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The Proper Motion of Sgr A*

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Abstract.
We have now been measuring the position of Sgr A*, the candidate supermassive black hole at the center of the Galaxy, with the VLBA for about 8 years. Sgr A* appears to move almost entirely along the Galactic Plane at a rate of 6.37 ± 0.02 mas yr^{-1}. For a distance to the Galactic Center of 8.0 ± 0.5 kpc, this translates to 241 ± 15 km s^{-1} , consistent with that expected for a stationary object observed from the Sun as it orbits the Galactic Center. The motion of Sgr A* out of the plane of the Galaxy, after removing the 7 km s^{-1} motion of the Sun in that direction, is less than about 2 km s^{-1} . Combining stellar orbital information (measured in the infrared) with the upper limit of 2 km s^{-1} for the intrinsic proper motion of Sgr A* (perpendicular to the Galactic plane), places a lower limit on the mass of Sgr A* of 2×10^6 M$_\odot$. Thus, most of the mass sensed by stellar orbits is tied to the compact radio source Sgr A*, whose size is less than 1 AU, yielding the strongest case ever for a SMBH. This also argues against "exotic" forms of mass, postulated to explain the extreme mass concentration at the Galactic Center.

1. Introduction

The proper motions, accelerations, and even orbits of stars about Sgr A* are now being determined to high accuracy in the infrared (Schödel et al. 2002; Schödel et al. 2003, Ghez et al. 2003). A total mass of about $3 - 4 \times 10^6$ M$_\odot$ is required within a radius of about 100 AU. If Sgr A* is indeed a super-massive black-hole (SMBH), than it should 1) lie at the center of the stellar cluster, and 2) be nearly stationary at the Galactic Center. Combining radio and infrared positions for stars near Sgr A*, the position of the central *gravitational* source (presumably Sgr A*) has been determined to 10 mas accuracy and found to coincide with the position of the compact radio source Sgr A* (Reid et al. 2003). This paper presents new results on the apparent motion of Sgr A*, measured against extragalactic sources, which show that Sgr A* is indeed stationary at the Galactic Center, within the uncertainty of the observations. We provide an upper limit to the motion of Sgr A* out of the plane of the Galaxy, which yields a highly significant lower limit to its mass.

2. VLBA Observations

The *apparent* proper motion of Sgr A*, with respect to extragalactic radio sources, was measured with the VLBA by Reid et al. (1999) and with the VLA by Backer & Sramek (1999). These papers concluded that Sgr A* is stationary at the Galactic center to within about 20 km s^{-1} .

In our VLBA program, Sgr A* was used as a phase reference to calibrate the interferometer phases for two compact radio sources (J1745-283 and J1748-291). In Figure 1 we plot the position residuals of Sgr A* relative to the compact extragalactic source J1745–283. (Results for J1748-291 are consistent with those for J1745–283 but of somewhat lower accuracy, since J1748-291 is much weaker than J1745–283.) The positions for 1995 through 1997 are from Reid et al. (1999), corrected by about 1 mas to account for a 0.1 arcsec offset in the absolute positions adopted at that time. The positions for 1998 through 2003 are new measurements. As one can see, the apparent motion of Sgr A* continues mostly along the Galactic plane.

The dominant term in the apparent motion of Sgr A* comes from the orbit of the Sun. This can be decomposed into a circular motion of the local standard of rest, $\Theta_0/R_0 \approx 220$ km s^{-1} /8.0 kpc (see Reid et al. 1999 for details), and the peculiar motion of the Sun, $V_\odot/R_0 \approx 20$ km s^{-1} /8.0 kpc. Removing these terms from the observed proper motion, yields estimates of the peculiar motion of Sgr A*.

While we currently do not know the component of $\Theta_0 + V_\odot$ in the plane of the Galaxy to better than about 10 to 20 km s^{-1} , independently of our observations, we do know the component *perpendicular* to the Galactic plane to better than 1 km s^{-1} . Since the circular motion of the LSR is, by definition, entirely in the plane of the Galaxy, the only contribution to the apparent motion of Sgr A* perpendicular to the plane of the Galaxy is the Z-component of the Sun's peculiar motions, $Vz_\odot$. This component can be estimated by averaging the motions of very large numbers of stars in the Solar neighborhood, which should directly indicate $-Vz_\odot$. An estimate, using the Hipparcos database, indicates $Vz_\odot = 7.16 \pm 0.38$ km s^{-1} toward the north Galactic pole (Dehnen & Binney 1998). After removing this contribution to the apparent motion of Sgr A* perpendicular to the plane of the Galaxy, we arrive at an upper limit of 2 km s^{-1} for this component of Sgr A*'s peculiar motion. This result significantly improves on the limits given by Reid et al. (1999) and Backer & Sramek (1999).

