Horizon Scale Positioning of the SgrA* and M87 Black Holes

1. Scientific Motivation

1.1. SgrA*

A supermassive black hole embedded in a cluster of stars and stellar remnants is expected to execute Brownian motion similar to a massive dust particle which is kicked around by the much lighter air molecules (Chandrasekhar 1943; Taga & Iye 1998; Chatterjee et al. 2002; Merritt et al. 2007). The black hole dynamics is driven by a random fluctuating force, a dynamical friction force, and a mean restoring force from the background galactic potential (Chatterjee et al. 2002). On short timescales, T, the variance in the displacement of the black hole $\langle r_{\rm BH}^2\rangle$ can be simply related to the variance in its velocity, $\langle v_{\rm BH}^2\rangle$ (see equation 25 in Chatterjee et al. 2002),

$$\langle r_{\rm BH}^2\rangle = \frac{1}{2}T^2\langle v_{\rm BH}^2\rangle. \tag{1}$$

We use angular brackets to denote the ensemble average over many statistical realizations of the system. On long timescales, the velocity dispersion of the black hole is expected to reach equipartition with the kinetic energy of the surrounding stars (Chandrasekhar 1943; Chatterjee et al. 2002; Merritt et al. 2007),

$$\frac{1}{2}M_{\rm BH}\langle v_{\rm BH}^2\rangle = \frac{3}{2}m_\star\sigma_\star^2, \tag{2}$$

where $\sigma_\star$ is the 1D velocity dispersion of the stars near the radius of influence of the black hole, $M_{\rm BH}$ is the black hole mass and $m_\star$ is the mass of a star. For SgrA*, we adopt $M_{\rm BH} = 4\times10^6 M_\odot$ (Ghez et al. 2008), $m_\star \sim 1M_\odot$, and $\sigma_\star \sim 150$ km s^{-1}, yielding (Reid & Brunthaler 2004; Merritt et al. 2007) $\langle v_{\rm BH}^2\rangle^{1/2} \approx 0.13$ km s^{-1}. Substituting this value in equation (1) gives,

$$\langle r_{\rm BH}^2\rangle^{1/2} \approx R_{\rm Sch}\left(\frac{T}{4\ {\rm yr}}\right), \tag{3}$$

where $R_{\rm Sch} \equiv (2GM_{\rm BH}/c^2) = 1.2\times10^{12}$ cm is the Schwarzschild radius of SgrA*.

We therefore find that SgrA* wanders a distance of order its Schwarzschild radius on a timescale of years. Observationally, this wandering would be detectable only if it deviates from a constant velocity motion – which cannot be disentangled on these short timescales from the uniform motion of the Sun (or the local standard of rest) relative to the Galactic center. The main random deviations from a uniform motion would be associated with perturbers that have dynamical timescale of years. Since the dynamical time is given by,

$$t_{\rm dyn} = \left(\frac{r^3}{GM_{\rm BH}}\right)^{1/2} = 1.4\ {\rm yr}\ r_{16}^{3/2}, \tag{4}$$

such perturbers have orbital radii $r_{16} \equiv (r/10^{16}\ {\rm cm}) \lesssim 1$.

The dominant perturbers at these close-in radii are expected to be a cluster of stellar-mass black holes which segregated to the inner parsec through dynamical friction over the lifetime of the Galaxy (Miralda-Escudé & Gould 2000). The expected number of black holes as a function of radius is, $N \sim 10^2 r_{16}$ (O'Leary et al. 2009; Alexander & Hopman 2009). Poisson fluctuations in their distribution would produce a random surplus of $\sim \sqrt{N}$ of black holes in one hemisphere which varies on a dynamical time. This transient surplus would result in a net acceleration of the black hole,

$$\langle g_{\rm BH}^2 \rangle^{1/2} \sim \sqrt{N} \frac{G m_\bullet}{r^2}, \tag{5}$$

and induce position wandering of SgrA* which fluctuates randomly on the dynamical timescale. Substituting $m_\bullet \sim 10 M_\odot$ for the characteristic mass of the black hole perturbers and relating the number of perturbers to their dynamical time $t_{\rm dyn}$, yields a fluctuating acceleration,

$$\langle g_{\rm BH}^2 \rangle^{1/2} \sim 0.6 \frac{R_{\rm Sch}}{(4\ {\rm yr})^2} \left[\frac{t_{\rm dyn}}{4\ {\rm yr}} \right]^{-1}, \tag{6}$$

with a velocity fluctuation amplitude, $\langle v_{\rm BH}^2 \rangle^{1/2} \sim \langle g_{\rm BH}^2 \rangle^{1/2} t_{\rm dyn} \sim 0.06\ {\rm km\ s}^{-1}$, that is independent of timescale. Interestingly, the velocity and displacement fluctuations produced by the close-in black holes on timescales of years are of comparable amplitude to those expected from equipartition with the background distant stars. We conclude that gitter in the position of SgrA* at the level of its Schwarzschild radius on timescale of years can be used to test for the existence of stellar mass black holes in its immediate vicinity.

1.2. M87

A fundamental question in the theoretical modelling of jets is whether they are powered by the inner accretion disk or the black hole spin. Localizing the black hole in M87 would reveal where the base of its large scale jet is and shed light on this question. Moreover, it would allow to predict where the fainter counter-jet should be localized and make it easier to find it in future data sets. Because of the much larger black hole mass $M_{\rm BH} \sim 6.4(\pm 0.5) \times 10^9 M_\odot$ (Gebhardt & Thomas 2009) and its larger distance, angular position wandering on the timescle of years should be negligible for M87.

*Show a theoretical image, marking the jet, counter-jet, and black hole position.

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