The Galactic Center
ASP Conference Series, Vol. 102, 1996
Roland Gredel, ed.

Observations of the Galactic Center with SHARP: First Stellar Proper Motions

A.Eckart and R.Genzel

Max-Planck Institut für extraterrestrische Physik Garching, FRG

Abstract. Speckle interferometric observations of the Galactic Center in the near-infrared with SHARP at the NTT have lead to the detection of stellar proper motions. The proper motion and radial velocity dispersions indicate a $2.4\times10^6 M_\odot$dark mass with a mass density of at the center of our Galaxy. This mass is either a core collapsed cluster of 10-20 $M_\odot$stellar black holes or, most likely, a single massive black hole.

1. Introduction

Over the past 5 years we have been conduction a program to study the properties of the central nuclear stellar cluster via near-infrared high spatial resolution measurements using the MPE speckle camera SHARP at the at the 3.5 m New Technology Telescope (NTT) of the European Southern

Observatory (ESO). The SHARP observations resolved the 2.2μm emission in the central parsec into about 600 stars (Eckart et al. 1992, 1993, 1994, 1995) and gave the first evidence for an extended infrared source (Sgr A*(IR)) at the position of the compact radio source Sgr A* (R) which is the most likely candidate for a possible massive black hole at the center of our Galaxy (e.g.Lo 1989). This central source was resolved into a small cluster of at least half a dozen stellar objects (Eckart et al. 1995). Imaging spectroscopy revealed a small cluster of luminous and probably massive, blue supergiants (Allen, Hyland, and Hillier 1990, Krabbe et al 1991). Sellgren et al. (1990) found evidence that the depth of the 2.3μm CO bandhead absorption decreases in the central 10", perhaps indicating a lack of late type stars there.

Over two decades now the observational evidence for a dark central mass concentration at the core of the our Galaxy has been steadily growing via studies of radial velocities of gas and stars (Lacy et al. 1980, Serabyn and Lacy 1985, Genzel et al. 1985, Sellgren 1990, Krabbe et al. 1995, Haller et al. 1986, Genzel 1996). By now for 222 stars within the central parsec (at 8 kpc 1"=3D0.04 pc) radial velocities are known. Genzel et al. 1996 found that a compact (core radius $\leq$0.06pc) central dark mass of 2.2 to 3.2×10^6 $M_\odot$(for a distance of 8.0 kpc) is required if the stellar motions are isotropic. Here we report the first results of a programme to determine the proper motions of stars which directly test the assumption of isotropy.

2. Observations

For this purpose we have been carrying out a program of high resolution 2.2μm (K-band) imaging at the 3.5 m New Technology Telescope (NTT) of the European Southern Observatory (ESO) in La Silla, Chile since 1991. Using a high resolution camera developed specifically for this project (SHARP, Hofmann et al. 1993), we have used speckle imaging techniques to obtain diffraction limited resolution (0.15" FWHM at 2.2.μm, ee Eckart et al. 1992, 1993, 1994 for details). The resulting images reach to K-magnitudes of about 16 and show $\approx$600 stars (dynamic range >8 mag) in the central 25" (1 pc) diameter field centered on or near Sgr A*.

3. Positional Reference Frame

Progress has been made in linking the infrared and radio reference frames for the Galactic Center. We identified 5 H_2O/SiO maser stars within the central 20" of Sgr A* (Menten, Reid et al. 1996). Observing in the near-infrared with SHARP there are 2 stars in the same field of view as Sgr A*. With this information the radio and IR positional reference frame can now be linked to better than one 50mas SHARP pixel. We determined the position of Sgr A* in the NIR to within $\approx$40 mas EW, and $\approx$25 mas NS. This analysis indicates that Sgr A*(R) is not coincident with any of the K=3D15^m members of the stellar cluster in the central 2". However, it clearly demonstrates that Sgr A* is a member of the cusplike cluster in the central 1" of the Galaxy.

