

## Radio observations of Galactic Center massive stars

Cornelia C. Lang

*Astronomy Program, University of Massachusetts,  
Amherst, MA 01003, USA*

**Abstract.** High-resolution multi-frequency observations made with the VLA have revealed the presence of stellar winds in two of the three known massive stellar clusters at the Galactic Center (GC). At a distance of only 8.0 kpc, we are able to resolve radio sources associated with individual near-infrared sources known to be losing mass at high rates. Herein, I discuss the spectral and spatial properties of the radio sources and their near-infrared counterparts, their inferred mass-loss rates, variability and the prospects for detecting stellar winds sources in the Central Cluster, near the supermassive blackhole SgrA\*. Such massive clusters as these three GC clusters have a profound impact on the interstellar medium, as evidenced by radio and X-ray observations of the surrounding regions.

### 1. Introduction

#### 1.1. The Galactic Center massive star population

Over the last ten years, very high resolution near-infrared (near-IR) studies have revealed several extraordinary clusters of stars within the central 50 pc of the Galaxy, where observations suffer 20-30 visual magnitudes of obscuration (*e.g.*, Krabbe *et al.* 1995; Nagata *et al.* 1995; Cotera *et al.* 1996, 1999; Figer *et al.* 1999a,b): (i) the Central Cluster, located within a parsec of SgrA\*; (ii) the Arches Cluster, located  $\sim 30$  pc N of SgrA\* at  $\ell = 0^\circ 12$ ,  $b = 0^\circ 02$ ; and (iii) the Quintuplet Cluster, also located  $\sim 35$  pc N of SgrA\*, at  $\ell = 0^\circ 16$ ,  $b = 0^\circ 06$ . Many of the stars detected in these clusters have near-IR signatures of blue supergiants and late-type Wolf-Rayet stars, including WN, WC and WN9/Ofpe types, and most are thought to be losing mass from their surfaces at high rates. High-resolution radio continuum and recombination line studies of the unusually-shaped filaments and streamers of ionized gas in the central 50 pc of the Galaxy made with the Very Large Array of the National Radio Astronomy Observatory<sup>1</sup> suggest that these regions are ionized by large numbers of young, massive stars (*e.g.*, Lang, Goss & Wood 1997; Lang, Goss & Morris 2001a).

#### 1.2. Radio detections of stellar winds

In addition to detecting the presence of massive stars based on the Lyman continuum flux they impart to adjacent H II regions, it is possible to detect the

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<sup>1</sup>The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

expanding, ionized envelopes around individual hot stars. The classic theory of Panagia & Felli (1975) and Wright & Barlow (1975) predicts that the spectrum of radio emission from a stellar wind is  $\propto \nu^{+0.6}$  for a spherically symmetric, isothermal, stationary wind expanding at a constant velocity. Previous surveys made with the VLA and the Australia Telescope Compact Array (ATCA) have detected centimeter radio continuum emission from OB supergiant and Wolf-Rayet stellar winds in both the Northern and Southern skies (*e.g.*, Abbott *et al.* 1986; Bieging *et al.* 1989; Leitherer, Chapman & Koribalski 1995, 1997; Chapman *et al.* 1999).

The rising spectral index ( $\alpha \simeq +0.6$ ) is an important characteristic of radio detections of stellar winds, however, there is some variation in the observed spectra of stellar wind sources. About 25% of stellar wind detections have much flatter, or even nonthermal, spectra in the centimeter range (Bieging *et al.* 1989). The exact mechanism for producing such spectra is not well understood, but internal shocks in the wind of a single star (White 1985) has been suggested, and the presence of interacting winds in close binary systems (Williams *et al.* 1990, 1994; van der Hucht *et al.* 1992; Contreras & Rodríguez 1999; Dougherty & Williams 2000; Setia Gunawan *et al.* 2000, 2001) has been proven.

