Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
Proceedings IAU Symposium No. 193, ©1999 IAU
K.A. van der Hucht, G. Koenigsberger & P.R.J. Eenens, eds.

Hot stars in the Galactic Center

Andreas Eckart, Thomas Ott, Reinhard Genzel, and Dieter Lutz

Max Planck Institut für extraterrestrische Physik,
D-85740, Garching, Germany

Abstract. The central parsec of our Galaxy is powered by a cluster of young massive hot stars which formed a few million years ago. Within that cluster the seven most luminous ($L > 10^{5.75}$ $L_\odot$) and moderately hot ($T < 10^{4.5}$ K) blue supergiants contribute half of the ionizing luminosity of that region. These stars probably formed when a dense cloud fell into the center $< 10^7$ years ago, was highly compressed there, and became gravitationally unstable. Over six years of high spatial resolution, near-infrared imaging and spectroscopy have made it possible to carry out a detailed investigation of the stars in the central cluster and its enclosed mass. As one result of a detailed variability study of the central cluster stars we found that the bright He I star IRS 16SW is a short-period variable with a period of ~9.72 days. It is most likely an eclipsing binary with a lower mass limit of ≥ 100 solar masses. Line of sight velocities and proper motions have been measured for these hot stars (as well as ~200 other stars) down to separations of less than five light days from the compact radio source Sgr A* at the dynamic center of the Milky Way. These confirmed measurements imply the presence of a central dark mass of 2.6×10^6 solar masses. The dark mass at the center of the Milky Way is currently the most compelling case for a massive black hole. Simple physical considerations show that this dark mass cannot consist of a stable cluster of stars, stellar remnants, substellar condensations or a degenerate gas of elementary particles but that at least 10^3 to 10^5 solar masses must be in the form of a massive black hole associated with Sgr A* itself.

1. Introduction

The Galactic Center is a unique laboratory in which physical processes relevant also for nuclei of other galaxies can be studied with the highest angular resolution possible. It is at a distance of only 8 kpc and is thus the closest nucleus of a galaxy, 100 to 1000 times closer than the nearest extragalactic systems. Of special interest are the enclosed mass located at the position of the compact radio source Sgr A* and the stellar content of the central cluster.

In the late seventies, spectroscopic observations of a mid-infrared fine structure line of Ne^+ (Wollman *et al.* 1977; Lacy *et al.* 1979) provided the first indications for a central mass concentration in the Milky Way. These measurements showed unusually large Doppler shifts (± 250 km s^{-1}) of ionized gas clouds in the central parsec, toward the maximum stellar density. As radio interferometric observations had discovered a compact, non-thermal radio source, SgrA*, in the same region (Balick & Brown 1974), a plausible interpretation — in analogy to quasars — was that the large gas velocities indicate orbital motions in the vicinity of a million solar mass black hole, coincident with SgrA* (Lynden-Bell & Rees 1971; Lacy, Townes & Hollenbach 1982). Further infrared (and radio) spectroscopic data taken by various groups in the eighties strengthened the gas dynamic evidence for this central mass concentration (*e.g.*, Serabyn & Lacy 1985; Genzel & Townes 1987). These measurements were, however, not considered compelling by many researchers in the field. In addition to gravitational forces, gas may be affected by magnetic fields, radiation pressure, stellar winds and friction with other gas components. All these phenomena are known to be present in the Galactic Center, thus making the interpretation uncertain. A more detailed analysis of the gravitational potential of the central cluster can be obtained by studying the photospheric emission of stars.

