Proper Motion of the Galactic Centre

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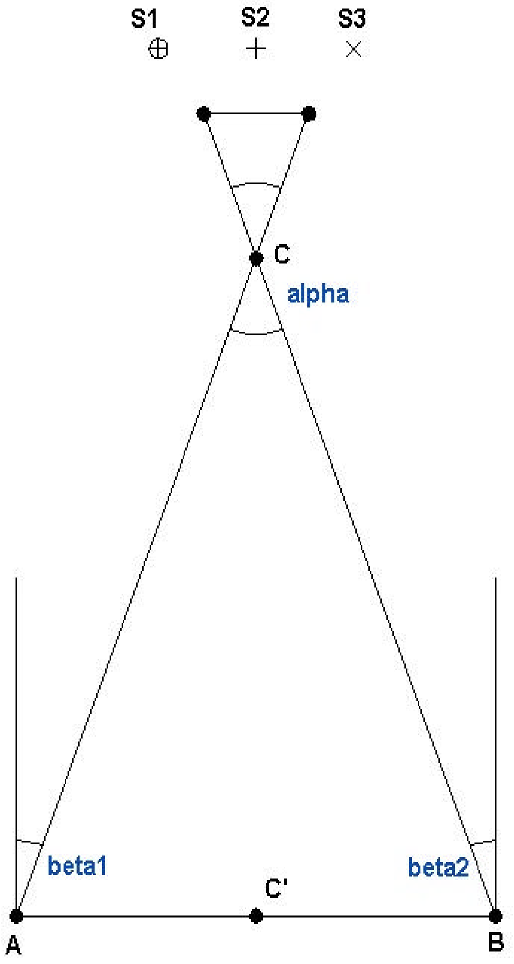
Mankind has been always interested in distances to far objects. From old civilizations to nowadays, we have always tried to measure distances from our position to other locations. Initially, and in a very local scale, it was as simple as locating a ruler over the things to be measured, counting the times needed for completing the task. Naturally, not only wood or metal rulers were used, but also ropes and similar simple instruments.

For bigger distances, or when it is impossible to use rulers, such as when you want to know with precision the distance to a building located at the other side of a river, this procedure can't be applied. This is specially true when astronomers began to try to measure distances to celestial objects several centuries ago. For this, they used a technique named "parallax".



In order to understand how parallax works, let us imagine we want to know the distance to an interesting building located in point C from C', assuming we know the distance from A to B and that we can't walk from C to C' due to reasons you can freely choose for this example. Surveyors use some instruments called theodolites[1] for this task. They simply locate this optomechanical measuring instrument in point A and look to point B through the Theodolite's built-in telescope. Then they rotate the instrument 90 degrees towards left and take note of the reading from built-in graduated circles. Then they look towards point C, obtaining angle beta1. The same procedure is applied in point B, and hence, getting angle beta2. From figure #1 is clear that angle alpha equals the sum of angles beta1 and beta2. Very interestingly, angle alpha is called the parallax of this geometrical model. Since we assume the baseline AB is known, the distance C-C' can be derived geometrically or using simple trigonometry. Observing again the figure it's easy to realize that longer baselines lead to higher precision in determining distances.

Using the same figure, let's see what happens when instead of using theodolites we use telescopes and points A and B are the locations of our planet Earth six months apart, that is, occupying diametrical locations in the orbit around the Sun, located in C'. If we are trying to measure a not too far star located in C, we shall observe this star displaced with respect to distant "fixed" stellar objects S1, S2 and S3 (the drawing in figure #1 is not scaled). That is, when the Earth is located in A, we would observe stellar objects S1 and S2 at left of C, while six months later, only stellar object S1 would be a bit at left from C. The angle alpha is called stellar parallax. However, astronomers have agreed to define a star's parallax formally as half of the angle alpha, that is, half of the star's total observed shift in the sky.

