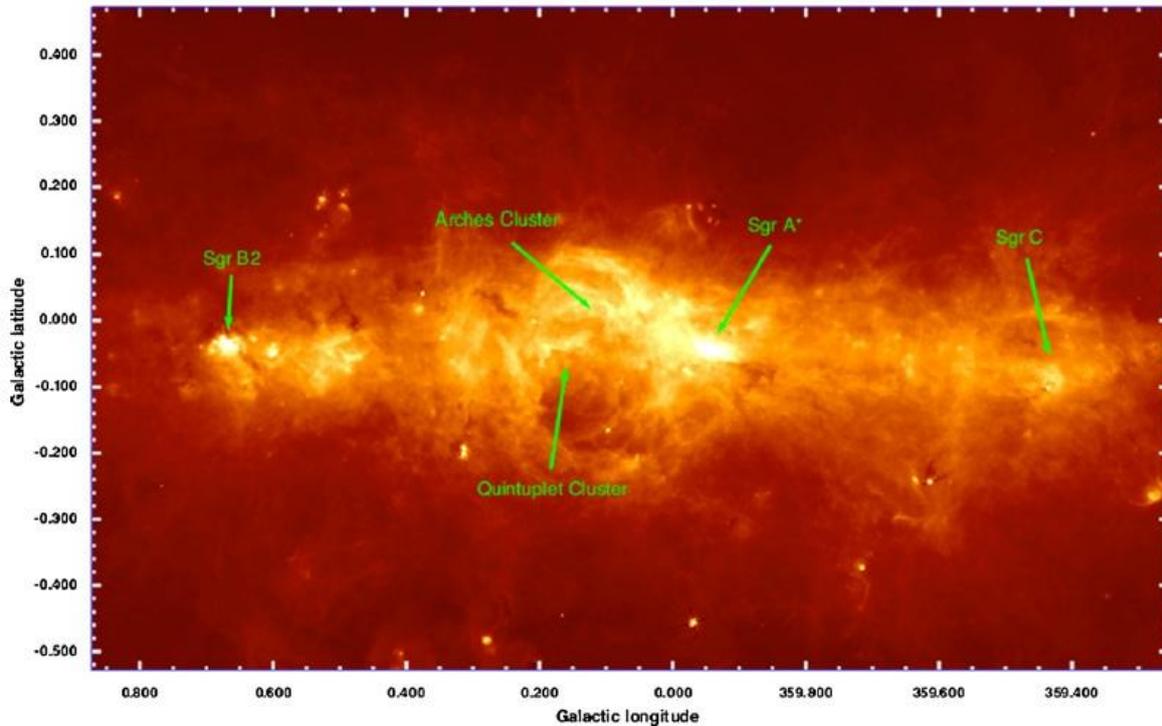

Figure 2: Far-infrared image of the Galactic nucleus [from Molinari et al. 2011, fig. 1, reproduced by permission of the AAS]. The field of view is 1° by 1.6^o, which is about 140 pc by 220 pc.

As can be seen from Figure 2, Sgr B2 is not at the precise location of the Galactic centre, which is taken to be at Sagittarius A* (Sgr A*). Reid et al. (2009) calculated that Sgr B2 is 0.1 kpc closer. However, more recent far-infrared observations of this region, using the Herschel space telescope, suggest that Sgr B2 is about 0.1 kpc behind Sgr A* (Molinari et al. 2011, fig. 5). In view of this extra uncertainty, it is reasonable to take $R_o = 7.8 \pm 0.8$ kpc as the determination from the Sgr B2 study. Reid et al. (2009) determined $R_o = 7.9$ +0.8 −0.7 kpc.

3.2 Statistical Parallax

The method of statistical parallax was originally developed for stars that were too far to employ annual parallax. The distance is determined by correlating the proper motions and line-of-sight velocities of a large group of stars. No actual parallax is involved.

