RADIO DETECTIONS OF STELLAR WINDS FROM THE PISTOL STAR AND OTHER STARS IN THE GALACTIC CENTER QUINTUPTET CLUSTER

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ABSTRACT

Very Large Array images of the Sickle and Pistol H II regions near the Galactic center at 8.3 and 4.9 GHz reveal six point sources in the region where the dense Quintuplet stellar cluster is located. The spectral indices of five of these sources between 6 and 3.6 cm have values of \( \alpha = 0.5 \) to 0.8 (where \( S \propto v^{\alpha} \)), consistent with the interpretation that the radio sources correspond to ionized stellar winds of the massive stars in this cluster. The radio source associated with the Pistol star shows \( \alpha = -0.4 \pm 0.2 \), consistent with a flat or slightly nonthermal spectrum.

Key words: Galaxy: center — stars: mass loss — stars: winds, outflows

1. INTRODUCTION

High-resolution near-infrared (near-IR) observations over the past decade have revealed the presence of massive, unusual stars in the inner 50 pc of the Galaxy, where observations suffer 20–30 visual magnitudes of obscuration. Three clusters of massive stars have been discovered (Glass, Moneti, & Moorwood 1990; Nagata et al. 1990; Okuda et al. 1990; Krabbe et al. 1995; Nagata et al. 1995; Figer, McLean, & Morris 1995; Cotera et al. 1996): (1) the central cluster, located within 1 pc of Sgr A*; (2) the Arches cluster, located \( \sim 30 \) pc north of Sgr A*, at \( l = 0^\circ12 \) and \( b = 0^\circ02 \); and (3) the Quintuplet cluster, also located \( \sim 35 \) pc north of Sgr A*, at \( l = 0^\circ16 \) and \( b = 0^\circ06 \). The stars detected in these clusters have near-IR signatures of OB supergiants and Wolf-Rayet-type stars. In the densely populated Quintuplet cluster alone, at least eight Wolf-Rayet stars and over a dozen OB supergiants have been discovered. Based on the evolutionary stages of the stars, this cluster is likely to be 3.5 Myr old, with a total estimated mass of \( \sim 10^4 \, M_\odot \) and a mass density of a few thousand \( M_\odot \, \text{pc}^{-3} \) (Figer, McLean, & Morris 1999b).

The near-IR emission-line spectra of stars in the three Galactic center clusters indicate that these stars have evolved away from the zero-age main sequence and have high-velocity stellar winds with terminal wind speeds of 500–1000 km s\(^{-1}\) (Nagata et al. 1993; Figer et al. 1999b; Cotera et al. 1996; Krabbe et al. 1995; Tamblyn et al. 1996). These powerful winds should be detectable at radio wavelengths, as the radio emission is thermal in nature (i.e., free-free) and arises from the outer parts of the ionized wind envelope. The classic theory of Panagia & Felli (1975) and Wright & Barlow (1975) predicts that in the radio regime, the spectrum of wind emission is proportional to \( v^{0.6} \) for a spherically symmetric, isothermal, stationary wind expanding at a constant velocity. Previous surveys made with the Very Large Array (VLA)\(^3\) have detected radio emission arising from the ionized winds surrounding OB supergiants and Wolf-Rayet stars (Abbott et al. 1986; Bieging, Abbott, & Churchwell 1989).

VLA continuum images at 6 cm (4.9 GHz) and 3.6 cm (8.3 GHz) of the Sickle and Pistol H II regions near the Galactic center reveal six point sources located in the vicinity of the Quintuplet cluster, including the radio source at the position of the Pistol star (Lang, Goss, & Wood 1997; Yusef-Zadeh & Morris 1987). The coincidence of the Pistol star in the near-IR with a peak in the 6 cm radio continuum image was first noted by Figer et al. (1998). In this paper, we report that two of the newly identified radio sources, in addition to the Pistol star source, are found to be coincident in position with massive stars in the \( \lambda = 2.05 \, \mu \text{m} \) Hubble Space Telescope (HST) NICMOS image of the Quintuplet cluster (Figer et al. 1999a). We discuss the nature of the radio sources and the association with stellar sources in the HST NICMOS image.

