The Distance to the Galactic Centre

Introduction

Four centuries ago, it was positively confirmed that the *Sun* is the centre of the *Solar System*. Despite its then highly inaccurate value, the distance from the *Earth* to the *Sun* (the *Astronomical Unit*) became not only a basic parameter directly related with all the *Solar System*'s properties, but *the* essential astronomical distance unit as well. Only when the *AU* value began to be precisely measured, not before 200 years later, the previously estimated magnitudes could start their transformation into accurate physical values.

History seems to repeat. During the last eight decades, from the very moment that it was certainly stated that the *Solar System* orbits around a very distant Galactic centre, astronomers have tried to know this distance as accurately as possible. The eagerness to success in this endeavour is simply explained by the fact that the Milky Way's properties building has been constructed over the distance-to-the-Galactic-centre's foundations.

The Galactic Centre

The *Milky Way Galaxy* centre lies in the direction towards the constellation of *Sagittarius*, precisely at *RA* = 17h 45.7m, *DEC* = -29° 00' (*epoch* 2000.0) [**1**], very close to the frontier with neighbour constellations *Scorpius* and *Ophiuchus*.

Dense regions of gas and dust block the view in the Galactic plane of everything farther than a few thousand *light-years*, as light going through is absorbed by gas (although reradiated in a different wave-band), and scattered by dust [**2**]. These effective losses, collectively known as *extinction*, become even worst in the direction towards the denser Galactic centre (typically 30 magnitudes at visual wavelengths).

However, in the last few decades, astronomers have been able to peer through this blocking curtain by observing at *non-visual* wavelengths (infrared, radio, X-ray, and gamma ray) with an ever increasing sensitivity and resolution[1] [**3**].

According to our current state-of-the-art knowledge about the Galactic centre, there lays a powerful radio source called *Sagittarius A* of more than 50 *light-years* wide. Inside it, millions of stars of all masses and spectral types crowd the field around the Galactic core (that is, in a region around only 5 *light-years* from the Galactic centre), but only the most luminous ones are directly visible by giant telescopes in the infrared. At the very centre, there is a particular strong, point-like radio source named *Sagittarius A**

[1] For example, in the near infrared the *extinction* is reduced by about an order of magnitude [**4**].

("*A-star*") which marks the true dynamical centre of our *Milky Way* and believed to be a *black hole* containing the mass of 3 million *Suns* [**3**].

The Distance to the Galactic Centre (R_O)

Prior to 1920, *Harlow Shapley* had realized that *RR Lyrae* variable stars have all about the same average luminosity, allowing an easy distance estimation just from their apparent magnitudes. *Shapley* systematically found *RR Lyrae* inside the 93 then known *globular clusters*[2], thus being able to determine, for the first time, their respective distance and their spherical three-dimensional distribution. By doing so, he was able not only to locate the geometric centre of the spherical distribution, the Galactic centre, but to estimate its distance as well. This first R_O value resulted too large because *Shapley* did not take into account the effects of interstellar *extinction* [**6**].

From those studies, *Shapley* came up with a faithful model of our Galaxy's structure[3], consisting of a halo of globular clusters, a central bulge and a large thin disk, several tens of *kiloparsec*[4] in diameter. *Shapley*'s model remains, in all its essential features, the same one we use today [**5**].

Since *Shapley*'s first attempt for the estimation of the distance to the centre of the globular clusters system, many other methods have been applied to find out R_O, decreasing its uncertainty as the technology has being improved.

Ten years ago, senior radioastronomer *Mark Reid*, an authority in the measurement of R_O, published an article comparing all the R_O values obtained by different methods and measurements prior to 1993 [**7**]. His "*weighted average*" of R_O = 8,000 *parsec* (26,000 *light-years*) with an uncertainty of ± 500 *parsec* (± 6.25 %) has remained as its best present value (although *IAU*'s recommendation still is R_O = 8,500 *parsec*).

Modern Techniques to Measure R_O

Astronomers continue trying to reduce the uncertainty of R_O, applying different methods and making full use of state-of-the-art observational techniques at different wavelengths. Besides modern satellites orbiting the *Earth* (of multiple wave-band like *Hubble* or specific ones like *ISO* and *COBE* at infrared, *Chandra* and *Newton* at X-ray, *Compton* at gamma-ray), two modern ground techniques are successfully being applied in the atmospheric *non-visual* transparent windows: the *VLBI* (*Very Large Baseline Interferometry*) for radio observations, and *adaptive-optics* for near infrared (and visual) observations [**6**].

