*Dynamics of Star Clusters and the Milky Way*
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# Dynamics of the Sgr A$^*$ Cluster

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**Abstract.** We model the dynamics of the star cluster around Sgr A$^*$ using a spherical potential and an arbitrary two-integral distribution function in order to fully include the uncertainties created by orbital anisotropy. Given spatial and kinematical data for the stars, we find the best-fit parameters of the mass distribution, assuming a point mass embedded in a singular isothermal sphere. We also determine the distance to the Galactic center using statistical parallax.

## 1. Introduction

A variety of techniques have now been used to provide observational support for the presence of supermassive black holes in galaxy centers, with one of the best cases made for the center of our own Galaxy. Building on a long history of observations of stellar motions, Genzel et al. (1997) and Ghez et al. (1998) have now provided evidence that the region of the radio source Sgr A$^*$ has a mass density of $\sim 10^{12} M_\odot$ pc$^{-3}$ inside a radius of $\sim$ 0.01 pc — too high to plausibly be anything other than a black hole or a dense cluster of exotic particles. Additionally, the advection-dominated accretion models of Narayan et al. (1998) indicate the presence of an event horizon, and thus a black hole.

Although the presence of this black hole seems clear, its exact mass $M_{\rm BH}$ is not, since the past analyses have used simplified dynamical models (e.g., assuming an isotropic stellar velocity distribution). We will use more general anisotropic dynamical models to infer $M_{\rm BH}$. We will also use the combined line-of-sight and proper motions of the stars to make a statistical parallax measurement of $R_0$, the absolute distance to the Galactic center.

## 2. Data and Methods

We use the line-of-sight velocity measurements for 327 stars from Rieke & Rieke (1988), Lindqvist et al. (1992), and Genzel et al. (1996), with projected radii of $1'' < R < 1000''$ ($25'' \sim 1$ pc). The proper motions of 91 stars come from Genzel et al. (1997) and Ghez et al. (1998), with $0\overset{''}{.}1 < R < 23''$. We take surface density constraints from Genzel et al. (1996), with $0'' < R < 1000''$.

We assume a spherical mass distribution consisting of a point mass and a singular isothermal sphere, corresponding to the black hole embedded in the stellar cluster. Although the giant stars' density flattens out at $\sim 4''$ (Genzel et al. 1996; Alexander 1999), we assume this is an effect specific to this population, with the dwarf stars' density (which dominates the mass) continuing unbroken into the center. This accords with simulations of a cluster in the presence of a point mass, which indicate that the cluster becomes symmetrized, with an $r^{-2}$ cusp (Quinlan et al. 1995; Sigurdsson et al. 1995; Merritt & Quinlan 1998).

We set up a two-integral distribution function $f(E, L^2)$, sampled at discrete intervals in energy and angular momentum; there are a total of 861 "orbits". We compute the contribution of each orbit to each observable. We then fit the data by adjusting the weights of the DF so as to maximize the likelihood.

## 3. Results

We fit the data with a grid of models over the parameters $(R_0, M_{\rm BH}, v_0)$, for both isotropic and anisotropic DFs (see Figure 1). Not surprisingly, the best-fit $M_{\rm BH}$ increases strongly with $R_0$. However, the statistical parallax constraints are effective at constraining $R_0$, and thereby at ruling out some values for $M_{\rm BH}$.

An anisotropic distribution function fits the data better at 3 $\sigma$ than an isotropic DF. With this, we find $R_0 = 7.5^{+1.2}_{-1.1}$ kpc, $M_{\rm BH} = 1.0^{+1.4}_{-0.4} \times 10^6 M_\odot$, and $v_0 = 120^{+23}_{-3}$ km s$^{-1}$ (corresponding to $1.0 \times 10^6 M_\odot$ in stars within $r = 4\farcs2$).

