Galaxies and Their Constituents at the Highest Angular Resolutions
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The Central Dark Mass of the Milky Way

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Abstract. Measurements of the proper motions and radial velocities of stars in the central cluster of the Milky Way have revealed the presence of a 2-3 million solar mass black hole at the position of the compact radio source Sagittarius A* (SgrA*). The overall stellar motions do not deviate strongly from isotropy and are consistent with a spherical isothermal stellar cluster. Speckle spectroscopy with SHARP at the NTT and slit spectroscopy with ISAAC at the VLT suggests that several of them are early type stars. This is consistent with the idea that these stars are members of an early type cluster with small angular momentum and therefore are now in the immediate vicinity of SgrA*. Most recent data now allows to measure the curvatures of the stellar orbits for a few of the stars that are closest to the center and have the largest proper motions of up to 1400 km/s. The curvatures indicate that the stars indeed orbit the central compact object and will allow to further determine its mass and compactness.

1. Introduction

High resolution near-infrared imaging with large telescopes resulted in a determination of the amount and concentration of the mass at the center of the Milky Way. Diffraction limited images, proper motions and most recently the detection of acceleration of stars in the vicinity of the compact radio source Sgr A* have lead to the conclusion that this source is associated with a central black hole with a mass of about 3×10^6 $M_\odot$. Future investigations, especially using interferometric techniques (VLTI, Keck I-II, LBT interferometer) will result in angular resolutions in the near-infrared ranging between a few to several 10 mas. For the LBT interferometer a NIR resolution of 20 - 35 mas will be combined with the unprecedented large field of view of 0.5 to 1.0 arcminutes diameter over which this resolving power will be available. The investigation of the black hole at the center of the Milky Way and the structure of the central stellar cluster will be one of the many fields in which future near-infrared interferometry will provide essential contributions.

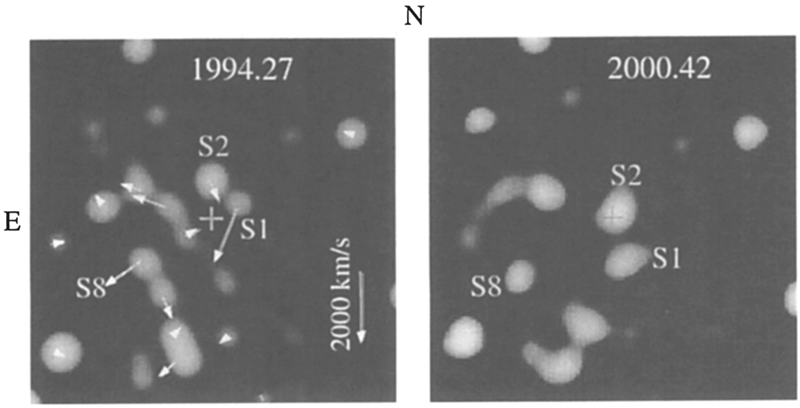

Figure 1. A comparison of two diffraction limited images taken at different epochs - 1994.27 and 2000.42 - using the MPE SHARP camera at the ESO NTT. The cross marks the position of the radio source SgrA*. The arrows indicate the velocities of stars in the central 1.5"×1.5". Sources S1, S2, and S8 are labeled.

2. Imaging and Proper Motions

Using the MPE speckle camera SHARP at the 3.5 m New Technology Telescope (NTT) of the European Southern Observatory (ESO) from 1992 to 2000 we have been conducting a program to study the properties of the central nuclear stellar cluster via near-infrared high spatial resolution measurements. This program has resulted in the very first detection of proper motions of stars that correspond to velocities of up to 1400 km/s in the central arcsecond in the vicinity of Sgr A^* (Eckart & Genzel 1996, 1997). These results had been confirmed by Ghez et al. (1996). On the 1.5σ to 3σ level we have now detected orbital curvatures which confirm the recent results by Ghez et al. (2000, 1999).

In Fig.1 we show the stars in the central 1.5" for two representative epochs: 1994.27 and 2000.42. The position of the compact radio source SgrA^* is indicated by a central cross. In the image on the left hand side the velocities are shown as vectors with their end points at the position of the corresponding stars at the later epoch. The comparison of both images shows that the density of sources especially the central arcsecond is high enough that at the currently reached point source sensitivity (mostly limited by the wings of bright neighboring stars) that field needs to be monitored at least once per year. Such a dense monitoring allows to identify and track the sources without any doubt. For the fastest star - S1 - the angular velocity of almost 40 mas/yr corresponds to a linear velocity of 1400 km/s.

