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First results from SPIFFI. I: The Galactic Center

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Abstract. In this and a companion paper (Eisenhauer et al. 2003b), we discuss some of the scientific results obtained during the SPIFFI guest instrument runs at the VLT in March and April 2003. This paper concentrates on results for the Galactic Center. Section 1 discusses the stellar population of the Galactic Center, in which we clearly detect, for the first time, an early, hot WN star, as well as a large number of WC stars. Analysis of the stellar population indicates that the young stars in the Galactic Center originated in a high metalicity starburst about 5 Myr ago. A surprising result is that essentially all young stars in the central 10″ belong to one of two well defined, rotating stellar rings/disks. Section 2 outlines a new determination of the distance to the Galactic Center which is essentially free of systematic uncertainties in the astrophysical modelling, and gives R_o as 7.94±0.42 kpc.

Key words: Galaxy: center

1. Stellar populations and dynamics of the Galactic Center star cluster

The center of the Milky Way is a unique laboratory for studying physical processes that are thought to occur generally in galactic nuclei (see Ott et al. 2003). High resolution, near-IR integral field spectroscopy offers a new opportunity for exploring in detail the properties, dynamics and evolution of the nuclear star cluster in the immediate vicinity of a supermassive black hole. We observed the central parsec region with SPIFFI (Tecza et al. 2000) during two nights (for about an hour each) and created two mosaics of the central region, one covering the central parsec (≈35″) with 0.25 pixel resolution (FWHM ≈0.75″) at R≈1300 in the combined H&K mode, and one of the central ≈10″with 0.1 pixels at R≈3500 in K. In the latter case, the effective spatial resolution was a remarkable 0.27″ FWHM (probably because of a relatively small outer scale of turbulence at the time of the observations), providing us with the by far deepest (K≈15-16) and highest resolution imaging spectroscopy data set obtained up to this time.

With this new data set it is possible to probe in more detail the stellar composition of the central parsec. We find about 40 massive early type stars in the region mapped, mostly from stellar emission lines, thereby almost doubling the number of spectroscopically identified early type stars. Previous spectroscopic observations, including data taken with 3D (Weitzel et al. 1996), detected the brightest emission line stars, mostly of type WN9-10, or Ofpe and about half a dozen luminous blue variables (LBVs) (e.g. Genzel et al. 2000, Gezari et al. 2002, Ghez et al. 2003, Paumard et al. 2001). Our new data clearly detect, for the first time, an early, hot WN star (WN5/6: T_{eff}≈40-45 kK), as well as a large number of WC stars (Fig.1, 2). The ratio of WC to WN stars is about 1, and the ratio of (narrow-line) LBVs, such as IRS16C, NW and SW, to WN stars is about 0.5. Despite the much superior high resolution, inner cube (much less susceptible to veiling of stellar Brγ absorption by the diffuse Brγ emission from the SgrA West HII region), there is (still) no evidence for main sequence O-stars, with the exception of the innermost arcsecond (see below). The WR/O star ratio in the nuclear star cluster thus appears to be greater than about 20. Several of the mid-IR excess stars in the central region, including the brightest 10μm source in the central parsec, IRS 3, are WC stars, in agreement with the earlier proposal of Figer et al. (1999) for dusty mid-IR excess stars in the Quintuplet cluster. As an early type WC star (WC5/6) IRS3 may be a prime