The value for $R_0$ is consistent with the consensus value of $8.0 \pm 0.5$ kpc (Reid 1993). However, $M_{\rm BH}$ is significantly lower than the masses inferred by Genzel et al. (1997) and Ghez et al. (1998) using isotropic mass estimators, and by Genzel et al. (2000) using restricted anisotropic models [cf. $1.8^{+0.3}_{-0.7} \times 10^6 M_\odot$ vs. $(2.61 \pm 0.35) \times 10^6 M_\odot$, $(2.6 \pm 0.2) \times 10^6 M_\odot$, and $(3.25 \pm 1.2) \times 10^6 M_\odot$, respectively, for $R_0$= 8.0 kpc]. We also examine the anisotropy of the solutions, finding a suggestive trend toward tangential anisotropy over most radii.

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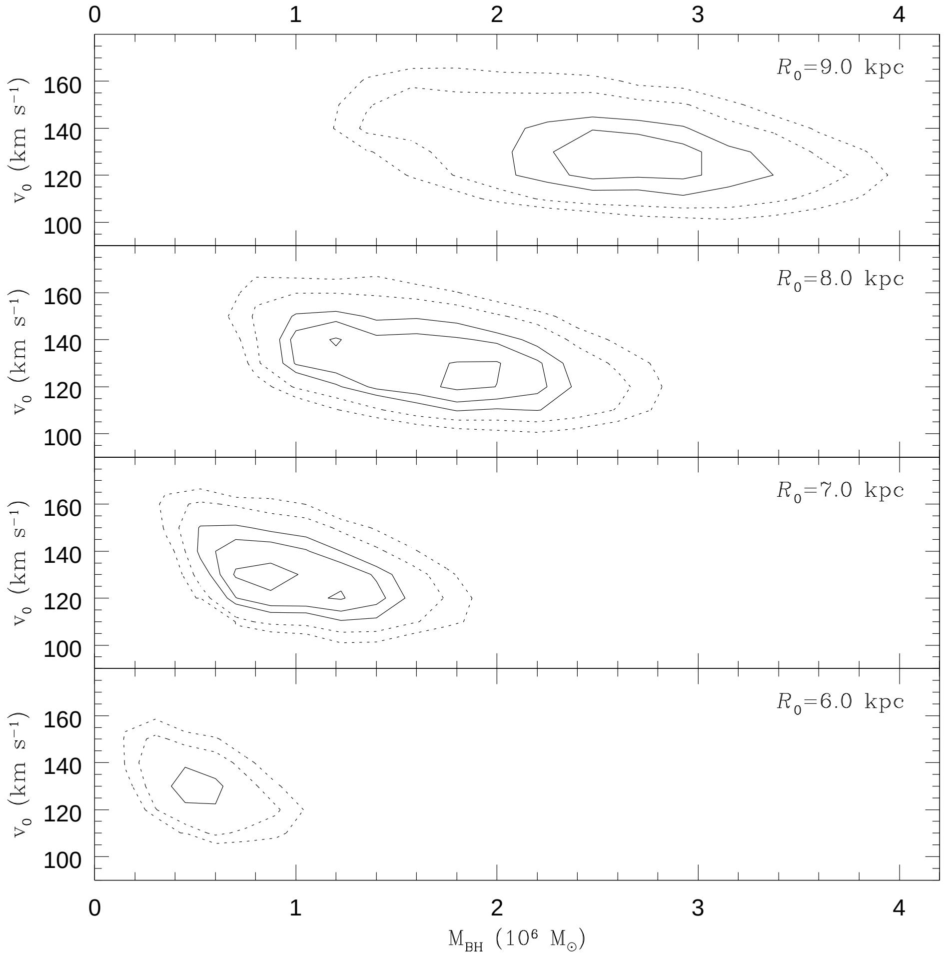


Figure 1. Maximum likelihood contours as a function of black hole mass and stellar cluster circular velocity, for several different Galactocentric distances $R_0$, and an anisotropic distribution function. The contours show one-parameter confidence limits at 68%, 90%, 95%, 99%, and 99.7% significance.