Over the past 8 years the observed motions translate into a one dimensional velocities dispersion of the stars in the central arcsecond (corrected for the measurement error) of the order of >400 km/s (within a radius of less than 0.5"). Overall the stellar motions do not deviate strongly from isotropy and are consistent with a spherical isothermal stellar cluster (Genzel et al. 2000). However, a small deviation from isotropy is found for the sky-projected velocity components of the young, early type stars. Most of the bright HeI emission line stars are on tangential orbits. This overall rotation could be a remnant of the original angular momentum pattern in the interstellar cloud from which these stars were formed. The fainter, fast moving stars within ≈1" from SgrA* (the 'SgrA* cluster') currently appear to be largely moving on radial orbits. Speckle spectroscopy with SHARP at the NTT (Genzel et al. 1997) and slit spectroscopy with ISAAC at the VLT suggests that several of them are early type stars. This is consistent with the idea that these stars are members of the early type cluster with small angular momentum and therefore fell into the immediate vicinity of SgrA* (Genzel et al. 2000, Gerhardt 2000).

3. Spectroscopy

Eckart, Ott, & Genzel (1999) report results based on new near-infrared observations of the central stellar cluster of our Galaxy conducted with the infrared spectrometer ISAAC at the ESO VLT UT1 and the MPE speckle camera SHARP at the ESO NTT (see also Figer et al. 2000). The ISAAC observations resulted in $\lambda/\Delta\lambda \sim 5000$ K-band spectra of the 2.058 μm He I, 2.165μm Brγ emission lines, and 2.29 μm CO bandhead absorption line. These data demonstrate that there is no strong CO bandhead absorption originating in the northern part (S1/S2 area) of the central stellar cluster at the position of Sgr A*. This makes it likely that these K∼14.5 stars are (if they are on the main sequence) O9 - B0.5 stars with masses of 15 to 20 $M_\odot$. Weaker CO bandhead absorption in the southern part of the cluster (S10/S11 area) is most likely due to contributions from neighbouring stars. Eckart, Ott & Genzel (1999) also report the detection of Brγ line emission at the position of the central stellar cluster which could be associated with the 'mini-spiral' rather than with the Sgr A* cluster itself.

4. Enclosed Mass

Together with the VLBI maser nucleus of NGC 4258 (Greenhill et al. 1995, Myoshi et al. 1995) the compact dark mass in the Galactic Center is currently the best and most compelling case for the existence of super-massive nuclear black holes (Maoz 1998). The new anisotropy-independent mass estimates (Leonard-Merritt estimators of the proper motions; see Fig.2; a detailed descriprion of the symbols in Fig.2 can be found in Genzel et al. 2000) as well as Jeans modeling (explicitely including the mentioned traces of velocity anisotropy) result in a compact (<0.0058 pc) mass close to $3.0\times10^{6} M_\odot$with a mass density of $3.7\times10^{12} M_\odot pc^{-3}$ (Genzel et al. 2000). One can show that any cluster of that mass at such a high density cannot be stable over more than 10^6 to 10^7 years (Maoz 1998; see also Fig.5). Equipartition arguments that include the known proper motions of the radio source Sgr A* (<16km/s, Backer 1996, Reid et al. 1999, Genzel et al. 2000) and the estimated mass and known proper motion of the inner fast moving stars (Eckart, Genzel 1997, Genzel et al. 1997) result in a lower limit of at least 10^3 $M_\odot$ that has to be associated with Sgr A*.

