THE NUCLEAR STAR CLUSTER OF THE MILKY WAY:
STAR FORMATION, DYNAMICS AND CENTRAL BLACK
HOLE

Reinhard Genzel
Max–Planck–Institut für extraterrestrische Physik
Garching, FRG
and
Department of Physics
University of California at Berkeley, USA

Abstract

High spatial resolution, near-infrared imaging and spectroscopy of the nuclear star cluster
have given key new insights about the dynamics, evolution and mass distribution in the
Milky Way Center. The central parsec is powered by a cluster of hot, massive stars which
must have formed a few million years ago. Either star formation was triggered in the central
parsec by the infall of a very dense cloud, or a dense, young star cluster formed outside
of the central parsec sank rapidly into the nuclear region through dynamical friction. The
presence of luminous asymptotic giant branch (AGB) stars suggests that there were earlier
such star formation episodes.

Measurements of radial and proper motions for more than 200 stars delineate the stellar
dynamics to a scale of a few light days from the dynamic center which is coincident with the
compact radio source (SgrA∗) within ∼0.1″ (800 AU). The stellar velocities increase toward
SgrA∗ with a Kepler law (to >1000 km/s for the innermost stars), implying the presence of a
three million solar mass central (dark) mass. The observations make a compelling case that
this mass concentration is a black hole which is currently accreting at a low rate or radiating
at low efficiency. With the exception of the young, massive stars the velocity field of the
central stellar cluster is close to isotropic. The young stars are characterized by a turbulent
rotation pattern that still carries the imprint of the angular momentum distribution in the
original cloud or star cluster.

1 INTRODUCTION

The nucleus of the Milky Way (distance ∼8 kpc) is one hundred times closer to us than the
nearest large external galaxy and a thousand times closer than the nearest active galactic nuclei.
We can study physical processes in our own Galactic Center at a level of detail that will never
be reached in the more distant, but often also more spectacular systems. What powers these
nuclei and how do they evolve? What are the properties of the star clusters located in their
cores? Is star formation happening there? Do massive black holes reside at the dynamical
centers and how do they form and evolve? In the present paper we summarize what is presently
known in the Galactic Center about some of these key issues. For more detailed recent reviews
see Genzel, Townes and Hollenbach (1994), Morris and Serabyn (1996), Mezger, Duschl and
Zylka (1996) and Genzel and Eckart (1998).

2 THE NUCLEAR STAR CLUSTER: PROPERTIES AND
EVOLUTION

The total UV and visible luminosity of the central parsec is 30 to 50 million solar luminosities
(Telesco et al. 1996, Mezger et al. 1996). About ten percent of that luminosity is emitted in
the hydrogen ionizing continuum (>13.6 eV), with a characteristic temperature of about 30,000
to 35,000 K (Lacy et al. 1980, Shields and Ferland 1994, Lutz et al. 1996). What powers this
fairly low excitation, ionized (HII) region and what are the properties of the central star cluster?
During the past decade high resolution near-infrared observations have significantly improved our knowledge of the distribution and characteristics of the nuclear stellar cluster and provided a fairly unambiguous picture of the energetics and evolution of the region. Through the advent of sensitive, large format infrared detector arrays and speckle/adaptive optics imaging it has become possible to image the central parsec at diffraction limited resolution. With D = 4 to 10m diameter telescopes the FWHM resolution that can be attained is $\sim 0.13''$ (3.5m/D) or 0.005 pc at 2.2 micrometers (K-band) (Eckart et al. 1992, 1993, 1995, Genzel et al. 1997, Davidge et al. 1997, Ghez et al. 1998, 2000). Rieke (1999) and Stolovy et al. (1999) describe the first HST-NICMOS results. The best current images resolve the near-infrared emission of the central parsec into almost 1000 stars with K-band magnitudes $m(K) < 15$ to 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 about B2 should be visible in Fig. 1. Nevertheless this image still only samples about 0.1% of the total stellar content of the cluster. Further progress can be expected from deeper near-infrared images that will be obtainable in the next few years with the adaptive optics systems on the Keck, Gemini and VLT.

