Proper Motion of the Galactic Centre

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Since the start of the twentieth century, when Harlow Shapley [8] first demonstrated that the Earth may not be the centre of the Universe, astronomers have wondered what lies at the centre of our galaxy. At the time only visual observation was possible but, unfortunately, the amount of dust in the galactic plane thoroughly obscured the view in that direction. In the 1930's, Karl Jansky, while studying static for Bell Laboratories, discovered that radio interference in his receivers was coming from the direction of the galactic centre. Bell Labs was not interested in further study, but scientists saw a potential way of observing the galactic centre – radio astronomy was born.

As radio astronomy instrumentation improved, surveys of the tumultuous galactic central region became more detailed. In 1974 Balick and Brown [2] published their observations of a very compact radio source in the central region. The emissions were not easily explained by reference to other stellar objects, more closely resembling weak emissions observed in other galactic nuclei. The object, which attracted a lot of research interest, came to be known as Sagittarius A* (Sgr A*).

Perhaps the most important question to be asked about Sgr A* is; What is it? Varying theories have been put forward to explain the nature of this object ranging from accretion onto a super-massive black hole, an ensemble of neutron or white dwarf stars, or an exotic, low-mass stellar object emitting near its theoretical maxima. Measurement of stars in the vicinity of Sgr A* by Eckart and Genzel [4] and Ghez et al. [5] showed high velocities, up to approximately 1000 km/sec, consistent with orbits about a very massive object. The expected location for the massive object seemed to very close to Sgr A*, with a minimum of approximately 2.5 million solar masses concentrated there. While these results did rule out many theories about the region of Sgr A*, they did not concretely identify it as the massive object. Further research was needed to determine if the source of the Sgr A* emission was truly the massive object predicted, and whether it occupied the dynamic centre of the galaxy.

One way to determine if Sgr A* was the central massive object, or just something coincidentally on the same line of sight, is to determine its actual motion. If Sgr A* is just another stellar object orbiting the unknown mass then we should expect to see similar proper motions to those identified in the other stars. Slow proper motion would be consistent with a high minimum mass for Sgr A* and inconsistent with an orbiting body. Fast proper motion would put Sgr A* firmly in the orbiting object category and leave the mystery of the central mass.

Two substantial attempts to measure the proper motion have been undertaken. Between 1981 and 1997, Backer and Sramek [1] used the Very Large Array (VLA) radio-telescope to observe Sgr A* at two frequencies (4.9 and 8.4 GHz). In particular, they were measuring the relative positions of Sgr A* and three objects of extra-galactic nature with a close line of sight. In 1999 Reid, Readhead, Vermeulen, and Treuhaft [7] published results of a two year survey using the Very Long Baseline Array (VLBA) radio-telescope at 43 GHz. For consistency, the VLBA survey observed Sgr A* and two of the background objects used by Backer and Sramek; the third reference object was not visible at the new frequency. The VLA survey derived an annual angular motion in galactic longitude and latitude of -6.18 ± 0.19 and -0.65 ± 0.17 milli-arcseconds respectively, and the VLBA survey -5.90 ± 0.35 and $+0.20 \pm 0.30$.

Assuming the extra-galactic reference objects are essentially motionless, three motions contribute to the apparent motion of Sgr A*:

- apparent motion caused by Sun traveling around the galaxy,
- very small motion induced by the annual motion of the Earth around the Sun, and
- proper motion of Sgr A* with respect to the dynamic centre of the galaxy.

With current technology the apparent annual motion induced by the Earth's orbit is below our ability to resolve (approximately 0.125 milli-arcseconds) and smaller than typical error tolerances. So, trigonometric parallax for Sgr A* cannot currently be measured on the usual baseline.

Apparent motion in the plane of the galaxy is by far the largest observed component in both surveys. However, most of this motion is due to the orbit of the solar system[1] about the galaxy, and must be factored out of Sgr A*'s apparent motion. The residual apparent motion is small, with the VLA survey giving 19 ± 19 km/sec and the VLBA giving 0 ± 15 km/sec. Despite the differing ranges, there is significant overlap between the two analyses, and both are consistent with an object largely at rest with respect to the dynamic centre of the galaxy.