2. Nuclear cluster of massive stars

Allen, Hyland & Hillier (1990) and Forrest *et al.* (1987) reported on broad lines toward the IRS 16 complex that were due to Ofpe/WN9 stars and a luminous object 8″ SW of the central cluster – the AF star. Krabbe *et al.* (1991, 1995) found a cluster of He I stars concentrated on the IRS 16 complex and the small IRS 13 cluster about 4″ to the east of the center. Najarro *et al.* (1994, 1997) for the first time performed detailed atmospheric model calculations of the brightest central hot stars. Eckart *et al.* (1992; see also Eckart & Genzel 1997; Genzel *et al.* 1997 and references therein) obtained diffraction limited images and derived for the first time stellar proper motions in the central cluster. Beginning in the late eighties several groups began measuring radial velocities of late type, red giant and supergiants (*e.g.*, Rieke & Rieke 1988; Sellgren *et al.* 1990; Krabbe *et al.* 1995; Haller *et al.* 1996). The combination of radial velocities of the red giant and supergiants as well as the young and massive He I stars (Genzel *et al.* 1996) and proper motions resulted in a confirmation of the presence of a $3\times10^6\,M_\odot$ dark mass associated with Sgr A*. The results of the high resolution NIR imaging and the proper motions measurements have been confirmed by Ghez *et al.* (1998). New infrared spectroscopic data obtained with *ISO* allowed a more detailed analysis of the ~35 000 K radiation field of the central stellar cluster (Lutz *et al.* 1996).

Very hot and luminous stars were also found in other regions near the central cluster. Nagata *et al.* (1990) and Okuda *et al.* (1990) found the Quintuplet cluster followed by the discovery of Wolf-Rayet and luminous blue variable stars

Table 1. Basic properties of hot Galactic Center stars

	AF-star	IRS 16NE	IRS 13E1
R_* ($R_\odot$)	40	85	60
L_* ($10^5\,L_\odot$)	2.0	22.0	22.6
T_{eff} (10^4 K)	1.93	2.41	2.89
He/H	1.7	1.0	>500
$\dot{M}$ ($10^{-5}\,M_\odot \mathrm{yr}^{-1}$)	8.7	9.5	79.1
v_∞ ($\mathrm{km\,s^{-1}}$)	700	550	1000

in that region by Figer *et al.* (1995). Cotera *et al.* (1996) discovered a second cluster of hot stars near the central parsec — the Arches cluster (see also Serabyn *et al.* 1998). Figer *et al.* (1998) performed a detailed investigation of the Pistol star, one of the most luminous stars known. In Table 1 we list some of the basic properties of three stars (Najarro *et al.* 1997). In Krabbe *et al.* (1995) there are listed 12 stars of type WN9/Ofpe a number of which are pure He I stars (IRS 13E, IRS 15SW, IRS 15NE, IRS 7W, IRS 7E, IRS 16NW, IRS 34W, and IRS 33E) and 5 WC9 stars (IRS 29N, IRS 6, MPE −1.0–3.5, MPE +1.6–6.8, and MPE +2.7–6.9). The WC9 stars show a broad emission-line feature at 2.110μm as a combination of He I, C III, and N III. In addition IRS 13E shows weak 2.189μm He II emission. The detection of similar luminous stars outside the central parsec (see above references) strongly suggests that the blue supergiants He I stars are indeed, as proposed by Allen *et al.* (1990), Krabbe *et al.* (1991, 1995) and Najarro *et al.* (1997), relatively young massive stars on their way off the main sequence, and not objects that are due only to the very dense environment of the central parsec.

3. Stellar proper motions and radial velocities

An important development has been the first measurement of stellar proper motions. The near-infrared maps reveal close to 10^3 stars in the central parsec, concentrated and centered on or very near the compact radio source Sgr A*. Combining about 70 independent high resolution images between 1992 and 1998, Eckart & Genzel (1996, 1997, and unpublished) and Genzel *et al.* (1997) have derived (relative) proper motions for about 70 stars.

