■ Scientific Justification

The discovery of a correlation between the mass of supermassive black holes (SMBH) and their host galaxy bulge velocity dispersion ($M_{BH} - \sigma$) has led to the conclusion that the formation of the two components are linked, though the nature of this connection is still debated (Ferrarese & Merritt, 2000; Gebhardt et al., 2000; Gültekin et al., 2009). As the search for SMBHs moved toward less luminous galaxies, a number of very compact massive nuclear star clusters (NSC), with half-light radii less than 2-4 pc, were found at the center of fainter galaxies without an SMBH (e.g. Carollo et al., 1998; Matthews et al., 1999; Böker et al., 2002, 2004). Intriguingly, these NSCs show a similar correlation between total cluster mass and host galaxy bulge velocity dispersion. In an attempt to unify observations of all nuclei, a theory has been proposed that galaxy formation in general results in a 'central massive object' (CMO) (Ferrarese et al., 2006; Wehner & Harris, 2006); high mass galaxies form SMBHs, while low mass galaxies form nuclear star clusters. However, it has been difficult for this theory to reconcile why a number of galaxies, including our own, are now known to contain both components. Detailed observations of the properties of nuclear star clusters, especially constraints on their formation mechanisms, are necessary to make progress. However, these types of observations are difficult in external galaxies, being only marginally resolved even with ACS at the distance to the Virgo cluster.

Given its vicinity, the NSC at the center of the Galaxy has the potential to provide us with the ideal example of a NSC with a SMBH to study the relationship between the two components and how they couple to the rest of the Galaxy. Unfortunately, fundamental properties such as the total mass, structure, and rotation curve of the cluster are still highly uncertain due to limitations from ground based observations. *We propose to derive the physical properties of the MW NSC from proper motion measurements of the NSC using WFC3 over a time baseline of 2 years; these observations will provide the first precise kinematic information on individual stars at high angular resolution from the center out to beyond the half-light radius of the NSC.*

The Milky Way as a window to understanding nuclear star clusters

In the last decade, research on the center of the Galaxy has proven it to be an ideal laboratory for testing theories of supermassive black holes and their local environments. High angular resolution monitoring of stellar orbits have conclusively established the existence of an SMBH of $\sim 4.0 \times 10^6$ $M_\odot$ at the Galactic center (Ghez et al., 2008; Gillessen et al., 2009). Located at a distance of only 8 kpc, the radius of the sphere of influence of the Galactic center black hole (~ 1 pc) has an angular scale of $\sim 25''$ in the plane of the sky, two orders of magnitude larger than that of any other SMBH. It has also become increasingly clear that the NSC at the Galactic center shares many of the properties seen in other galaxies (e.g. Schödel et al., 2007; Graham & Spitler, 2009); recent observations have shown that the cluster has a multiple-age stellar population (e.g. Maness et al., 2007; Paumard et al., 2006; Do et al., 2009), a mass that may be comparable to that of the SMBH at 1 pc from the center (Schödel et al., 2009), and there are some tentative evidence that the star cluster as a whole is rotating in the same direction as the disk of the Galaxy (Schödel et al., 2009; Trippe et al., 2008). These properties make the Galactic center NSC an ideal representative of not only NSCs in general, but will help us understand the co-existence of a NSC and SMBH in the same galactic nucleus.

In order to compare our NSC to external galaxies, its total mass, structure, and rotation must be well measured. Measurement of its mass is necessary to place it on the $M_{CMO} - \sigma$ and $M_{CMO} - M_{bulge}$ relationships. For example, Schoedel (2010) found that adding an estimated NSC mass of $\sim 10^7$ $M_\odot$ to the mass of the black hole places the Milk Way much more consistently on the $M_{BH} - M_{bulge}$ relationship than with the mass of the black hole alone. Measurement of its rotational signature will help us distinguish between the two major theories for NSC formation: 1) globular clusters sink into the center through dynamical friction and merge over time to form a compact stellar system (e.g. Capuzzo-Dolcetta & Miocchi, 2008; Lotz et al., 2001); 2) build up of molecular gas over time leads to episodic star formation events at the center of the galaxy (e.g. Morris, 1993; Milosavljević, 2004; Seth et al., 2006). The merger of globular clusters will result in an isotropic velocity distribution since they originate from random directions. In contrast, infalling gas clouds will likely come from the disk of the galaxy resulting in star clusters formed with a preferential angular momentum direction.