The K-band surface brightness and surface density increase approximately with the inverse of the distance to about $1''$ from the central compact radio source SgrA* (see below). The centroid of the stellar surface density distribution is within $0.1''$ of SgrA* (Ghez et al. 1998). Near SgrA* the most prominent feature is a group of two dozen or more bright stars (the ‘IRS16’ complex) centered 1–2'' east of the radio source. About 3.5'' south-west of SgrA* lies another compact group of bright stars (the ‘IRS13’ complex). There is also an additional enhancement of fainter stars within $<1''$ of SgrA* (Eckart et al. 1995, Ghez et al. 1998). This so called ‘SgrA* cluster’ (Fig. 1) is particularly striking on the 0.05'' resolution K-band image taken by Ghez et al. (1998) with the 10m Keck telescope (right inset of Fig. 1). The core radius (= radius at which the surface density is half of the central value) of the m(K) $< 15$ stellar surface number density distribution is $\sim 2''$ (0.08 pc: Genzel et al. 2000, Alexander 2000). It is debatable whether this value is also a good estimate of the core radius of the overall (old) stellar cluster since the observed stars only sample the brighter (and more massive) members of the cluster, as discussed above. Allen (1994) and Rieke and Rieke (1994) have deduced larger values of the core radius (0.5 to 0.8 pc) from the near-IR surface brightness distribution of the late type stars only. Genzel et al. (1996) have proposed a core radius of $\sim 0.4$ pc as a compromise between these extremes in which case the stellar density in the core is about $4 \times 10^5 M_\odot / pc^3$. There are a total of about $10^{5.5}$ stars within the core. The SgrA* cluster may represent a central stellar ‘cusp’ associated with the radio source. From an analysis of recent high resolution, near-IR data sets Alexander (2000, and references therein) concludes that a cusped distribution with a power law density distribution of exponent $-1.5$ to $-1.75$ is a better fit (at $>2\sigma$) to the data than a distribution that has a flat central core. If this conclusion is correct, the stellar density in the SgrA* cluster may be $10^8 M_\odot / pc^3$ or greater, compared to the 100 times lower value averaged over the central 0.4 pc. One consequence then would be that the absence of bright late type giants in the innermost few arcseconds (Sellgren et al. 1990, Genzel et al. 1996, Haller et al. 1996) may be explained by envelope destruction in close impact, giant-dwarf or giant-binary collisions (Alexander 2000, Davies et al. 1998). Another important consequence is that with future sensitive adaptive optics and interferometric imaging ($m(K) \sim 19$) it should be possible to detect up to 100 stars residing within $0.1''$ and several stars within $0.01''$ of SgrA*.

Another important aspect has been the discovery of a cluster of about 25 bright HeI/II-emission line stars centered on the IRS16/IRS13 complex (Forrest et al. 1987, Allen et al. 1990, Krabbe et al. 1991). As shown in Fig. 2 several of the brightest members of the IRS16 complex are HeI-stars, as is IRS13E (Krabbe et al. 1995, Eckart et al. 1995, Libonate et al. 1995, Blum et al. 1995b, Genzel et al. 1996, 2000, Tamblyn et al. 1996, Morris et al. 2000). From non-local thermodynamic equilibrium (NLTE), stellar atmosphere modeling of the observed emission
characteristics Najarro et al. (1994, 1997, 1999) have inferred that the Hel-stars are moderately hot (17,000 to 30,000 K) and very luminous (1 to 30 $\times 10^5 L_\odot$). Their 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 $70 \times 10^{-5} M_\odot$/year. Fig. 3 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 probably appropriate for the Galactic Center: Lacy et al. 1980, Shields and Ferland 1994, but see Carr et al. 2000, Ramirez et al. 2000 and below). The Hel-stars thus appear to be blue supergiant stars of initial mass 40 to $>100 M_\odot$ that have evolved off the main sequence. Figure 2 shows that nucleosynthesis products (He, N, C) are clearly present in their outer atmospheres. They are probably on their way to becoming hot Wolf-Rayet stars and then to exploding as supernovae. Empirically they are similar to late WN/WC 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). Combining the contributions from all its members, the Hel-star cluster can plausibly account for most of the bolometric and Lyman-continuum 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. The Hel-star cluster also provides in excess of $10^{38}$ erg/s in mechanical wind luminosity which probably has a significant impact on the gas dynamics in the central parsec (Genzel, Hollenbach and Townes 1994). 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. This conclusion is in excellent agreement with earlier proposals by Rieke and Lebofsky (1982), Lacy, Townes and Hollenbach (1982) and Allen and Sanders (1986). In the analysis of Krabbe et al. the Hel-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. A similar object is the R136 star cluster powering the 30 Doradus nebula in the Large Magellanic Cloud. The presence of a number of highly dust-enshrouded and spatially resolved infrared sources (e.g. IRS1, 3 and 21, apparent in the upper right of Fig. 3, Krabbe et al. 1995, Ott et al. 1999, Tanner et al. 1999) may indicate that stars are still forming at the present time. However, the star formation activity appears to be significantly less now than during the peak of the burst. Likewise the small number of red supergiants (1 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. 3 as a group to the right from the top of the giant branch) may signify other such starburst episodes that probably happened between 100 and 1000 million years ago (Haller and Rieke 1989, Krabbe et al. 1995, Blum et al. 1996b, Sjouwerman et al. 1999).

The present gas density in the central parsec is far 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 gas cloud about 10 million years ago. This cloud may then in addition have been compressed by shocks and cloud-cloud collisions in the central parsec, thus triggering gravitational collapse. The cloud-infall model is also supported by an overall counter-rotation (in the sense of Galactic rotation) of the Hel-star cluster (Genzel et al. 1996, 2000 and below). Another possibility is that a young star cluster came into the nuclear environment on a highly elliptical or parabolic orbit. If that star cluster was initially dense enough to have been tidally stable, it could have rapidly sunk in due to dynamical friction, followed by tidal disruption in the innermost region (Gerhard 2000). As an alternative to the starburst scenario Eckart et al. (1993) had considered formation of massive stars by sequential merging in star-star collisions. Fokker-Planck modeling of an evolving Galactic Center type, dense cluster shows, however, that merging can account for only
\(~10\) 20 M}_\\odot\) stars and no \(>30\) M}_\\odot\) stars (Lee 1994). The basic reason is that in the calculations a sufficiently dense stellar core (density \(10^7\) M\_\\odot\)/pc\(^3\) or greater) cannot be maintained for a long enough time to build up very many massive stars. Further Morris (1993) had suggested that the HeI-stars are not classical blue supergiants at all but transitory objects that have been created in collisions between \(~10\) M\_\\odot\)) stellar black holes and solar mass, red giants. Both accounts of the HeI-stars just cited are very specific to the high density environment of the central parsec. However, the ‘Quintuplet’ and ‘Arches’ clusters several tens of parsecs north of SgrA have a massive star content and evolutionary state (including HeI-stars) remarkably similar to that of the central, high density nuclear region (Cotera et al. 1996, Figer et al. 1995, 1999a,b). Further Ott et al. (1999) found that the HeI-star IRS16SW is an eclipsing binary with a minimum mass of 100 solar masses. These facts and the presence of heavy element nucleosynthesis products discussed above (Fig. 2) strongly favor the star formation model over the other scenarios. If the Galactic Center is representative of other galactic nuclei as well, nuclear star formation may be a dynamic and highly time variable process that is the result of a complex interplay of the triggering effects of cloud infall and compression on the one hand, and of the destructive effects of stellar winds and supernova explosions on the other hand.

