Recent Direct Measurements of the Distance to the Center of the Galaxy

Introduction

Since the earliest days of man's contemplation of the cosmos, most cultures have put the Earth firmly in the middle of the universe. Beginning in the 17^{th} century, that notion has slowly been eroded by first displacing the Earth from the center of the Solar System in the Copernican Revolution, and then in 1918, by displacing the Solar System from the center of our Galaxy (Shapley 1918). For the rest of the 20^{th} century, astronomers studying the distance to the center of the Galaxy using a variety of methods arrived at a distance of around 8 kpc[1] with varying levels of uncertainty (Reid 1993).

Understanding the true nature of the Earth's place in the Milky Way Galaxy is essential to our understanding of the nature of the universe, since much of our cosmological analysis relies on the value of R_0, the distance of the Earth to the center of the Galaxy (Reid 1993).

In the 21^{st} century, advances in adaptive optics have enabled astronomers to determine the distance with increasing accuracy by observing the motion of stars around a supermassive black hole at the center of the Galaxy, and now the latest estimates converge around 7.94 ± 0.42 kpc (Eisenhauer et al 2003).

Historical Background

Shapley's seminal 1918 paper, "Globular Clusters and the Structure of the Galactic System", plotted the spatial distribution of globular clusters, based on brightness estimates derived from Cepheid Variable stars in the clusters, to arrive at a conclusion that they were not uniformly distributed around the earth, but rather around a point in the direction of Sagittarius some 13 kpc from the Earth.

Since then, a variety of methods have been employed by astronomers to determine R_0. These can be separated into three broad categories: using "standard candle" measurements of objects thought to be in spherical distribution around the core (Shapley's method); methods that combine observations with Galactic models to arrive at a distance; and direct measurements to objects at the Galactic center (Reid 1993). This paper will focus on recent direct measurement techniques.

Direct Measurements from Orbits

In 1997 Eckhart and Genzel were able to use near-infrared imagery specially processed to get diffraction-limited images of stars at the Galactic center. They monitored the positions and velocities of several stars over the course of 4 years. They found that the velocities of the stars dropped off as a function of their distance in such a way to suggest a supermassive object at the very center of the Galaxy that coincided with the X-ray source Sgr A*.

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[1] MegaParsec, or 10^6 times one parallax second, equivalent to ~ 3×10^{19} m.

Ghez et al. followed up with their 1998 paper detailing solid evidence for a supermassive black hole coincident with the position of SgrA*, primarily by noting the high proper motions of stars very close to the Galactic center. Using specially processed near-infrared imagery from the 10 m W. M. Keck telescope Ghez and his colleagues were able to pinpoint the position of 90 stars in the crowded field within several arcseconds of SgrA* over a period of two years. By following the stars over the two-year period, they were able to show that stars close to SgrA* had radial velocities consistent with Keplerian orbits. The closeness of the orbits to the purported central mass and the high orbital velocities were evidence for a compact central mass of $2.6 \pm 0.2 \times 10^6$ times the mass of the sun.

With the mass of the central object determined, and several years of baseline position and velocity data in hand, in 1999 Samir and Gould proposed a direct geometrical method for determination of R_0. The method is essentially the Keplerian one that's been employed for decades to estimate the masses of, and distances to, visual binaries.

Keplerian Orbital Mechanics

In order to analyze how the mass and distance to Sgr A* can be determined, we need to know a bit more about orbital dynamics.

Kepler's Second Law states that, for an object in orbit around another orbit, the object sweeps out equal areas of the orbit over equal time intervals. By repeated measurements of the orbital velocity of an object in orbit separated by some time interval, a determination can be made of the orbital period of the object.

Kepler's Third Law tells us that $P^2 \propto a^3$, where P is the orbital period, and *a* is the semi-major axis of the orbit. If the period has been determined by applying the Second Law, it's a simple matter to determine a, the semi-major axis length in absolute units.

By comparing the absolute length of the orbit to its apparent length, we can determine the distance to the orbit. We use the small angle approximation since the orbital diameter is very small compared to our distance from the orbit:

$$R_0 = \frac{a(206{,}265)}{\alpha}$$

$$where\, a = semi-major\, axis \quad and \quad \alpha = angular\, diameter\, of\, orbit\, in\, arc\sec onds$$

Figure 1

The constant in figure 1 is the number of arcseconds in a circle, and R_0 will be in whatever units *a* is in.

Coupled with Newton's law of gravitation, the Third Law becomes: (where M is the mass of the central object, and m is the mass of the orbiting object)

$$\left(\frac{P}{2\pi}\right)^2 = \frac{a^3}{G(M+m)} \quad or \quad \left(\frac{P}{2\pi}\right)^2 = \frac{a^3}{GM}$$

$$if \;\; M >> m$$

Figure 2

With *P* and *a* known, assuming that the central mass is much larger than the orbiting mass, we can easily determine the actual value of the central mass, M, by solving figure 2 for M.

The Orbit of S2

Calculations of R_0 and M rely on accurate stellar positional observations and velocity measurements to determine orbital velocities that predict (by Kepler's Second Law) period and semi-major axes of stellar orbits.

By 2003, three quarters of the orbit of one of the stars orbiting around Sgr A*, S2, had been observed by various teams. Using 19 positions and 5 line of sight velocities, Eisenhauer et al (2003) computed the period and semimajor axis of its orbit to come up with an estimate of 7.94 ± 0.42 kpc for R_0.

