Metallicity in the GC

Francisco Najarro

1 Instituto de Estructura de la Materia, CSIC, Serrano 121, 29006 Madrid, Spain
E-mail: najarro@damir.iem.csic.es

Abstract. We review quantitative spectroscopic studies of massive stars in the three Galactic Center clusters: Quintuplet, Arches and Central cluster. Thanks to the impressive evolution of IR detectors and the new generation of line blanketed models for the extended atmospheres of hot stars we are able to accurately derive the physical properties and metallicity estimates of the massive stars in these clusters. For the Quintuplet cluster our analysis of the LBVs provides a direct estimate of $\alpha$-elements and Fe chemical abundances in these objects. For the Arches cluster, we introduce a method based on the N abundance of WNL stars and the theory of evolution of massive stars. For the Central cluster, new observations reveal IRS 8 as an outsider with respect to the rest of massive stars in the cluster both in terms of age and location. Using the derived properties of IRS 8, a new method is presented to derive metallicity from the OIII feature at 2.115 $\mu$m. Our results indicate solar metallicity in the three clusters.

1. Introduction
The detection of a He I emission line cluster (Krabbe et al. [26]) in the central parsec raised the question about the physical nature of its members and their role on the energetics of this region and triggered a substantial improvement in the atmospheric models for hot stars in the near-infrared. Thus, reliable values for luminosities, temperatures, mass-loss rates, helium abundances and ionizing photons were obtained for the brightest members of the He I cluster (Najarro et al. [34], [35]), which solved the energy puzzle of the Central cluster and placed important constraints on the theory of the evolution of massive stars.

Today, we know that the Galactic Center is clearly a unique environment in the Galaxy concerning massive star formation as it represents 10% of the present Galactic star formation activity. Hence, this region is ideal to address crucial questions such as the universality of the initial mass function (IMF) or the maximum mass a star can possess (Figer [19]). In fact, the Galactic center hosts three dense and massive star clusters that have formed in the inner 30 pc within the past 5 Myr. The Central cluster and the Quintuplet and Arches clusters host more stars with initial masses above 100M$_\odot$ than anywhere else in the Galaxy. Each cluster has a mass around $10^6$M$_\odot$. The extreme youth (2-2.5Myr, Figer et. al [18], Najarro et al. [36]) of the Arches cluster allows to address the above questions using photometry alone (Figer [19]), while the Central and Quintuplet clusters being twice older may have lost their most massive members into the supernova stage.

On the other hand, a fundamental aspect such as metallicity, remains to be addressed. Indeed, the metallicity issue in the galactic center is still a source of controversy. Based on measurements of the gas-phase, Shields & Ferland ([42]) obtained twice the solar metallicity from Argon and Nitrogen emission lines while a solar abundance was derived for Neon. For the cool stars, and
based on LTE-differential analysis with other cool supergiants, Carr, Sellgren, & Balachandran ([4]) and Ramirez et al. ([38]) have obtained strong indications for a solar Fe abundance. Further, Maeda et al. ([29]) obtained four times the solar abundance by fitting the X-ray local emission around Sgr. A East, while Koyama et al. ([28]) have recently derived 3.5 times solar abundance from the diffuse GC X-ray emission. It is therefore crucial to obtain metallicity estimates from direct analyses of hot stars and confront them with those from the cool-star and gas-phase analyses. Spectroscopic studies of photospheres and winds of massive hot stars are ideal tracers of metal abundances because they provide the most recent information about the natal clouds and environments where these objects formed.

In this paper, we review progress in both infrared observations and quantitative infrared spectroscopy of massive stars in the Quintuplet, Arches and Central clusters, which allow us to obtain direct abundance estimates of N, C, O, Si, Mg and Fe in the Galactic Center.

