Multi-Array $\lambda 2$ and 6cm Radio Continuum Observations of Sgr A West

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Abstract: Sub-arcsecond (down to $0.1'' \times 0.2''$) radio continuum observations using the VLA[2] in a number of configurations have been carried out in order to investigate the fine-scale morphological details of the ionized gas and the distribution of spectral index along the triskelian-shaped figure of Sgr A West. In addition to finding a number of isolated patches of thermally-emitting gas and an absorbing feature at λ6cm within three arcminutes of the Galactic center, we have observed:

1) radio continuum emission from IRS-7, implying that the stellar wind from this supergiant is externally ionized. An improved position for this object was obtained.

2) the circular mini-cavity located along the east-west bar of Sgr A West. This feature has a diameter of 2-arcseconds and may have been created by a spherical wind, the source of which is yet to be identified; the seemingly most plausible candidate, IRS-16, is offset by $3''$ from the center of the cavity.

Spectral index maps having a resolution of $0.7'' \times 0.3''$ were made from scaled array observations at λ2cm and 6cm. They show that the eastern arm has a spectral index near -0.1, while the northern arm and the bar have positive spectral indices, indicating perhaps a partial opacity effect. The spectral index of IRS-7 is +0.6, consistent with that expected from a completely ionized stellar wind.

Introduction and Results

The elusive nature of ionized gas within the triskelian-shaped or "three-arm" spiral configuration of Sgr A West (Ekers *et al.* 1983; Lo and Claussen 1983) has been the center of much attention in recent years. This ionized source engulfs (in projection) the dynamical center of the Galaxy, and is thought to lie within the central cavity which is surrounded by the gaseous circumnuclear ring, and which is otherwise relatively devoid of neutral gas. Radio and infrared line observations reveal a continuous flow of ionized gas along the three arms of Sgr A West (Lacy

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et al. 1980; van Gorkom *et al.* 1983) but with no conclusive evidence about flow directions.

We have used the VLA in its A, B, and C configurations at λ1.2, 2 and 6cm over the last few years to make radio continuum images with the highest resolution possible with this instrument. When the data corresponding to different array configurations are combined, the dynamic ranges of the final images are limited by the sidelobes of the variable compact source, Sgr A*. A detailed description of the observations and data processing will be given elsewhere. Here, we present some of the highlights, including the spectral index distribution within Sgr A West, obtained by comparing the λ6cm and 2cm maps made with data from the A and B-arrays, respectively.

IRS-7

We have detected continuum emission at λ6, 2, and 1.2cm from IRS-7. Figures 1a,b show contour maps of this source at λ2 and 6cm, with a spatial resolution of $0.35'' \times 0.7'' (\alpha \times \delta)$. This object is the brightest 2μm source near Sgr A*, and is the only cool M2 supergiant known to be projected onto the inner pc of the Galactic center (Sellgren *et al.* 1987). The position of this source is obtained by Gaussian fitting to the λ2cm image:

$$\alpha(1950) = 17^h\ 42^m\ 29.319^s\ (\pm \leq 0.001^s)$$
$$\delta(1950) = \text{-}28^\circ\ 59'\ 12.66''\ (\pm 0.01''),$$

where the quoted errors are the standard errors of the fit.

This is remarkably close to the astrometric position (Becklin *et al.* 1987). The λ6cm peak is shifted to the northeast of the above coordinates by 0.021^s and $0.06''$, respectively. The spectral index determined from λ2 and λ6cm peak fluxes (2.3 mJy and 1.2 mJy, respectively) is $\alpha \sim +0.6$, where $F_\alpha \propto \nu^\alpha$. We also note that the angular size of the extended emission surrounding IRS-7 is larger at λ2cm than at λ6cm. Because of the lack of complete (uv) coverage and the complex nature of ionized gas from Sgr A West, it is possible that the elongated structure to the north of IRS-7 is physically associated with the star and that the observed discrepancy in the angular size of IRS-7 at λ6 and at λ2cm may not be physical.

Ionized gas around IRS-7 is also inferred from the Bracket lines (Rieke, these proceedings). We suggest that the envelope of the mass-losing cool supergiant is photoionized externally by ultraviolet radiation. This radiation which bathes the central few pc of the Galactic center arises from the central luminosity source, i.e., Sgr A* or IRS-16 (see Brown and Liszt 1984; Werner and Davidson, this volume). This picture is analogous to that described by Morris and Jura (1983) for another mass-losing supergiant, NML Cygnus. It is also akin to symbiotic systems in which a distant hot companion ionizes the mass-losing red giant. The model of Taylor and Seaquist (1984) for symbiotic stars can be applied to the system of IRS-7 and Sgr A* where X (the parameter specifying the location of the ionization front) is $\geq \pi/4$ and $\alpha \sim +0.6$. A more detailed application of these treatments to IRS-7 and other mass-losing stars in the Galactic center will be published separately. Here, as a limiting case, we assume that the envelope is completely ionized.