Figure 4 shows a K-band spectrum of the central 0.6" centered on SgrA\(^*\), obtained with the ISAAC infrared spectrometer on the ESO-VLT (from Eckart et al. 1999, see also Genzel et al. 1997, Figer et al. 2000). The integrated spectrum of the SgrA\(^*\) cluster is blue and featureless and requires stars hotter than K-type giants. Given the typical K-band magnitudes (m(K) \(~14–16\)) the SgrA\(^*\) cluster members thus are likely early B or late O stars (Genzel et al. 1997).

An interesting new application of infrared spectroscopy is the study of element abundances in the Galactic center stars. As mentioned above, the metallicity of the SgrA West HII region is probably greater than solar, with a best estimate of twice solar abundances (e.g. Shields and Ferland 1994). Najarro et al. (1999) have reported that the Mg- and Fe-abundance in the luminous ‘Pistol’ blue supergiant in the Quintuplet cluster is also at least twice solar. Recent high resolution near-IR spectroscopy of IRS7 (Fig. 5, Carr et al. 2000, Ramirez et al. 2000) and half a dozen other M-supergiants within 30 pc of SgrA\(^*\), on the other hand, results in a near solar, Fe-abundance. It is not clear yet whether these results are in conflict with each other, or whether the uncertainties in the analysis allow a common solution.

In summary, the stellar and nebular observations of the central parsec are quite well described by a modest, aging starburst that currently dominates the energetics of the SgrA West HII region. Several puzzles remain. OB main sequence stars and early Wolf-Rayet stars have not yet been unambiguously observed. It is surprising that rare, short-lived stars (such as WN9/Ofpe and LBVs) dominate the stellar census (e.g. Tamblyn et al. 1996). Quantitative estimates of the emerging (E)UV spectral energy distribution of an evolving star cluster based on current tracks predict an overall increase of the effective temperature of the radiation field a few million years after the burst (Lutz 1999, see Fig. 3). This is due to hot WN/WC stars dominating the EUV radiation field that controls the excitation of the HII region. This prediction is at odds with the observations; they indicate that most of the energetics/excitation of the SgrA HII region can be plausibly accounted for by the HeI emission line cluster. It appears that the evolutionary tracks do not properly describe the stellar census in the central parsec. One issue in this context is the role of stellar rotation in the appearance and characteristics of the massive stars (e.g. Langer and Maeder 1995, Heger and Langer 2000). Rotational mixing may bring up efficiently nucleosynthesis products into the outer atmospheres of the stars. Hanson et al. (1996) have proposed that the enhanced nitrogen abundances apparent in the spectra of several of the Galactic center stars (e.g. IRS13E in Fig. 2, similar to ON supergiants) may be related to this effect.
Ever since its original discovery the compact, nonthermal radio source SgrA* at the core of the nuclear star cluster 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 measurements have confirmed the unique nature of SgrA* in the Galaxy. Recent very long baseline radio interferometry (VLBI) observations in the mm-range show its intrinsic size, after correction for interstellar scattering, to be less than about 3 AU (Bower and Backer 1998, Lo et al. 1999, Krichbaum et al. 1999). Yet SgrA* is relatively faint in any wavelength range other than the cm-mm band. Using several several bright stars with radio masers in their envelopes (present on both radio and near-infrared maps) Menten et al. (1997) have been able to register SgrA* on near-infrared maps with an uncertainty of ±30 milli-arsec (asterisk in Fig. 1). SgrA* is located near the centroid of the SgrA* cluster but it is not coincident with any steady source of m(K) < 16 (Genzel et al. 1997, Ghez et al. 1998). On the June 1996 and July 1997 NTT images (Genzel et al. 1997) there is a m(K) ~ 15.5 source at the nominal position of SgrA*, possibly implying a time variable source associated with SgrA*. Alternatively one of the nearby faint stars may have moved there (Ghez et al. 1998). Nevertheless it is fairly clear that SgrA* has been infrared-quiet during the past one or two decades. This limits its infrared luminosity to less than a few thousand solar luminosities. Recent arcsecond-resolution observations with CHANDRA have established that there is a (weak), compact keV-source at the position of SgrA* (Baganoff et al. 2000). Its luminosity in the 1–10 keV band is less than a few L⊙. Observations with ASCA and GRANAT suggest that SgrA*'s X-ray luminosity may have been larger in the past few hundred years (a few 10^5 L⊙, 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).