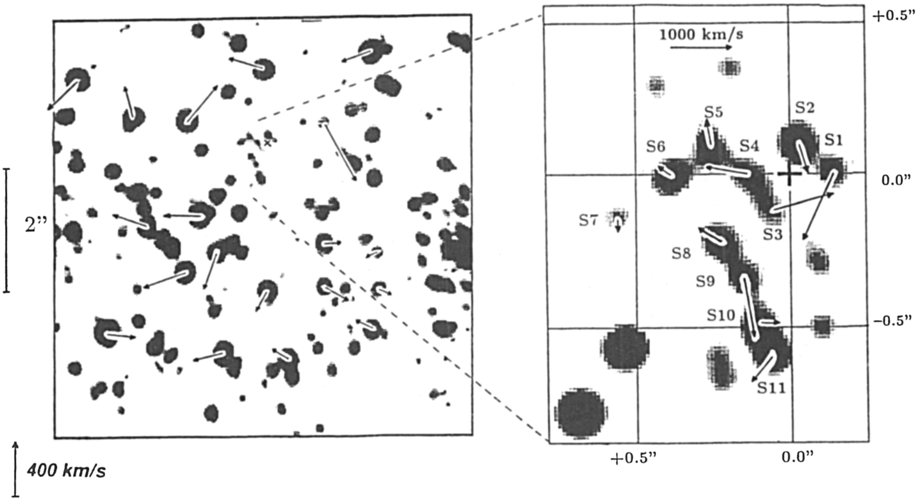


Figure 1. Proper motion vectors for the central few arcseconds (*left*) including the vectors for the central sources close to Sgr A* (at the position of the cross) in April 1994 (*right*).

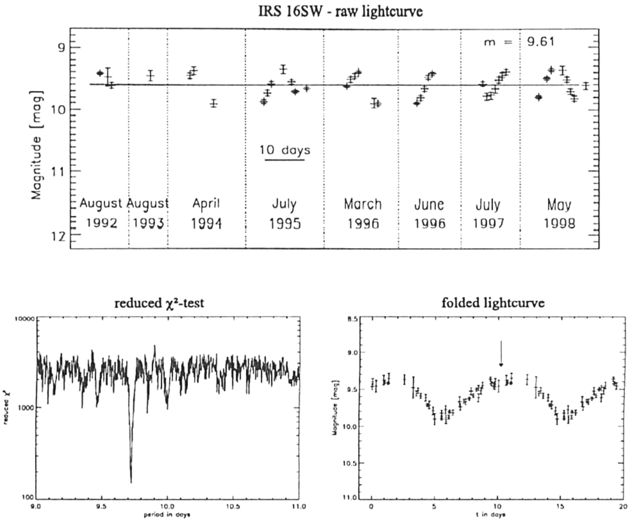
In Fig. 1 the derived proper motion vectors (without error bars) are plotted for a number of stars on the high resolution image. These results have recently been confirmed by Ghez *et al.* (1998) using the *Keck* telescope. Of special interest is the immediate vicinity of Sgr A* (right inset in Fig. 1) where one finds $a \simeq 1''$ diameter concentration of faint stars. Several of these stars in this so-called SgrA* cluster show proper motions in excess of 1 000 km s^{-1}, the fastest one (S1: $v \simeq 1400\,\mathrm{km\,s^{-1}}$) is currently also one of the stars closest to Sgr A* ($\sim 0\overset{''}{.}13$). Stars further out have velocities of only a few hundred km s^{-1}). This finding is exactly what one would expect if Sgr A* were coincident with a large compact mass. The continuous motion of the stars measured and the fact that they cluster around Sgr A*, and have similar colors as the He I stars shows that the positional changes present orbital motions in the central gravitational field and that the stars are actually located in the Galactic Center (see Eckart & Genzel 1996, 1997).