2. OBSERVATIONS

2.1. VLA Continuum Observations

Table I summarizes the VLA continuum images in which the radio point sources are detected. Standard procedures for data reduction and imaging in AIPS have been used in all cases. Both images were made with uniform weighting and have been corrected for primary-beam attenuation. The 6 cm continuum image was made with the data published by Yusef-Zadeh & Morris (1987), observed with the VLA in the B, C, and D configurations, and later supplemented with A-configuration data, to achieve a resolution of \( 1^\prime\,33 \times 1^\prime\,05 \), at \( P.A. = 10^\circ \).

2.2. HST NICMOS Imaging

In order to search for stellar counterparts to the radio point sources, a careful alignment was made between the HST NICMOS \( \lambda = 2.05 \, \mu \text{m} \) image of the Quintuplet cluster (Figer et al. 1999a) and the VLA 8.3 GHz continuum image of this region. The Quintuplet cluster was imaged by HST NICMOS in a mosaic pattern in the NIC2 aperture (19'2 on a side) on 1997 September 13–14 UT in the F205W filter (\( \lambda = 2.05 \, \mu \text{m} \)). The MULTIACCUM read mode with NREADS = 11 was used for an effective exposure time of 255 s per image. The plate scale was 0.076 pixel\(^{-1}\) (x) by 0.075 pixel\(^{-1}\) (y), in detector coordinates. The cluster was imaged in a 4 \( \times \) 4 mosaic, and the +y-axis of the detector was oriented 135° east of north. The images were reduced via the standard NICMOS pipeline (CALNICA, 87801; clang@nrao.edu).

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Table 1: VLA Continuum Image Parameters

| Wavelength (cm) | Resolution (arcsec) | rms Noise (mJy beam$^{-1}$) | Configuration | Reference |
|----------------|---------------------|----------------------------|---------------|-----------|
| 3.6            | $2.04 \times 1.71$ (P.A. = 59°) | 0.2 | DnC, CnB | Lang et al. 1997 |
| 6              | $1.33 \times 1.05$ (P.A. = 10°) | 0.2 | A, B, C, D | Yusef-Zadeh & Morris 1987 |

3. RESULTS

3.1. Radio Flux Density Measurements

Figure 1 shows the 3.6 cm continuum image of Lang et al. (1997) in the vicinity of the Pistol Nebula and the Quintuplet cluster. The six radio point sources discussed in this paper are labeled QR1–QR5 and “Pistol star.” The plus signs in the image represent the positions of HST NICMOS sources that are associated with the radio sources; these associations are further discussed in § 3.2.

In previous radio observations, Yusef-Zadeh & Morris (1987) identified the Pistol Nebula as the prominent pistol-shaped source at the center of Figure 1; it has a stellar source near its center of curvature, the Pistol star (Figer et al. 1998 and references therein). The H92α recombination line study of Lang et al. (1997) characterizes the Pistol Nebula as having an electron temperature of $T_e = 3300$ K, a complex velocity structure with central velocity near $V_{LSR} \sim 120$ km s$^{-1}$, and extremely broad lines ($\Delta V \sim 60$ km s$^{-1}$). In addition, a possible detection of He92α was made, with a helium-to-hydrogen abundance $Y^+ = 14\% \pm 6\%$. The continuum emission from the Pistol Nebula suggests an H II mass of 11 $M_\odot$. The absence of molecular material associated with the Pistol Nebula, coupled with the low value of $T_e$ as compared with other Galactic center H II regions, suggests that this nebula may in fact be the ejecta from a previous stage of the Pistol star’s evolution (Figer et al. 1995, 1998). The ionization of the Pistol Nebula is primarily due to the radiation field from several of the Quintuplet cluster members (Figer et al. 1995, 1999c, Lang et al. 1997).