3. The Mass of Sgr A*

Measurements of the orbits of stars about Sgr A* from infrared data (Schödel et al. 2002, Ghez et al. 2003), require a mass of $\approx 3 - 4 \times 10^6$ M$_\odot$ contained within a radius of $\approx$ 100 AU. With this information, and an upper limit on the Z-component of the velocity of Sgr A*, V_z, one can estimate a lower limit to the mass of Sgr A*.

In the past, two limiting cases of mass estimators have been discussed for this problem: equipartition of kinetic energy (see Backer & Sramek 1999) and momentum (see Reid et al. 1999). It turns out that both estimators are correct, but for answering different questions. If one asks what is the expected velocity

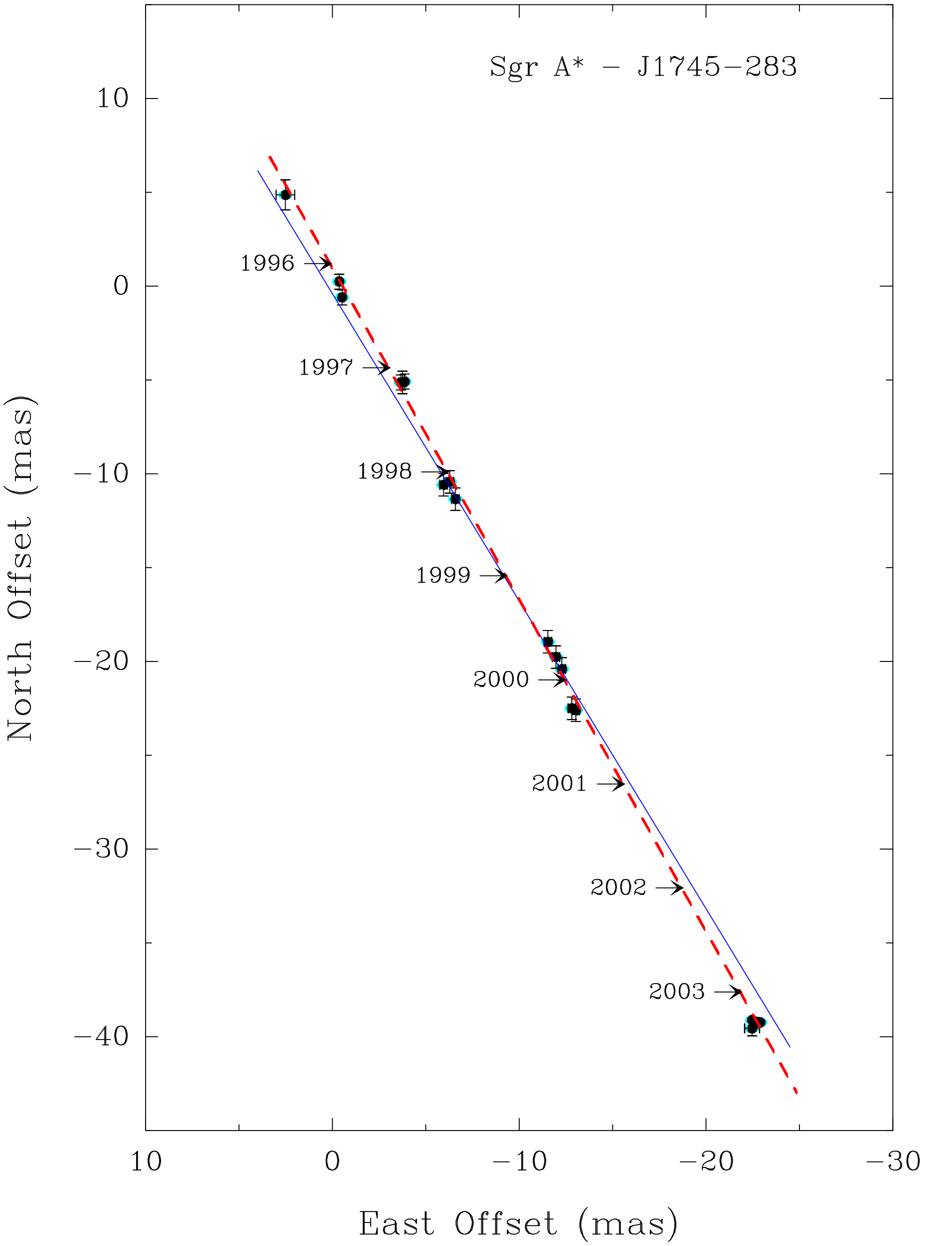

Figure 1. Apparent motion of Sgr A*on the plane of the sky. Position residuals of Sgr A* relative to J1745–283, with 1σ error bars, are plotted. Each measurement is indicated with an ellipse, approximating the apparent scatter broadened size of Sgr A* at 43 GHz. The dashed line is the variance-weighted best-fit proper motion, and the solid line gives the orientation of the Galactic plane. The expected position of Sgr A* at the beginning of each calendar year is indicated. Note that Sgr A* moves on a track that is slightly steeper than the Galactic Plane, as expected for the 7 km s^{-1} motion of the Sun toward the North Galactic Pole (Dehnen & Binney 1998).

of a SMBH that is perturbed by close passages of stars which orbit it, then a momentum relation applies. This is almost surely the case for Sgr A* and nearby stars such as S1 and S2. For star S2, which has a mass m of ≈ 15 M$_\odot$ (Ghez et al. 2003), during pericenter passage $v \approx 6500$ km s^{-1} and one expects a $3-4\times10^6$ M$_\odot$ SMBHs peculiar motion to be $V \sim 0.03$ km s^{-1}. Following this approach one can calculate an extremely conservative lower limit for Sgr A*'s mass. While this is valid, it is not an optimum estimate.