4. Spectra of the stars close to Sgr A*

Of special interest is also the nature of the high velocity stars in the central arcsecond. There spectroscopic measurements are very difficult. Low resolution spectra with $\mathrm{R} = \lambda/\Delta\lambda = 35$ have been obtained in speckle spectroscopy mode using a dual-prism as a dispersing element. Since the field around Sgr A* is very crowded most of the spectra are contaminated by other nearby stars. The central Sgr A* cluster, however, is located west of the IRS 16 complex in a void of bright stars. The separation to any bright star is larger than $1''$ and the contaminating effects of neighboring sources is comparatively small. About half of the Sgr A* cluster sources are distributed in north-south direction. This coincidence has been exploited to extract low resolution spectra of the sources S1, S2, S8 and S11 in this region Genzel *et al.* (1997). The resulting spectra are fairly flat and increase slowly in flux toward longer wavelength. CO band-head absorption is absent so S1, S2, S8 and S11 cannot be late type giant stars. While somewhat redder than the most prominent He I emission line stars in the IRS 16 complex their spectral characteristics are consistent with early type stars located in the central cluster (*i.e.*, $A_K \simeq 3$). There is also no indication for very strong line emission (or absorption) at the wavelength of the He I and/or Brγ emission lines. This is not surprising, however, as the narrow HeI/Brγ emission lines cannot be seen even in the classical He I emission line stars at the low spectral resolution. These results are fully consistent with the broad band *JHK* colors and narrow band filter data presented in Eckart *et al.* (1995). From these data one can conclude that the $K \simeq 14.5$ sources in the central Sgr A* cluster are most likely moderately luminous ($L \simeq 5\,000$–$10\,000\,\mathrm{L_\odot}$) early type stars. If they are on the main sequence they would have to be O9–B0.5 stars with masses of 15–20 $\mathrm{M_\odot}$.

5. Stellar variability:
dynamical confirmation of the upper mass cut-off

A variability study was performed doing aperture photometry on deconvolved images using three different deconvolution methods. The results are presented in detail in Ott, Eckart & Genzel (1999). With our time coverage, we are able to


IRS 16SW - raw lightcurve

reduced χ^2-test

folded lightcurve

Figure 2. Light curve of IRS 16SW and determination of its period. *Top:* Raw light curve. *Bottom left:* Result of the χ^2-test used to determine the period of 9.72 days. *Bottom right:* Data folded back into a 2-period interval. The arrow indicates the possible secondary minimum.

show that IRS 16SW is variable over time scales of a few days, showing a period of 9.72 days.

In Fig. 2, top, we show the raw light curve as deduced from our data. Since the longest observing run in May 1998 was just slightly longer than the period of IRS 16SW, we performed a reduced χ^2-test of 1 000 periods in the range between 9 and 11 days in order to get a plot of a single period. In the reduced χ^2-test, the absolute minimum corresponds to the period that best fits to the observed data. There are, of course, other local minima in the distribution which correspond to the harmonics of the period of 9.72 days at 19.44 days, 29.16 days, and so on. There is, however no minimum at a period of 4.86 days, so the period given above should be the correct value, since there is no reason why IRS 16SW should be variable in one of its harmonics.

The symmetrical shape of its light curve and a hint for a second local minimum, however, suggest that this star is an eclipsing binary. A more detailed discussion on the nature of IRS 16SW is given in Ott, Eckart & Genzel (1999). We give an estimation of the mass of IRS 16SW, with the only assumption that it is a semi-detached β-Lyrae-system as suggested by the shape of the light curve. Kepler's third law relates the period P, the separation r and the sum of the masses $M_1 + M_2$ of a 2-body system independent of inclination and ellipticity: $P^2 = 4\pi^2 r^3 G^{-1}(M_1 + M_2)^{-1}$. In this equation, G denotes the gravitational constant. Solving for the total mass, we can give a relation between the separation of the components and the mass M of the system, which yields $M = (M_1 + M_2) = \frac{4\pi^2 \cdot r^3}{G \cdot P^2}$. We now can give a *lower* limit to the mass of IRS 16SW when considering a minimum separation which can be derived the following way: The radius of IRS 16SW has been estimated by model calculations to be of the order of $\sim 90\,\mathrm{R}_\odot$ (Najarro *et al.* 1997). Assuming that the total luminosity originates predominantly from the main component, this would be the minimum separation possible for an eclipsing binary. Inserting this value into above equation then gives a lower limit to the total mass of $M = 104\,\mathrm{M}_\odot$.

Finally, we give an estimate of the spectral resolution necessary for confirming the binarity of IRS 16SW using its bright Brγ emission line feature. In the case of the separation of the two components of $130\,\mathrm{R}_\odot$, an upper limit to the orbital velocity for the system would be $677\,\mathrm{km\,s}^{-1}$. In order to spectrally resolve the Doppler-shift in the emission line, one then would need a minimum spectral resolution $\lambda/\Delta\lambda \simeq 1\,000$.