Limits to current measurements

Fundamental properties of the MW NSC such as its mass and rotation curve are still highly uncertain. The lack of knowledge about the NSC stems from the fact high precision velocity measurements with high angular resolution over a wide field are necessary to derive these parameters reliably. High precision astrometry and high spatial resolution imaging of the NSC have been achieved in the past decade from adaptive optics observations from the ground, but these measurements have been limited to the very center of the cluster (the inner $20''$ or 1 pc). This has severely limited our ability to determine the total mass of the cluster as the black hole dominates the potential in the inner ~ 1 pc of the cluster, with the current best estimate of a mass $> 0.5 \times 10^6$ $M_\odot$ (Schödel et al., 2009). Due to deprojection effects from measuring stars only in the inner region of the cluster, Schödel et al. (2009) was unable to place any strong constraints on the mass density distribution, which would be necessary to measure a total cluster mass.

Uncertainties in the rotation curve of the NSC comes from incomplete azimuthal coverage of the cluster beyond $\sim 20''$ (0.7 pc) from the center as well as systematic biases that come from combining different data sets. The most recent attempt at measuring the rotation curve of the NSC comes from Trippe et al. (2008), which concluded that the NSC is rotating in the Galactic plane (Figure 1). Their conclusions comes from combining AO spectroscopy of the inner region of the cluster with integrated light spectroscopy from McGinn et al. (1989) that samples predominantly in the plane of the Galaxy (see Figure 2 for the locations of these fields). In addition, Trippe et al. (2008) left out several points from the McGinn et al. (1989) study when they combined the two datasets (as pointed out by Schödel et al. (2009), see Figure 1). With the inclusion of these points, the significance of a continuous rotation curve for the entire cluster is decreased. In order to truly characterize the NSC, wide-field kinematic measurements such as those proposed here are necessary to address these types of biases.

Without wide-field measurements, even the physical size of the NSC is highly uncertain. Estimates range from 3-5 pc for the half-light radius of the cluster based on surface brightness profiles from Spitzer and SIRIUS/IRSF (Graham & Spitler, 2009; Schoedel, 2010). Major uncertainties in using surface brightness profiles stem from variable extinction and the fact that the majority of the light from the NSC may be from a few massive stars. With just the first cycle of our proposed multi-cycle program, we can measure the true size of the cluster using number counts corrected for extinction using medium-band filters on WFC3.

Proposed proper motion observations with WFC3

We propose to characterize the mass, structure, and ration the MW NSC to place constraints on its formation by measuring the proper motion of stars out to 7.2 pc, 10 times further than any comparable study to date. To do so requires high resolution, wide-field imaging in the near-IR, which WFC3 on HST is now well poised to fulfill. The density of stars beyond about 1 pc ($\sim 20''$) from the Galactic center (the region poorly probed in the past) is still too high to be well resolved with typical seeing limited observations and the region is too large for the narrow field of view of AO imagers to survey efficiently. With observations over 3 cycles, a time baseline of two years, proper motion measurements with WFC3 will be able to determine the kinematic structure of the cluster with a predicted precision better than 1 mas/yr (Bellini & Bedin, 2009), or $\sim$ 35 km/s, for stars as faint as H = 19 mag with full azimuthal coverage out to $\sim$ 7 pc ($3'$) from the black hole (see Figure 2). The error in the velocity dispersion measurement will be considerably better as it scales with the number of stars, N, as $1/\sqrt{2(N-1)}$. For comparison, the stars in this region have a velocity dispersion predicted to be about 100 km/s (Schödel et al., 2007). We expect to be complete to below red clump stars at $H \sim 16.5$ where most of the stars are expected to be from luminosity function in this region. These wide-field measurements are necessary to determine the true extent of the cluster as well as the magnitude and orientation of the rotation. We also propose to carry out narrow-band imaging with WFC3 during the first cycle to correct for the highly variable extinction in this region. This measurement of the extinction is crucial to determine the number counts and to gauge the completeness of the sample.