If SgrA* is a black hole, it must be radiating at a surprisingly low level.

4 GAS AND STELLAR DYNAMICS: EVIDENCE FOR CENTRAL DARK MASS

The evidence for a (dark) central mass 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 with a Kepler law 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 the 12.8 micrometer [NeII] emission line by Wollman et al. (1977) and Lacy et al. (1980). These authors and others following interpreted the >250 km/s gas velocities as signaling 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 motions can be affected by magnetic, frictional and wind forces, in addition to gravity. Stellar velocities are required for an unambiguous determination of 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 (Rieke and Rieke 1988, McGinn et al. 1989, Sellgren et al. 1990, Lindqvist et al. 1992, Krabbe et al. 1995, Haller et al. 1996, Genzel et al. 1996). The most recent determinations by Krabbe et al. (1995), Haller et al. (1996) and Genzel et al. (1996) are all in excellent 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.

A breakthrough in the evidence for a central dark mass occurred when the first measurements
of stellar proper motions became available. These sample the stellar dynamics to a few light
days from SgrA*. Eckart and Genzel (1996, 1997) and Genzel et al. (1997) reported proper
motions for more than 50 stars between \(\sim 5''\) (0.2 pc) and \(\sim 0.1''\) (0.004 pc) from SgrA* (Eckart
and Genzel 1996, 1997, Genzel et al. 1997). The MPE group originally derived their results from
0.15'' speckle images obtained on the ESO New Technology Telescope (NTT) in 8 observing
runs at least once a year between 1992 and 1997. Independently, Ghez et al. (1998) reported
proper motions for 90 stars between 0.1'' and 4.3'' from SgrA*. The UCLA group determined
their results from 0.05'' resolution speckle imaging with the 10m Keck telescope in three epochs
between 1995 and 1997. More recently, Eckart et al. (1999) and Genzel et al. (2000) have
updated their proper motion data set (including two more NTT runs in 1998 and 1999 and
combining the NTT data with the Ghez et al. (1998) Keck data) to yield more than 100 proper
motions of significantly improved quality (Fig. 6). Likewise Ghez et al. (2000) have also updated
and improved their proper motions, including the first detection of curvature in the proper
motion trajectories of three stars very close to SgrA*. With a few exceptions the proper motions
deduced independently by the two groups are in excellent agreement.

5 CONSTRAINTS ON ANISOTROPY

For those 32 stars between 1 and 5'' from SgrA* for which both radial and proper motions are
available, the deduced velocity dispersions in the three spatial directions agree very well (Genzel
et al. 2000, for an adopted 8 kpc distance). Moreover and more significantly, for all 104 stars
with proper motions in the list of Genzel et al. (2000), the sky-projected, tangential and radial
velocities of each star are also in good agreement with an isotropic distribution (Fig. 7, lower
right). Large scale anisotropy of the velocity field does not play a major role in the central
parsec of the Galaxy. This fact substantially increases the robustness of the mass distribution
discussed in the next section.

The picture changes if only the proper motions of the early type, massive stars are considered.
11 out of 12 HeI emission line stars within 5'' from SgrA* are on projected tangential orbits
(Fig. 7, upper left). Most of the HeI emission line stars and the brighter members of the IRS16
complex follow a clockwise (on the sky) and counter-rotating (with respect to the Galaxy)
coherent streaming pattern (Fig. 6). This pattern indicates that the young stellar component
is in overall rotation, albeit with large, local random motions. The rotation is likely a remnant
of the original angular momentum distribution of the cloud (or young star cluster) the massive
stars came from. The age of the massive stars is significantly less than the relaxation time at
0.5 pc (10 to 30 million years).

For the late type stars the proper motions are fully consistent with isotropy (Fig. 7, lower
left), as expected for their greater age. Still, there are some indications in the radial velocity
data (Ott et al. 2000) for bright late type (= AGB) stars projected in a similar part of the sky to
also have similar radial velocities. This clumping in phase space is puzzling and not consistent
with the fact that these stars are likely much older (a few hundred million years) than their
relaxation time (50 to 200 million years).