6. The radiation field

The hot stars essentially power the Galactic Center and determine the radiation field there. Near- and mid-infrared spectroscopy allow one to investigate the radiation field within the central nuclear stellar cluster. Recently the Short Wavelength Spectrometer (SWS, de Graauw *et al.* 1996) on board the *Infrared Space Observatory* made it possible to observe a wide range of ionic fine structure lines (Lutz *et al.* 1996). Three independent line-ratios ([SIV]/[SIII], [ArIII]/[ArII], [NeIII]/[NeII]) yielded an average effective temperature for the ionizing stars of $35\,000 \pm 2\,000$ K. This value implies only a small contribution of hotter stars as they have been revealed via direct near-infrared detection of WN9 to WN5 stars (Krabbe *et al.* 1995; Blum *et al.* 1995; Genzel *et al.* 1996).

Using the currently available stellar evolutionary tracks (Schaller 1992; Schaerer 1993) and hot star model atmospheres (Pauldrach, private communication) it is difficult to reproduce the measured line-ratios. Model calculations have been performed (Lutz *et al.* 1996, and private communication) for a stellar cluster with initial parameters as suggested by the observations (*i.e.*, solar metallicity, a star formation time scale of 1 Myr, an upper mass cut-off of $100\,\mathrm{M}_\odot$, an ionization parameter of $\log U = -1$ and a density of $3\,000\ \mathrm{cm}^{-3}$ as derived in Lutz *et al.* 1996). Assuming an age of the most recent burst of 7 Myr, as suggested by the stellar census, results in a [NeIII]/[NeII] line-ratio of 1 to 2, well above the the observed extinction corrected value of 0.05. While this discrepancy could be due to problems in the model atmospheres as well as the evolutionary tracks, near-infrared observations show the tracks to be responsible: Already the 7 most luminous and hottest stars (Najarro *et al.* 1997) with $T < 10^{4.5}$ K and $L > 10^{5.75}\ \mathrm{L}_\odot$ contribute half of the ionizing luminosity of the central stellar cluster. However, in the same temperature and luminosity range current stellar evolutionary tracks only predict less than 1% of the ionizing luminosity. This result remains unchanged when using tracks with twice solar metallicity (Schaller 1992) and higher mass loss (Schaerer 1993). The Galactic Center observations suggest to revise the current evolutionary tracks, in the direction of a more pronounced B supergiant phase. Such a revision would have strong implications also for the interpretation of starburst galaxies.

7. The mass distribution

A first analysis of the radial and proper motions shows that the projected velocity dispersions of a number of stars in a given annulus of projected radius p increase with $p^{-1/2}$ between $p \simeq 1$ pc and $p \simeq 0.01$ pc, as expected in the potential of a central point mass (a 'Kepler law'). The location of the largest stellar velocities (the dynamic center), the stellar density maximum, and the position of Sgr A* (now determined relative to the stars to ~30 mas, Menten *et al.* 1997) all agree to within ±0.004 pc ($0\overset{\prime\prime}{.}1$, Ghez *et al.* 1998). Between $5'' \geq p \geq 1''$ — where both radial and proper motions, sometimes from the same stars, are available — the mean velocities in all three directions agree within the error bars. This means that anisotropy of the stellar orbits — caused, for instance by predominantly very elliptical orbits — does not play a very strong role in the Galactic Center.