Alternatively, if one asks for the minimum mass of a central object which does *not* dominate the enclosed mass, M_R, within a given radius R, and which complies with the observed velocity limit, then we have a different case. For this case, equipartition of kinetic energy should apply. Conceptually, as the velocity limit for Sgr A* improves, the estimated mass limit increases quadratically in V. This continues until the estimated mass dominates over the stellar component and our assumption is violated. At this point, however, one has already ascribed most of the enclosed gravitational mass to Sgr A*.

A recent paper by Chatterjee, Hernquist & Loeb (2002) analyzes the mass estimation problem in a manner similar to that described above. The basic parameters of the problem are the total enclosed mass, M_R, including a possible SMBH and stars with typical individual mass, m, that are enclosed within a radius, R, and an upper limit on the Z-component of the velocity, V_z, of a "test" object (Sgr A* in our case) of mass M. They assume a black hole at the center of a stellar cluster, which is distributed in space according to a Plummer profile with a characteristic scale a. The mass estimator (from their equation 42) is as follows:

$$\frac{M}{M_R} = (1 + \frac{9}{2}\frac{V_z^2 a R^3}{Gm(R^2+a^2)^{3/2}})^{-1} \quad . \tag{1}$$

By the following simple analysis, one can see that this estimator approximates equipartition of kinetic energy when the black hole mass is significantly less than the total enclosed mass. The *minimum* black hole mass occurs for a approximately equal to the radius, R, within which the enclosed mass is measured. Setting $R = a$, Eq. (1) can be simplified to the following: $\frac{M}{M_R} \sim \frac{Gm}{V_z^2 R}$, provided $V_z^2 > Gm/R$ as expected for a "lower-mass" object. Defining a characteristic orbital velocity for a star, v, as $v^2 = GM_R/R$, yields $MV_z^2 \sim mv^2$.

Adopting $m = 1$ M$_\odot$and $R = a = 100$ AU, then Eq. (1) gives a lower limit to the mass of Sgr A*of $\approx 60\%$ of the total enclosed mass for our observed limit to the motion of Sgr A*of $V_z < 2$ km s^{-1} . For an enclosed mass of $3-4\times10^6$ M$_\odot$, this requires Sgr A* to account for more than about 2×10^6 M$_\odot$. Thus, we have reached a motion limit that suggests that most of the mass sensed gravitationally by stellar orbits must come from Sgr A* itself. Currently, we know that Sgr A* is $\lesssim 1$ AU in size, which is only $\lesssim 25$ R_{Sch}. Should future VLBI measurements at $\lesssim 1$ mm wavelength show that the intrinsic size of Sgr A* is $\lesssim 0.1$ AU, then we may be in a position to conclude that for Sgr A* most of the mass required for a SMBH is contained within a few R_{Sch}!

4. "Exotic" Dark Matter in the Galactic Center

While a SMBH has been the standard candidate to explain the high concentration of mass at the Galactic Center, other possibilities have been explored. For example, a ball of self-gravitating degenerate fermions have been proposed as a possible source for a supermassive dark object, other than a SMBH (e.g., Bilić, Tupper & Viollier 2003). Such a ball could provide the gravitational mass sensed by orbiting stars. One obvious difference between the SMBH and the fermion ball cases is that the gravitation potential of the SMBH increases down to the event horizon, whereas the potential of a fermion ball vanishes at its center. Until stars with pericenter distances that penetrate the interior of such a fermion ball are observed, stellar orbits will not discriminate between the SMBH and the fermion ball cases.

Now with most of the *gravitation* mass within 100 AU tied directly to the *radiative* source Sgr A*, there is little reason remaining to warrant consideration of "exotic" dark matter possibilities, unless these possibilities can also explain the emission of Sgr A* across the electromagnetic spectrum. This includes both quasi-steady state and flaring emissions now seen in the radio, IR, and x-ray bands. Bilić, Tupper & Viollier (2003) point out the possibility of x-ray line emission from neutrino decay; however we know of no mechanism to generate continuum emission consistent with that observed from Sgr A*. Thus, the association of the strong radiative source Sgr A* with most of the mass of the gravitational "dark" object at the Galactic Center would seem to rule out a fermion ball and, probably, other "exotic" forms of dark matter.

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