In their most recent analysis Genzel et al. (2000) also find some evidence that the fainter
‘SgrA* cluster’ stars have a tendency for more radial orbits (Fig. 7, upper right). This would fit
with the fact that the innermost fast moving stars (S1, S2 and S8) have orbits with relatively
small curvature (Genzel et al. 2000, Ghez et al. 2000). Genzel et al. (2000) propose that the
SgrA* cluster stars may be somewhat lower mass (10–20 M⊙) members of the HeI-star cluster
which happen to be on plunging, highly elliptical orbits and thus make it to the immediate
vicinity of SgrA*. However, this conclusion must be regarded as tentative and more statistics
is required for making a conclusive statement.
The most exciting aspect of the proper motion data is that they provide measurements of stellar velocities in the SgrA* cluster. Several faint stars within 0.6″ of SgrA* have proper motions in excess of 1000 km/s. The fastest star (S1) at a distance of only ~0.1″ (~800 AU or 5 light days) from the radio source has a proper motion of ~1470 km/s. The combined radial and proper motion data show that stellar velocities increase with a Kepler law ($v \sim R^{-1/2}$) to a scale of ~0.01 pc. Fig. 8 gives the present best mass distribution (from Genzel et al. 2000) derived from various analyses, including projected mass estimators and Jeans equation modeling for both radial and proper motions of the stars. Using the (anisotropy-independent) mass estimator proposed by Leonard and Merritt (1989) the central mass is $2.7(\pm 0.4) \times 10^6 M_{\odot}$ for a Galactic center distance of $R_0 = 8.0 \text{kpc}$ (which is also the best estimate of $R_0$ from a comparison of the radial velocity and proper motion data, Genzel et al. 2000). Overall the measurements are fitted very well by a combination of a central point mass, plus an extended, near-isothermal stellar cluster with core radius ~0.4 pc and core mass density of $4 \times 10^{12} M_{\odot}/\text{pc}^3$. If the central point mass is replaced by a compact dark cluster with a Plummer density distribution, its core density must exceed $3.7 \times 10^{12} M_{\odot}/\text{pc}^3$, almost a million times denser than the visible stellar cluster, or the densest globular clusters. The Plummer model also requires that such a dark cluster would have to have a very steep density distribution outside of its core radius (density ~ $R^{-4}$, ~ $R^{-5}$, for $R > R_{\text{core}}$ ~ 5.8 milli-parsec), very different from an isothermal distribution. The mass to bolometric luminosity ratio of this central dark mass thus is a few hundred (in solar units) or greater.

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 cannot be stable for longer than ~ $10^7$ years (Maoz 1995, 1998, Genzel et al. 1997). It is also not possible that the dark mass concentration is the very dense (= core-collapsed) state of a dynamically evolving cluster of above objects. In that case, the distribution — while very dense in its very small core — would have a soft, quasi-isothermal envelope, unlike what is observed in the Galactic Center (Genzel et al. 1997). The most likely configuration of the dark Galactic Center mass distribution thus is a black hole. Maoz (1998) points out that the only — albeit highly improbable — alternatives to a massive black hole are a concentration of heavy bosons and a compact cluster of light ($<0.005 M_{\odot}$) black holes.

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 SgrA* itself is known from VLBI measurements to have a proper motion less than about 20 km/s relative to the Galactic Center reference frame (Backer and Sramek 1999, Reid et al. 1999). Hence the two order of magnitude difference in velocities between the radio source and the nearby SgrA* cluster stars means that SgrA* must have a mass $\gg 10^5 M_{\odot}$ (Reid et al. 1999), unless its true motion is exactly along the line of sight (Genzel et al. 1997). If one further assumes that the mass of SgrA* must be at least as concentrated as its radio emission (1 AU corresponds to 17 Schwarzschild radii of a 3 million solar mass black hole), the inferred density of SgrA* must be $> 10^{18} M_{\odot}/\text{pc}^3$. The second argument is an inversion of the well known dilemma that if SgrA* is a three million solar mass black hole it is currently radiating at a rest mass energy to radiation, conversion efficiency of only $10^{-5}$ to $10^{-6}$, considering the accretion of stellar wind gas from its environment (Melia 1992, Genzel et al. 1994). The only possible way for explaining this feeble emission (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 et al. 1982, Melia 1992, 1994, Narayan et al. 1995, 1998). This explanation, however, requires the existence of an event horizon and does not work with any configuration but a black hole (Narayan et al. 1998). 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.

Further progress can be expected soon. The first detections of curvature in the trajectories of S1, S2 and S8 from the Keck proper motion experiment (Ghez et al. 2000) demonstrate that SgrA* indeed is near the focus of the orbits and that fairly accurate orbits for individual stars can be determined over the next few years. Further details of the mass distribution (single massive black hole?, halo of massive objects surrounding the central mass?) will then come from the precision analysis of individual orbits, rather than from the present coarse, statistical tools. Deep diffraction limited, adaptive optics imaging and spectroscopy will result in observations of more stars and of even faster moving stars within <0.1″ of SgrA* (cusp?). The AO imaging also will probe deeper down the main sequence and make feasible the detection of gravitational microlensing of background stars by the central black hole (Alexander and Sternberg 1999). Imaging spectroscopy will lead to a better understanding of the evolution of this unique stellar cluster.

