10. Case for Black Hole in the Galactic Center

THE NUCLEAR STAR CLUSTER OF THE MILKY WAY: STAR FORMATION AND CENTRAL DARK MASS

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Abstract. High spatial resolution, near-infrared imaging and spectroscopy of the nuclear star cluster obtained in the last few years have given key new insights about the structure, evolution and mass distribution in the Milky Way Center. The central parsec is powered by a cluster of hot, massive stars. Their characteristics imply that there was an active phase of star formation a few million years ago, probably triggered by the infall and collapse of a very dense gas cloud. Other such starburst episodes may have taken place between 100 and 300 million years ago. Measurements of radial and proper motions for more than 200 stars show that stellar velocities increase with a Kepler law down to a scale of a light week from the compact radio source Sgr A*. The data make a compelling case for the presence of a compact, central dark mass of about 2.6×10^6 $M_\odot$. Simple physical considerations show that this dark mass cannot consist of a stable cluster of stars, stellar remnants or substellar condensations. Energy equipartition requires that at least five percent of the dark mass ($\geq10^5$ $M_\odot$) must be associated with Sgr A* itself and likely is enclosed within less than 8 light minutes. If one accepts these arguments it is hard to escape the conclusion that Sgr A* is indeed a massive black hole at the core of the Milky Way.

1. What Powers the Central Parsec ?

During the past decade high resolution near-infrared observations have elucidated the distribution and characteristics of the nuclear stellar cluster and provided a fairly unambiguous picture of what powers the central parsec (e.g. Mezger et al. 1996 for a review). Through the advent of sensitive, large format infrared detector arrays and speckle/adaptive optics imaging it has

Y. Sofue (ed.), The Central Regions of the Galaxy and Galaxies, 421-431.

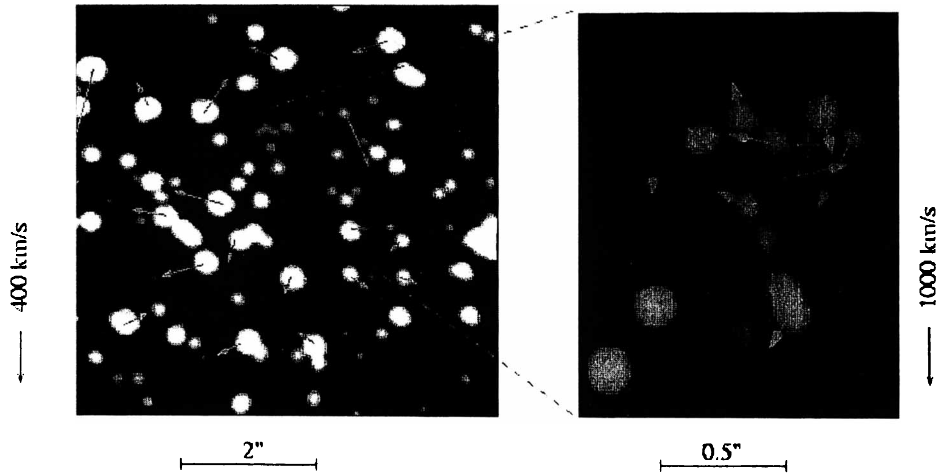

Figure 1. Grey scale K-band image of the central ~6" of the Galactic center, obtained with speckle imaging at 0.15" resolution at the 3.5m ESO NTT (Eckart et al.1995, Eckart and Genzel 1997). The right inset shows the central Sgr A* cluster of faint stars in the immediate vicinity of the compact radio source Sgr A* (cross, positioning and error bars from Menten et al. 1997). Stellar proper motions from Eckart and Genzel (1996, 1997, and unpublished) and Genzel et al. 1997 are shown as arrows with lengths proportional to the velocities.

become possible in the last few years to image the central parsec at ~0.1" resolution (Eckart et al. 1993, 1995, Rigaut et al. 1997, Ghez et al. 1997). The best current images resolve the near-infrared emission of the central parsec into about 700 stars with K-band magnitudes <16 (Fig.1). Thus all red and most blue supergiants, all red giants (including bright, asymptotic giant branch (AGB) stars) of spectral type later than K5, and all main sequence stars earlier than B0 or B1 should be visible in Fig.1. Further progress can be expected from deeper near-infrared images taken with the NICMOS camera onboard the HST.