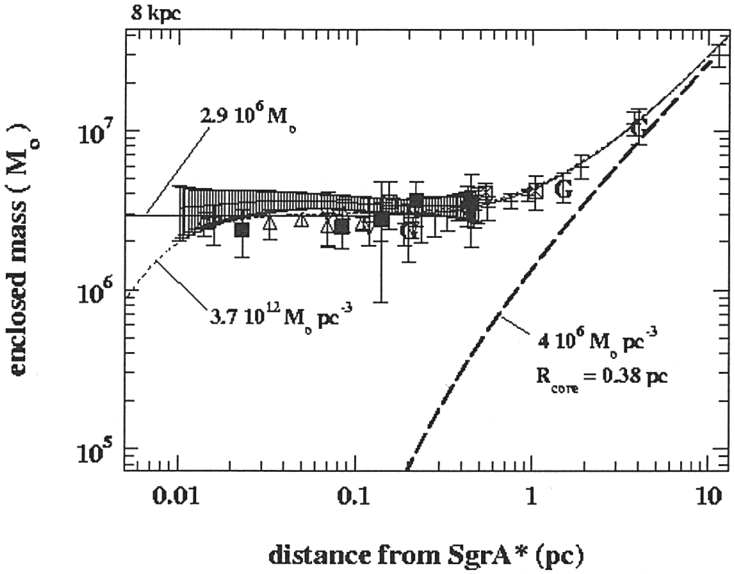

Figure 2. The enclosed mass contained in circular apertures plotted as a function of their radius. The apertures are centered on the position of SgrA*.

The current conclusion is that this mass is most likely a single massive black hole (see also discussion in section 7).

Due to the limited number of detected stars we currently use a minimum radius for our determination of the mass and mass density of 0.01 pc (0.25"). The α=5 Plummer model of a dark cluster results in a core radius of such a hypothetical cluster of r_{core}=0.0058 pc (0.23") and corresponding central density of $3.7\times10^{12}M_\odot pc^{-3}$ (see above and Fig.2). The star S2 currently (2000) is at a distance of only about 60mas from the center - 4 times closer than the minimum radius mentioned above. If the orbit of S2 remains consistent with a compact mass of $3.0\times10^6M_\odot$ the mass density is at least 64 times higher i.e. $2.4\times10^{14}M_\odot pc^{-3}$. In this case the collapse life time would shrink to only a few 10^6 years, making the Galactic Center **the** strongest of all massive black hole candidates.

5. Curvature

For three sources S1, S2 and S8 (see Fig.1 and Fig.4) we have detected a curvature of the orbits on the 1.5σ to 3σ level. In Fig.3a we show the offset positions for S2 in declination and right ascension as a function of time. Linear fits to the first and second half of the data set clearly result in different slopes. Their difference devided by the time difference between the two invervalls is a direct measure of the orbital curvature. The data was divided in an early (1992 - 1996) and a late epoch (1997-2000). For each epoch we calculated three velocities (from data in different sub-intervalls). Individual accelerations a were then

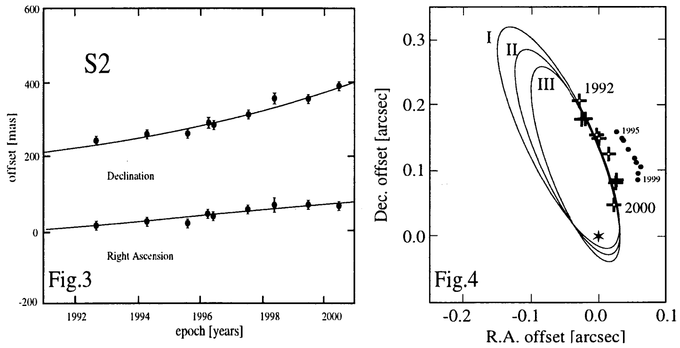

Figure 3. a) The relative positions of S2 in Dec. and R.A. as a function of the observing epoch. The variation in slopes defines the orbital curvature. b) Three inclined Keplarian orbits that have line of sight velocities and separations from SgrA* as mentioned in the text. The orbits represent the range of best fits to the 1992 to 2000 SHARP data for S2. From the proper motions alone we find a velocity of >860 km/s - the results of the orbit modeling suggests a full space velocity of up to ~1050 km/s. For comparison the data presented by Ghez et al. (2000; Fig.2) for S2 are shown shifted by 30mas to the west.

estimated from quotients of all combinations of velocity and time differences between the early and late epoch. For S2 we find a curvature of 2.3±0.9 mas/yr^2 corresponding to an acceleration of 95 km/s/yr. For S1 and S8 we find a curvature of 3.8±2.4 mas/yr^2 and 3.3±1.1 mas/yr^2, respectively. The slopes are in agreement with those expected from fits of Keplerian orbits to the data (for S2 shown in Fig.3a,b). As an example the SHARP data now starts to constrain the possible orbits for S2. For S2 a likely solution (obtained from least-square fits of Keplerian orbits to the data) is that this star has a line of sight offset of 0.008 to 0.009 pc and a line of sight velocity in the range of -200 to -600 km/s. Due to current uncertainties in the inclination a combination of -0.008 to -0.009 pc and 200 to 600 km/s is possible as well. Three possible orbits that represent good fits to the data are shown in Fig.3b. The current data and analysis indicate that S2 is aproaching its periastron.