4. Stellar Proper Motions

For the present study we analysed $\approx$50 independent images from observing runs in 1992.25, 1992.65, 1993.65, 1994.27 and 1995. 6. For our 50mas pixel scale PSF cross-correlation and Gaussian fitting in the raw SSA images (Christou 1991), the LUCY (Lucy 1974) deconvolved images and the diffraction limited restored maps give the same positions to within 5mas for bright isolated sources and 10mas for close multiple or very faint isolated sources.
To obtain the proper motions we proceeded as follows: Relative pixel offsets from IRS16NE were then determined for each image image from a cross correlation within the central 3×3 pixels around the peak of each star with a mean PSF of the 3 brightest stars in each image. We determined the zero order (centroid position), first order (rotation angle and pixel scale) and the three second order instrumental parameters for each coordinate and image with respect to a reference frame constructed from the 1994.27 epoch data. For this purpose the 2×6 instrumental parameters were obtained by solving an over-determined nonlinear equation for N stars via orthonormalization of the 12×N matrix. The solutions turned out to be very stable in terms of selection of the N stars, as long as N>>20>N_{min}=3D6. The fitted pixel scales differed by less than 0.5% between different images and the second order distortion parameters were of the order of less than 10^{-3}. Therefore the main fit parameters were the position of the centroid of the N stars and the camera rotation angle. After correction we

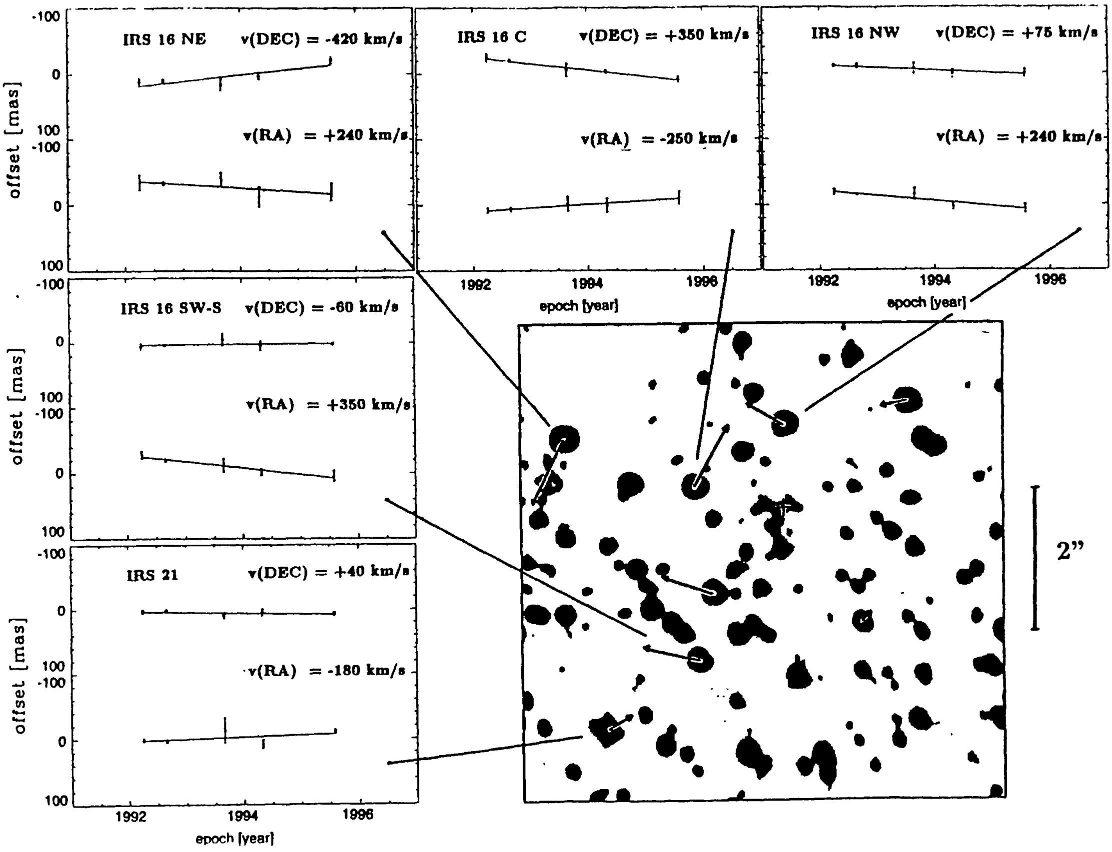


Figure 1. Proper motion measurements of selected stars in the central few arcseconds.

found that the final positional fit errors ranged between 8 and 20mas per images for the brighter, isolated stars.