The central IRS16 complex located within 1' 1" of the compact radio source Sgr A* consists of about two dozen single (or perhaps multiple) bright stars. The core radius of the m(K)<15 stellar surface number density distribution is between 0.2 and 0.4 pc (Eckart et al. 1993, Genzel et al. 1996). A larger core radius of about 0.5 to 0.8 pc has been derived from the surface brightness distribution of the late type stars (Allen 1994, Rieke and Rieke 1994). If the stars with m(K)<15 are representative of the overall mass distribution of the cluster a ~0.4 pc core radius together with the mass of stars estimated to lie within a few parsecs indicates that the stellar density in the core is about 4×10^6 $M_\odot pc^{-3}$. The high resolution images also indicate an additional enhancement of fainter stars centered within 0.1 of Sgr A* (Eckart et al. 1995, Ghez et al. 1997). This so called Sgr A* cluster (Fig.1) is particularly striking on a very recent, 0.05" resolution 2μm image taken by Ghez et al.(1997) with the 10 m Keck telescope (see also Ghez et al. in these proceedings). The Sgr A* cluster may represent a central stellar cusp associated with the radio source. It plays a key role in the context of the stellar proper motions discussed below.

Imaging spectroscopy with the MPE 3D field imaging spectrometer show that within the core radius bright late type stars (supergiants and the brightest AGB stars) are absent but that the core is surrounded by a ring of red supergiants/AGB stars (Genzel et al. 1996). This confirms earlier observations of Sellgren et al.(1990) and Haller et al.(1996) and suggests that the brightest (and hence largest) late type giant stars are destroyed in the very dense cluster core, plausibly by collisions with main sequence stars (Lacy et al.1982, Phinney 1989). Forrest et al. (1987), Allen et al. (1990), and Krabbe et al. (1991) have discovered that about 25 of the bright near-infrared stars centered on the IRS16/IRS13 complex show in their spectra prominent broad HeI and HI recombination lines in emission. Recent <1" resolution line imaging (Eckart et al. 1995, Tamblyn et al. 1996) and 3D imaging spectroscopy (Krabbe et al. 1995, Genzel et al. 1996) now unambiguously show that several of the brightest members of the IRS16 complex are HeI-stars, as is the nearby bright source IRS 13 (see also Libonate et al. 1995, Blum et al. 1995a,b, Tamblyn et al. 1996). From non-LTE, stellar atmosphere modeling of the observed emission characteristics of several of the HeI-stars Najarro et al. (1994, 1997) have inferred that these objects are moderately hot (17,000 to 30,000 K), very luminous (1 to 30×10^5 $L_\odot$) massive stars whose helium rich surface layers are expanding as powerful stellar winds with velocities of 200 to 800 km/s and mass loss rates of 1 to 70×10^{-5} $M_\odot$/year.

Fig.2 shows the location of these stars in a Hertzsprung-Russell diagram, along with stellar evolutionary tracks (Meynet et al. 1994) for twice solar metallicity element abundances (Lacy et al. 1980, Shields and Ferland 1994, but see Sellgren et al. in these proceedings). The HeI stars thus appear to be blue supergiant stars of initial mass 40 to >100 $M_\odot$that have left the main sequence. They are on their way to becoming hot Wolf-Rayet stars and then to exploding as supernovae. Empirically they are similar to late WN stars, Luminous Blue Variables and Of (pe) supergiants (Allen et al. 1990, Krabbe et al. 1991, Najarro et al. 1994, Libonate et al. 1995, Blum et al. 1995a,b, Tamblyn et al. 1996). The HeI-star cluster can plausibly account for essentially all of the bolometric and Lyman-continuum