REFERENCES

Alexander, T. 1999, Ap.J. 527, 835
Alexander, T. and Sternberg, A. 1999, Ap.J. 520, 137
Allen, D.A. and Sanders, R.H. 1986, NATURE 319, 191
Allen, D.A., Hyland, A.R. and Hillier, D.J. 1990, MNRAS 244, 706
Allen, D.A. 1994, in ”The Nuclei of Normal Galaxies”, eds. R.Genzel and A.Harris (Dor-drecht:Kluwer), 293
Backer, D.C. and Sramek, R.A. 1999, Ap.J. 524, 805
Baganoff et al. 2000, in prep.
Blum, R.D., Sellgren, K. and DePoy, D.L. 1996a , A.J. 112, 1988
Blum, R.D., Sellgren, K. and DePoy, D.L. 1996b , Ap.J. 470, 864
Blum, R.D., dePoy, D.L. and Sellgren, K.1995b, Ap.J.441, 603
Blum, R.D., Sellgren, K. and dePoy, D.L..1995a ,Ap.J.440, L17
Bower, G.C. and Backer, D.C. 1998, Ap.J. 496, L97
Carr, J.S., Sellgren, K. and Balachandian, S.C. 1999, submitted (astro-ph 9909037)
Cotera, A.S., Erickson, E.F., Colgan, S.W.J., Simpson, J.P., Allen D.A. and Burton, M.G. 1996, Ap.J. 461, 750
Davidge, T.J., Simons, D.A., Rigaut, F., Doyon, R. and Crampton, D. 1997, A.J. 114, 2586
Eckart, A., Ott, T. and Genzel, R. 1999, Astr.Ap. 352, L22
Eckart, A. and Genzel, R. 1997, MNRAS 284, 576
Eckart, A. and Genzel, R.1996, NATURE 383, 415
Eckart, A. Genzel, R., Hofmann, R., Sams, B.J. and Tacconi-Garman, L.E. 1995, Ap.J. 445, L26
Eckart, A. Genzel, R., Hofmann, R., Sams, B.J. and Tacconi-Garman, L.E. 1993, Ap.J. 407, L77
Figer, D. et al. 2000, Ap.J. in press (astro-ph 0001171)
Figer, D., McLean, I. And Morris, M. 1999a, Ap.J. 514, 202
Figer, D., Kim, S.S., Morris, M., Serabyn, E., Rich, R.M., and McLean, I. 1999b, Ap.J. 525, 750
Figer, D. F., McLean, I.S. and Morris, M. 1995, Ap.J. 447, L29
Forrest, W.J., Shure, M.A., Pipher, J.L. and Woodward, C.A 1987, ,in ”The Galactic Center”, ed.D.Backer, AIP Conf. Proc 155, 153
Genzel, R., Pichon, C., Eckart, A., Gerhard, O., Ott, T. 2000, MNRAS in press (astro-ph 0001428)
Genzel, R. and Eckart, A. 1998, C.R.Acad.Sci.Ser.II 326, 69
Genzel, R., Eckart, A., Ott, T. and Eisenhauer, F. 1997, MNRAS 291, 219
Genzel, R., Thatte, N., Krabbe, A., Kroger, H. and Tacconi-Garman, L.E. 1996, Ap.J.472, 153
Genzel, R., Hollenbach, D.J. and Townes, C.H. 1994, Rep.Progr.Phys. 57, 417
Genzel, R. and Townes, C.H. 1987, Ann.Rev.Astr.Ap. 25, 377
Gerhard, O. 2000, in prep.
Ghez, A. et al. 2000, in prep.
Ghez, A., Becklin, E., Morris, M. and Klein, B. 1998, Ap.J. 509, 678
Haller, J.W. and Rieke, M.J. 1989, in "The Center of the Galaxy" , ed. M.Morris, (Dordrecht:Kluwer), 487
Haller, J.W., Rieke, M.J., Rieke, G.H., Tamblyn, P., Close, L. and Melia, F. 1986, Ap.J. 456, 194
Hanson, M.M., Conti, P.S. and Rieke, M.J. 1996, Ap.J.Suppl.107, 281
Heger, A. and Langer, N. 2000, submitted Astr.Ap. [astro-ph 0005110]
Koyama, K., Maeda, Y., Sonobe, T., Takeshima, T., Tanaka, Y. and Yamauchi, S. 1996, PASJ 48, 249
Krabbe, A. et al. 1995, Ap.J. 447, L95
Krabbe, A., Genzel, R., Drapatz, S. and Rotatciuc, V. 1991, Ap.J. 382, L19
Krichbaum, T.P., Witzel, A. and Zensus, J.A. in 'The Central Parsecs of the Galaxy', eds. H.Falcke, A.Cotera, W.Duschl, F.Melia and M.Rieke, ASP Conf.Series Vol. 186 (ASP: San Francisco), 89
Lacy, J.H., Townes, C.H. and Hollenbach, D.J.1982 J. 262, 120
Lacy, J.H., Townes, C.H., Geballe, T.R. and Hollenbach, D.J. 1980, Ap.J. 241, 132
Langer, N. and Maeder, A. 1995, Astr.Ap. 295, 685
Lee, H.M. 1994, in "The Nuclei of Normal Galaxies", eds. R.Genzel and A.I. Harris (Dordrecht: Kluwer), 335
Leonard, P.J.T. and Merritt, D. 1989, Ap.J. 339, 195
Libonate, S., Pipher, J.L., Forrest, W.J. and Ashby, M.L.N.1995 , Ap.J. 439, 202
Lindqvist, M., Habing, H. and Winnberg, A. 1992, Astr.Ap. 259, 118