In Fig.1 we show the RA- and Dec-offsets of 5 selected bright and isolated stars as a function of time, along with the fitted proper motions. The locations of these stars can be seen from the grey-scale 2.2 μm image which also shows the best fit proper motion vectors.

Significant motions ($\geq 4\sigma$) in at least one coordinate are detected for 7 stars. For 35 stars between 0.035 pc and 0.35 pc from the compact radio source Sgr A* the intrinsic proper velocity dispersion per coordinate is 160($\pm$15) km/s at a mean projected radius of 0.12 pc. This value is in excellent agreement with the recent radial velocity dispersion results and indicates that the stellar velocity field is indeed close to isotropic. The full space velocities of early type stars in the central 0.1 pc are of the order of 500 km/s. In addition to the best 7 cases with motions statistically detected at least at the 4σ level, we have included

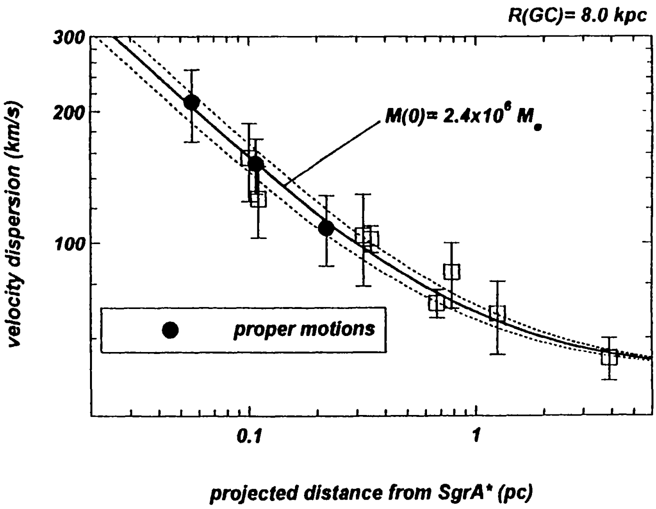


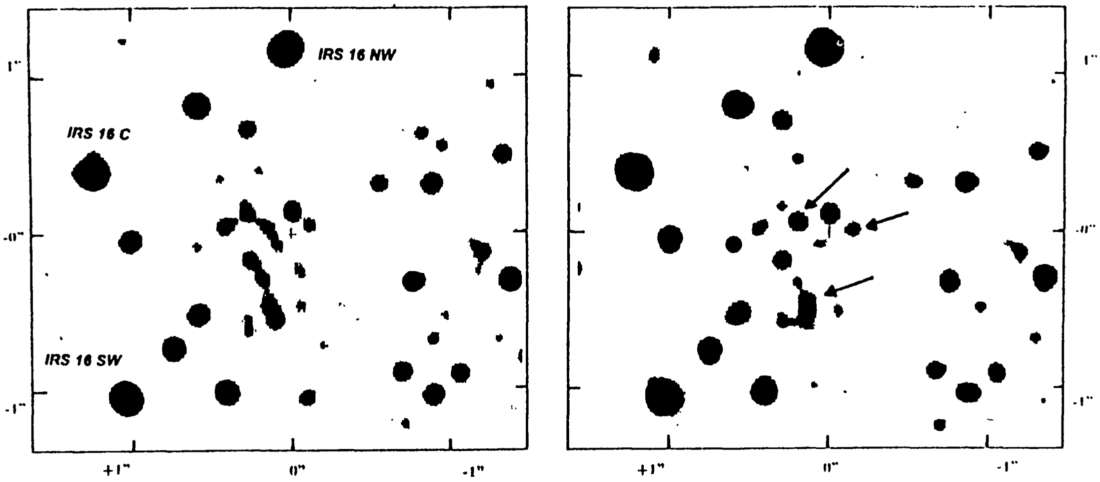
Figure 2. Projected stellar velocity dispersions as a function of projected distance from Sgr A*.