2. Improved observations and models
In the field of hot stars, high quality IR-spectra have been obtained during the last decade (Morris et al. [33]; Hanson, Conti & Rieke [21]; Figer, McLean, & Najarro [14]; Blum et al. [3]). Most of these spectra were obtained with low-mid (R~500-2000) resolution, which is enough to classify the stars but insufficient in most of the cases to perform accurate quantitative spectroscopic studies. An example of mid-high resolution observations of early type stars with strong winds is shown in Fig. 1 which displays the spectra at several IR bands of the “Pistol Star”, a LBV in the Quintuplet cluster, which were obtained with UKIRT-CGS4 with a resolution of R~5000. The number of new observational constraints provided by the new spectroscopic data is striking when compared to previous low-mid observations from which we could gather information only from some H and He lines. Inspecting Fig. 1 we immediately note that the key diagnostic lines would be fully blurred at R~1000. The availability of high-quality IR spectroscopic data has been substantially improved with a new generation of IR-spectrographs on 8-m class telescopes (ISAAC, NIRSPEC, SINFONI, etc).

The new model (Hillier & Miller [23]) is a line blanketing method based on the standard iterative, non-LTE method to solve the radiative transfer equation for the expanding atmospheres of early-type stars. New species O, Mg, Ca, Si, Na, Al, Fe, etc are included and the blanketing ensures that the effect of continua on lines and lines on the continua as well as overlapping lines are automatically handled (see Hillier & Miller [23, 25] for a detailed discussion of the method). The new model is then prescribed by the stellar radius, , the stellar luminosity, , the mass-loss rate , the velocity field, , the volume filling factor and the abundances of the element considered.

3. The Quintuplet Cluster
The Quintuplet Cluster (Glass, Catchpole, & Whitelock [8], Figer et. al. [16], [17]) contains a variety of massive stars, including WN, WC, WN9/Ofpe, LBV and less evolved blue-supergiants. The presence of such stars constrains the cluster age to be about 4Myr old, assuming coeval formation. The cluster provides enough ionizing flux (~10³¹ photons s⁻¹) to ionize the nearby “Sickle” H II region and enough luminosity (~10⁷.5 L⊙) to heat the nearby molecular cloud, M0.20-0.033. Its total mass is estimated to be ~10⁴M⊙. The presence of two LBVs (“Pistol Star” & #362, Geballe et al. [9]), with IR-spectra rich in metal lines (see Fig. 1), allows to obtain a direct estimate of the metallicity of the objects and hence constrain the metal enrichment history of the region. Furthermore, using the the Fe II, Si II & Mg II lines (Najarro et. al, in prep.) we can measure the α-elements vs. Fe ratio and infer whether the initial mass function (IMF) is dominated by massive stars or is like in other clusters in the Galaxy with a steeper slope. If the IMF is dominated by massive stars, we should expect enhanced yields of α-elements compared to Fe through a higher than average SNII vs SNIa events.
3.1. The “Pistol Star” and Star #362

To model the “Pistol Star” and star #362 we have assumed the atmosphere to be composed of H, He, C, N, O, Si and Fe. The new blanketed models provide a significant improvement in our knowledge of the physical properties of the “Pistol Star” compared to the results we obtained in Figer et al. ([15]) using non-blanketed models. The new model solves the dichotomy between the “high” and “low” Luminosity (Teff) solutions in Figer et al. ([15]) through the analysis of the metal lines (see the excellent fits in Fig. 1). The Si II, Mg II and Fe II lines “choose” the low luminosity model. We find a luminosity around $1.75 \times 10^6 L_\odot$ and an effective temperature of $T_{\text{eff}} \sim 11000K$. This result, which reduces the previous estimate of the star luminosity by a factor of two shows the importance of the new generation of models. Given the $T_{\text{eff}}$ and high wind density of the object we do find a degeneracy in the H/He ratio (see also Hillier et al. [24]). In principle, fits of virtually equal quality may be obtained with H/He ratios varying from 10 to 0.05 by number. The only line that may help to break this degeneracy is the He I $2.112\mu m$ absorption line, which seems to favor H/He ratios between 3 and 0.05 by number. An important consequence of this degeneracy are the mass fractions derived for Fe, Si and Mg. Our models show that once the H/He ratio falls below one, the resulting metal abundances have to be scaled down. In other words, if H/He$\leq 1$ then we will obtain only an upper limit on the metal
Mass function of the Arches Cluster ([19]). The Salpeter mass function is overplotted for comparison purposes. The hatched regions demonstrate that one would expect a significant number of massive stars exceeding 120M⊙. Right. Observed spectra (solid) and model fits (dashed) for the three WNL and two OIf+ Arches stars.