---

[2] *Shapley* originally called *RR Lyrae* variables as "*cluster-type Cepheids*" [**5**].

[3] Technically, *Shapley*'s original model represented the *Universe*'s structure, as at that time he thought that the whole *Universe* was comprised by just a single galaxy [**5**].

[4] Professional astronomers tend to prefer use of the *parsec* as the unit of distance measurement, while among the general public, amateur astronomers included, the *light-year* is more welcomed (1 *pc* = 3.26 *light-years*).

Interferometry is a technique that allows to hook together radio images from different radio telescopes, making the combined signal sharp and clear. The more radio telescopes and their farther separation (the *baseline*), the better angular resolution that can be achieved.

Adaptive-optics is a technique that allows to differentially deform tiny areas of the mirrors of large telescopes to "instantaneously" compensate the atmospheric turbulence, making the obtained image nearly as sharp as it would have been obtained from space.

In the next decade, new space projects (*SIM*, *GAIA*) will revolutionize astrometric measurements. Specifically, one of the stated goals for the *Space Interferometry Mission* is "*the determination of two fundamental parameters that play a central role in virtually every problem in Galactic astronomy, namely* R_O *and* w_O[5]" [**8**].

Meanwhile, some of the current applied methods to find out R_O are:

- ***RR Lyrae stars in Baade's window***

During the *II World War*, *Walter Baade* identified a particular sky region near the Galaxy's centre, now called "*Baade's window*", where there is comparatively little opaque dust [**9**]. Despite of being so close to the Galaxy's centre, the relative lack of dust make it possible that millions of stars can actually be seen.

Searching into the "*Baade's window*", *RR Lyrae* were found long ago quite near the Galaxy's centre, which allowed an immediate -although indirect- estimation of R_O.

The most recent R_O measurement applying this method at near infrared (*McNamara et al*, 2000) [**10**], results $R_O = 7.9 \pm 0.3$ *kpc*.

- ***Circumstellar Masers in the Galactic centre***

Masers are interstellar molecular clouds that emit such intense microwave radiation that they can be detected even at thousands of *kpc* away. Just as an electric current stimulates a laser to emit an intense beam of visible light, nearby luminous *OB* stars can stimulate water and other molecules in a maser to emit intensely at microwave wavelengths [**6**].

It has been discovered maser emission (43 *Ghz*) from SiO, H_2O and OH molecules in the circumstellar environment of evolved stars, mostly *AGB* (*Asymptotic Giant Branch*), within the central parsec of our Galaxy [**12**]. Using *VLBA*[6] observations, the maser positions can be registered with *milliarcsecond* (*mas*) precision relative to the radio source *Sgr A** (the equivalent of a measure 2 meter long on the surface of the Moon).

[5] w_O represents the solar *angular velocity* around the Galactic centre.
[6] The *Very Long Baseline Array* is a *VLBI* system of ten radiotelescopes antennas, each 25 meters in diameter, stretching some 8,000 km from *Mauna Kea* in *Hawaii* to *St. Croix* in the *U.S. Virgin Islands*. It offers the greatest resolving power of any telescope system currently operational [**11**].

This high precision makes it possible to measure their respective *proper motions*[7], and thus obtaining, after assuming a *rotational model* for the masers, a geometric estimation for R_O [**13**].

Recent studies from water maser *proper motions* [**14**], have resulted in $R_O = 7.2 \pm 0.7$ *kpc*.

- ***Observations of stars at*** R_O

The high central stellar density has been inferred from 2.2 μm (near infrared) adaptive-optics observations of old *Population I* cool red giant (*K* and *M types*) stars [**15**]. Many individual stars have been detected orbiting very closely (less than 1 *arcsec*[8]) around *Sgr A** in *Keplerian* orbits.

A group headed by *Andrea Ghez* has precisely tracked those stellar *proper motions*, showing that they are moving extremely fast, some over 1,500 *km/s*. By knowing their respective radial velocities and *proper motions* it is possible to solve the orbital parameters for each one of those stars, which has led to our current estimation of the 3 million solar masses for the black hole at *Sgr A** [**3**].