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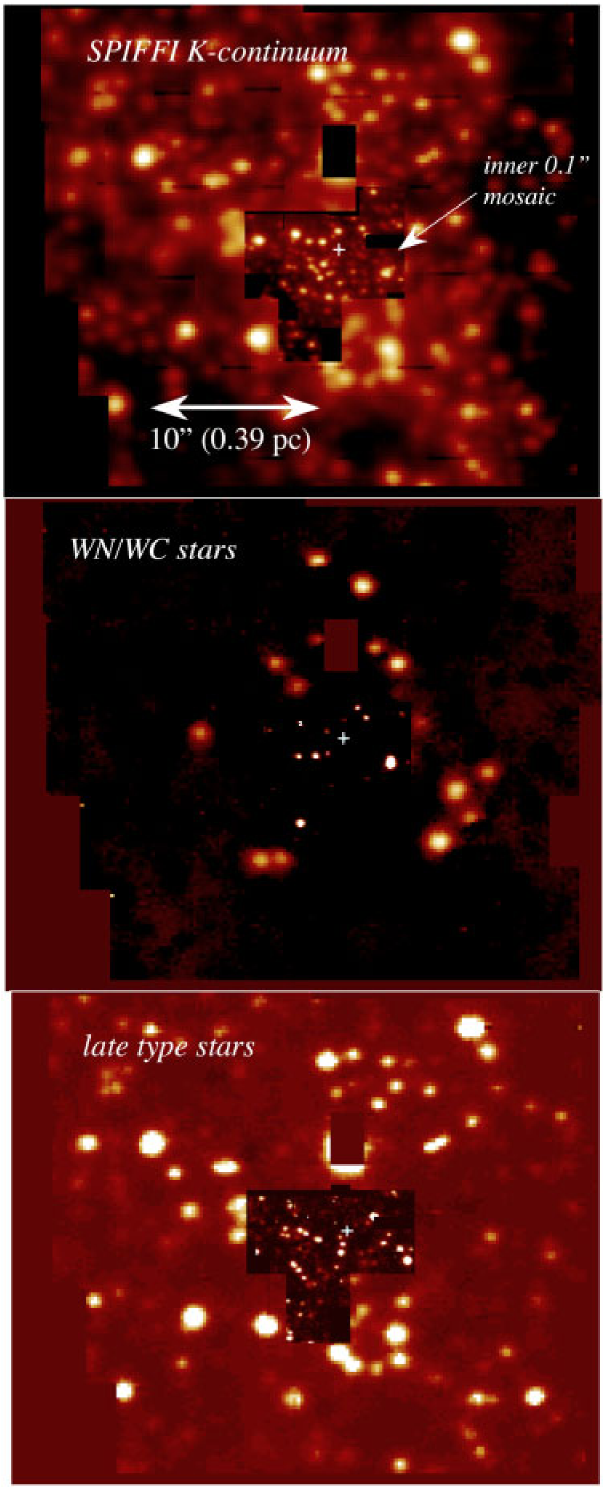

Fig. 1. (online colour at www.interscience.wiley.com) SPIFFI continuum and line images of the Galactic Center. In all images east is to the left, and north is up, the cross marks the position of the supermassive black hole/SgrA*. Top: K-band image, of the central parsec, constructed from an outer mosaic of 0.25 pixel data cubes ($\approx$0.75$''$ resolution), as well as an inner mosaic of the central $\approx$10$''$, at a pixel scale of 0.1$''$ and FWHM 0.27$''$. Middle: continuum subtracted line image near HeI 2.113μm, marking the positions of the Wolf-Rayet (WN, WC) stars in the cluster. Bottom: continuum subtracted CO 0-2 absorption line flux, marking the positions of late type stars: red giants and supergiants, and (extreme) asymptotic giant branch (AGB) stars.

candidate for exploding as a supernova in the next few 10^4 years. Other such dusty sources can now be shown from their spatial distribution and proper motions to be luminous early type stars that happen to move into and strongly heat the dust in the HII region (Tanner et al. 2002, Genzel et al. 2003).

The unique simultaneous H&K capability allows us to unambiguously distinguish moderately late type (K2-5) supergiants from AGB stars. Both types have equivalent near-IR flux densities. The much later type (M4-9 III) AGB stars, however, exhibit deep water vapour, steam troughs between the H and K-bands that can be easily recognized in our data (source IRS9 in the lower left inset of Fig.2). These data finally settle a long debate about the properties of the brightest late type stars in the central parsec: of the dozen or so K<10.5 late type stars (M_K<-7.2), a maximum of two are supergiants, the rest are clearly AGB stars.

The large ratio of Wolf-Rayet stars to O-stars, the large WC/WN ratio, and the large blue to red supergiant ratio, in comparison with recent star cluster models (e.g. Schaerer & Vacca 1998), indicate that the young stars in the Galactic Center originated in a high metalicity starburst about 5 Myr ago, in agreement with Krabbe et al. (1995). The unusually large number of luminous LBV stars, most of them in the central IRS16 cluster, suggests that this burst had a duration of several Myr and that the massive stars may be fast rotators, thereby allowing the presence of very massive ($\geq$100 $M_\odot$) stars near the Humphreys-Davidson limit of stability.

The combination of proper motions and radial velocities of the massive stars allows a detailed analysis of their dynamical properties. The surprising result (Genzel et al. 2003) is that essentially all young stars in the central 10$''$ belong to one of two well defined, rotating stellar rings/disks. The two young star disks are at fairly large angles with respect to each other but share a common, counter-Galactic rotation (Fig.3). Combined with the fact (see above) that both disks have essentially the same stellar content, including the ratios of the specific Wolf-Rayet subclasses, these data offer valuable constraints on one of the most perplexing current riddles in Galactic Center research: how can the central 0.1-10$''$ host so many young, massive stars? The environment and the presence of the strong tidal forces from the black hole make star formation from cloud collapse extremely difficult, if not impossible, and mass segregation of the massive stars from further out is excluded because of their short lifetimes. The presence of two, coeval stellar disks would argue that a highly dissipative and sudden event was at play in the formation of the massive stars. One possibility is the collision of two infalling clouds, followed by the settling of the remaining debris into two separate disks orbiting the central black hole. Further angular momentum loss, cooling and contraction may then eventually have pushed the gas disks into the regime of gravitational instability, thus overcoming the tidal shear from the hole.