We obtain solar iron abundance as upper limit for the “Pistol Star” (see line fits in Fig. 1). This estimate is rather robust as there is a large number of Fe II diagnostic lines. Further, if we assume that the object displays He enrichment consistent with an LBV evolutionary phase, H/He \geq 1, we may conclude that the “Pistol Star” shows solar Fe abundance, in agreement with previous estimates from differential analysis of cool stars in the GC (Carr et al. [4], Ramirez et al. [38]). The silicon abundance is obtained from the two Si II lines in the H band. These lines are extremely sensitive to the effective temperature of the star as well as to the transition zone between the star’s photosphere and wind. Therefore, our Si=1.4Si⊙ result should be regarded with some caution. Magnesium, on the other hand, provides more diagnostic lines through Mg II both in the H and K-Band. We regard Mg=1.6Mg⊙ as our current best estimate. This slightly α-elements vs Fe enrichment seems to favor the situation of a IMF dominated by massive stars in the GC.

For star #362 (Geballe et al. [9]), a nearly twin of the “Pistol Star” we also obtain a luminosity around 1.7106×L⊙ and a effective temperature of T_{eff}≈10500K. We derive a solar iron abundance as upper limit as well and obtain Si≈1.8Si⊙ and Mg≈2.2Mg⊙ in agreement with the slightly α-elements vs Fe enrichment found for the “Pistol Star”.

4. The Arches Cluster
The Arches Cluster (Figer et. al [17], [18]) is the youngest and densest cluster at the Galactic center containing thousands of stars, including at least 160 O stars and around 10 WNLs (WN stars still showing H at their surface, Chiosi & Maeder [6]). The cluster is very young (≤2.5Myr), and the only emission line stars present are WNLs and OIf+ having infrared spectra dominated by H, He I, He II, N III lines. Some have weak C III/IV lines. The cluster gathers all requirements to study the high mass IMF slope and to estimate an upper mass cutoff: individual members can be resolved, large amount of mass in stars, young enough so that most massive members are not pre-supernovae and old enough for its stars to have emerged from their natal cocoons. Figure 2 (from Figer [19]) shows the mass function in the Arches cluster extended to very high masses as measured by Figer et al. ([16]). Its slope appears to be shallow with respect to the Salpeter value favoring the formation of very massive stars. Further, we see that one might expect massive stars up to 500-1000M⊙, yet none are seen beyond ∼120M⊙. Figure 2, thus clearly suggests the existence of an upper mass cutoff at ∼150M⊙.
4.1. Metallicity studies

The absence of late B-supergiants and LBVs prevents one from obtaining direct estimates of the important $\alpha$-elements vs. Fe metallicity ratio as in the Quintuplet cluster or the Central cluster. Being the youngest cluster at the Galactic center, any hint about its metallicity would constitute our “last-minute” picture of chemical enrichment of the central region in the Milky Way. To analyze the stars in the Arches cluster we have assumed the atmosphere to be composed of H, He, C, N, O, Si and Fe. Observational constraints are provided by the K-Band spectra of the stars (see Figure 2) and the narrow band HST/NICMOS photometry (filters $F_{F110W}$, $F_{F160W}$ & $F_{F205W}$) and P$\alpha$ equivalent width (filters $F_{F187N}$ & $F_{F190N}$). Object identifications are given according to Figer et al. ([18]). Below we present the results of our analysis (Najarro et al. [36]).