For each of the three sources S1, S2, and S8 the acceleration values define an acceleration vector that should point towards the central source. The errors define an error cone. For the presentation in Fig.4 we chose a common error cone (±$\Delta\phi$ with $\Delta\phi$=35^o; dashed lines) for all sources that corresponds to twice the mean width of the three individual error cones. The two contours shown in Fig.4 are the 1/e (inner contour) and 1/2e (outer contour) of a probability proportional to $exp(-\chi^2_{S1} - \chi^2_{S2} - \chi^2_{S8})$ with $\chi^2 = (\phi - \phi_0)^2/\Delta\phi$ and ϕ_0 being the angle of the acceleration vector and ϕ the angle of any radial line within the corresponding cone. The central cross in Fig.4 marks the position of SgrA*. The width of the cross correspond to ±50 mas combining the uncertainty on the IR position of SgrA* of ±20mas and an estimated uncertainty in the overall mean position of the individual sources S1, S2, S8 as shown in Fig.4. The large cross in thin lines represents the median location and median errors of the positions of all combinations of intersection points of the central and boundary lines of the

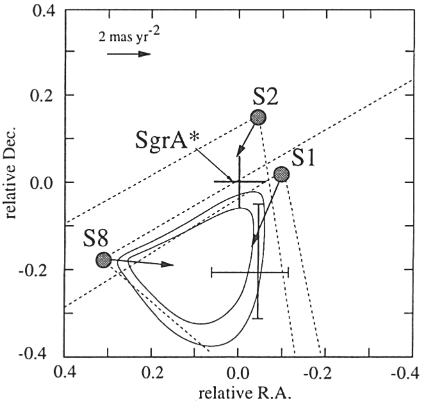

Figure 4. The acceleration vectors of the sources S1, S2, and S8 as derived from the current SHARP data. An explanation of the symbols is given in the text. The motion of the stars is consistent with orbits around a central $3\times10^6 M_\odot$ object.

three error cones. The accelerations are consistent with recent results by Ghez et al.(2000, 1999) and imply that the three sources orbit a central, compact mass.

6. Is there an IR counterpart of Sgr A*

Menten et al. (1996) identified 5 H_2O/SiO maser stars within the central 20" of Sgr A* and identified the position of the radio source Sgr A* to within about ±20 milliarcseconds. It is located within the central stellar cusp-like cluster. In 1994, 1995 and March/April 1996 it did not coincide with any of the $\approx 15^{mag}$ sources therein. However, in the SHARP June 1996 and the July 1997 data the is evidence for an additional source between S1, S2, and S3 - right at the radio position of Sgr A* . In the diffraction limited SHARP maps taken with a 50mas and a 25mas pixel scale this source manifests itself as an extension of S1 toward S2 (Genzel et al. 1997). In the high SNR (resulting from a combination of several 10.000 frames) ~70 mas FWHM maps presented in Genzel et al. (1997) the additional source is clearly separated from S1, S2, and S3. This object may represent the best candidate for the long sought for NIR Sgr A* counterpart.

7. NIR Interferometry and the Galactic center

Since the central dark mass concentration is very compact and most likely a point mass NIR interferometry is ideally suited to further determine the compactness of the enclosed mass, and to search for and monitor the flux of a Sgr A* NIR counterpart. Any configuration other than a point mass must have a central density of $\rho_h > 3.7\times10^{12}\ M_\odot pc^{-3}$ and a core radius of <5.8 milliparsec (see section 4). For this estimate we have adopted a Plummer model with a density profile that decreases as $\alpha \sim -5$ outside of the core radius. The point corresponding to this mass and mass density is shown in Fig.5 and labeled with GC1. Backer (1996) has shown that the proper motion of SgrA* itself is <16 km s^{-1}, or 50 to 100 times smaller than the fast-moving stars in its vicinity. Thus the mass enclosed within the radio size of SgrA* (less than 1 A.U.) is $\sim 10^3$ or $\sim 10^5$