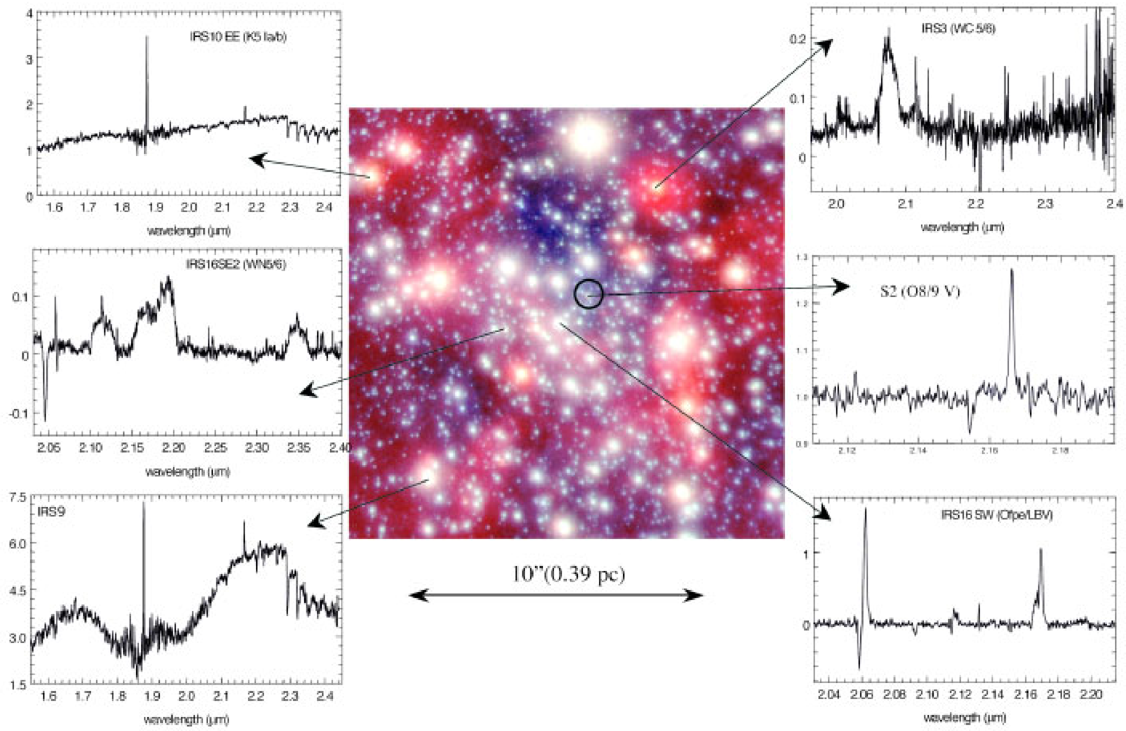

Fig. 2. (online colour at www.interscience.wiley.com) Selected SPIFFI spectra (corrected for atmospheric absorption but not for interstellar extinction) superposed on a NACO H/K/L' image of the central region. The spectra display the wide range of stellar types found in the cluster, ranging from late type main sequence O stars (the star S2 near SgrA*, oval in image), to luminous blue variables (IRS16SW, lower right), early WN (middle left) and WC (top right) Wolf-Rayet stars, to red supergiants (the brightest star IRS7 at the top/middle of the image), bright asymptotic giant branch stars (IRS9, lower left) and normal red giants (top left). Note that in the case of the dusty WC5/6 star IRS 3 (top right) we first subtracted a strong featureless power-law to emphasize the characteristic carbon-features. The strong emission spike at 1.87μm is the HI Pα recombination line in the HII region.