Despite the distance from points A to B is about 16 minutes-light, or two Astronomical Units, (enormous, for terrestrial standards), distances to stars are so large that it required some centuries of efforts to astronomers to get their first results. Although there is some controversy about who won the Parallax race, two great astronomers where head to head, both getting the historical achievement: Friedrich Bessel determined the parallax of 61 Cygni in 1838, located about 11 light-years from us, while Wilhelm Struve detected the parallax on Vega, Alpha Lyrae in 1837-1839, located about 25 light years from our solar system. They were outstanding observers using the best technology available at the moment. Incidentally, this revealed a bigger model of our Universe than no human-being had previously imagined. It was only the beginning[2].

Altius, Citius, Fortius

In the same way as the Olympics, this seems to be the fate of science. Nowadays parallax is effective for distances up to 500 parsecs[3], but even having into account this is not a far distance in astronomical terms, Astronomers soon became interested in measuring the distance R_0 to a singular point in the Universe: Our Milky Way Galactic Centre.

The reasons explaining this interest are easy to understand. First, distances from the solar system to stars inside our Galaxy determined by observed stellar radial velocities and having into account a rotational model of the Galaxy are proportional to R_{0}., while estimations of luminosity and gravitational mass of our Galaxy depend also on this distance, so obtaining a good value of R_0 would give us enriched astronomical data. In a bigger scale, extragalactic distances are based in calibrations and measures of Cepheids and RR Lyrae variable stars, so knowing R_0 with high precision would allow us to refine the standard astronomical distance ladder and a bigger precision about the age of stars, thus getting a better estimation of the age of globular cluster, a better value of the Hubble constant, H_0 and thus, a better value for the entire Universe age[4,5].

It was Harlow Shapley who in 1918 first gave some values for the size of our Milky Way based on distances to variable stars inside Globular Clusters orbiting the Galaxy. Although Shapley was wrong by within a factor of 2.0 (R_0 about 13kpc) in their calculations due to interstellar absorption and mistakinly identifying RR Lyrae variables as Cepheids (different relationships between absolute magnitude and period), he established the basis for a much bigger Galaxy than previously imagined.

About 70 years later, better values have been obtained applying actual measuring techniques to basically the same concept followed by Shapley, that is, assuming a symmetrical distribution of globular clusters around the galactic centre, getting values of R_0 between 7.0 kpc (de Vaucouleurs & Buta, 1978) to 10.1 ± 0.7 kpc (Surdin, 1980). The uncertainty between obtained values arises from using different statistical estimators, stellar extinction due to interstellar dust and crowding of stellar images due to compactness of globular clusters.

New formed, luminous massive stars can stimulate water molecules from surrounding molecular material associated with them, intensely emitting at microwave wavelengths. In this way, so named Masers (Microwave Amplification by Stimulation Emission of Radiation) from bright stars located very near the Galactic Centre are useful for estimating R_0 because these sources of radiation are characterized by their small sizes and strong bright, yielding good astrometric measures. In fact, using VLBI (Very Long Baseline Interferometry) techniques[6], astronomers have got precisions of about 10 μas (microseconds of arc) across fields ~ 3 arcseconds in size. Sadly, maser spots do exhibit a strong random component in their movements as well as significant flux density variations[7]. Moreover, maser spots are not uniformly distributed around their exciting stars, so again some uncertainty arises, obtaining results for R_0 in the range of 6.5 ± 1.5 kpc (Reid et al, 1998) to 8.1 ± 1.1 kpc (Gwinn et al, 1992)

Also, some measures have been made through fortuitous small "galactic windows" opened towards the galactic centre where stelar extinction is lower due to random distribution of dust. In this way, RR as well as Mira type variable stars have been observed for obtaining an estimation of R_0. At first sight, Mira giant variables seem specially suitable for this task, because they are luminous and suffer from low extinction in the infrared region of the spectrum. Sadly, uncertainty can't be eliminated at all because Mira stars are relatively speaking cold stars that are characterized by very opaque atmospheres due to complex molecules formed in them. This is a big obstacle in order to calibrate their absolute magnitudes. Obtained results for R_0 are in the range of 7.9 kpc (Glass & Feast, 1982) to 9.2 ± 2.2 kpc (van den Bergh & Herbst, 1974). Table #1 resumes obtained values from different methods and authors.