The final distribution of the enclosed mass as a function of true separation from Sgr A* is shown in Fig. 3 and is the result of applying the 'Jeans' equation as well as projected mass estimators to all available stellar radial and proper motion data (Eckart & Genzel 1997; Genzel *et al.* 1997). The data are fitted extremely well by the combination of a central point mass ($2.61\ [\pm 0.15_{\rm stat}, \pm 0.35_{\rm stat+sys}] \times 10^6\ M_\odot$) and a nearly isothermal stellar cluster of core radius ~0.38 pc and core density $4 \times 10^6\ M_\odot {\rm pc}^{-3}$. The latter is a good fit to the stellar

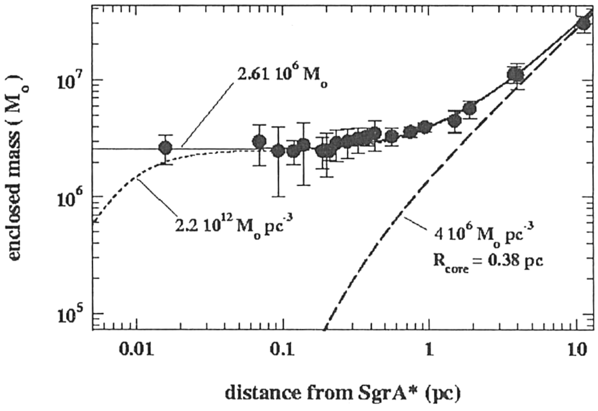


Figure 3. Mass modelling of the stellar proper and radial motions, with the addition of two points from gas kinematics at R = 1.5 and 4 pc. Shown as filled circles with 1σ error bars are the various mass estimates listed in Table 2 of Genzel *et al.* (1997) and discussed in the text, assuming a Sun-Galactic Center distance of 8 kpc. The thick dashed curve represents the mass model for the (visible) stellar cluster ($M/L(2\mu{\rm m}) = 2$, $R_{\rm core} = 0.38$ pc, $\rho(R{=}0) = 4 \times 10^6\ M_\odot {\rm pc}^{-3}$, Genzel *et al.* 1996). The thin continuous curve is the sum of this stellar cluster, plus a point mass of $2.61 \times 10^6\ M_\odot$. The thin dotted curve is the sum of the visible stellar cluster, plus a $\alpha = 5$ Plummer model of a dark cluster of central density $2.2 \times 10^{12}\ M_\odot {\rm pc}^{-3}$ and $R_o = 0.0065$ pc. It provides a χ^2 fit 1σ worse than the best fit with central density $> 7.5 \times 10^{13}\ M_\odot {\rm pc}^{-3}$.

light distribution with a mass to 2μm-band luminosity ratio of 2 (as indicated as a thick dashed line in Fig. 3). The central mass is 'dark', as it exhibits a mass to luminosity ratio of 100 or greater. If the central point mass is replaced by a dark cluster its central density has to be in excess of 2×10^{12} $M_\odot pc^{-3}$ to still be consistent with the data. This density is about 500 000 times larger than that of the visible cluster. Simple physical considerations (Eckart & Genzel 1997; Genzel *et al.* 1997) show that this dark mass cannot consist of a stable cluster of stars, stellar remnants, substellar condensations or a degenerate gas of elementary particles but that at least 10^3 to 10^5 solar masses must be in the form of a massive black hole associated with Sgr A* itself. Together with the nearby H_2O maser disk galaxy NGC 4258 (Greenhill *et al.* 1995; Myoshi *et al.* 1995) the Galactic Center is the best case for a super massive black hole (see also Maoz 1995).

Acknowledgments. We are grateful to the Director General and staff of *ESO* for their continuing support of our operation of SHARP at the *NTT*. R. Hofmann has contributed to the construction of the SHARP camera.

References

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

Backer, D.C. 1996, in: L. Blitz & P. Teuben (eds.), Unsolved Problems of the Milky Way, Proc. IAU Symp. No. 169 (Kluwer: Dordrecht), p. 193

Balick, B., Brown, R.L. 1974, ApJ 194, 265

Blum, R.D., Sellgren, K., DePoy, D.L. 1995, ApJ 440, L17

Cotera, A.S., Erickson, E.F., Colgan, S.W.J., Simpson, J.P., Allen, D.A., Burton, M.G. 1996, ApJ 461, 750

Eckart, A., Genzel, R., Krabbe, A., Hofmann, R., van der Werf, P.P., Drapatz, S. 1992, Nature 335, 526