Why astrometry is necessary?

Mass measurements from stellar velocity dispersions are highly dependent on the velocity anisotropy in the system. Without a measurement of the anisotropy, the mass measurement would not be unique (e.g. Leonard & Merritt, 1989). Since the velocity dispersion in the plane of the sky can be decomposed into a radial component and a tangential component, the cluster anisotropy can be measured directly. Radial velocities on the other hand can only provide one dimension of the velocity dispersion, resulting in a measurement of the anisotropy that is highly model dependent.

The additional advantage of proper motions is the sheer number of stars that will be measured simultaneously with WFC3. Given the radial number density profile of the nuclear star cluster, we predict that we would be able to measure proper motions for about 300,000 stars in our field. Monte Carlo simulations of this astrometric experiment with realistic cluster parameters and our expected measurement uncertainties (35 km/s) shows that the mass of the nuclear star cluster can be measured over a factor of X more precisely with these wider field measurements (See Figure 3). Ultimately, the limits to the measurement of the mass will come from the contamination in to the field by bulge stars in the field. Using proper motion measurements of the nearby Arches and Quintuplet clusters, we find that the field contamination is about 0.35 stars per square arcsecond. Our simulations show that for a similar field contamination at the Galactic center, the field population will begin to dominate the velocity dispersion measurements beyond the edge of our proposed field at$\sim 200''$ from the black hole.

Additional scientific possibilities

While the most important goals of this proposal is to measure mass and rotation of the MW NSC, a number of other scientific studies could be carried out with this dataset. Because of the large number of stars surveyed, this project would likely find XX hypervelocity stars; these stars have velocities greater than the escape speed of the Galaxy and are thought to be former members of tight binaries that were disrupted by the Galactic black hole. Finding a hypervelocity star will validate this scenario and place strong constraints on their ejection rates. Additionally, the color information provided by the first cycle proposed for this dataset will enable a determination of the stellar population of the NSC and possibly the star formation history through population synthesis modeling of the luminosity function.

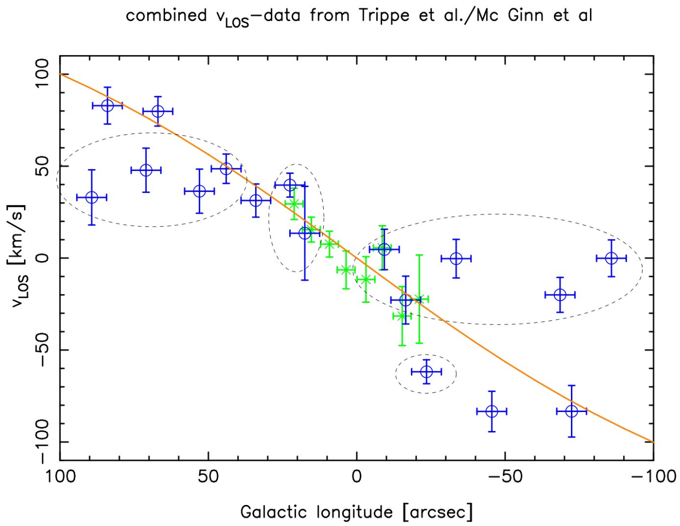

Figure 1: Rotation curve of the NSC with data from Trippe et al. (2008) (green) and McGinn et al. (1989) (blue) (figure from Schödel et al. (2009)). The best fit rotation curve is from Trippe et al. (2008), which excludes the McGinn et al. (1989) points circled in the dashed lines. As pointed out by Schödel et al. (2009), the exclusion of these points strongly affected the interpretation of the rotation of the NSC.