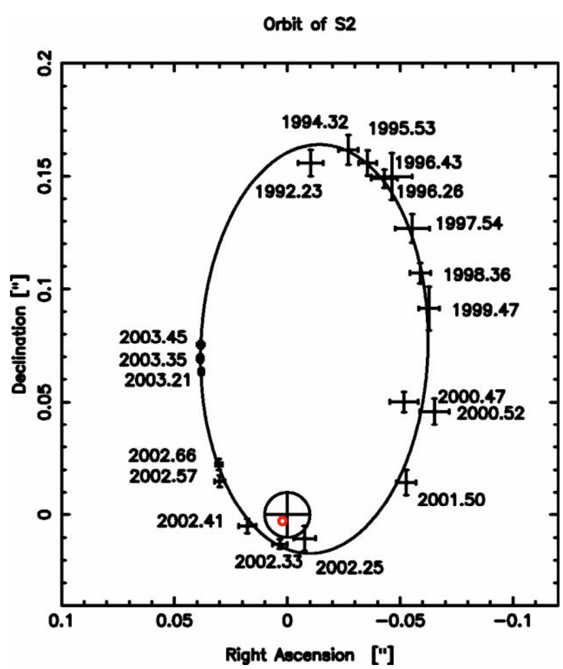

Figure 2: The orbit of S2 (From Eisenhauer et al 2003). The red dot is the position of Sgr A*

Error Considerations

The error in the proper motion component of the stellar velocities depends primarily on the angular resolution of the detector. These errors have come down from 6-10 milli-arcseconds (mas) in 1992 to 1-3 mas in 2003 (Eisenhauer et al 2003). Note the changing length of error bars in Figure 3.

Figure 3 shows the apparent orbit of S2, but in order to know the actual semi-major diameter, we need to know the orbital inclination. By measuring the line of sight component of stellar velocity for points around the orbit, we can tell how the orbit is tilted to our line of sight. Imagine an orbit that is perfectly perpendicular to our line of sight: since the stars are neither approaching us or receding from us, the line of sight component will be zero for all measurements. If the orbit were completely edge-on, we'd see the star approaching for half the orbit, and receding for the other half. By analyzing the line of sight components, we can get an accurate inclination geometry that will allow us to correct figure 3 distances. Eisenhauer et al had a total of 5 line of sight measurements obtained from spectral Doppler shifts. Figure 4 shows the data and the best-fit curve of line of sight velocity. More data points will help to constrain this curve and yield a better estimate of *a*.

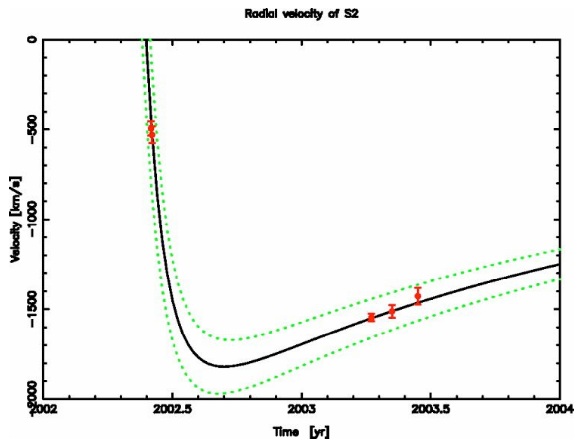

Figure 4: Line of Sight Velocity of S2 (from Eisenhauer et al 2003)

There are other concerns with the accuracy of this method. Reid (Personal communication 2008) notes that telescopic resolution limits the accuracy of the stellar positions when they are very close to the central black hole or when two stars are close together in the crowded field because the two sources can blend together. Both Ghez and Genzel have agreed to eliminate these questionable positional data, and unpublished analysis from them now puts R_0 at 8.4 ± 0.4 kpc.

In 1999 Salim and Gould did a careful statistical analysis of just how the error in R_0 should decrease over time given careful observations of just three of the orbiting stars. Their conclusion was that after 8 years of observation (2003), the accuracy should be within 2.5% of the actual value, and after 10 years should be within 1%. They go on to suggest that as the accuracy of position continues to improve as angular resolution improves with larger and larger telescopes, the method should yield accuracies of 0.2%.

How have Salim and Gould’s error prediction been borne out? Eisenhauer et al’s 2003 estimate of 7.94 ± 0.42 kpc, has an error of just less than 5%, not 2.5%. That analysis looked at the orbit of one star; Salim and Gould’s error analyisis was predicated on observing at least three orbits. S2 has the shortest period of stars under observation, but as the orbits of more stars become better understood and fitted into Salim and Gould’s method, that error should decrease.

Future Direct Measurements

Besides the Keplerian method, continuing advances in very large baseline interferometric observations should make another direct measurement technique viable in the next few years. This involves measuring the parallax of Sgr A* with respect to distant quasars. The error of any parallax method hinges primarily on the angular resolution of the radio data, and so far, the resolution of detectors is on the order of the total parallax movement expected (0.1 mas) and hasn’t improved much in the last decade (Reid et al 1999 and Personal communication 2008). We’ll have to wait for the resolution to improve before any improvement in the value of R_0 coming from parallax methods.

Conclusion

Since Shapley displaced the center of the Galaxy in 1918, estimates of R_0 have converged around 8 kpc. Recent direct measurements of stellar motion around our Galaxy's central supermassive black hole using near-infrared imagery have approached to within 5% of the actual value. As orbital data of other central stars continues to accrue, the error will continue to decrease to within less than a percent. As very large baseline interferometry resolution advances, direct parallax measurements of Sgr A* should be feasible.

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