[1] The solar system's average motion about the galaxy has been measured relative to

For motion in galactic latitude, where there is only a small motion of the solar system to remove from the measurements, there is less agreement. The two surveys disagree on the direction of the apparent motion but agree roughly in the magnitude. The VLBA analysis leads to a proper motion of 15 ± 11 km/sec, while the VLA analysis gives VLA -19 ± 7 km/sec. Clearly, with error bounds as large as these, and disagreement of the direction, there is room for improvement in the measurements. Nevertheless, both figures are consistent with a near-stationary object.

The Sgr A* derived proper motion figures are small in comparison to those found for other stellar objects in the vicinity. From their measurements Backer and Sramek calculated that the minimum mass for Sgr A* of 20000 solar masses. The lower limit for Sgr A* mass derived by Reid et al. is 1000 solar masses. The mass density required to achieve these minimum masses within the limited bounds of the Sgr A* source is high. The minimum mass and density have eliminated some possible models for the nature of the Sgr A* source, which is more likely to be a singular black hole than an exotic ensemble of neutron stars or the like.

Both the VLA and VLBA measurements are affected by the distorting effects of the Earth's atmosphere, and by clouds of material in the line of sight that scatter, refract and diminish the signal en route from Sgr A*. The VLBA survey could use only part of the array, limiting resolution, because the full array resolved the scatter affected image of Sgr A* as an inconstant collection of separate objects. To some degree the effects of these distortions were minimised by cycling between the reference targets so that each observation cycle worked through a roughly identical atmosphere. For the Earth's atmosphere some effects were adequately countered by measuring the temporal disturbances of the atmosphere on a known source and and using the measurements to correct the received signals. Distortions occurring en route, that tend to smear the image of the various targets, were more difficult to deal with. Concrete location fixes were problematic, so the approaches taken to calculate the motion in both surveys suffered from relatively large error margins.

During 1999, Bower, Backer, and Sramek [3] revisited the reference sources to determine their nature. In doing so they confirmed that the object characteristics match those of active galactic nuclei. They concluded 0.1 milli-arcseconds per year of the measure Sgr A* motion could be attributed to proper motion in some components of the reference objects, which displayed frequency dependent asymmetry. Most interestingly though, their analysis of scattering of these sources was not entirely consistent with existing models. Scattering from the intense scattering region in the galac-

objects well outside our galaxy as approximately 220 km/sec. This, coupled with estimates of the distance to the galactic centre (8 kPc) allow us to calculate the apparent motion expected of a stationary object in the centre.

tic centre was not seen on any source probably because the sources lay just outside the boundaries of this region. The galactic scattering observed was stronger than current models predict, leading Bower et al. to suggest that the model needs refinement to better support future measurements.

Reid et al. suggest that future VLBA studies should be able to reduce the margin of error on Sgr A*'s proper motion to approximately 0.2 km/sec, at which point knowledge of the solar system motion becomes the limiting factor. To achieve this level of accuracy will require improvements in several areas:

- selection of observing frequencies to minimise the effects of scattering and refraction,
- configurations of the telescope arrays to extract the maximum usable data,
- modeling of the Earth's atmospheric effects at the wavelength being observed, and
- modeling of scattering in both the central core and general galactic plane so that positions may be be better constrained.

Effects of the Earth's atmosphere can be eliminated entirely by placing an array of antennas in space. However, such an option is very expensive and probably not justifiable until the limits of existing ground based facilities are reached. A less expensive possibility is combining existing ground-based telescopes with one or two placed in space to increase the baseline, hence resolution, of the instrument. In any case, a substantially better understanding of radio frequency scattering in the galaxy would be required to extract the most from such a system. Perhaps, with scattering better modeled, a space based interferometer could directly measure the annual trigonometric parallax of Sgr A* and give us a direct measure of our place in the galaxy.

The measurements of proper motion of Sgr A* by Backer and Sramek, and Reid et al. are important because they are steps toward a more thorough understanding of the structure of our galaxy's core region. The surveys have eliminated low mass theories of our galactic nucleus leaving a single black hole or unlikely ensemble of neutron/white dwarf stars. Armed with this knowledge astronomers will have a better basis from which to make the leap to interpretation of other galaxies.

References

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