With an rms noise level in the 3.6 cm image of 0.2 mJy beam$^{-1}$, the six point sources shown in Figure 1 (QR1–QR5 and the Pistol star source) are detected with S/Ns between 5 and 10. These sources are also detected at 6 cm with S/Ns between 5 and 8. In order to calculate the flux densities at both frequencies, crosscuts were made in both right ascension and declination across each point source. Table 2 lists the positions of the point sources, the flux densities at each wavelength, and the spectral index and deconvolved source size derived from these measurements. The radio sources QR1–QR5 have rising spectral indices, $\alpha = 0.5 \pm 0.4$ to $0.8 \pm 0.4$ (where $S_v \propto \nu^\alpha$), whereas the Pistol star source has a spectral index of $\alpha = -0.4 \pm 0.2$, consistent with a flat or slightly falling spectrum.

3.2. HST NICMOS Counterparts to VLA Sources

The plus signs in Figure 1 show three HST NICMOS sources (q15, q10, and the Pistol star) that are likely associated with the radio point sources QR4, QR5, and the Pistol star source. The angular offsets in the radio/near-IR positions are $\lesssim 3$ $\sigma$; the error in the alignment is dominated by the uncertainty in the near-IR positions of $\sigma = 0.5$. Figure 2 shows the overlay between the HST NICMOS image and the 8.3 GHz continuum image (shown in Fig. 1). It is also apparent in Figure 2 that three of the radio sources (QR4, QR5, and the Pistol star source) are coincident with NICMOS sources and that three of the radio sources (QR1, QR2, and QR3) do not have NICMOS counterparts. Given the relatively large surface density of stars in the NICMOS image of the Quintuplet cluster, the possibility of a chance superposition of a radio source and any NICMOS source is nonnegligible. However, the probability is much smaller that a randomly placed radio source with a flux density greater than 1 mJy ($5\sigma$) is coincident with a near-IR source...
that has been classified as a hot, massive star with a high mass-loss rate (16 sources total in a 77" × 74" region of the HST NICMOS image; see Figer et al. 1999a). Excluding the Pistol star as a special case, we calculate that the combined probability that two out of five radio sources would be randomly aligned (within the 3 σ positional uncertainty of 1′) with one of the 16 near-IR supergiants is 4 × 10^{-5}. Therefore, it is highly unlikely that these coincidences are due to chance superposition; instead, they represent real associations.

4. DISCUSSION

4.1. Nature of the Radio Sources

The near-IR counterparts of QR4 and QR5 have been classified as hot, massive stars with high mass-loss rates: q15 has been classified as an OB I supergiant and q10 as WN9/Ofpe, according to Figer et al. (1999b). The radio point sources QR4 and QR5 are presumably detections of the stellar winds arising from the near-IR stars, since their spectra are consistent with $\nu^{0.6}$ and they have near-IR counterparts. In addition, based on the classic theory of Wright & Barlow (1975) and Panagia & Felli (1975), it is possible to predict the radio flux density of the stellar wind arising from an OB supergiant found in the Quintuplet cluster at 3.6 cm. Assuming the following wind parameters (near the extreme values) for an OB supergiant at the Galactic center—a maximum mass-loss rate of $M_0 = 10^{-4} M_\odot$ yr^{-1}, an electron temperature of $T_e = 25,000$ K, a terminal wind velocity of $v_\infty = 500$ km s^{-1}, and a distance of $d = 8.0$ kpc—the predicted radio flux density at 3.6 cm is ~4 mJy. At this frequency, QR1–QR5 have flux densities in the range 2–6 mJy, consistent with this prediction.
the rms noise in our images of 0.2 mJy beam\(^{-1}\), we are
able to detect emission from the winds of OB super-
giants in the region of the Quintuplet cluster, and the
radio sources are most likely detections of these ionized winds.
Since there are at least eight Wolf-Rayet type stars in the
Quintuplet cluster, we can also estimate the radio flux
density at 3.6 cm for these stars, using the following wind
parameters: \( M = 5 \times 10^{-5} M_\odot \) yr\(^{-1}\), \( T_e = 40,000 \) K, \( v_\infty =
2000 \) km s\(^{-1}\), and \( d = 8.0 \) kpc; the predicted flux density for
a Wolf-Rayet star at the Galactic center is \( \sim 0.05 \) mJy at 3.6
cm. Since the rms noise in both of the VLA continuum
maps is 0.2 mJy beam\(^{-1}\), we would clearly not have
detected the mass-losing Wolf-Rayet stars in the current
data; therefore, these observations are only sensitive to the
winds arising from OB supergiants.

