The Galactic Center: A Window to the Environment of Disk Galaxies

ASP Conference Series, Vol. 439, © 2011
Mark Morris, Daniel Q. Wang, and Feng Yuan, eds.

The Formation of Stellar Cusps in Galactic Nuclei

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Abstract. The dynamics of galactic nuclei can be affected by several mechanisms. Among these are stellar evolution, stellar collisions, mass segregation, and tidal disruptions of stars due to the central black hole. In this presentation I will address how each of these affects the stellar cusp and the resulting observational signatures. Using a set of dynamically evolving Fokker-Planck simulations I present the dynamical evolution a nuclear stellar cluster and the growth of the central massive black hole within the Galactic Nucleus. In addition to the Galactic Center I explore a wide variety of galactic nuclei and their resulting stellar cusps.

1 Introduction

Simulations by Hénon (1961) were among the first to suggest that dense stellar systems may generate central stellar cusps, that is a surface-brightness or stellar density that rises as a power-law into the cluster center. One of the first hints of stellar cusps in dense stellar systems was observed by King (1966). His observations indicated central brightness excesses in the most concentrated globular clusters. Wyller (1970) and Wolfe & Burbidge (1970) suggested that such excesses could be due to a central massive black hole of several thousand solar masses that may have formed via a collapse of the cluster core, what are currently considered intermediate mass black holes. Shortly thereafter this central black hole view was strengthened by the detection of X-ray sources in globular clusters (Giacconi et al. 1974). Bachall & Ostriker (1975) proposed that the source of these X-rays were accreting massive black holes. This view changed in 1980’s with more precise positions of X-ray sources measured with the Einstein X-Ray Observatory (Grindlay et al. 1984). These positions indicated that the sources were only 1.5 $M_{\odot}$ and ruled out massive black holes as their origin because of their distances from the cluster centers. Today we know that roughly one fifth of globular clusters show brightness excesses (Djorgovski & King 1986). Though there is some indication that intermediate mass black holes could perhaps exist in some globular clusters and galactic nuclei, it is now generally thought that most of these cusps in clusters are due to a collapsed stellar distribution of neutron stars, white dwarfs, and main sequence stars mimicking the presence of a massive black hole (Baumgardt et al. 2003).

Though most globular clusters are not thought to harbor massive black holes, they have provided us with a laboratory to test stellar dynamics and our knowledge of the formation of stellar cusps in dense stellar systems. Also the same computational methods applied to globular clusters can easily be adapted
to their larger mass cousins, galactic nuclei. Young et al. (1978) found such a cusp in the galaxy M87. This was followed by yet more observations of not only our Galaxy but other galaxies showing stellar cusps at their centers.

2 Cusp Formation

2.1 Stellar Systems Without Central Black Holes

One of the focal points in the dynamical evolution of globular clusters has been the phenomenon of core collapse. Core collapse is a result of energy slowly being transferred via star-star scatterings from the core of a cluster to its halo, causing the core to contract and the halo to expand (Lightman & Shapiro 1978). In time this contraction accelerates so that within a finite time the core will collapse. In the idealized identical star scenario this would take roughly 15 half-mass relaxation times. Simulations of the core collapse of globular clusters show that a cusp replaces the initially flat core. This stellar density cusp has the form of $\rho \propto r^{-\beta}$ where $\beta$ has the value 2.2 for a system that is composed of stars of a single mass (Cohn 1980). This slope can vary significantly though if stars are of differing masses. Due to equipartition of energy more massive objects will have lower velocities, fall inward, and in time dominate the inner regions of the cluster (Inagaki & Saslaw 1985). Because of this disparity in mass the observed power-law can differ significantly from the actual mass distribution within the cluster (Murphy & Cohn 1988 and Grabhorn et al. 1992). In this multi-mass case the slope of the power-law density profile is given by

$$\beta \simeq 1.9 \frac{m_{rg}}{m_{rem}} + 0.3$$  \hspace{1cm} (1)

where $m_{rg}$ is the mass of the red giants and $m_{rem}$ is the mass of the dominant remnants.

Because neutron stars of 1.4 $M_\odot$ and white dwarfs over 1 $M_\odot$ are likely to be the most massive objects in globular clusters they will dominate the inner regions of the cluster. On the other hand the observed red giants will be the most luminous stars and have a mass close to 0.8 $M_\odot$. This mass difference leads to a $\beta$ near 7/4 which, as will be discussed later, is strikingly similar to the power-law cusp found near a black hole. Figure 1 shows an example of such a cluster without central massive black hole. The power-law slope of the red giant cusp flattens moving inward due to massive white dwarfs and neutron stars dominating the innermost part of the cluster. For reference a -7/4 slope is indicated in Figure 1. Roughly 20% of globular clusters appear to have undergone core collapse (Djorgovski & King 1986) and the most of these have power-law slopes in projection close to -3/4. The velocity-profile will also be quite shallow in projection, $v \propto r^{-0.2}$. It is important to note that the presence of a stellar cusp need not be caused by a massive black hole but can also be caused by mass segregation. To distinguish between the two possibilities other parameters such as the velocity profile must be observed. The velocity profile in a Keplerian potential takes the form of $v \propto r^{-0.5}$. 
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2.2 Stellar Systems With Central Black Holes