Method	Author(s) and date	Min-Max R_0 Estimation (kpc)
Globular Clusters	Vaucouleurs & Buta, 1978 Surdin, 1980	7.0 - 10.1±0.7
H_2O Masers	Reid et al, 1998 Gwinn et al, 1992	6.5±1.5 - 8.1±1.1
Giant and Mira stars	Glass & Feast, 1982 v. den Bergh & Herbst, 1974	7.9 - 9.2±2.2
RR Lyrae	Blanco & Blanco, 1985 Oort & Plaut, 1975	6.9±0.6 – 8.7±0.6
Other (Rotational models of the Galaxy)	Caldwell & Coulson, 1987 Byl & Ovenden, 1978	7.8±0.7 – 10.4±0.5

Table #1: Estimations of R_0 from different authors and methods[4]

Parallax revisited

In 1974, Balich & Brown discovered an enigmatic, compact, non-thermal radio-source in the center of the Galaxy while looking for HII regions. Nowadays Astronomers are almost sure this radio source is produced from matter falling into a supermassive black hole located in the galactic centre with a mass about of 10^6 Solar masses[8,9], but since nothing escapes a black hole, radiosource Sgr A* is not a black hole itself but radiation produced by the accretion disk rotating the black hole residing in the galactic centre. This subtle detail is important because some popular science sources usually claim Sgr A* is a black hole itself[10].

In any case, Sgr A* soon exerted great interest between Astronomers, so resources were allocated into the research of this enigmatic object. Don Baker from Berkeley in California started to study this radiosource in 1976 in order to get astrometric measures with the Green Bank radiotelescopes. Along five years of studies and observations, it was determined that Sgr A* was indeed galactic in nature, that is, it was not a superposition by change of an extragalactic object.

In 1981, Baker and his team joined R. Sramek from the Very Large Array (VLA), National Radio Astronomy Observatory with the ambitious goal of measuring the proper motions of Sgr A* in mind (Baker tried it first in the Green Bank experiment, but uncertainties were large enough to get scientific results). After all, radio frequency observations using the straightforward technique of trigonometric parallax using the VLA could be an extremely accurate method for determining R_0. After centuries of star parallax race, we can see the works of Backer and Sramek as another exciting chapter in the history of Astronomy.

It seems it was a “lateral thinking” issue: After removing the parallax of our solar system rotating the center of our Milky Way Galaxy, would it be possible to observe some proper motion of the galaxy center with respect to far, extragalactic, celestial objects?. The basic technique is the same as the exposed previously: Assuming our solar system needs 220 million years to rotate the Galaxy, then 16 years of observations would yield a baseline, in a first approximation, of about 754 Astronomical Units. Comparing this distance to the 2 AUs baseline used by Bessel and Struve to measure first stellar parallaxes seems at first a huge advantage. Would it be enough to detect proper movements of Sgr A*?

The Very Large Array (VLA) is an impressive tool for hearing radiofrequencies coming from the Universe, consisting in a set of 27 antennas arranged in a huge Y pattern (wye configuration) up to 36km across. Some cities in the world such as Madrid or Rome would entirely fit inside this area[11]. Furthermore, the VLA enjoys from an excellent location for phase stability and its receivers are from the more sensitive in the world, so this scientific facility brang new capabilities very well suited to the planned study.

As we have seen, parallax techniques need background references in order to observe the desired apparent shift of the object under study. For determining proper motions of Sgr A*, Baker found three radiosources located million parsecs from us, named W56, W109 and GC441, characterized for their compact structure (less than 1 arcsecond in apparent size) and with sufficiently strong fluxes. Although these objects could not be identified as quasars or AGNs (Active Galactic Nuclei), their observed features allowed the researchers to be confident they were extragalactic in nature. Moreover, these 3 radiosources are closer to Sgr A* than the radiosources of reference used previously in the Green Bank experiment, thus allowing more precise observations. Along 16 years of work using the VLA, Baker and his team observed that Sgr A* drifts away from these reference objects, corresponding to a movement in galactic longitude specially compatible with the rotation of the solar system around the center of the Galaxy.