Eckart, A., Genzel, R., Hofmann, R., Sams, B., Tacconi-Garman, L.E. 1995, ApJ 445, L26

Eckart, A., Genzel, R. 1996, Nature 383, 415

Eckart, A., Genzel, R. 1997, MNRAS 284, 576

Figer, D.F., McLean, I.S., Morris, M. 1995, ApJ 447, L29

Figer, D.F., Najarro, F., Morris, M., McLean, I.S., Geballe, T.R., Ghez, A., Langer, N. 1998, ApJ 506, 384

Forrest, W.J., Shure, M.A., Pipher, J.L., Woodward, C.A. 1987, in: D. Backer (ed.), The Galactic Center, AIP-CP 155, 153

Genzel, R., Townes, C.H. 1987, ARAA 25, 377

Genzel, R., Thatte, N., Krabbe, A., Eckart, A., Kroker, H. Tacconi-Garman, L.E. 1996, ApJ 472, 153

Genzel, R., Eckart, A., Ott, T., Eisenhauer, F. 1997, MNRAS 291, 219

Ghez, A., Klein, B., Morris, M., Becklin, E. 1998, ApJ 509, 678

de Graauw, Th., Haser, L.N., Beintema, D.A., van der Hucht, K.A., *et al.* 1996, A&A 315, L49

Greenhill, L.J., Jiang, D.R., Moran, J.M., Reid, M.J., Lo, K.Y., Claussen, M.J. 1995, ApJ 440, 619

Haller, J.W., Rieke, M.J., Rieke, G.H., Tamblyn, P., Close, L., Melia, F. 1996, ApJ 456, 194

Krabbe, A., Genzel, R., Drapatz, S., Rotaciuc, V. 1991, ApJ 382, L19

Krabbe, A., Genzel, R., Eckart, A., Najarro, F., Lutz, D., Cameron, M., Kroker, H., Tacconi-Garman, L.E., Thatte, N., Weitzel, L., Drapatz, S., Geballe, T., Sternberg, A., Kudritzki, R. 1995, ApJ 447, L95

Krichbaum, T.P., Graham, D.A., Witzel, A., Greve, A., Wink, J.E., Grewing, M., Colomer, F., de Vicente, P., Gómez-González, J., Baudry, A., Zensus, J.A. 1998, A&A 335, L106

Lacy, J.H., Baas, F., Townes, C.H., Geballe, T.R. 1979, ApJ 227, L17

Lacy, J.H., Townes, C.H., Geballe, T.R., Hollenbach, D. 1980, ApJ 241,132

Lacy, J.H., Townes, C.H., Hollenbach, D.J. 1982, ApJ 262, 120

Lester, D.F., Dinerstein, H.L., Werner, M.W., Watson, D.M., Genzel, R., Storey, J.W.V. 1987, ApJ 320, 573

Lutz, D., Feuchtgruber, H., Genzel, R., *et al.* 1996, A&A 315, L269

Lynden-Bell, D., Rees, M. 1971, MNRAS 152, 461

Maoz, E. 1995, ApJ 447, L91

Menten, K.M., Reid, M., Eckart, A., Genzel, R. 1997, ApJ 475, L111

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

Nagata, T., Woodward, C.E., Shure, M., Pipher, J.L., Okuda, H. 1990, ApJ 351, 83

Najarro, F., Hillier, D.J., Kudritzki, R.P., Krabbe, A., Genzel, R., Lutz, D., Drapatz, S., Geballe, T.R. 1994, A&A 285, 573

Najarro, F., Krabbe, A., Genzel, R., Lutz, D., Kudritzki, R.P., Hillier, D.J. 1997, A&A 325, 700

Okuda, H., Shibai, H., Nagakawa, T., Matsuhara, H., Kobayashi, Y., Kaifu, N., Nagata, T., Gatley, I., Geballe, T.R. 1990, ApJ 351, 89

Ott, T., Eckart, A., Genzel, R. 1999, ApJ submitted

Ramirez, S.V., Sellgren, K., Carr, J., Balachandran, S., Blum, R.D., Terndrup, D. 1997, BAAS 191, #107.05