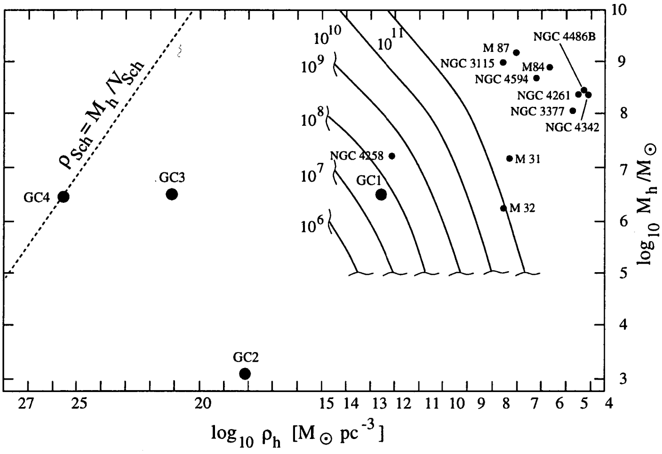

Figure 5. Mass density plotted as a function of compact dark mass at the center of the Milky Way. The contour lines indicate the maximum possible lifetime of a corresponding dark cluster (Maos 1998) as a result of evaporation and destruction due to physical collisions. The points present the current data for observed black hole candidates. NGC 4258 and our Galaxy are the best candidates for a point mass. GC1, GC2, GC3, GC4 are discussed in the text.

$M_\odot$, depending on whether the radio source is in momentum or energy equilibrium with the fast-moving stars (Genzel et al. 1997; Reid et al. 1999). Even the more conservative of these two limits implies a central density in excess of 10^{18} $M_\odot pc^{-3}$ (GC1 in Fig.5). If the total mass of $\sim 3\times10^6$ $M_\odot$ is contained within such a small radius the corresponding mass density is 3000 times higher (GC3). As a comparison the Schwarzschild density is plotted as a function of mass. This is the density of the black hole as calculated by dividing its mass by the volume contained within the Schwarzschild radius (GC4). For a black hole mass of $3\times10^6 M_\odot$the corresponding Schwarzschild mass density is 3×10^{25} $M_\odot pc^{-3}$.

Interferometry with 8m class mirrors will provide the required sensitivity and accuracy to separate the Sgr A* NIR counterpart from neighboring stars. In the case of the LBT the unprecedented combination of high sensitivity, high angular resolution over a large field of view will allow to detect significant motions in most of the 600 stars brighter that m_K<14 covering the inner parsec of the central stellar cluster. Combined with imaging spectroscopy this may result in a large number of sources with measurements of all three velocity components. Full space velocities are essential to improve the current analysis and to further analyze the dynamical properties of the late type stars and the inner bright higher velocity He I stars. This will undoubtedly help to determine the origin of the HeI stars which may represent remains of a dissolved young cluster (see Gerhard 2000, astro-ph/0005096). Spectra of the fast moving stars will be of special importance. Knowing their full space velocity will result in complete information on on their orbits.

It is even more desirable to find and track the motion of stars that are as close to the center as possible. Orbital time scales at the resolution limit of the

LBT interferometer could be in the range of a few months. A detection of a relativistic or Newtonian periastron shift would ultimately result in a determination of the compacntess of the encolsed central mass (Rubilar & Eckart 2000 see also Fragile & Mathews 2000). The prograde relativistic periastron rotation is of the order of 17 arcminutes per revolution for a 60mas (2.4 mpc; orbital time scale 6.8 years) orbit with an excentricity of ϵ=0.9. For a 15mas (0.6 mpc; orbital time scale 0.9 years) orbit with the same excentricity the shift is already of the order of 1.1 degrees per revolution. Periastron shifts of 2 degrees could be observed with the LBTI with $\sim 1\sigma$/yr or better.

In the case that a small amount of the compact mass is extended the retrograde Newtonian periastron shift would be much larger. For orbits with half axis as above and modest excentricity of ϵ=0.5 the shift may amount to several 10 degrees per revolution. This assumes that the extended mass is contained in a compact cluster of less the 6 mpc core radius. Comparing the relative magnitues of the relativistic and Newtonian periastron shift for S2-like stars one finds that if only about 0.1% of the currently measured $3\times10^6 M_\odot$ is extended the periastron shifts of the two mechanisms compensate each other. The percentage will be higher for stars on closer orbits of similar of even higher eccentricity.

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