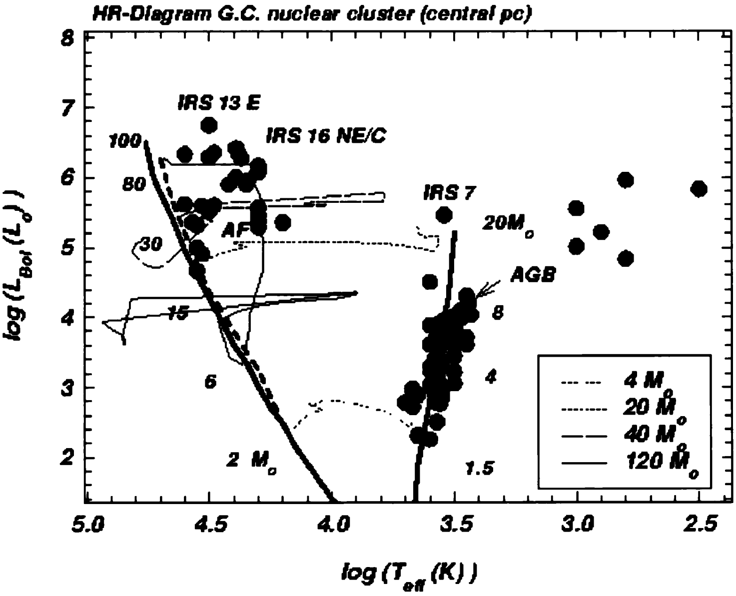

Figure 2. Hertzsprung-Russell diagram of ~10^2 stars with m(K)<13 in the central parsec. Each star is marked as a filled circle. Temperatures and luminosities of the late type stars are derived from K-band spectroscopy and K-magnitudes (Genzel unpublished, Blum et al. 1996a). Temperatures and luminosities of the early type stars (He I stars) are derived from the non-LTE modelling of Najarro et al. (1994,1997). Identifications of a few He I-stars and thered supergiant IRS 7 are given. Several very cold objects have featureless K-band spectra (see Krabbe et al. 1995) with strong long-wavelength dust excess, indicating that they may be dust enshrouded young stellar objects, or dusty massive stars. Heavy and dashed lines denote the main sequence and giant branches for solar and twice solar metallicity, respectively, with masses marked. Stellar tracks for twice solar metallicity from the work of Meynet et al. 1994 are plotted for 4 different masses.

luminosities of the central parsec (Krabbe et al. 1995, Najarro et al. 1997). As yet unobserved hotter Wolf-Rayet and O stars are required, however, to account for the helium ionizing luminosity of SgrA West.

Krabbe et al.(1995) have fitted the properties of the massive early type stars in the central parsec by a model of a star formation burst between 2 and 9 million years ago in which a few hundred OB stars and perhaps a few thousand stars in total were formed, supporting earlier proposals by Rieke and Lebofsky (1982), Lacy, Townes and Hollenbach (1982) and Allen and Sanders (1986). In the model of Krabbe et al. the HeI stars are the most massive cluster members that have already evolved off the main sequence. In this scenario the central parsec is now in the late, wind-dominated phase of the burst. The starburst model accounts naturally for the low excitation of the SgrA (West) HII region. Although there is also evidence for a few very young, embedded OB stars the present star formation activity appears to be significantly less than during the peak of the burst. Likewise the small number of red supergiants (2 to 3 in the central parsec, Blum et al. 1996a) shows that the star formation rate prior to 10 or more million years ago also was substantially smaller. The relatively large number (~30 in central parsec, Genzel et al. 1996) of very cool (<3000 K, Blum et al. 1996a) and very bright red giants with luminosities 10^3 to 10^4 $L_\odot$ (AGB stars, apparent in Fig.2 as a group to the right from the top of the giant branch) may signify other such starburst episodes that probably have happened between 100 and 300 million years ago (Haller and Rieke 1989, Krabbe et al. 1995, Blum et al. 1996b). The present gas density in the central parsec is too low for gravitational collapse of gas clouds to stars in the presence of the strong tidal forces (Morris 1993). Perhaps the most recent episode of star formation was triggered by infall of a particularly dense and compressed gas cloud less than 10 million years ago. This scenario is also supported by an overall counter-rotation (in the sense of Galactic rotation) of the HeI star cluster (Genzel et al. 1996). Alternative explanations of the He I stars as the result of stellar collisions in the very dense nuclear cluster (Eckart et al. 1993, Morris 1993) now appear very unlikely (Lee 1994), especially since a number of stars similar to the SgrA HeI stars have now been found in several clusters 2' to 13' away from the central, high density SgrA region (Cotera et al. 1996, Figer et al. 1995).