In addition to determining the spectral index of a stellar wind source, there are other important physical diagnostics that can be obtained through radio observations. The flux density of the stellar wind emission can be used to calculate the mass loss rate ( $\dot{M}$ ). Based on Panagia & Felli (1975), the mass loss rate can be estimated for observations at 8.5 GHz using:

$$\frac{\dot{M}}{10^{-5} M_{\odot} \text{ yr}^{-1}} = 0.52 \left( \frac{S_{8.5}}{\text{mJy}} \right)^{3/4} \left( \frac{v_{\infty}}{10^3 \text{ km s}^{-1}} \right) \left( \frac{d}{\text{kpc}} \right)^{3/2} \quad (1)$$

where  $S_{8.5}$  is the flux density of the source at 8.5 GHz,  $v_{\infty}$  is the terminal velocity of the wind, and  $d$  is the distance to the source, *i.e.*,  $\sim 8$  kpc for the Galactic Center (GC). We have assumed an electron temperature of  $10^4$  K,  $Z = 1$ , and a mean molecular weight,  $\mu = 2$ , due to the enrichment in heavy elements of the late-type WN stars (Leitherer *et al.* 1997).

## 2. Radio detections of Galactic Center stars

The types of stars observed in the GC clusters should be losing mass at fairly high rates in expanding envelopes, and these stellar winds should be detectable at centimeter wavelengths. A number of detections of stellar wind sources in the GC clusters have been made to date using multi-frequency VLA observations. A summary of all observations is presented in Table 1. Initial results for the Quintuplet and Arches Clusters are published (Lang *et al.* 1999; Lang, Goss & Rodríguez 2001b), but important follow-up work including pointed observations and searches for time-variability have been subsequently carried out. The focus of this paper is to discuss these newer results as well as the implications of such detections.

### 2.1. The Arches Cluster

Multi-frequency, multi-epoch radio observations of the Arches cluster (Figure 1) have revealed eight compact sources (AR1-AR5, AR7-AR9) with  $\alpha \approx 0.3 - 0.9$

Table 1. Log of radio observations detected in Galactic Center clusters.

source name	$\nu$ (GHz)	VLA array	obs. date	resolution (")	rms (mJy beam <sup>-1</sup> )	ref.
Arches	43.3	BnA	10-99	0.29×0.07	0.3	Lang <i>et al.</i> 2001b
Arches	8.5	A	7-99	0.41×0.16	0.025	Lang <i>et al.</i> 2001b
Arches	8.5	A	1-02	0.42×0.17	0.025	this paper
Arches	4.9	A	7-99	0.79×0.33	0.045	Lang <i>et al.</i> 2001b
Quin.	4.9/8.5	ABCD	87	1-2	0.2	Lang <i>et al.</i> 1999
Quin.	4.9	BnA	6-02	1.15×0.94	0.1	this paper
Quin.	8.5	BnA	6-02	0.62×0.49	0.04	this paper
Sgr A*	43.3	A	3-01	0.1×0.1	0.4	this paper

(Lang *et al.* 2001b). The ninth radio source, AR6, has a nonthermal spectrum ( $\alpha = -0.7$ ), which is consistent with the spectrum from  $\sim 25\%$  of radio stellar winds (Bieging *et al.* 1989). Seven of these nine sources have firm near-IR counterparts, of which the majority are Of/WN9 stellar types. The near-IR counterpart of AR6 lies outside the  $1''$  positional error radius, and AR9 has no counterpart. These near-IR counterparts are known to be mass-losing emission-line stars (Nagata *et al.* 1995; Cotera *et al.* 1996). Therefore, the radio detections are thought to be detections of the stellar wind emission arising from these massive stars. The mass loss rates are calculated according to Equation 1, and they vary between  $3 - 17 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ . Our second epoch 8.5 GHz observations (January 2002) produced one new source, AR9, and three of the sources (AR1, AR4, AR7) showed variations in their flux densities of 10-35%. This modest variability may be indicative of (i) the presence of a time-variable non-thermal component (due to shocks in the wind; or rather colliding winds in binaries, see van der Hucht *et al.* 1992; Dougherty & Williams 2000; Watson *et al.* 2002); and/or (ii) variability in the mass-loss rate or wind velocity.