A study by Trippe et al. (2008), employing the Very Large Telescope array (VLT) in the near-infrared, measured the proper motions of thousands of stars and the line-of-sight velocities of hundreds of stars in the central cluster, orbiting within about 1 pc of Sgr A*. The adaptive-optics capability was used to obtain the required resolution.

The authors measured the dispersion in proper motion in Galactic longitude to be equal to 2.93 milliarc seconds per year, which is 4.50×10^{-16} radians per second. The dispersion in line-of-sight velocity was measured to be 112 km/s, which is 3.63×10^{-15} kpc/s. By assuming axisymmetry, these proper motion and velocity values are equivalent, hence $4.50 \times 10^{-16} \times R_o = 3.63 \times 10^{-15}$ kpc/s, giving $R_o = 8.1$ kpc. Allowing for the uncertainties in the measured dispersions, the determination obtained was $R_o = 8.1 \pm 0.4$ kpc.

3.3 Orbit-fitting

The orbits of individual stars in the Galactic nucleus have been used to determine R_o in recent years (see Figure 3). The method uses high-precision near-infrared measurement of proper motions together with line-of-sight velocities from high-resolution spectroscopy. The projected Keplerian orbit of the star S2 about Sgr A* was determined from measurements made from 1994 to 2003, involving speckle imaging and adaptive optics images from the VLT. Even though the data did not cover the whole orbit, they allowed the first determination of R_o using this technique, yielding a value of 7.9 ± 0.4 kpc (Eisenhauer 2003).

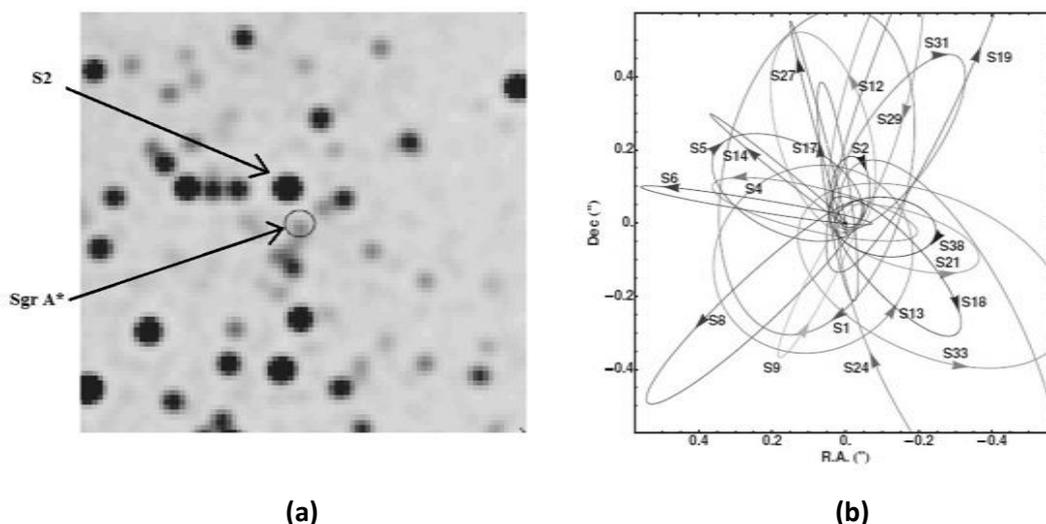(a)   (b)

Figure 3: Near-infrared Image (a) and Orbits of stars within the Galactic nucleus (b)

The two regions are the same field of view, which is about 0.05 pc square.