2. Is Sgr A* a Massive Black Hole?

Ever since the original discovery of the nonthermal compact radio source Sgr A* at the core of the nuclear star cluster (Balick and Brown 1974) that source has been the primary candidate for a possible massive black hole at the Galactic Center, in analogy to compact nuclear radio sources in other nearby normal galaxies (Lynden-Bell and Rees 1971). In fact ever more detailed radio observations have confirmed the unique nature of Sgr A* in the Galaxy. Recent very long baseline radio interferometry (VLBI) observations between 1.3cm and 1.3 mm show its size to be less than about 2 AU (Backer 1996, Krichbaum et al. 1994, Duschl these proceedings), Shen et al.these proceedings).Yet observations at shorter wavelengths indicate nothing particularly impressive toward the radio position of Sgr A*. Using several several bright stars that are present on both radio and near-infrared maps Menten et al. (1997) have been able to register Sgr A* on near-infrared maps with an uncertainty of ±30 milli-arsec (cross in Fig.1). As mentioned above Sgr A* is located near the centroid of the Sgr A* cluster of >20 faint stars with m(K)>13.5 (Fig.1), yet it is not coincident with any steady source of m(K)<16 (Genzel et al. 1997, Ghez et al. 1997). On the June 1996 and July 1997 NTT images (Genzel et al.1997 and unpublished) there is a m(K)~15.5 source at the nominal position of Sgr A*, possibly implying a time variable source associated with Sgr A*. However, more measurements are needed to decide whether this interpretation is correct or whether one of the nearby faint stars (S3) has moved there. There probably is also a faint 10μm source located at or near Sgr A* (Stolovy et al. 1996, Becklin et al. these proceedings). Nevertheless it is fairly clear that Sgr A* has been fairly infrared-quiet during the past one or two decades. This limits its infrared luminosity to less than a thousand solar luminosities or so. Likewise, the 1 to 30 keV X-ray luminosity of SgrA (West) and Sgr A* is less than a a few hundred $L_\odot$ (Goldwurm et al. 1994). Recent observations with ASCA and GRANAT suggests that Sgr A*s X-ray luminosity may have been larger in the past few hundred years (a few 10^5 $L_\odot$, Koyama et al. 1996) but still orders of magnitude smaller than the Eddington rate of a million solar mass black hole (Sunyaev et al. 1993).

The evidence for a (dark) central mass concentration in the Galactic Center thus is based entirely on the gas and stellar dynamics. While the velocities of gas clouds and of stars are approximately constant outside of a few parsec - as expected if the mass is dominated by the dense, near-isothermal nuclear star cluster - velocities are observed to increase within the inner core (e.g. Genzel and Townes 1987). The first evidence for this increase in gas velocities came from mid-infrared spectroscopy of 12.8mm [NeII] by Wollman et al. (1977) and Lacy et al.(1980). These authors and others following interpreted the >250 km/s gas velocities as signalling a concentration of non-stellar mass in the Galactic Center, possibly caused by a few million solar mass black hole at the dynamic center (Lacy et al. 1982, Serabyn and Lacy 1985). However, gas is affected by magnetic, frictional and wind forces, in addition to gravity, so that stellar velocities are required to unambiguously determine the mass distribution. Beginning with the pioneering work of Rieke and Rieke (1988), McGinn et al.(1989) and Sellgren et al.(1990) ever better stellar velocities from Doppler shifts of stellar absorption and emission lines have become available during the past decade, fully supporting the earlier measurements of gas velocities and very substantially strengthening the evidence for a compact central dark mass in the Galactic center. The most recent determinations by Sellgren et al. (1990), Krabbe et al.(1995), Haller et al.(1996) and Genzel et al.(1996) are all in agreement and show a significant increase of stellar radial velocity dispersion from about 55 km/s at 5 pc to about 180 km/s at 0.15 pc.