## 2.2. The Quintuplet Cluster

Radio observations of the Quintuplet cluster have revealed eight compact sources (Figure 2). The initial observations of Lang *et al.* (1999) were pointed up to  $4'$  away from the cluster and did not have resolutions  $< 1''$ , although six radio sources were detected. Three of these sources (QR4, QR5, and the Pistol Star) have near-IR massive star counterparts. Sources QR1-3 do not have counterparts and their nature is not as clear. It is possible that they represent enshrouded massive stars in the process of forming; their location at the edge of the cluster is also peculiar. The recent pointed observations (June 2002) had  $0.5''$  resolution at 8.5 GHz and revealed a total of eight radio sources, including five of the original sources. One of the original sources, QR4, did not appear, suggesting that it might be a time-variable source, as has now been detected in the Arches Cluster. Two additional sources, QR6 and QR7, appeared and have near-IR counterparts. The mass-loss rates implied for the Quintuplet Cluster sources are high — ranging from  $1 - 20 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ .

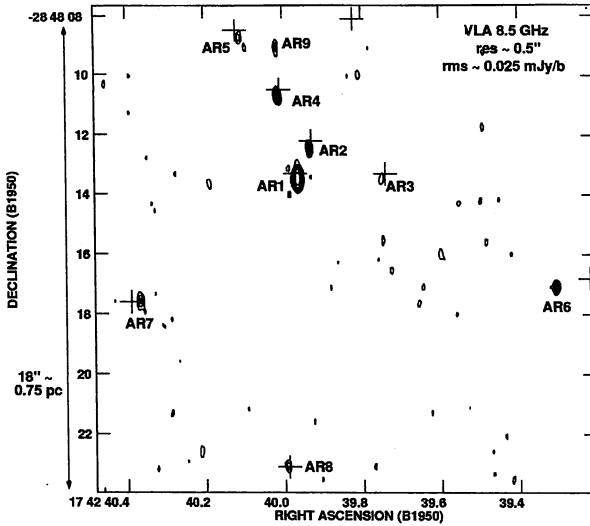


Figure 1. VLA 8.5 GHz continuum image of the inner  $16''$  ( $0.7$  pc) of the Arches Cluster, with a resolution of  $0''.41 \times 0''.16$ ,  $PA = 2^\circ 8'$ , and rms-noise of  $25 \mu\text{Jy beam}^{-1}$ . Contours correspond to 0.075, 0.15, 0.25, 0.5, 1.0, 1.5, 1.75  $\text{mJy beam}^{-1}$ . Crosses show positions of near-IR sources of Nagata *et al.* (1995), detected in  $\text{Br}\gamma$  and  $\text{Br}\alpha$  recombination lines.