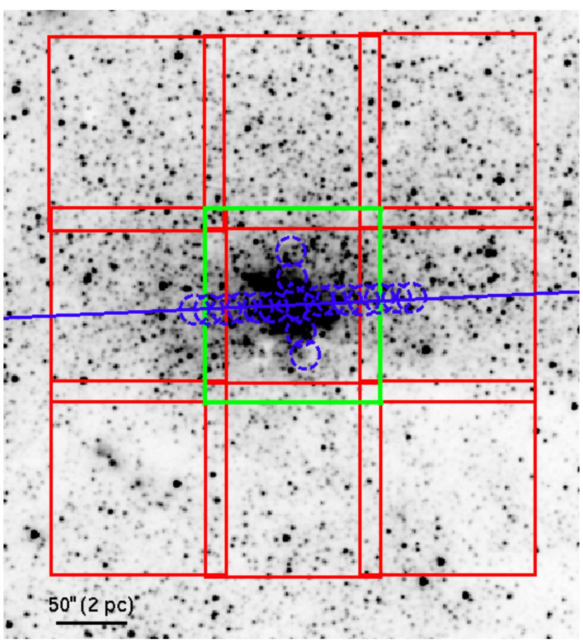

Figure 2: Proposed WFC3 fields covering out to $\sim 3'$ (7.2 pc) from the Galactic center on a Spitzer 4.5 μm image (red). The solid blue line shows the orientation of the Galactic plane. Previously observed fields are labeled with dashed blue lines. The central dashed box indicates the region with previous integral-field spectroscopic and proper motion observations (Trippe et al., 2008; Schödel et al., 2009), while the dashed circles are the locations of integrated light spectroscopy with $20''$ apertures (McGinn et al., 1989). The proposed observations will be the highest angular resolution study of the kinematics and stellar population of the Milky Way NSC. The green box indicates the location of our previously approved program. The red boxes are the newly proposed fields. These fields are necessary to constrain the physical properties of the cluster as they extend beyond the half-light radius of the cluster (~ 3 pc).

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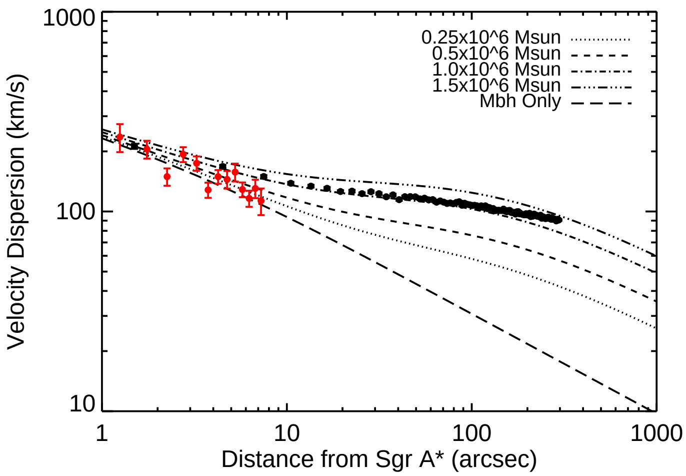

Figure 3: Predicted WFC3 measurements of the velocity dispersion profile from MC simulations, which includes expected measurement error and foreground contamination (black points). These measurements will be able to much better distinguish between different mass models for the cluster (dashed lines) than with the current AO proper motion measurements from Keck (red points).

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■ Description of the Observations

■ Special Requirements

■ Coordinated Observations

■ Justify Duplications

■ Past HST Usage and Current Commitments