for an un-biased analysis another 28 isolated stars at radii between 0.9 and 8.8 from Sgr A* . Eight of those are HeI emission line stars, five are late type supergiants/AGB stars. Our analysis also shows that the velocity dispersion is very similar in all three coordinates and hence any anisotropy of the stellar motions must be small. For Galactic Center distances between 7 and 9 kpc the proper motion and radial velocity dispersion for the thirteen stars agree very well with 163(±25) km/s and 187(±40) km/s, respectively. In Fig.2 we plot of radial and proper motion velocity dispersion as a function of projected distance from Sgr A*, including 35 stars from this study, and 222 stars for which radial velocity stars are available (Genzel et al. 1996, McGinn et al. 1989, Rieke and Rieke 1988, Lindqvist, Habing and Winnberg 1992).

Inspecting the proper motion vectors within the central few arcseconds it appears that the (early type, HeI) stars in the IRS16 cluster show a coherent streaming pattern that may be interpreted as rotation about a centroid located within 0.5"(0.02 pc) of Sgr A*. In contrast the late type stars near the center (which are likely at much larger true distance; Sellgren et al. 1990, Haller et al. 1986, Genzel et al. 1996) show no such pattern and also much smaller velocities.

5. Evidence for a Massive Black Hole

Fitting to the projected velocity dispersion data in Fig.2 a model with a central point mass plus an extended isothermal cluster of dispersion ≈50 km/s, or calculating the enclosed masses from the Bahcall-Tremaine projected mass estimator, the Virial theorem and the Jeans equation results in central masses between 2 and 2.7×10^6 $M_\odot$within a linear distance of 0.15 pc, and between 1.4 and 3.2×10^6 $M_\odot$within 0.075 pc of the dynamic center. For central dark mass the combined data indicate a density of at least 6.5×10^9 $M_\odot pc^{-3}$ and a core radius less than 0.035pc.



1994.3 1995.6

Figure 3. Comparison of the best 2μm maps of the central Sgr A* cluster, taken in 1994 and 1995. Arrows indicate stars with high velocities.

Large proper motions consistent with a large central mass are also indicated by a structural comparison of the images of the stellar cluster in the central 2". Fig.3 shows grey-scale representations of our best images (1994,1995) of the Sgr A*(IR) cluster (Eckart et al. 1994) in the direct vicinity of the compact radio source. There are significant changes of the positions of the stars very close to Sgr A* (radii 0.01 pc), suggesting $>10^3$ km/s motions. This evidence will be tested by future observations, but the data are consistent with a location and concentration of the $\approx 2.4\times10^6 M_\odot$ dark mass directly on Sgr A*.

The Galactic Center, along with the mega-maser galaxy NGC 425 (Greenhill et al. 1995, Myoshi et al. 1995) are now known to contain dark masses with densities approaching 10^{10} $M_\odot pc^{-3}$. Given our knowledge about the stellar content of the Galactic Center, it appears unlikely that the mass concentration is a cluster of solar mass remnants (neutron stars or white dwarfs, Genzel et al. 1996). It is either a core collapsed cluster of 10-20 $M_\odot$stellar black holes (Morris 1993, Lee 1995) or, most likely, a 2.4×10^6 $M_\odot$ single massive black hole.

Acknowledgments. A number of people at MPE and ESO have been involved in making this experiment possible and carry it out. We would like to especially thank N.Ageorges, S.Drapatz, R.Hofmann, A.Krabbe, B.Sams, L.E.Tacconi-Garman, P.M. Duhoux and H.van der Laan. We thank L.Tacconi and N.Thatte for valuable comments.