Very recently two groups have made the first measurements of proper motions for more than 50 stars between ~5" (0.2 pc) and ~0.1" (0.004 pc) from Sgr A* (Eckart and Genzel 1996, 1997, and unpublished, Genzel et al. 1997, Ghez et al. 1997). The MPE group derived their results from an 8 epoch set of 0.15" speckle images obtained between 1992 and 1997 on the NTT. The UCLA group determined their results from a 0.05" resolution, 3 epoch data set between 1995 and 1997. For more detailed descriptions of the methods and specific results of these crucial experiments we refer to the original literature, as well as to Ghez et al. in these proceedings. The proper motions deduced independently by the two groups are in excellent agreement. In the range $1'' < p < 5''$ from Sgr A* where both radial and proper motions are available, the deduced velocity dispersions in the three spatial directions also agree very well (for an adopted 8 kpc distance). This indicates that large scale anisotropy of the velocity field does not play a role. There is also no evidence for strong anisotropy in individual orbits, as inferred from the radial and proper motions of a dozen stars for which these are available simultaneously. Without doubt the most important aspect of the new proper motion data is the fact that they provide measurements of stellar velocities in the Sgr A* cluster, at distances as small as 0.1" (~800 AU or 0.7 light weeks) from Sgr A*. The key finding is that several faint stars in the Sgr A* cluster have proper motions in excess of 1000 km/s, the fastest one (S1) with ~1400 km/s being also the closest to Sgr A*. The combined radial and proper motion data thus unambiguously show that stellar velocities increase with a Kepler law ($v \sim R^{-1/2}$) to a scale of ≤ 0.01pc.

Fig.3 shows the present best mass distribution (from Genzel et al. 1997), derived from a Jeans equation analysis as well as from projected mass estimators for both radial and proper motions of the stars. Masses estimated from the gas dynamics (triangles, Serabyn and Lacy 1985, Güsten et al. 1987, Lacy et al. 1991) are fully consistent with the stellar data. The measurements are fitted very well with the combination of a central point mass ($2.61 \pm 0.15_{stat}, \pm 0.35_{stat+sys} \times 10^6\ M_\odot$(Genzel et al. 1997), $2.7 \pm 0.2_{stat} \times 10^6$ (Ghez et al. 1997)), plus an extended, near-isothermal stellar cluster with core radius ~0.38 pc and core mass density of $4 \times 10^6 M_\odot/pc^3$. If the central point mass is replaced by a compact dark cluster its core density must exceed $2 \times 10^{12}\ M_\odot/pc^3$, at least 500,000 times denser than the visible stellar cluster or the densest globular clusters. In terms of a Plummer model its density distribution outside of the core radius (<6.5 milli-parsec) must have a very steep falloff ($\rho \sim R^{-5}$), very different from an isothermal distribution. The mass to bolometric luminosity ratio of this central dark mass is greater than a few hundred. Simple physical considerations show that clusters of low mass stars (e.g. white dwarfs), neutron stars, stellar black holes or sub-stellar entities (e.g. brown dwarfs, rocks) with the observed properties of the dark mass all cannot be stable for any longer than 10^5