Samir Salim and *Andrew Gould* have presented "*a new geometrical method for measuring* R_O" after finding out those orbital parameters. [**16**]. They stated that their direct method (in essence, the classic *visual binary method*) will allow to know R_O with an ever increased accuracy, as each new stellar measurement will lead to obtain its orbital parameters more precisely, and hence contributing to a final better value for R_O. The authors anticipate its accuracy between 0.5 to 2 % after 30 years of observing [**16**].

- ***Proper motion of Sgr A* from VLBI***

By precisely registering radio and infrared images in the Galactic centre, *Mark Reid et al* have been capable of measuring the *proper motion* of the very Galactic centre [**18**].

This technological feat implied the capability of measuring accurately positions within nearly 0.1 *mas* compared to distant quasars, that is, a precision 500 times greater than that of the *Hubble Space Telescope*. From this work, the apparent *proper motion* of *Sgr A** has been measured as $\mu_O = 6.0 \pm 0.4$ *mas/y*, almost entirely in the Galactic plane, thus supporting the theory that *Sgr A** is the true dynamical Galactic center [**18**].

This *measured* value of the Galactic centre's *proper motion* implies that the orbital

---

7 The *proper motion* of a star is its apparent angular movement *per year* on the celestial sphere. Thus, it represents the true overall motion of the star perpendicular to our line of sight [**17**], becoming completely independent of the annually repeated round trip apparent motion due to the *parallax* effect.
8 At a distance about 8,000 *pc*, 1 *arcsec* from the Galactic centre implies 0.039 *parsec* or just 46 *light-days*.

velocity of the Sun, equivalent to the product R_O times $w_{O,}$ is 217 km/s. Over the next years, the already obtained *proper motion* of *Sgr A** will increase its accuracy, making feasible the final attempt to measure its *trigonometric parallax*.

- ***Annual parallax of Sgr A* from VLBI***

The most fundamental and straight-forward method of measuring distances to sidereal objects is the *trigonometric parallax*. But at distances like R_O, the expected maximum shift due to the *parallax* effect[9] (p_{annual}) is about

$$p(SgrA*)_{annual} = 2/R_O \approx 2/8{,}000 \Rightarrow p(SgrA*)_{annual} = 0.00025\ arcsec = 250\ \mu as$$

Therefore, in a six months span the angular *parallactic* motion of *Sgr A** (250 μ *as*) is more than one order of magnitude (actually 12 times) smaller than the angular apparent shift due to its own *proper motion* (3,000 μ *as*).

Last year, *Hosokawa et al* have analyzed the current practical difficulties of measuring the diminutive *annual parallax* of *Sgr A** by using *VLBI* [**19**].

The team found out that "*the apparent position of Sgr A* with respect to the nearby extragalactic radio sources wanders because of the gravitational deflection by intervening stars in the Galaxy*", "*degrading the measurements of trigonometric parallax of Sgr A* significantly*" [**19**]. That means that the today so obtained R_O value would imply an inaccuracy greater than our current standard error.

Hosokawa et al's final recommendation is that an observation period of at least 6 *years* will finally separate the observed *Sgr A** positional wander from its *parallatic* motion, and thus allowing the measurement of the accurate *trigonometric parallax* of *Sgr A**.

The importance of R_O

The aforementioned radioastronomer *Mark Reid* has underlined the importance of the R_O value by stating that any change in its value "*has widespread impact on astronomy and astrophysics*" [**20**].

The general equations for the circular motion in the Galactic plane derived by *Jan Oort*[10] make full use of the parameters R_O and w_O [**21**], as any other *rotation model* does as well. Therefore, all the distances estimated from measured radial velocities and whatever *rotation model* used, are directly proportional to R_O.

Given any distance from the Galactic centre, from the rotation curves it can be obtained the amount of the overall enclosed mass. Hence, most estimates of the gravitational and

[9] The maximum *parallactic* angular variation, the *annual parallax*, is twice the *trigonometric parallax*.and corresponds to measurements done from *geocentric* vantage orbital points six months apart.
[10] The well known *Oort's (general) formulae*.

luminous mass of the Galaxy depend on R_O. Likewise, the mass and luminosity of other special galactic objects, like giant molecular clouds, are also directly related to R_O.

Last but not least, since extra-galactic distances are based on our *Milky Way Galaxy*'s calibrations, even the most important cosmological parameter, the *Hubble constant* (H_O), is somehow related to R_O [**20**].