[Figure 3 (a) reproduced from Eisenhauer et al. 2005, fig. 1; Figure 3 (b) from Gillessen et al. 2009, fig. 16, both reproduced by permission of the AAS]

As shown in Figure 3, S2 is just one of many stars orbiting close to Sgr A*. At present, the orbits of the others are less well defined, whereas further observations of S2 have enabled its complete orbit to be measured, from which Gillessen et al. (2009) determined R_o = 8.3 $\pm$ 0.3 kpc. Ghez et al. (2008) obtained R_o = 8.4 $\pm$ 0.4 kpc from independent observations of the same star, made using the Keck telescope. The stated uncertainties are mostly from coordinate system imprecision, image distortion and image confusion arising from the high concentration of sources in the nucleus. However, there are other sources of error, which are not included in these estimates.

The orbit of S2 is very eccentric and it approaches Sgr A* to within the uncertainty of the position data at pericentre (Eisenhauer et al. 2003, fig. 1). The derived value of R_o is particularly sensitive to whether this data is included. Another source of error is the assumption that the orbit is Keplerian, around an extremely compact high mass. Ghez et al. (2008, fig. 9) found that if Sgr A* is accepted to be moving then the orbit is open. The derived value then changes from R_o = 8.4 $\pm$ 0.4 kpc to R_o = 8.0 $\pm$ 0.6 kpc. In the Galactic centre region, helical motion is known to occur on different scales.

There are many unsolved mysteries in relation to behaviour within the Galactic nucleus and it is not known for certain what is at the very centre. It is assumed that the velocities of the stars orbiting close to the centre are determined by the gravitational constant, *G*, with magnetic fields being ignored in this respect. It is also assumed that something at the very centre is causing the observed behaviour in its surroundings, rather than the Galactic environment being the prime mover.

3.4 Galactic Rotation, Solar Circle Method

Galactic rotation was used as an early means of determining R_o. The method usually assumes the rotation is circular. A simple approach, in theory, is to determine the distance to an object on the same rotation circle as the Sun, the solar circle, as illustrated in Figure 4 (a). By trigonometry, R_o = $D/(2 \cos l)$ where D is the distance to the object and l is its Galactic longitude.

Unfortunately, it is very difficult to identify an object that is co-rotating exactly on the solar circle. For this to be the case, there must be no relative motion in the Galactic frame of reference, so the object's line-of-sight velocity should be zero. As the Sun has its own peculiar motion in addition to its motion around the Galaxy, it is the velocity of the object relative to the Local Standard of Rest (LSR) that must be considered, which introduces additional uncertainty.
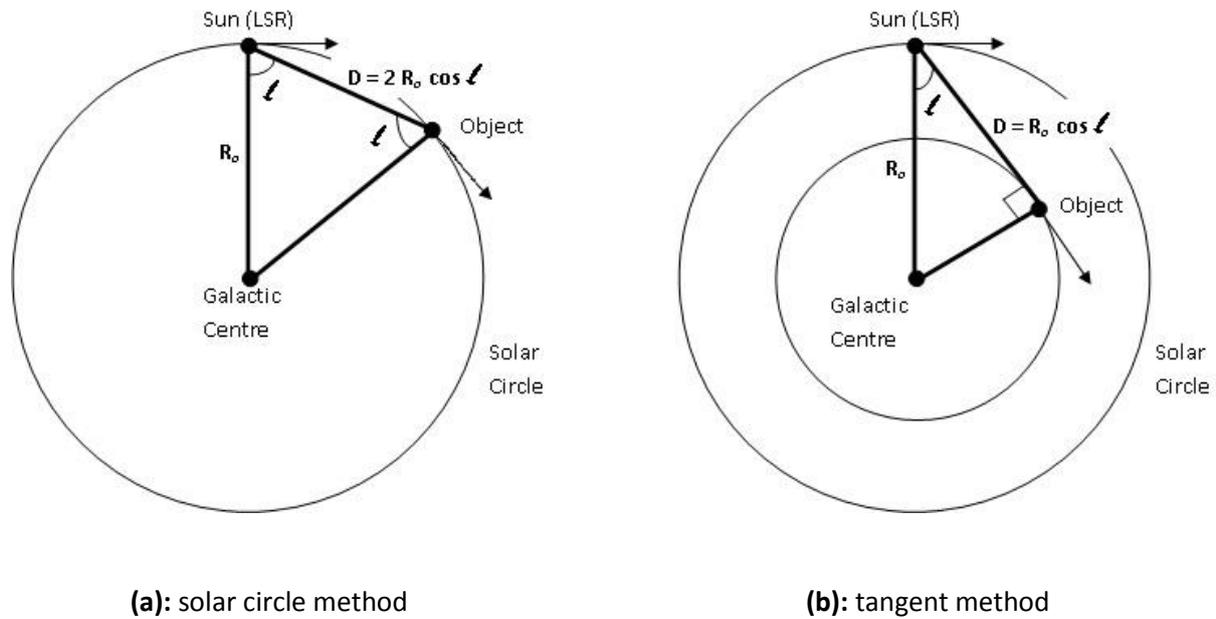
(a): solar circle method   **(b):** tangent method