Discussion

Rene Mendez': In your astrometric solution I noticed that you have not included color and/or magnitude terms. Color terms will arise because of different color refraction, while magnitude terms could arise because of the Cassegrain nature of NTT.

A. Eckart: The sources in the Galactic Center have very similar apparent colors due to the large amount of extinction. Also they have very similar magnitudes over the different epochs. Possible residual effects due to color and magnitude are taken care of by the second order terms in our solution. Furthermore we are currently only interested in the relative proper motions not in the absolute once, so that differential color and magnitude variations will have little effect on our solution.

References

Allen, D.A., Hyland, A.R. and Hillier, D.J., MNRAS 244, 706 (1990)

Christou, J.C. , Experimental Astr. 2, 27 (1991)

Eckart, A., Genzel, R., Krabbe, A., Hofmann, R., van der Werf, P.P. and Drapatz, S. , Nature 355, 526 (1992)

Eckart, A. Genzel, R., Hofmann, R., Sams, B.J. and Tacconi-Garman, L.E. , Ap.J. 407, L77 (1993)

Eckart, A. , Genzel, R., Hofmann, R., Sams, B.J., Tacconi-Garman, L.E. and Cruzalebes, P. , in The Nuclei of Normal Galaxies, eds. R.Genzel and A.I. Harris, Kluwer (Dordrecht), 305 (1994)

Eckart, A. Genzel, R., Hofmann, R., Sams, B.J. and Tacconi-Garman, L.E. , Ap.J. 445, L26 (1995)

Genzel, R., Watson, D.M., Crawford, M.K. and Townes, C.H., Ap.J. 297, 766 (1985)

Genzel, R., Thatte, N., Krabbe, A., Kroker, H. and Tacconi-Garman, L.E. 1996, Ap.J. in press

Greenhill, L.J, Jiang, D.R., Moran, J.M., Reid, M.J., Lo, K.Y. and Claussen, M.J., Ap.J. 440, 619 (1995)

Haller, J.W., Rieke, M.J., Rieke, G.H., Tamblyn, P., Close, L. and Melia, F., Ap.J. 456, 194 (1986)

Hofmann, R., Blietz, M., Duhoux, P. , Eckart, A., Krabbe, A. and Rotaciuc, V. , in Progress in Telescope and Instrumentation Technologies, ed. M.H. Ulrich, ESO Report 42, 617 (1993)

Krabbe, A. et al., Ap.J. 447, L95 (1995)

Krabbe, A., Genzel, R., Drapatz, S. and Rotaciuc, V., Ap.J. 382, L19 (1991)

Lacy, J.H., Townes, C.H., Geballe, T.R. and Hollenbach, D.J., Ap.J. 241, 132 (1980)

Lucy, L.B. , A.J. 79, 745 (1974)

Lee, H.M., MNRAS 272, 605 (1995)

Lindqvist, M., Habing, H. and Winnberg, A. 1992, Astr.Ap. 259, 118 (1992)

Lo, K.Y., "The Center of the Galaxy", (ed.) Morris, M., (Kluwer:Dortrecht), p.527. (1989)

McGinn, M.T., Sellgren, K., Becklin, E.E. and Hall, D.N.B. , Ap.J. 338, 824 (1989)

Morris, M., Ap.J. 408, 496 (1993)

Rieke, G.H. and Rieke, M.J., Ap.J. 330, L33 (1988)

Reid, M., Ann.Rev.Astr.Ap.31,345 (1993)

Sellgren, K., McGinn, M.T., Becklin, E.E. and Hall, D.N.B., Ap.J. 359, 112 (1990)

Serabyn, E. and Lacy, J.H., Ap.J. 293, 445 (1985)

Menten, K.M., Eckart, A., Reid, M.J. and Genzel, R., in prep. (1996)

Myoshi, M., Moran, J.M., Hernstein, J., Greenhill, L., Nakai, N., Diamond, P. and Inoue, M. , Nature 373, 127 (1995)