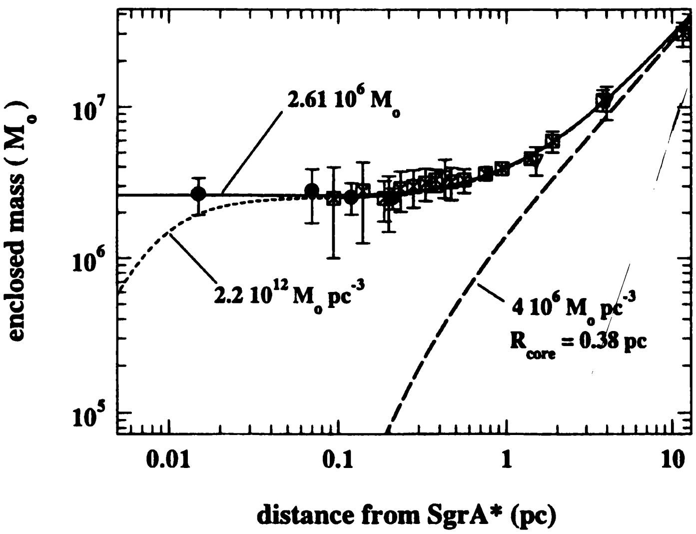

Figure 3. Mass modelling of the stellar proper and radial motions. Shown as filled and crossed rectangles with 1σ error bars are the Jeans equation and projected mass estimator, mass estimates obtained from proper motions and radial motions, respectively, assuming a Sun-Galactic Center distance of 8 kpc (Genzel et al. 1997). Mass estimates from the proper motion data of Ghez et al. 1997 are in excellent agreement with these values. The thick dashed curve represents the mass model for the (visible) stellar cluster ($M/L(2\mu m)=2$, $R_{core}=0.38$ pc, $\rho(R=0)=4\times10^6$ $M_\odot pc^{-3}$, Genzel et al. 1996). The thin continuous curve is the sum of this stellar cluster, plus a point mass of $2.61\times10^6 M_\odot$. The thin dotted curve is the sum of the visible stellar cluster, plus a $\alpha=5$ Plummer model of a dark cluster of central density 2.2×10^{12} $M_\odot pc^{-3}$ and $R_0=0.0065$ pc. It provides a χ^2 fit 1σ worse than the best fit (Genzel et al. 1997).

to 10^7 years (Maoz 1995, Genzel et al. 1997, Maoz these proceedings). It is also not possible that the dark mass concentration is the core-collapsed state of a dynamically evolving cluster of such objects. In that case the distribution – while very dense in a tiny core – would have a soft, quasi-isothermal envelope, unlike what is observed in the Galactic Center (Lee 1995, Genzel et al. 1997). Finally, if the dark mass is conjectured to consist of Fermionic elementary particles supported by 'Pauli principle' pressure, the m^{-2} dependence of the Chandrasekar mass on the mass of the particles requires that the mass of the Fermions cannot be much larger than the electron mass. The only realistic configuration without net electric charge would then be a positron-electron gas which would, however, rapidly decay through annihilation radiation.

Two further arguments substantially strengthen the conclusion that the dark mass in the Galactic center in fact must be a massive black hole. The first comes from the fact that Sgr A* itself is known from VLBI measurements to have a proper motion less than about 16 km/s (Backer 1996). In the very dense Galactic center core the fast moving stars near Sgr A* and Sgr A* should have approximately the same kinetic energy. Hence the large (factor 100) difference in observed motions means that Sgr A* must be at least 10^4 times more massive than the nearby stars, or $\geq 10^5$ $M_\odot$, unless its true motion is exactly along the line of sight (Genzel et al. 1997). If one further assumes that the mass of Sgr A* must be at least as concentrated as its radio emission (1 AU corresponds to 15 Schwarzschild radii of a 2 million solar mass black hole), the inferred density of Sgr A* is $10^{20.5}$ $M_\odot/pc^3$. The second argument is an inversion of the well known dilemma that if Sgr A* is a 2.6×10^6 $M_\odot$ black hole it is currently radiating at a rest mass energy to radiation, conversion efficiency of 10^{-5} to 10^{-6}, considering the accretion of stellar wind gas from its environment (Melia 1992, Genzel et al. 1994). The only possible way out (other than very large time variability of the accretion) is the argument that in purely radial (Bondi-Hoyle) or in low density, non-radial flows most of the rest mass energy of the accretion flow can be advected into the hole, rather than radiated away (Rees 1982, Rees et al. 1982, Melia 1992, 1994, Narayan et al. 1995, 1997, these proceedings). This explanation, however, requires the existence of an event horizon and does not work with any configuration but a black hole (Narayan et al. 1997 and these proceedings).

Taking all these arguments together it is hard to escape the conclusion that the core of the Milky Way in fact harbors a million solar mass, central black hole.

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