Conclusion

The distance to the Galactic centre has been estimated by different methods for the last eight decades. Its best current value is 8.0 *kpc*, with a standard error of about 0.5 *kpc*. Each lessening in its uncertainty directly makes that all the related Galactic magnitudes also become more accurately known.

The accuracy of the distance to the Galactic centre will continue to be progressively improved until it could reach a satisfactory value (around 1 %). The current technological development allows to accomplish this endevour, but many more years of measurements will have to be invested. Anyway, the new satellite generation promises to definitively become this Galactic cornerstone clearer within the next decade.

References

[1] "*Observer's Handbook 2003*", *The Royal Astronomical Society of Canada*
[2] "*Interstellar Extinction and Reddening*" from "*The CCD Photometric Calibration Cookbook*" by *J. Palmer & A.C. Davenhall* at http://www.starlink.rl.ac.uk/star/docs/sc6.htx/node30.html
[3] "*A trip to the galactic centre*", article by *Angelle Tanner*, *Sky & Telescope* magazine, April 2003 issue, pages 44 to 50
[4] "*Where is the Galactic Center?*" by *Mark Reid* at http://cfa-www.harvard.edu/~reid/sgra_position.html
[5] "*The Cepheid Distance Scale: A History*" at http://institute-of-brilliant-failures.com
[6] "*Universe, Stars and Galaxies*" by *Roger A. Freedman* and *William J. Kaufmann III*, 6th edition, 2002, *R.R. Donnelley et Sons Company*
[7] "*The Distance to the Center of the Galaxy*" by *Mark Reid*, "*Annual Reviews of Astronomy and Astrophysics*", 1993, volume 31
[8] "*Taking Measure of the Milky Way*" from "*Science with the Space Interferometry Mission*" at http://planetquest.jpl.nasa.gov/Navigator/library/science_AAS_Jan02.pdf
[9] "*Baade's Window*" at http://www.kaal.org/present020/sld022.htm
[10] "*The Distance to the Galactic Center*" by *McNamara et al*, "*The Publications of the Astronomical Society of the Pacific*", Volume 112, Issue 768, pp. 202-216, 02/2000, at http://adsabs.harvard.edu/cgi-bin/nph-bib_query?2000PASP..112..202M
[11] "*Radio Astronomers Set New Standard for Accurate Cosmic Distance Measurement*" by *National Radio Astronomy Observatory*, June 1, 1999 at http://www.aoc.nrao.edu/pr/4258.distance.html
[12] "*SiO and H_2O Masers in the Central Parsec of the Galaxy*" by Karl M. Menten et al. at http://cfa-www.harvard.edu/ep/preprint/julaug97/4582.html

[13] "*Circumstellar Masers in the Galactic Center*" by *Lorant Oliver Sjouwerman* at http://www.aoc.nrao.edu/~lsjouwer/_html/papopers.html
[14] "*The Case for a Leaner Milky Way*" by Rob Olling, at http://www.cv.nrao.edu/~jhibbard/Colloq/abs/olling.html
[15] "*The Galactic Centre*", module 4, activity 2 of *SAO HET 604's CD-ROM*, 2003
[16] "*Sgr A* 'Visual Binaries': A Direct Measurement of the Galactocentric Distance*" by *Samir Salim* and *Andrew Gould*, submitted to *Astrophysical Journal 2001*, at http://arxiv.org/PS_cache/astro-ph/pdf/9812/9812292.pdf
[17] "*Hipparcos: High Proper Motion Stars*" from "*The Hipparcos Space Astrometry Mission*" at http://astro.estec.esa.nl/Hipparcos/properm.html
[18] "*VLBA Detects Earth's Motion Around the Milky Way's Center*" by *National Radio Astronomy Observatory*, June 1, 1999, at http://www.aoc.nrao.edu/pr/sagastar.html
[19] "*Possible fluctuation of the position of Sgr A* relative to Extragalactic Radio Sources*" by *M. Hosokawa et al, The Astronomical Society of Japan*, 2002
[20] "*The Distance to the Center of the Milky Way*" by *Mark J. Reid* at http://cfa-www.harvard.edu/~reid/trigpar.html
[21] "*The Disk Rotation of the Milky Way Galaxy*" by *Vincent Kong* and *George Rainey* at http://www.csupomona.edu/~jis/1999/kong.pdf