In dense stellar systems with central massive black holes, the nature of the resulting cusp will differ from that of globular clusters. If it is assumed that the massive black hole dominates the central potential of the cluster then it will be Keplerian in nature. Driven by the hypothesis that globular clusters harbored massive black holes one of the first attempts to determine the nature of cusps in Keplerian potentials was Peebles (1972). He found, using a semi-quantitative approach, that the signature of a central black hole should be an observable cusp with a power-law form of $\rho \propto r^{-9/4}$. Later Bachall & Wolf (1976) derived detailed expressions for diffusion coefficients and numerically solved the Boltzmann equation to find that the cusp should have the form $\rho \propto r^{-7/4}$. Bachall & Wolf (1977) extended this to stellar systems containing stars of two different masses. In their models they found that the power-law slope of the less massive component will be flatter than the massive component. The resulting relation for the slope of the stellar density cusp was given by

$$\beta = -\frac{d \ln \rho_i}{d \ln r} = -\left(\frac{m_i}{4m_1} + \frac{3}{2}\right)$$  \hspace{1cm} (2)
From this relation there is a range of power-law slopes, -3/2 to -7/4 depending on the mass of stars dominating the stellar density profile. This behavior is easily seen in the model shown in Figure 2. This model has a mass similar to that of the Galactic Nucleus but has a relatively flat stellar mass function. This mass function produces a sizable number of stellar-mass black holes which by a Hubble time dominate the inner 2 parsecs of the nucleus. As would be expected from equation 2 the black holes have a slope of -7/4 whereas the lower-mass stars progressively approach the -3/2 limit.

At the other extreme of a steep stellar mass function Alexandar & Hopman (2009) have shown that when stellar-mass black holes do not dominate the density profile their profile can be much steeper. In this case which they refer to as “strong segregation” the low-mass main sequence stars will dominate the stellar density profile and have a-7/4 slope, causing the more massive stellar mass black holes to have a power-law profile much steeper than -7/4. In this case the much less dominant but much more massive stellar-mass black holes have a slope of -11/4. An example of such a steep mass function is shown in Figure 3. Note that where the stellar-mass black holes do not dominate they show this -11/4 slope. But in the inner most regions, 10^{-3} pc and inward, they dominate the density profile and revert back to the Bachall & Wolf -7/4 slope.
2.3 The Effect of Stellar Collisions on the Cusp

Stellar collisions can alter a cusp by removing stars from it. Typically collisions remove stars from the high density, high velocity regions of a nuclear cluster. Therefore collisions have the largest effect in the innermost regions of the nucleus. Even though few stars bound to the central black hole will remain in the most massive nuclei, stars from larger radii, on high eccentricity orbits will still populate the inner region of the nucleus. In this scenario, collision dominated regions of the cusp will have a much shallower profile, typically showing a power-law slope of -1/2. In projection this slope would appear nearly flat.

3 Realistic Models of Galactic Nuclei

3.1 The Galactic Nucleus

The stellar system in the Galactic Nucleus is most likely dynamically relaxed and nearly spherically symmetric. Using these assumptions it is possible to model the mass distribution of differing mass groups such as stellar-mass black holes, evolved giant stars, and main sequence stars. For this model, and the models shown in the previous section I have used Fokker-Planck simulations similar to
those presented in Murphy, Cohn, & Durisen (1991). Those models presented a set of generic nuclei with varying mass function slopes and nucleus masses. The primary focus of the Murphy et al. models was active galactic nuclei and quasars. Here I present a realistic model of the Galactic Center. A Kroupa (2001) mass function is used with initial stellar masses ranging from 0.1 to 40 $M_\odot$. The stellar system starts with a seed central black hole of 700 $M_\odot$ and is allowed to dynamically evolve. The stars are also allowed to evolve using the prescription of Hurley, Pols, & Tout (2000). The central seed black hole is fed mass from the surrounding stellar population due to tidal disruptions of stars, stellar collisions, and stellar evolution. All mass loss due to stellar collisions and tidal disruptions is fed to the central black hole due to the proximity of these events to the black hole. A preset fraction of mass loss due to stellar evolution is allowed to be fed to the central black hole and the remainder is assumed to be ejected from the nucleus. This preset fraction is a model parameter that can be varied from 0 to 1.