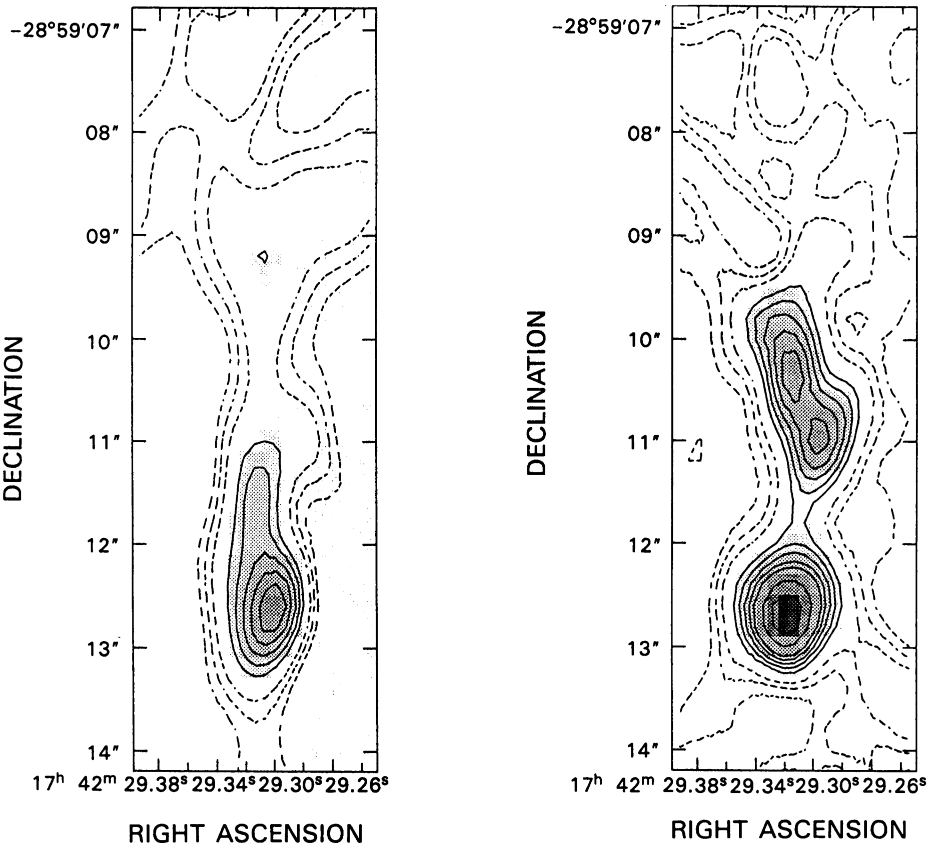


Figure 1a,b: Radio continuum maps of IRS-7 at λ6 (left) and λ2cm (right) based on observations made in the A and B arrays, respectively. Contour levels are set at -6, -4, -2, 2, 4, 6, 8, 10, 15, 20 mJy/ beam area.

By assuming that IRS-7 is 8.5 kpc distant, and has integrated flux density equal to 1.28 mJy at λ6cm, the ratio of mass-loss rate to the terminal velocity of the outflowing matter is estimated to be $\sim 1.2\times10^{-6}$ (Panagia and Felli 1975; Wright and Barlow 1975). Adopting an outflow velocity typical of mass-losing supergiants, 25 km s^{-1}, we estimate the mass-loss rate from IRS-7 to be $\sim 3\times10^{-5}$ $M_\odot$ yr^{-1}. If the envelope is not completely ionized, then this is a lower limit.