Lo, K.Y., Shen, Z.-Q., Zhao, J.H., Ho, P.T.P. in 'The Central Parsecs of the Galaxy', eds. H.Falcke, A.Cotera, W.Duschl, F.Melia and M.Rieke, ASP Conf.Series Vol. 186 (ASP: San Francisco), 72
Lutz, D. 1999, in The Universe as seen by ISO, eds.P.Cox and M.F.Kessler, ESASP 427 (ESA: Nordwijk), 623
Lutz, D. et al. 1996, Astr.Ap. 315, L269
Lynden-Bell, D. and Rees, M. 1971 , MNRAS 152, 461
Maoz, E. 1998, Ap.J. 494, L131
Maoz, E. 1995, Ap.J. 447, L91
McGinn, M.T., Sellgren, K., Becklin, E.E. and Hall, D.N.B. 1989, Ap.J. 338, 824
Melia, F. 1992, Ap.J. 387, L25
Melia, F. 1994, Ap.J. 426, 577
Menten, K.M., Eckart, A., Reid, M.J. and Genzel, R. 1997, Ap.J. 475, L111
Meynet, G. et al. 1994, Astr.Ap.(Suppl.) 103, 97
Mezger, P.G., Duschl, W.J. and Zylka, R. 1996, Astr.Ap. Rev. 7, 289
Morris, M., Maillard, J.-P. et al. 2000, in prep.
Morris, M. and Serabyn, E.1996, Ann.Rev.Astr.Ap. 34, 645
Morris, M. 1993, Ap.J. 408, 496
Morris, P.W., Eenens, P.R.J., Hanson, M.M., Conti, P.S., Blum, R.D. 1996, Ap.J. 470, 597
Najarro, F., Hillier, D.J., Figer, D. and Geballe, T.R. 1999, in 'The Central Parsecs of the Galaxy', eds. H.Falcke, A.Cotera, W.Duschl, F.Melia and M.Rieke, ASP Conf.Series Vol. 186 (ASP: San Francisco), 340
Najarro, F., Krabbe, A., Genzel, R., Lutz, D., Kudritzki, R.P.and Hillier, D.J. 1997, Astr.Ap.325, 700
Najarro, F. et al. 1994, Astr. Ap. 285, 573
Narayan, R., Mahadevan, R., Grindlay, J., Popham, R.G. and Gammie, C. 1998, Ap. J. 492, 554
Narayan, R., Yi, I. and Mahadevan, R. 1995, NATURE 374, 623
Ott, T. et al. 2000, in prep.
Ott, T., Eckart, A. and Genzel 1999, Ap. J. 523, 248
Phinney, E.S. 1989, in "The Center of the Galaxy", ed. M. Morris (Kluwer:Dordrecht), 543
Ramirez, S.V., Sellgren, K., Carr, J.S., Balachandran, S.C., Blum, R., Terndrup, D.M. and Steed, A. 2000, submitted [astro-ph 0002062]
Rees, M., Phinney, E.S., Begelman, M.C. and Blandford, R.D. 1982, NATURE 295, 17
Reid, M.J., Readhead, A.C.S., Vermeulen, R.C. and Treuhaft, R.N. 1999, Ap. J. 524, 816
Rieke, G.H. and Rieke, M.J. 1994 in "The Nuclei of Normal Galaxies", eds. R. Genzel and A. Harris, 283
Rieke, G.H. and Lebofsky, M.J. 1982, in "The Galactic Center", eds. G. Rieger and R.D. Blandford, AIP conf. proc. 83 (New York), 194
Rieke, G.H. and Rieke, M.J. 1988, Ap. J. 330, L33
Rieke, M.J. 1999, in 'The Central Parsecs of the Galaxy', eds. H. Falcke, A. Cotera, W. Duschl, F. Melia and M. Rieke, ASP Conf.Series Vol. 186 (ASP: San Francisco), 32
Sellgren, K., McGinn, M.T., Becklin, E.E. and Hall, D.N.B. 1990, Ap. J. 359, 112
Shields, J.C. and Ferland, G.J. 1994, Ap. J. 430, 236
Sjouwerman, L.O., Habing, H.J., Lindqvist, M., H.J. van Langenvelde and A. Winnberg in 'The Central Parsecs of the Galaxy', eds. H. Falcke, A. Cotera, W. Duschl, F. Melia and M. Rieke, ASP Conf.Series Vol. 186 (ASP: San Francisco), 379
Stolovy, S.R., McCarthy, D.W., Melia, F., Rieke, G.H., Rieke, M.J. and Yusef-Zadeh, F. 1999, in 'The Central Parsecs of the Galaxy', eds. H. Falcke, A. Cotera, W. Duschl, F. Melia and M. Rieke, ASP Conf.Series Vol. 186 (ASP: San Francisco), 39
Sunyaev, R., Markevitch, M. and Pavlinsky, M. 1993, Ap. J. 407, 606
Stolovy, S. R., Hayward, T.L. and Herter, T. 1996, Ap. J. 470, L45
Tamblyn, P., Rieke, G.H., Hanson, M.M., Close, L.M., McCarthy, D. W. and Rieke, M.J. 1996, Ap. J. 456, 206
Tanner, A.M., Ghez, A., Morris, M. and Becklin, E. 1999, in 'The Central Parsecs of the Galaxy', eds. H. Falcke, A. Cotera, W. Duschl, F. Melia and M. Rieke, ASP Conf.Series Vol. 186 (ASP: San Francisco), 351
Telesco, C.M., Davidson, J.A. and Werner, M.W. 1996, Ap. J. 456, 541
Wollman, E.R., Geballe, T.R., Lacy, J.H., Townes, C.H. and Rank, D.M. 1977, Ap. J. 218, L103
FIGURE CAPTIONS