In Figure 4 a model for the Galactic Nucleus at a Hubble time is shown. By this time the central black hole has reached a mass of $4.4 \times 10^6 M_\odot$. Most of this growth was fueled by mass loss from evolving stars, with less than 20% being due to tidal disruptions of stars, and nearly nothing from collisions. As would be expected mass segregation has caused stellar-mass black holes to dominate the

![Figure 4. Stellar density profiles of a simulation of the Galactic Center.](image-url)
stellar density distribution. These black holes have a power-law density slope of -7/4 while less massive stars have progressively smaller slopes that approach -3/2 (Bachall & Wolf 1977; Murphy et al. 1991; and Freitag, Amaro-Seoane, & Kalogera 2006). Even though the central massive black hole dominates the gravitational potential of the inner few parsecs the extended distribution of stellar-mass black holes will play a significant role in the dynamics of the observed giant stars. Their presence could be found via retrograde precession of observed stars. It may also be possible to observe scattering events due to this unseen population of massive remnants. Inside of $10^{-3}$ pc the densities and velocities are high enough so that collisions begin to dominate and destroy stars on orbits bound to the central black hole. It should be noted that this is a statistical representation of the stars. In reality less than 50 $M_\odot$ lie within this radius, most of which would be stellar-mass black holes.

### 3.2 The Depletion of Late-Type Giant Stars

Recent observations show what appears to be a depletion of late-type giants in the Galactic Center (Do et al. 2009 and Buchholz, Schödel, & Eckart 2009). One common misconception is that this is due to collisions. But because this phase is relatively short giants are unlikely to undergo a collision during post-main-
sequence evolution. A more careful investigation of the Galactic Nucleus model presented in the previous section indicates that for a Kroupa mass function collisions of late-type giants cannot account for their depletion (Geiss et al. 2010). In fact collisions of giants are insignificant in our Galactic Nucleus model. The results indicate that tidal disruptions of giants play a much more important role in the resulting observed cusp, or lack thereof. Our results show that for the late-type giants the projected slope ranges from 0 for the inner 1" to a slope of -0.4 at 10". This flattening is solely due to the tidal disruptions of giants and not collisions. Another possible alternative has been mentioned by Davies in these proceedings. It may be possible to account this depletion of giants by assuming it is due to a top heavy mass function, one in which the number of stellar-mass black holes is much larger than what a Kroupa mass function would produce. In this top-heavy scenario main sequence stars would be destroyed before evolving into giants by the large excess of stellar-mass black hole (Bartko et al. 2010). Because giants would be preferentially destroyed in the inner regions of the nucleus a flat profile would presumably be produced. If this is the case the relaxed population of main sequence stars should have a density cusp with a -1/2 slope per section 2.3. Unfortunately confirmation of such a slope of the main sequence stars cannot be made with present-day technology.
3.3 More Massive Galactic Nuclei

Besides the Galactic Center many other galactic nuclei are believed to contain massive black holes. The Andromeda Galaxy is believed to harbor a black hole of $3 \times 10^7 M_\odot$, and M87 may have a black hole of $3 \times 10^9 M_\odot$. As the mass of the nuclear cluster increases so does the amount of matter available to grow the black hole. And depending on the mass of the galaxy, collisions can play and important role in its growth and the observed stellar cusp. Figures 5 and 6 present the stellar density profiles of nuclei with 10 and 100 times the mass of our own nucleus, respectively. As would be expected the model ten times more massive than the Galaxy produces a black hole roughly 10 times more massive than the black hole at the Galactic Center. Perhaps the most representative example of this model nucleus would be the Andromeda Galaxy. It is also interesting to note that though still small, collisions of stars are playing a more important role in the model shown in Figure 5. In Figure 6 collisions dominate over tidal disruptions. This is easily seen in the slope of the density profiles. Though the black holes are close to a $-7/4$ slope the main sequence stars have a power-law slope of $-1/2$ out to 1 pc. This slope is indicative of collisions depleting these stars. Compare this to the identical model shown in Figure 7 which does...
not include stellar collisions. One other item to note is that more massive nuclei will actually have fewer stellar-mass black holes interior to 0.01 pc.

4 Conclusion

Because stellar evolution and tidal disruptions of stars are the predominant mass-loss mechanisms; the relaxed stellar system at the Galactic Center should have a cusp with a density power-law slope of -7/4 for stellar-mass black holes to -3/2 for main sequence stars. But for the late-type giant stars the slope will be significantly less than this, due not to collisions, but due to tidal disruptions of these large stars. For massive nuclei stellar collisions play a much more important role in the development of a stellar cusps. Because collisions dominate these more massive nuclei their cusps will have a -1/2 power-law slope.

Acknowledgments. The assistance of K. Phifer, B. Geiss, M. McFall, and the Butler Institute for Research & Scholarship with this research is appreciated.

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