The reduced spectra and model fits are shown in Figure 2. The top three spectra correspond to some of the most luminous stars in the cluster. As described in Figer et al. ([18]), these are nitrogen-rich Wolf-Rayet stars with thick and fast winds. The bottom two spectra in the figure correspond to slightly less evolved stars with the characteristic morphology of OIf$^+$ stars. Of concern are the N$\text{III}$ 8-7 lines at 2.103 $\mu$m and 2.115 $\mu$m as well as the N$\text{III}$ 5p$^2P$–5s$^2S$ doublet at 2.247 $\mu$m and 2.251 $\mu$m. Figer et al. (1997) showed that these N$\text{III}$ lines appear only for a narrow range of temperatures and wind densities, which occur in the WN9h (WNL) stage. The fairly distinct nature and energies of the multiplets involved in each of both N$\text{III}$ line sets provide strong constraints for the determination of the nitrogen abundance. Thus, at the S/N of our spectra, our models show that the WNLs N$\text{III}$ lines can easily track relative changes as low as 20% in the nitrogen abundance, and a 30% error should be regarded as a safe estimate, as shown in Figure 3-left.

Of particular importance is the roughly same surface abundance fraction of N, $Z(N)$, obtained in our analysis for all three WNL objects ($\sim$1.6%) well above the upper limit found for the OIf$^+$ stars ($\sim$0.6%). WNL stars do not exhibit any primary diagnostic line in their K-Band spectra to estimate metallicity. However, the crucial rôles of $Z(N)$ in determining metallicity from WNL stars can be immediately anticipated if we make use of the stellar evolution models for massive stars.
According to the evolutionary models by Schaller et al. ([41]) and Charbonnel et al. ([5]), a star entering the WNL phase still shows H at its surface together with strong enhancement of helium and nitrogen and strong depletion of carbon and oxygen as expected from processed CNO material. During this phase, the star maintains a nearly constant $Z(N)$ value, and the amount achieved essentially depends only linearly on the original metallicity (see Figure 3-right), being basically unaffected by the mass-loss rate assumed and the presence of stellar rotation during evolution (Meynet & Maeder [32]). Since we expect the CNO abundance in the natal cloud to scale as the rest of metals, the nitrogen surface abundance must trace the metallicity of the cluster. The parameters derived for these stars (Najarro et al. [36]) indicate that this is indeed the case for objects #3, #4 & #8. The derived $Z(N)$ ($\sim 1.6\%$) is the one expected for solar metallicity from the evolutionary models. The reliability of our method is demonstrated in Figure 3-right, where we display the nitrogen mass fraction as a function of time for stars with initial masses of 60, 85, and 120 $M_\odot$, and metallicities equivalent to 2, 1, and 0.4 times solar, assuming the canonical mass-loss rates (Schaller et al. 1992). Our results for the WNL and O stars (cross-hatched region) require solar metallicity and an age of 2-2.5 Myr (see also Najarro et al. [36]).

Figure 4. New K-Band high resolution observations and model fits to the AF star. Our models indicate a slightly higher but still consistent temperature and luminosity with the values obtained by Najarro et al. [34], [35].

5. The Central Cluster Revisited
The Central cluster hosts a large number of massive stars that have formed in the past 10 Myr (Becklin et al. [2], Krabbe et al. [26], [27], Najarro et al. [34], [35]). The latest census by Eisenhauer et al. [7] and Paumard et al. [37] (see also these proceedings) includes at least 80 massive stars, with $\sim$50 OB stars close to the main sequence or in their early supergiant phase and 30 more evolved massive stars which appear to be confined to two disks (Paumard et al. [37]). There is also a group of about a dozen of B stars within the central arcsecond (the “S”-stars, see these proceedings for thorough discussions on this topic). Interestingly Paumard et al. [37] do not detect any OB star outside the central 0.5pc and find that the stellar contents of both disks indicate a common age of 6$\pm$2 Myr, with O8-9I as earliest spectral type detected.