Some interesting calculations

In order to get an easy to understand picture of the operations involved, it can be useful to make an analogy: Let’s think about the expected Sgr A* proper movement as the “signal” and the secular parallax of an object at rest located in the center of gravity of the Galaxy as the “noise”. Cleaning this “noise” implies obviously to subtract the secular parallax from the observed shift of position of Sgr A*. This secular parallax (SP) is the sum of movement of galactic rotation (GR) and the solar motion (SM) with respect to the Local Standard of Rest (a frame of reference moving with the average velocity of the nearby stars out to about 50 pc from the Sun). That is:

$$SP = GR + SM$$

And using galactic coordinates:

$$GR = -[(A - B), 0]$$
$$SM = -[V_s/R_0, W_s/R_0]$$

Where A and B are the Oort’s constants, giving the galactic rotational speed, while V_s and W_s give the solar movement with respect to the Local Standard of Rest (LSR). R_0 is the distance to the Galactic Centre. Using the admitted IAU values for Oort’s constants A and B, Baker and Sramek give a GR value in galactic longitude and latitude (milliarcseconds per year) of:

$$GR = [-5.57\pm0.42, 0.0] \text{ mas y}^{-1}$$

The values for SM are obtained from the observations of the Hipparcos[12] satellite. Taking a R_0 of 8.5 Kpc:

$$SM = [-0.13\pm0.02, -0.17\pm0.01] \text{ mas y}^{-1}$$

So the secular parallax is:

$$SP = [-5.70\pm0.42, -0.17\pm0.01] \text{ mas y}^{-1}$$

Taking the observed VLA shift of Sgr A*, and removing the SP value, Baker and Sramek give a final motion value[14] of:

$$[-0.48\pm0.46, -0.48\pm0.17] \text{ mas y}^{-1}$$

Again, taking R_0= 8.5 kpc, this corresponds to a Sgr A* peculiar velocity[13] of

$$[-19\pm19, -19\pm7] \text{ Km s}^{-1}$$

Although Baker and Sramek don't rule out systematic errors in the observed measures and other deviations, they are confident that the low peculiar motion of Sgr A* is compatible with the idea of radiation coming from the atmosphere (accreting disk) of a 2.5 x 10^6 solar masses black hole.

And that's not all!

More recently, a research group led by Andreas Eckart and Reinhard Genzel from the Max-Plank-Institut, have studied movements of stars very close to Sgr A*, founding extremely fast stelar motions reaching and even exceeding 1,000 km s^{-1} for some of them. The best model fitting these data is the existence of a massive black hole of about one million solar masses.[14,15]. Ghez, Morris, and Becklin from UCLA also arrive at the same conclusions[16].

Continuing the works of Baker and Sramek, Mark Reid from the Harvard-Smithsonian Center for Astrophysics used the Very Long Baseline Array (VLBA)[17], basically a network of radiotelescopes spanning a distance larger than 4,000 miles, thus providing a higher resolution than the VLA. Along two years of studies, and using a similar technique like the one exposed in this essay for his predecessors, Reid concludes also that peculiar movement of Sgr A* is less than 20 km s^{-1}, ruling out the hypothesis of Sgr A* being a star or group of stars and reinforcing the hypothesis of a black hole residing at rest in the center of our Galaxy[15,18].

The actual research seems to point towards more and more precise measurements of proper movements of Sgr A* in the future. Not only by using radioastronomic observations, but more precise measures of giant stars in the very vicinity of the galactic centre using the Next Generation Space Telescope[19] and other parallax measures by the planned orbital telescopes such as NASA's SIM Space Interferometry Mission[20] will allow astronomers to determine R_0 with much higher precision, obtaining, as usually engineers say, a "good enough value". It seems we are not far in time from the goal.

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