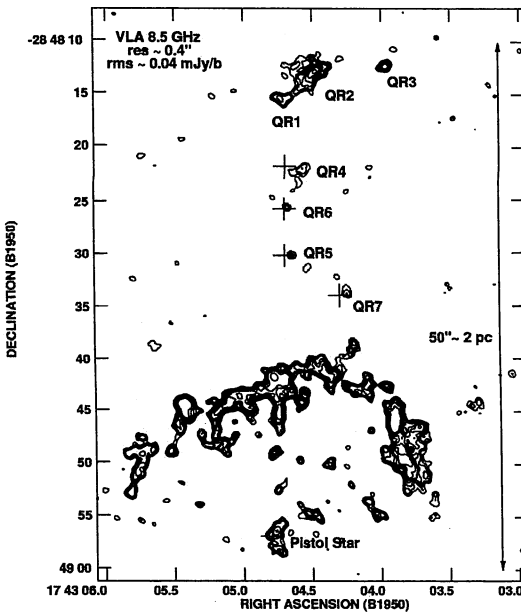


Figure 2. VLA 8.5 GHz continuum image of the Pistol Star H II region and Quintuplet Cluster, with a resolution of  $0''.41 \times 0''.16$ ,  $PA = 2^\circ 8'$ , and rms-noise of  $0.1 \text{ mJy beam}^{-1}$ . Contours correspond to 0.12, 0.2, 0.28, 0.36, 0.48, 0.64, 1.3, 1.9  $\text{mJy beam}^{-1}$ . Crosses show positions of near-IR sources of Figer *et al.* (1999b).

Table 2. Summary of radio sources detected in Galactic Center clusters.

source ID	other design. Nag95	Cot96	$S_{8.5 \text{ GHz}}$ (mJy)	$S_{4.9 \text{ GHz}}$ (mJy)	spectral index $\alpha^*$	$\dot{M}$ ( $M_{\odot} \text{ yr}^{-1}$ )	stellar type counterpart
AR1	#8	#8	$1.70 \pm 0.05^{\dagger}$	$1.4 \pm 0.03$	$0.35 \pm 0.04$	$1.7 \times 10^{-4}$	WN9/Ofpe <sup>a</sup>
AR2	#7	#6	$0.23 \pm 0.02$	$< 0.13$	$> 0.9$	$3.9 \times 10^{-5}$	WN8-9
AR3	#4	#9	$0.17 \pm 0.02$	$< 0.13$	$> 0.4$	$3.2 \times 10^{-5}$	WN9/Ofpe
AR4	#10	#5	$0.17 \pm 0.02^{\S}$	$0.16 \pm 0.03$	$0.65 \pm 0.13$	$3.9 \times 10^{-5}$	WN9/Ofpe
AR5	#11	#2	$0.16 \pm 0.02$	$< 0.13$	$> 0.3$	$3.0 \times 10^{-5}$	WN8
AR6	#17	#13?	$0.27 \pm 0.02$	$0.40 \pm 0.03$	$-0.7 \pm 0.08$	$4.5 \times 10^{-5}$	WN8 <sup>b</sup>
AR7	#14	#11	$0.25 \pm 0.02^{\S}$	$0.21 \pm 0.03$	$0.31 \pm 0.05$	$4.2 \times 10^{-5}$	WN9/Ofpe
AR8	#9		$0.20 \pm 0.02$	$< 0.13$	$> 0.7$	$3.6 \times 10^{-5}$	no type
AR9			$0.17 \pm 0.04$	$< 0.13$	$> 0.4$	$3.2 \times 10^{-5}$	no cp.
	Nag90	Fig99					
QR1 <sup>c</sup>			$2.0 \pm 0.3$	$< 1.5$	$> 0.5$	...	no cp.
QR2			$6.5 \pm 0.5$	$3.0 \pm 0.5$	$1.0 \pm 0.2$	...	no cp.
QR3			$1.2 \pm 0.2$	$1.2 \pm 0.2$	$0.0 \pm 0.2$	...	no cp.
QR4	#C	#270N	$< 0.15$	$< 0.30$	$> -1$	$1.4 \times 10^{-5}$	OB I <sup>d</sup>
QR5	#F	#241	$0.44 \pm 0.05$	$< 0.30$	$> 0.7$	$6.5 \times 10^{-5}$	WN9/Ofpe
QR6			$0.42 \pm 0.05$	$< 0.30$	$> 0.6$	$6.1 \times 10^{-5}$	no type
QR7	#GCS3-2	#231	$1.1 \pm 0.03$	$< 0.90$	$> 0.4$	$1.3 \times 10^{-4}$	DWCL?
Pistol			$2.0 \pm 0.2$	$4.7 \pm 0.5$	$-1.7 \pm 0.3$	$1.9 \times 10^{-4}$	LBV

Notes: Cot96: Cotera *et al.* 1996; Fig99: Figer *et al.* 1999b; Nag90: Nagata *et al.* 1990; Nag95: Nagata *et al.* 1995.