To test whether the new generation of models and observations could alter considerably our current picture of the evolved massive stars in the Central cluster (Najarro et al. [34], [35]) as it has been the case for the “Pistol Star” (see above), we have started a re-analysis campaign using high resolution observations obtained with NIRSPEC (Keck) and our up-todate line blanketed code. Figure 4 displays K-Band obs and new model fits to the AF star. Our new fits indicate a slightly higher temperature and luminosity for this object but still consistent with the values and error estimates obtained by Najarro et al. [34], [35].
5.1. IRS 8: an outsider in the GC

The nature of the Galactic center source IRS 8 (Becklin & Neugebauer, [1]), one of the brightest compact mid-infrared sources in the central infrared cluster, was unknown until adaptive optics H- and K-band imaging revealed that the bulk of its infrared emission originates in a classic bowshock (Rigaut et al. [39], Geballe et al. [10]). Geballe et al. [10] showed that the IRS 8 bowshock is a straightforward consequence of the interaction of a dense and high velocity wind from a hot star (hereafter IRS 8*) that is traversing moderately dense interstellar gas. To investigate the nature of the central source we obtained mid resolution (R ∼ 900) K-Band spectra using the Gemini adaptive optics module ALTAIR to feed the near-infrared spectrograph NIRI (see also Geballe et al. [12]).

Figure 5. Spectral type determination of IRS 8*. Comparison of the resulting normalized spectrum with K-band spectra from Hanson et al. [21] degraded to a resolution of R=800. Also displayed (dashed) is a model fit with stellar parameters corresponding to an O5.5If star (see text).

Figure 5 shows the resulting normalized K-band spectrum of IRS 8* compared with online-available K-band spectra from the Hanson et al. [21] catalog for O stars ranging from O4 to O6.5 and different luminosity classes. The resolving powers for all template spectra have been degraded to 800 for direct comparison with the observed spectrum. From Fig. 5 we judge that IRS 8* falls within the O5-O6.5 and III-If ranges, with likely O5-O6 If spectral type and luminosity class. Given the strong spectral similarities of IRS 8* with the O5-6 supergiants in Cyg OB2 (see Fig. 5), we computed model fits covering that parameter domain, drawing from our analysis of the Cyg OB2 stars for which UV, optical and IR spectra are available (Najarro et al. in prep.). Figure 5 displays our best-fitting model (dashed line) using the line blanketing method presented in previous sections (see Geballe et al. [12] for a thorough discussion of the analysis).

Of concern is the re-identification of the strong emission feature at 2.116 μm in IRS 8* which has been attributed in the past to C III and N III n=8–7 transitions and is present over a very wide range of O spectral types and luminosities (Hanson et al. [21]). Our investigation (Geballe et al. [12]) indicates that the 2.116 μm feature in IRS 8* is dominated by O III n=8–7 transitions. Further, the O III component of the 2.116 μm feature largely depends on the oxygen abundance and only slightly on gravity, effective temperature, wind density, and velocity field. Thus, this feature may be a powerful diagnostic of oxygen abundance, and therefore an important metal abundance determiner, over a wide range of O spectral types (Najarro et al. in preparation). Using it we obtain an oxygen abundance of 0.8 to 1.1 times solar in IRS 8*, which indicates solar metallicity for the cloud in which IRS 8* formed.

Our analysis suggests that IRS 8*, although only 1 pc from the center, does not fit into the current picture of the central cluster of hot stars. It is of much earlier spectral type than any
of the stars classified by Paumard et al. [37]. Currently it is the only known OB star outside the central 0.5 pc region of the cluster. Figure 6 shows the position of IRS 8* (solid cross) as estimated from our model fits in the HR diagram compared with different evolutionary scenarios. The age of 2.8 Myr and no surface enrichment obtained with tracks of stars without rotation as used by Paumard et al. [37] (Maeder & Meynet [30]) is clearly at odds both with the current estimate for the age of the Galactic center cluster and with the abundance pattern derived from our models. The situation improves when evolutionary models accounting for rotation (dashed lines in Fig. 6) are considered (3.5 Myr and CNO-processed material on the stellar surface). Except for the age, still well below the estimate obtained by Paumard et al. [37], using rotating models for a single burst scenario we obtain stellar parameters fully consistent with those derived from our modelling.