Rieke, G.H., Rieke, M.J. 1988, ApJ 330, L33

Rieke, M.J. 1996, ApJ 456, 206

Schaerer, D., Meynet, G., Maeder, A., Schaller, G. 1993, A&AS 98, 523

Schaller, G., Schaerer, D., Meynet, G., Maeder, A. 1992, A&AS 96, 269

Sellgren, K., McGinn, M.T., Becklin, E., Hall, D.N.B. 1990, ApJ 359, 112

Sellgren, K., Carr, J.S., Balachandran, S.C. 1997, in: Y. Sofue (ed.), The Central Regions of the Galaxy and Galaxies, Proc. IAU Symp. No. 184 (Dordrecht: Kluwer), p. 21.

Serabyn, E., Lacy, J. 1985, ApJ 293, 445

Serabyn, E., Shupe, D., Figer, D.F. 1998, Nature 394, 448

Shields, J.C., Ferland, G.J. 1994, ApJ 258, 134

Tamblyn, P., Rieke, G.H., Hanson, M.M., Close, L.M., McCarthy, D.W., Rieke, M.J. 1996, ApJ 456, 206

Wollman, E.R., Geballe, T.R., Lacy, J.H., Townes, C.H., Rank, D.M. 1977, ApJ 218, L103

Yusef-Zadeh, F., Wardle, M., Cotton, W., Walker, C., Zhao, J.-H., Melia, F. 1993, ApJ 405, 584

Discussion

Ian Stevens: What is the angular separation between IRS 16SW (the eclipsing binary) and Sgr A*? Comment: Perhaps this source (as a colliding wind binary) could be responsible for the weak X-ray source seen at the position of Sgr A* by the *ROSAT*-PSPC.

Eckart: It is about $0\rlap{.}''95$ E and $1\rlap{.}''20$ W of Sgr A*. If IRS 16SW is a colliding wind binary it may contribute to the X-ray flux from that area.

Tim Heckman: For the Galactic Center you can compare the inferences about the stellar populations made from the *ISO* data using nebular emission lines to the direct census of individual stars. Are these consistent? In particular, the small [NeIII]/[NeII] mid-IR emission-line ratio in starbursts has been used to argue for an absence of the most massive stars in starbursts. In the GC you see a small [NeIII]/[NeII] ratio, yet find very massive (>100 $M_\odot$) stars. How do you interpret this?

Eckart: A revision of evolutionary tracks would introduce softer stellar spectra for a massive star population. The small [NeIII]/[NeII] mid-IR emission-line ratio will then not be in conflict with the presence of massive stars in the central cluster.

Claus Leitherer: You mentioned the importance of detecting very massive stars in a high-metallicity environment for the question of the IMF. What actually is the metallicity of the Galactic Center stars? Is it consistent with the observed metallicity gradient in the Galaxy?

Eckart: Due to the repeated star formation activity the metallicity at the Galactic Center is probably mostly influenced by local events and not so much connected to overall trends in the Galaxy. While the metallicity in the hot gas phase ($T_{\rm ion} \simeq 35\,000$ K as given by NIR-MIR line-ratios) is approximately two times higher than solar (*e.g.*, Lacy *et al.* 1980; Shields & Ferland 1994; Lester *et al.* 1987, also in agreement with latest *ISO* data in Lutz *et al.* 1996) and the He I stars show an increase in He abundance (*e.g.*, Krabbe *et al.* 1991, 1995; Najarro *et al.* 1994, 1997), the metallicity of the late-type stars is probably closer to solar (Ramirez *et al.* 1997; Sellgren *et al.* 1997).

André Maeder: Do your recent observations confirm the presence of some kind of cometary tail around a red supergiant in the galactic center, possibly generated by the external radiation pressure?

Eckart: The cometary tail of IRS 7 cannot be inferred from our near-infrared data. It is, however, clearly visible in *VLA* radio maps (*e.g.*, Yusef-Zadeh *et al.* 1993).