Figure 4: Galactic rotation methods used to determine R_o

A recent study that claims to have succeeded in finding such a solar circle object is by Ando et al. (2011), using very long baseline radio interferometry. The object is the massive star-forming region Onsala2N at Galactic longitude 75.78^o. The measured annual parallax from maser observations gave a distance, *D*, of 3.8 kpc. Allowing for the parallax measurement uncertainty and also uncertainty in the line-of-sight velocity, the value $R_o = 7.8 \pm 0.4$ kpc is derived.

Sofue et al. (2011) used the solar circle method for the giant molecular cloud W49, which is at Galactic longitude 43.17^o and whose distance is 11.4 ± 1.2 kpc. This gives the value $R_o = 8.0 \pm 0.8$ kpc, allowing for a small line-of-sight velocity, putting it slightly inside the solar circle.

A possible source of error in the solar circle method is the assumption that the object has no significant motion in addition to its Galactic rotation. As part of the study of Onsala2N, its proper motion was measured. The component in the direction of Galactic latitude was found to be negligible, which the authors argue supports the view that Onsala2N rotates circularly around the Galactic centre (Ando 2011, 47).

3.5 Other Galactic Rotation Methods

Another theoretically simple method involving Galactic rotation is to measure the distance to an object at the tangent point of an inner circle, so that $R_o = D/\cos l$ (see Figure 4 (b)). The practical difficulty is in determining whether the object is at the required position. If it is, then the measured

line-of-sight velocity should be a maximum at that Galactic longitude. However, the calculation of the required maximum velocity value is itself uncertain. In a study by Sato et al. (2010), the distance to the massive star-forming region W51, at Galactic longitude 49.49^o, was determined by annual parallax to be 5.4 kpc. Allowing for the uncertainty in the position of W51, the authors derived R_o = 8.3 $\pm$ 1.1 kpc, the wide limits being because the method is particularly sensitive to this aspect.

A statistical method, involving measuring the distances and the line-of-sight velocities of a large number of objects at different Galactic longitudes, has also been employed. (This is actually a hybrid between a remote method and a ruler method, as it usually depends upon the use of LROs for determining distances.) A model of Galactic motion has to be adopted, usually assuming circular rotation together with a rotation velocity curve for the Galaxy. If enough objects are observed, a statistical analysis can be conducted from which the most likely value of R_o is able to be determined. By using a large data source, it is hoped that the effects of the peculiar motions of the objects, relative to Galactic rotation, are averaged out.

Metzger et al. (1998) carried out such a study using about 300 classical Cepheids, determining R_o= 8.0 $\pm$ 0.5 kpc, assuming circular rotation. However, the authors found evidence of slight ellipticity of the LSR orbit, its major axis roughly corresponding with the Galactic bar. Assuming this to be the case, the value of R_o obtained was 7.7 $\pm$ 0.7 kpc.