Although the sources QR1, QR2, and QR3 are detected
with S/N > 5 and have spectral indices consistent with
stellar wind sources, they have no obvious HST NICMOS
stellar counterparts. A possible explanation is that near-IR
extinction varies across the cluster and that the stellar
counterparts of QR1, QR2, and QR3 are masked by greater
extinction than the stellar counterparts of QR4 and QR5.
If we invoke extinction to explain the lack of counterparts for
QR1–QR3, then a near-IR extinction of \( A_K > 8 \) is required,
corresponding to a visual extinction of \( A_V > 80 \). This kind
of extinction is only possible if a dense molecular cloud is
located in front of part of the Quintuplet cluster. In that
case, the unseen counterparts could still be members of the
cluster. However, there is no evidence of such a molecular cloud in this region, which makes this suggestion unlikely.

4.2. The Pistol Star

The spectral index of the Pistol star (\( \alpha = -0.4 \pm 0.2 \)) is
consistent with a flat or slightly falling spectrum. It does not
follow the classic theory for a fully ionized wind, which
predicts a rising spectrum, \( \alpha = 0.6 \). The Pistol star, a promi-
nent source in the near-IR HST NICMOS image, has been
classified as a luminous blue variable by Figer et al. (1998)
and has a stellar wind. Based on the stellar parameters for
the Pistol star (see Figer et al. 1998, the “L” model)—\( \dot{M} = 3.8 \times 10^{-5} M_\odot \) yr\(^{-1}\), \( T_e = 12,000 \) K, \( v_\infty = 100 \) km s\(^{-1}\), and
\( d = 8.0 \) kpc—the predicted radio flux density at 3.6 cm is
\( \sim 9 \) mJy, using the formulation of Panagia & Felli (1975)
and Wright & Barlow (1975). At 3.6 cm, the flux density of the
Pistol star is \( 5.8 \pm 1.0 \) mJy, and at 6 cm the flux density is
\( 7.4 \pm 1.0 \) mJy.

The radio emission of the Pistol star source is likely a
result of ionized wind arising from the Pistol star. One pos-
sible explanation for the slightly falling spectrum is that the
Pistol star may have a nonthermal component in its wind
over the centimeter wavelength range. This type of spectral
index has been observed from other supermassive stars,
with \( \alpha \) in the range from \(-0.8\) to \(0.0\) (Abbott, Bieging, &
Churchwell 1984; Persi et al. 1985). In fact, the VLA survey
of Galactic OB stars made by Bieging et al. (1989) finds that
24% of luminous supergiants are observed to have non-
thermal spectra. This fraction is consistent with our results:
one of the six radio point sources we detect has a slightly
falling spectral index. Nonthermal emission is thought to
arise either by means of shocks in the wind itself, in the
shock between the stellar wind and a binary companion
(Contreras et al. 1996), or from the interaction of the stellar
wind with the remnant of a star’s previous evolutionary
mass-loss phase (Leitherer et al. 1997).

5. CONCLUSIONS

Six point sources were detected at 3.6 and 6 cm, with the
VLA, in the vicinity of the Quintuplet cluster. These sources
have rising spectra in the range \( \alpha = 0.5–0.8 \), with the excep-
tion of the Pistol star (\( \alpha = -0.4 \)). Based on the overlay of the
HST NICMOS and 8.3 GHz VLA continuum images,
three of these radio sources, including the Pistol star source,
can be identified with hot, massive stars with high mass-loss
rates. Therefore, the radio sources detected are most likely
ionized stellar winds emanating from the supermassive stars
in the Quintuplet cluster.

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