\* : where  $S_{\nu} \propto \nu^{\alpha}$ .

† :  $S_{8.5 \text{ GHz}}$  increased by  $\sim 10\%$  in second epoch (2002 Jan).

§ :  $S_{8.5 \text{ GHz}}$  increased by  $\sim 30\%$  in second epoch (2002 Jan).

a : spectral type from Cotera *et al.* (1996).

b : identification with near-IR source not firm.

c : all Quintuplet measurements from 2002 June 1 data.

d : spectral type from Figer *et al.* (1999b).

### 2.3. The Central Cluster

Exploratory observations of the central parsec were made at 7 mm in the A-array in order to assess whether detections of any of the Central Cluster stellar winds would be possible. Detections of stellar wind emission at such close proximity to the central supermassive black hole, Sgr A\*, would shed new light on the history of star-formation in this unique environment. The envelopes of highly evolved stars, such as IRS 7 and IRS 13, are known to be affected by their location in the central parsec. Our A-array observations showed Sgr A\* as a strong source ( $\sim 1 \text{ Jy}$ ), however, the sensitivity (even in a 4-hour observation) was not high enough for the dynamic range required to detect a 0.2 mJy source.

### 3. Implications of Galactic Center stellar wind detections

The detection of stellar wind emission (and high mass loss rates) in the Arches and Quintuplet Clusters is one of the first detections of stellar wind emission from individual stars in a massive cluster. Further, the detection of stellar wind emission, coupled with the large ionizing fluxes of the clusters and the size of

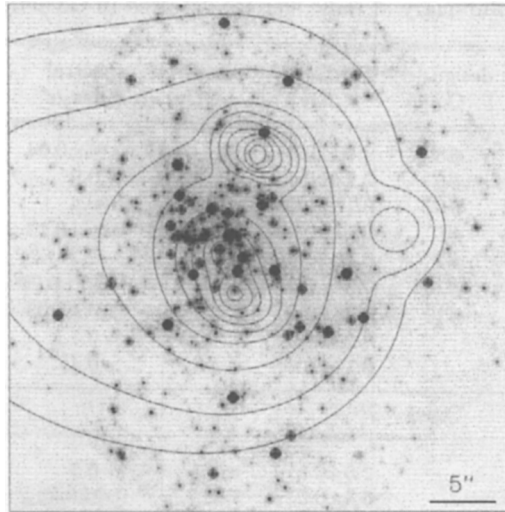


Figure 3. Overlay of contours of *Chandra* X-ray data on a *HST-NICMOS* image of the Arches Cluster (courtesy of A. Cotera).

the associated H II nebulae, makes them comparable to the starbursting regions NGC 3603 (Lang *et al.* 2001a; Moffat *et al.* 2002, and these Proceedings) and 30 Doradus in the LMC. Similarly, the rich population of massive stars in the GC region will have a profound impact on the interstellar environment. Ionization of the surfaces of dense molecular clouds and formation of the morphologically-unique Arched Filaments and Sickles and Pistol H II nebulae have been shown to be due to the large ionizing fluxes of both the Arches and Quintuplet Clusters (Lang *et al.* 1997; Lang *et al.* 2001a; Figer *et al.* 1999a,b). Because of the densely-packed nature of these clusters, especially in the Arches Cluster (where the stellar density may exceed  $\rho \approx 5 \times 10^5 \text{ M}_{\odot} \text{ pc}^{-3}$ ), collisions between the expanding stellar winds may occur. Such collisions are thought to produce shocks which may create gas with temperatures as high as  $10^7 \text{ K}$ . Cantó *et al.* (2000) predict that such collisions may create a ‘cluster wind’, detectable in the X-ray regime. Raga *et al.* (2001) model the distribution of point-like and diffuse X-ray emission arising from clusters similar to the Arches Cluster.