4. Assessment

The paper presented here is a summary of the investigation conducted, in which a total of 63 evaluations were studied and assessed (Clayton, 2012 and references therein). There is no single value of R_o, without uncertainty limits, that is consistent with all of them. Therefore, it is meaningless to obtain an overall average value. In order to refine the derived value, it is necessary to look closely at the studies and find which are the most indicative.

4.1 Assessment of the Remote Methods

The remote method studies are all based on the fundamental assumption that measurement of the mean distance of the chosen objects gives the Galactic centre distance. Sampling bias occurs when objects on the far side of the Galactic centre are undetected because of obscuration. In the case of LROs such as RR Lyraes and Miras, compensation for this is made by ignoring the faintest ones. In the case of the globular cluster method, different approaches have been tried. However, the

disparity in values of R_o is so large that the success of these attempts is doubtful. Therefore, the globular cluster studies are unusable in refining the value of R_o.

Sampling bias can also occur if only positive Galactic longitudes are observed, because the near side of the Galactic bar may be in view (see Figure 1 and Babusiaux 2005, fig. 6). Moreover, there is the potential for error if the observed group is eccentrically located in any direction. Most of the RR Lyrae studies employ only those stars in Baade's window, which is at a projected distance of 0.6 kpc from the Galactic centre. The preferred RR Lyrae study is by Majaess (2010), which used nearly two thousand stars from different regions around the centre. Similar considerations apply to the Mira studies, leaving only that of Matsunaga et al. (2009). Of the red clump studies, only the later ones are based upon observations of fields close to the centre. Of the other LRO studies, those using Type II Cepheids are preferred, by reason of object location and number.

The chosen remote method studies to be used in refining the value of R_o are given in Table 1. The mean value is $R_o = 7.9 \pm 0.3$ kpc.

Table 1: Remote method studies used for refining the value of R_o

Date	Author	R_o (kpc)	Method
2005	Babusiaux & Gilmore	7.7 ± 0.4	Red clump study, based upon tens of thousands of stars in the Galactic bulge, within 1° of the Galactic centre
2006	Nishiyama et al.	7.8 ± 0.4*	Red clump study, based upon hundreds of thousands of stars in the Galactic bulge, within 1° of the Galactic centre
2008	Groenewegen et al.	8.0 ± 0.6	Using 39 Type II Cepheids in the Galactic bulge, mainly within 3° of the centre
2009	Majaess et al.	7.8 ± 0.6	Using 54 Type II Cepheids in the Galactic bulge, mainly within 3° of the centre
2009	Matsunaga et al.	8.2 ± 0.5	Using 143 Mira stars in the Galactic nucleus, within 30 pc of the centre
2010	Majaess	8.1 ± 0.6	Using 1900 RR Lyrae stars in the Galactic bulge, mainly within 4° of the centre

* This value is calculated without using the authors' population correction (see text)

4.2 Assessment of the Ruler Methods

The annual parallax measurement of Sgr B2 by Reid et al. (2009) appears to be the only study employing the most fundamental and accurate distance determination method on an object within the Galactic nucleus. The statistical parallax study of the central star cluster by Trippe et al. (2008) employed large numbers of stars close to the Galactic centre and is also included here for refining R_o.

The orbit-fitting of stars close to Sgr A* was seen as a breakthrough in the determination of R_o. However, there is a significant difference in values depending upon the constraints that are employed in the calculation. The Ghez et al. (2008) determination using the star S2 that excluded the doubtful 2002 data and did not fix the motion of Sgr A* is chosen here for refining the value of R_o. The Gillessen et al. (2009) study used fewer line-of-sight measurements.

Both of the solar circle method studies investigated can be assessed in relation to how near the object is to the required position and are therefore judged reliable, given the uncertainty limits. On the other hand, the tangent method determinations are unhelpful in refining the value of R_o, because it is too unsure whether the objects are at the required position.

Of the statistical Galactic rotation studies, the one by Metzger et al. (1998) is considered here to be the most indicative. Unlike the others investigated, this determination used non-axisymmetric Galactic models in addition to those assuming circular motion. A combined value is taken.