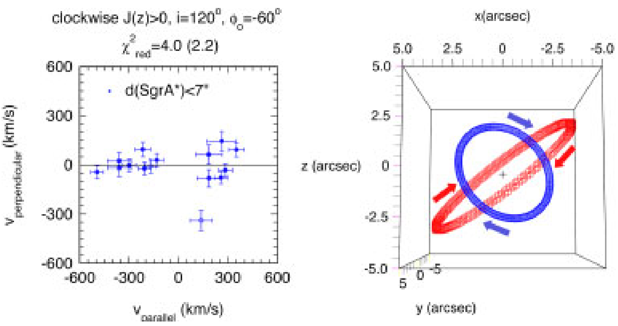

Fig. 3. (online colour at www.interscience.wiley.com) Dynamical properties of early type stars in the Galactic Center. Left: projection of three-D space velocities of clockwise (on the sky) rotating stars, perpendicular to the best fitting plane, at inclination 120° with respect to the sky, and 60° from the line of nodes, east of north. 14 of the 15 stars with three space velocities adhere to rotation in a fairly thin plane in this orientation. Likewise most of the counter-clockwise stars largely also follow a disk rotation pattern. Right: Orientation of the two young star disks. East-west on the sky is left-right, and the line of sight direction is up-down (the observer sits at z=-∞). The two disks counter-rotate with respect to each other, but both exhibit rotation that is counter to Galactic rotation (adapted from Genzel et al. (2003).

2. A geometric determination of the distance to the Galactic Center

The distance between the Sun and the Galactic Center (R_o) is a fundamental parameter for determining the structure of the Milky Way. Through its impact on the calibration of the basic parameters of standard candles, such as RR Lyrae stars, Cepheids and giants, the Galactic Center distance also holds an important role in establishing the extragalactic distance scale. Ten years ago Reid (1993) summarized the state of our knowledge on R_o. At that time the only primary (geometric) distance indicator to the Galactic Center came from the 'expanding cluster parallax' method applied to the H_2O masers in SgrB2 (believed to lie within $\approx$0.3 kpc of the Galactic Center), resulting in values of 7.1 and 6.5 kpc for the distances to the masers in SgrB2(N) and SgrB2(M), respectively, with a combined statistical and systematic (1σ) uncertainty of $\pm$1.5 kpc. In addition there existed a number of secondary (standard candle) determinations, based on RR-Lyrae stars, Cepheids, globular clusters and giants, as well as a number of tertiary indicators, derived from theoretical constraints (e.g. Eddington luminosity of X-ray sources, Galaxy structure models). Since then Genzel et al. (2000) reported a somewhat improved primary (statistical parallax) distance,

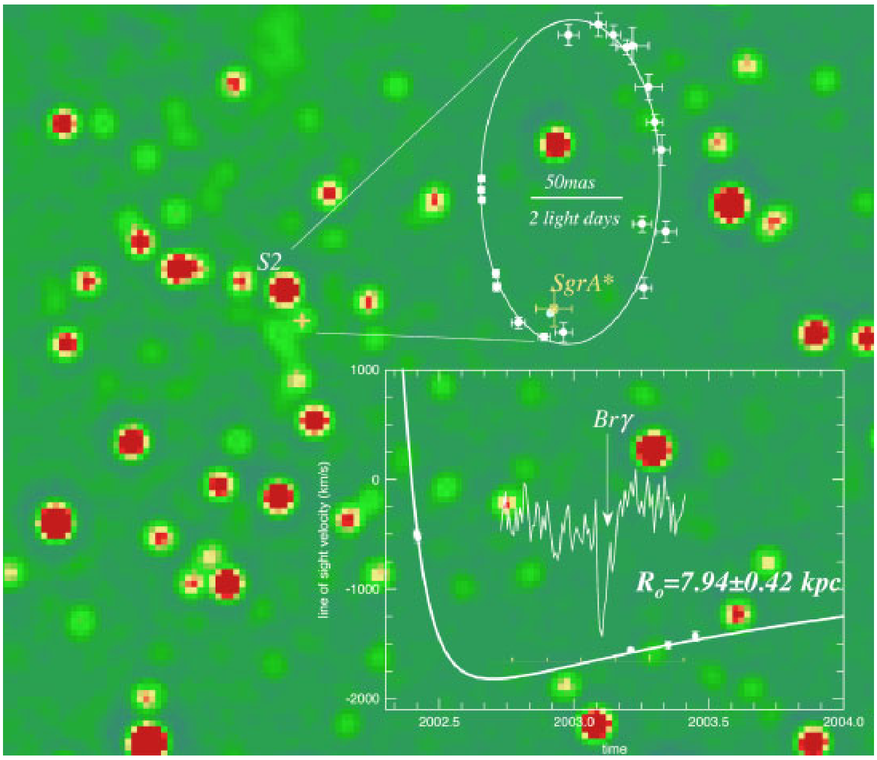

Fig. 4. (online colour at www.interscience.wiley.com) Geometric determination of the Sun-Galactic Center distance R_o from a precision measurement of the orbital parameters of the star S2 that is orbiting the central supermassive black hole. The star's line-of-sight motion is measured via the Doppler shift of the Brγ line in terms of an absolute velocity (SPIFFI data as well as spectroscopic data from NIRSPEC (Keck, Ghez et al. (2003) and from NACO), whereas its proper motion is measured in terms of an angular velocity (data from SHARP/NTT and NACO). The orbital solution ties the angular and absolute velocities, thereby yielding the distance to the S2/SgrA* binary system (adapted from Eisenhauer et al. 2003a).