The crucial question thus is whether this star is really much younger than the cluster and probes the existence of ongoing (or at least much more recent) star formation, or if on the contrary the star is either an impostor or a cluster member that underwent a rejuvenation cure. A possible way out is provided if the star originally was a member of a massive close binary system. In such a case, we could be looking now at the secondary star, with the primary either exploded as supernova or in an evolutionary phase when it is much dimmer at K than the secondary. Using the models by Wellstein & Langer [44] we have found that for a massive close binary system with initial masses of 25 M⊙ and 24 M⊙ (their model 10a) the current position of IRS 8* may be elegantly explained (see Geballe et al. [12] for a thorough discussion) without violating the age of the Galactic center cluster (solid lines in Fig. 6). Similar scenarios are a possible explanation for some of the overluminous He I objects in the central parsec.

6. Conclusions

Our result of solar metallicity for the Central Cluster, the Arches Cluster and the Quintuplet Cluster runs counter to the trend in the disk (Rolleston et al. [40], Smartt et al. [43]) but is consistent with the findings from cool star studies (Carr et al. [4], Ramirez et al. [38]). This may imply that the ISM in the disk does not extend inward to the GC, or that the GC stars are forming out of an ISM that has an enrichment history that is distinctly different from that in the disk. Our result is more consistent with the values found for the bulge (Frogel et al. [20], Felzing & Gilmore [13]).

Figure 6. Position of IRS 8* (solid cross) in the HR diagram as estimated from model fits, compared with different evolutionary scenarios. The current location of IRS 8* is reached after 3.6 and 7.1 million years for the single star (dashed) and massive close binary (solid) evolutionary cases respectively (see Geballe et al. [12] for a thorough discussion).
Acknowledgments
I would like to thank Don Figer, John Hillier, Rolf Kudritzki and Tom Geballe for invaluable
discussions. F. N. acknowledges PNAYA-2003-02785-E and AYA2004-08271-C02-02 grants.
Thanks Rainer for your patience with the manuscript.