Fig. 1 Grey scale K-band image of the central \(\sim 19''\) (0.8 pc) of the Galactic Center, obtained with speckle imaging at 0.15'' resolution at the 3.5m ESO NTT (Eckart et al. 1993, 1995, Eckart and Genzel 1997). The right inset shows the central SgrA* cluster of faint (SgrA* cluster) stars in the immediate vicinity of the compact radio source SgrA* (cross, positioning and error bars from Menten et al. (1997), as obtained with 0.05'' speckle imaging on the 10m Keck telescope (Ghez et al. 1998).

Fig. 2 K-band spectrum (R = 2000) of IRS13E (left) and of an average of IRS16NE, C, NW and SW (right) obtained with the MPE 3D spectrometer on the ESO-MPG 2.2m telescope on La Silla (Genzel et al. 2000, Ott et al. 2000). Wavelengths of important transitions/species are marked by arrows. IRS13E has a spectrum characteristic of a late WN or WC star. The IRS16 stars have spectra similar to Luminous Blue Variables (LBVs, like AG Car, P-Cyg or \(\eta\) Car), or ON stars (Tamblyn et al. 1996).

Fig. 3 Hertzsprung-Russell diagram of stars in the central parsec. With the exception of the location of the ‘SgrA* cluster’ (large circle with long arrow), all stars entering this diagram have \(m(K) < 13\). 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 (Ott et al. 2000, Blum et al. 1996a). The temperatures and luminosities of the early type stars (HeI-stars) are derived from the non-LTE modelling of Najarro et al. (1994, 1997). Identifications of a few HeI-stars and the red supergiant IRS7 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 heavy 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.

Fig. 4 VLT-ISAAC spectroscopy (0.6'' slit) of the SgrA* cluster stars (Eckart et al. 1999, see also Genzel et al. 1997, Figer et al. 2000). The SgrA* cluster stars have featureless K-band spectra, indicating that their temperature is greater than about 5000 K (large circle and arrow in Fig. 3). If they are main sequence stars they are of type O9–B2 and of mass 10 to 20 solar masses.

Fig. 5 High resolution (R \(\sim\) 40,000, CSHELL on IRTF) H-band spectra of three supergiant stars of similar spectra type, IRS7 in the Galactic Center (upper histogram), VV Cep (lower histogram) and \(\alpha\) Ori (continuous line overplotted on both histograms) (from Carr et al. 2000, see also Ramirez et al. 2000). VV Cep and \(\alpha\) Ori have near solar abundances.

Fig. 6 Proper motion vectors of early type stars (lighter grey arrows: HeI emission line stars and brighter members of IRS16 cluster), late type stars (darker grey arrows) and of SgrA* cluster stars (right inset). The data are from Genzel et al. 2000 which include the most recent NTT proper motion results, as well as the Keck results from Ghez et al. 1998. The fastest star (S1 near SgrA*) has a velocity of 1470 ± 100 km/s.

Fig. 7 The anisotropy measure \(\gamma_{RT} = (v_T^2 - v_R^2)/(v_T^2 + v_R^2)\) for different sub-samples of proper motion stars. Here \(v_T\) and \(v_R\) are the sky-projected tangential and radial components of the proper motion of a given star. Bottom right: all stars with proper motions at R < 5'' from SgrA*. Bottom left: Late type stars only. Upper left inset: HeI emission line stars only. Upper right inset: Stars in the SgrA* cluster (R < 0.8'').
Fig. 8 Mass distribution in the central 10 pc of the Galaxy, as obtained from stellar (and gas) dynamics. Shown as filled rectangles (with typical 1σ error bars for two points) are mass estimates from Jeans equation analysis and projected mass estimators, obtained from proper motions and radial motions and assuming a Sun-Galactic center distance of 8 kpc (Genzel et al. 1997, 2000, Ghez et al. 1998). The grey curve with error bars is a Jeans analysis including anisotropy (Genzel et al. 2000). The thick dashed curve represents the mass model for the (visible) stellar cluster (M/L₂micron = 2, Rₖₐₜₜ = 0.38 pc, ρₖₐₜₜ = 4 × 10⁶ M⊙/pc³, Genzel et al. 1996). The thick continuous curve is the sum of this stellar cluster, plus a point mass of 2.9 × 10⁶ M⊙. The thin dotted curve is the sum of the visible stellar cluster, plus an a = 5 Plummer model of a dark cluster of central density 4 × 10¹² M⊙/pc³ and R₀ = 0.0065 pc.
R.A.-offset from SgrA* (arcsecs)

Dec.-offset from SgrA* (arcsecs)
The images depict spectra with various emissions labeled. The spectra are labeled as 'IRS 13 E' and 'average IRS16 Hel stars'. Peaks are labeled with symbols such as Hel, CIV, NIII, HeI, and MgII. The x-axis represents wavelength (μm), and the y-axis represents relative flux or flux in the case of the right graph.
\[
\frac{(v_T^2 - v_R^2)}{(v_T^2 + v_R^2)} = 1.5 - 1.0 - 0.5 - 0.0 0.5 1.0 1.5
\]

He I stars

0 1 2 3 4 5

offset from SgrA* (arcsecs)

\[
\frac{(v_T^2 - v_R^2)}{(v_T^2 + v_R^2)} = 1.5 - 1.0 - 0.5 - 0.0 0.5 1.0 1.5
\]

late type stars

0 1 2 3 4 5

offset from SgrA* (arcsecs)

innermost stars

0 0.2 0.4 0.6 0.8

all stars

1.5 - 1.0 - 0.5 - 0.0 0.5 1.0 1.5

0 1 2 3 4 5