based on a statistical comparison of proper motions and line-of-sight velocities of stars in the central 0.5 pc of the Galaxy. Hipparcos data have improved the uncertainties of the secondary determinations (Stanek & Garnavich 1998). The best present value of R_o is about 8 kpc, with a combined statistical and systematic uncertainty of $\pm$0.5 to $\pm$1 kpc.

The SPIFFI observations allowed us to derive the first primary distance measurement to the Galactic Center with an uncertainty of only 5%. This determination has become possible through the advent of precision measurements of proper motions and line-of-sight velocities of the star S2 (Schödel et al 2003). This star is orbiting the massive black hole and compact radio source SgrA*. As discussed by Salim & Gould (1999), the classical 'orbiting binary' technique can then be applied to obtain an accurate determination of R_o that is essentially free of systematic uncertainties in the astrophysical modelling. The essence of the method is that the star's line-of-sight motion is measured via the Doppler shift of its spectral features in terms of an absolute velocity, whereas its proper motion is measured in terms of an angular velocity. The orbital solution ties the angular and absolute velocities, thereby yielding the distance to the binary. For the analysis of our measurements we fitted the positional and line-of-sight velocity data to a Kepler orbit, including the Galactic Center distance as an additional fit parameter. In principle the dynamical problem of two masses orbiting each other requires the determination of 14 parameters: 6 phase space coordinates for each mass, plus the values of the two masses. At the present level of accuracy, four of these 14 parameters can be safely neglected: the mass of the star (since $m_*/M_{SgrA*} \approx 5\text{x}10^{-6}$) and the three velocity components of SgrA*. Likewise the uncertainty in the local standard of rest velocity ($\leq$10 km/s) can also be neglected at the present level of analysis. Including the first radial velocity data of S2 obtained by Ghez et al. (2003), the SPIFFI data and two NACO spectroscopy points obtained since April, our measurements deliver 43 data points to fit 9 parameters of the S2 orbit as well as the Galactic Center distance, resulting in R_o=7.94$\pm$0.42 kpc (Eisenhauer et al. 2003a). Our result confirms and significantly improves the earlier primary distance measurements and gives confidence in the quality and robustness of the standard candle methods that are at the key of the second rung of the extragalactic distance ladder. With further SINFONI observations of S2 and several other orbiting stars over the next five years, we expect to improve the accuracy to about 2%.

References

Eisenhauer, F., Schödel, R., Genzel, R., et al.: 2003a, ApJ 597, L121
Eisenhauer, F., Tecza, M., Thatte, N., et al.: 2003b, AN 325, 120
Figer, D., McLean, I.S., Morris, M.: 1999, ApJ 514, 202
Genzel, R., Pichon, C., Eckart, A., et al.: 2000, MNRAS 317, 348
Genzel, R., Schödel, R., Ott, T., et al.: 2003, ApJ 594, 812
Gezari, S., Ghez, A., Becklin, E., et al.: 2002, ApJ 576, 790
Ghez, A., Duchêne, G., Matthews, K., et al.: 2003, ApJ 586, L127
Krabbe, A., Genzel, R., Eckart, A., et al.: 1995, ApJ 447, L95
Ott, T., Schödel, R., Genzel, R., et al.: 2003, Messenger 111, 1
Paumard, T., Maillard, J.P., Morris, M., Rigaut, F.: 2001, A&A 366, 466
Reid, M.J.: 1993, ARA&A 31, 345
Salim, S., Gould, A.: 1999, ApJ 523, 633
Schaerer, D., Vacca, B.: 1998, ApJ 497, 618
Schödel, R., Ott, T., Genzel, R., et al.: 2003, ApJ 596, 1015
Stanek, K.Z., Garnavich, P.M.: 1998, ApJ 503, L131
Tanner, A., Ghez, A., Morris, M., et al.: 2002, ApJ 575, 860
Tecza, M., Thatte, N., Eisenhauer, F., et al.: 2000, SPIE 4008, 1344
Weitzel, L., Krabbe, A., Kroker, H., et al.: 1996, A&AS 119, 531