The first high-resolution ( $1''$ ) X-ray observations of the Arches Cluster with *Chandra* reveal it to be one of the brightest X-ray sources in the GC region (Yusef-Zadeh *et al.* 2002; Wang, Gotthelf & Lang 2002). Several point-like sources are detected in the cluster (see Figure 1) with  $L_x \approx 10^{35} \text{ erg s}^{-1}$ . These sources could represent colliding wind binaries of extremely massive stars in the Arches Cluster. The presence of strong diffuse X-ray emission from the central 50 pc of the GC which has a spectrum consistent with  $10^7 \text{ K}$  gas, suggests that much of the energetic activity in this region is driven by massive star formation activity (Wang, Gotthelf & Lang 2002).

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## Discussion

KOENIGSBERGER: Weren't many of your mass-loss rates for the Arches Cluster stars ( $\sim 10^{-5} \text{ yr}^{-1}$ ) smaller than what Najarro presented?

LANG: I think that most of them are agreed. Yes, we are detecting mass loss rates for the same stars he is modeling.

CHEREPASHCHUK: Could you comment on the possible clumping structure of stellar winds, which should be taken into account for the correct determination of mass loss rates from observations of radio fluxes of hot stars?

LANG: Currently, we have not taken any clumping factors into consideration for our mass loss calculations.

HILLIER: The influence of 'optically thick' clumps has to be considered. For continuum formation it is 'probably' not an issue. For line formation, the situation is more problematical. Of course, it depends on the clump properties, which are uncertain. If the clumps are thick and numerous, there is also an issue of driving them from the star.

LEITHERER: Can you say something about your non-detections? The upper limits are equally important for constraining mass loss rates, because they lower the mass loss rate averaged over the sample.

LANG: This is an important point which we need to explore further — you are right to point out that we are detecting the brightest (and therefore highest mass loss rate) sources in the cluster, and a more thorough analysis of our combined (two epoch) data on the Arches cluster will provide the full range of mass loss rates.

NAJARRO: Have you measured the mass loss rate for the dusty WC Wolf-Rayet stars? Is it consistent with other values from the literature?

LANG: The mass loss rates of the radio Quintuplet source QR 7, which appears to be related to the DWCL? type star (WCd?) is estimated to be  $1.3 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$  from our 8Ghz observations.

DWARKADAS: You calculated the mass loss rates by assuming that all the emission was thermal. Yet you have mentioned that there is some variation in the spectra, which may be due to the presence of a non-thermal component. How have you taken the non-thermal flux into account, and how will that change the mass loss rates you quoted?

LANG: Only about 25% of our sources appear to have spectra flatter than  $\nu^{+0.6}$ , and we haven't currently taken the non-thermal component into consideration for calculation of the mass loss rate (where this might lead to overestimation of  $\dot{M}$ ). Higher frequency (7 mm) observations are a good way to detect the thermal component. In one case (AR1) we do detect the wind emission at 7 mm and the mass loss rate based on the 7 mm flux density is 25 % lower, so it needs to be considered.

KNÖDLSIEDER: Concerning your X-ray data: you find that the previously claimed diffuse emission from the GC region is indeed partly due to point sources, which reduces the temperature from  $10^8$  K to  $10^7$  K. Do you have information if this applies also to the Galactic ridge emission?

LANG: We would like to be able to address that important issue (the origin of the Galactic ridge emission), but we haven't gotten to it yet.

MARCHENKO: The young, compact cluster NGC 3603 is a good example of diffuse faint X-ray emission. The emission is relatively soft, in the few-keV range. The phenomenon might be a common feature in young clusters.

LANG: Indeed, we do see a diffuse component of X-ray emission surrounding the Arches Cluster (in addition to several point-like sources). Unfortunately, the lack of sensitivity  $< 2$  keV prevents us from seeing an even softer diffuse component.