The chosen ruler method studies to be used in refining the value of R_o are given in Table 2. The mean value is $R_o = 7.9 \pm 0.3$ kpc.

Table 2: Ruler method studies used for refining the value of R_o

Date	Author	R_o (kpc)	Method
1998	Metzger et al.	7.8 ± 0.6	Statistical Galactic rotation using classical Cepheids (combined value using axisymmetric and elliptical models)
2008	Trippe et al.	8.1 ± 0.4	Statistical parallax of the central star cluster
2008	Ghez et al.	8.0 ± 0.6	Orbit-fitting of the star S2 about Sgr A* (accepting that Sgr A* is moving)
2009	Reid et al.	7.8 ± 0.8*	Annual parallax using masers in Sgr B2 (the limits include allowance for uncertainty in the position of Sgr B2)
2011	Ando et al.	7.8 ± 0.4*	Solar circle method using object ON2N (the limits include allowance for uncertainty in the line-of-sight velocity)
2011	Sofue et al.	8.0 ± 0.8*	Solar circle method using object W49 (the value is obtained assuming the line-of sight velocity is 5 km/s)

* These values are slightly different from those given by the authors

5. Derived Value

The assessments of the remote method studies and the ruler method studies, given above, have both yielded mean values of $R_o = 7.9 \pm 0.3$ kpc. Uncertainty limits can be interpreted as meaning that

there is a realistic possibility of the true value being outside them. However, taking into consideration the agreement of the two basic methods, which are independent of each other, it is judged reasonable to be unequivocal here. Accordingly, it is concluded that the value of R_o is more than 7.6 kpc and less than 8.2 kpc.

In comparison, the International Astronomical Union recommended value of R_o is 8.5 kpc. This was put forward in 1985. The value of R_o derived here shows that a revision downwards of at least 0.3 kpc is required.

6. The Future

The uncertainty in the overall determination of R_o derived here is about 4%, which is still unacceptably large. The forthcoming astrometry mission GAIA will provide astrometric, spectroscopic and photometric data from vast numbers of Galactic stars. Although it will not directly provide more accurate measurement of distances to objects close to the Galactic centre, its extensive database should facilitate a reliable statistical Galactic rotation determination of R_o. GAIA will also refine the calibrations of LROs. By comparing properties in different locations, including the LMC, it will be able to test for population effects. The space mission Kepler, which is currently successfully searching for extrasolar planets (Clayton, 2012), is also obtaining sensitive photometric data on LROs that will aid their accurate calibration.

However, astrometry of objects within the Galactic nucleus has the potential to make the most accurate determinations. Further study of the annual parallax of masers close to the Galactic centre using radio interferometry is to be expected. More high-resolution near-infrared observations of the S-stars orbiting close to Sgr A*, using advanced adaptive-optics telescopes, are being made. The use of near-infrared interferometry should improve resolution still further.

7. Conclusions

All methods used to determine the distance to the Galactic centre have their limitations, whether remote objects or local rulers are used as the reference quantity. The uncertainty in remote methods arises mainly from calibration of luminosity reference objects, measurement of extinction, and group eccentricity. The uncertainty in ruler methods arises mainly from error in the observed object's location and the unknown specifics in relation to Galactic rotation. The annual parallax measurement of masers in the Galactic nucleus and the orbit-fitting of stars close to Sgr A* have the potential to provide the highest precision.

Although remote methods and ruler methods are totally independent, they are both found upon investigation to provide the same determination. From the six remote method studies and the six ruler method studies identified from the investigation as being most indicative, it is concluded that the distance to the Galactic centre is more than 7.6 kpc and less than 8.2 kpc. During the next few years, the uncertainty in the value of R_o is expected to be reduced further using GAIA data, high-resolution infrared observations and high-precision radio astrometry.

Acknowledgement

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