References
[1] Becklin, E. E. & Neugebauer, G. 1975, ApJ, 200, L71
[2] Becklin, E. E., Matthews, K., Neugebauer, G. & Willner, S. P., 1978, ApJ, 219, 121
[3] Blum, R.D, Ramond, T.M., Conti, P.S., Figer, D.F., & Sellgren, K., 1997, AJ, 113, 1855
[4] Carr, J.S., Sellgren, K., & Balachandran, S.C., 2000, ApJ, 530, 307
[5] Charbonnel, C., Meynet, G., Maeder, A., Schaller, G., & Schaerer, D. 1993, A&As, 101, 415
[6] Chiosi, C. & Maeder, A. 1986, Annual Review of A&A, 24, 329
[7] Eisenhauer, F., et al., 2005, ApJ, 628, 246
[8] Glass, I. S., Catchpole, R. M., & Whitelock, P. A. 1987, MNRAS, 227, 373
[9] Geballe, T.R., Najarro, F., & Figer, D.F., 2000, ApJ, 530, L97
[10] Geballe, T. R., Rigaut, F., Roy, J.-R., & Draine, B. T. 2004, ApJ, 602, 770
[11] Feltzing, S., & Gilmore, G. 2000, A&A, 355, 949
[12] Geballe, T. R., Najarro, F., Rigaut, F., & Roy, J. -. 2006, arXiv:astro-ph/0607550
[13] Feltzing, S. & Gilmore, G., 2000, A&A, 355, 949
[14] Figer, D.F., McLean, I.S., & Najarro, F., 1997, ApJ, 486, 420
[15] Figer, D.F., Najarro, F., Morris, M., McLean, I. S., Geballe, T. R., Ghez, A. M., & Langer, N. 1998, ApJ, 506, 384
[16] Figer, D.F., McLean, I.S., & Morris, M., 1999a, ApJ, 514, 202
[17] Figer, D.F., Kim, S.S., Morris, M., Serabyn, E., Rich, R.M., & McLean, I.S., 1999b, ApJ, 525, 750
[18] Figer, D.F., Najarro, F., Gilmore, D., et al., 2002, Morris, M., Kim, S.S., ApJ, 581, 258
[19] Figer, D.F., 2004, in proceedings of “IMF50”
[20] Frogel, J.A., Tiede, G.P., & Kuchinski, L.E. 1999, AJ, 117, 2296
[21] Hanson, M. M., Conti, P. S., & Rieke, M. J. 1996, ApJS, 107, 281
[22] Hanson, M. M., Kudritzki, R.-P., Kenworthy, M. A., Puls, J., & Tokunaga, A. T. 2005, ApJS, 161, 154
[23] Hillier, D.J., & Miller, D.L., 1998a, ApJ, 496, 407
[24] Hillier, D.J., Crowther, P.A., Najarro, F., Fullerton, A.W., 1998b, A&A, 340, 483
[25] Hillier, D.J. & Miller, D.L. 1999, ApJ, 519, 354
[26] Krabbe, A., Genzel, R., Drapatz, S., & Rotaciuc, V., 1991, ApJ, 382, L19
[27] Krabbe, A., et al., 2006, ApJ, 447, L95
[28] Koyama, L., et. al., 2006, PASJ, arXiv:astro-ph/0609215
[29] Maeda, Y., et. al., 2002, ApJ, 570, 671
[30] Maeder, A. & Meynet, G. 2003, A&A, 404, 975
[31] Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&A Supp., 103, 97
[32] Meynet, G., & Maeder, A., 2004, A&A, 404, 975
[33] Morris, P.W., Eenens, P.R.J., Hanson, M.M., Conti, P.S., & Blum, R.D, 1996, ApJ, 470, 597
[34] Najarro, F., Hillier, D.J., Kudritzki, R.P., Krabbe, A., Genzel, R., Lutz, D., Drapatz, S., & Geballe, T.R., 1994, A&A, 285, 573
[35] Najarro, F., Krabbe, A., Genzel, R., Lutz, D., Kudritzki, R.P., & Hillier, D.J., 1997, A&A, 325, 700
[36] Najarro, F., Figer, D.F., Hillier, D.J., Kudritzki, R.P., 2004, ApJ, 611, L108
[37] Paumard, T., et al. 2006, ApJ, in press (astro-ph 0601268)
[38] Ramirez, S.V., Sellgren, K., Carr, J.S., Balachandran, S.C., Blum, R., Terndrup, D.M., & Steed, A., 2000, ApJ, 537, 205
[39] Rigaut, F., Geballe, T. R., Roy, J.-R., & Draine, B. T., 2003, in Galactic Center Workshop 2002: The Central 300 Parsecs of the Milky Way, ed. A. Cotera et al., Astron. Nachr., 324, S1, 551
[40] Rolleston, W.R., Smartt, S.J., Dufton, P.L., & Ryans, R.S.I., 2000, A&A, 363, 537
[41] Schaller, G., Schaerer, D., Meynet, G., & Maeder, A., 1992, A&A, 269
[42] Shields, J.C., & Ferland, G.J., 1994, ApJ, 430, 236
[43] Smartt, S.J., Venn, K.A., Dufton, P.L., Lennon, D.J., Rolleston, W.R., & Keenan, F.P., 2001, A&A, 367, 86
[44] Wellstein, S. & Langer, N., 1999, A&A, 350, 148