Circular Mini-Cavity

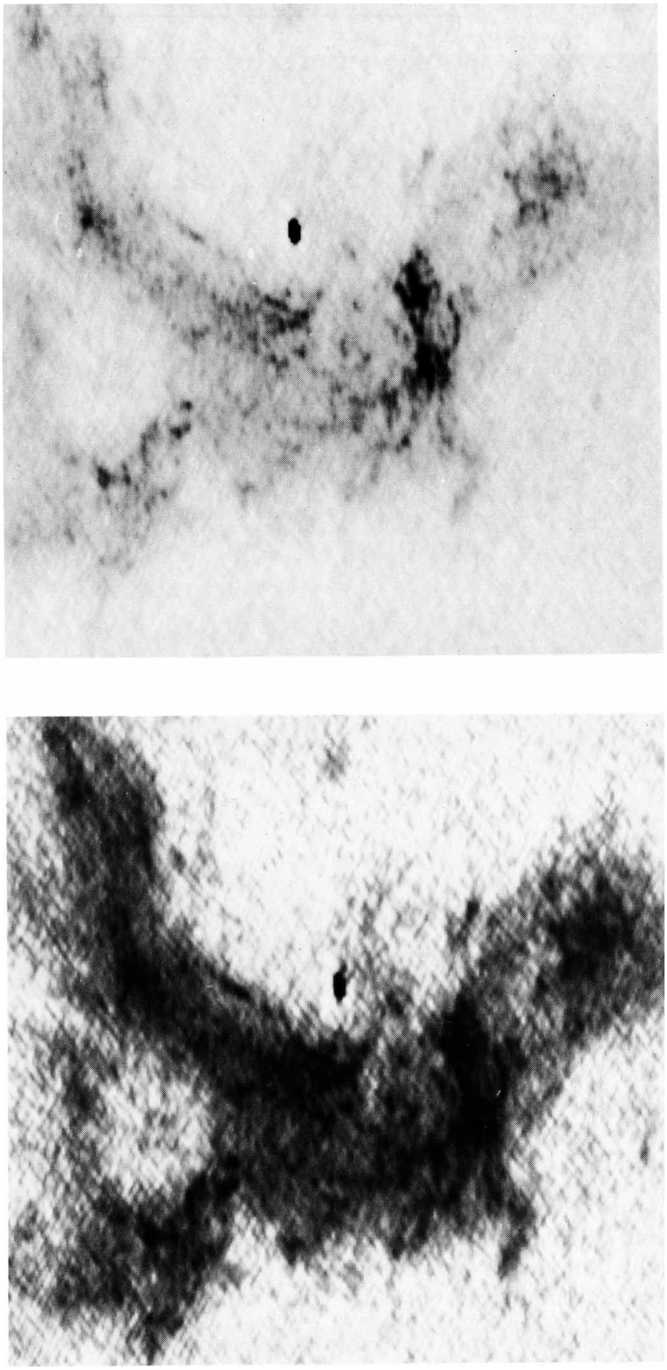
One of the most striking structures in Sgr A West is the mini-cavity centered near the junction of the northern and eastern arms of Sgr A West. This feature, first described by Morris and Yusef-Zadeh (1987), is a distinct hole in the distribution of radio continuum emission with a diameter of 2″, corresponding to a linear dimension of 0.08 pc. It is best recognized in the λ2cm images portrayed in Figs. 2(a,b), which have a spatial resolution of $\sim 0.1'' \times 0.2''(\alpha \times \delta)$. (another rendition of this feature can be seen in Fig. 4 of Morris and Yusef-Zadeh 1987). The sharp edge of the mini-cavity does not trace a closed circle; it is open at the north along a line coincident with the boundary of the radio "bar" (Brown and Liszt 1984). Diffuse and weak emission arises within the cavity and persists continuously through the opening and further north. The bright western rim coincides with IRS-13 (a bright 10μm source) and IRS-2 (a bright 2μm source) and shows a spectrum consistent with optically thick, ionized gas. The λ2cm map of the mini-cavity is seen in Fig. 3 at a resolution of $0.1''\times0.2''(\alpha \times \delta)$. The radio counterpart of IRS-13 and IRS-2 is resolved into at least 15 discrete radio sources.

The morphology of the mini-cavity suggests that the ionized material in the bar has been swept up, possibly by a stellar wind, to form the rim of the cavity. As was described by Morris and Yusef-Zadeh (1987), the responsible wind may be the one emanating from IRS-16 (Hall *et al.* 1983; papers in these proceedings by Allen, by Maillard, and by Geballe), although IRS-16 lies at the northeastern periphery of the mini-cavity, 3″ from the center, so it is difficult to imagine how such a circular cavity could have resulted from a displaced source of wind. Geballe (1987) considers such a situation in a schematic diagram showing how a wind from IRS-16 might create a 0.1-pc bubble at the surface of the ionized radio bar.

A second possible source of a wind is a Wolf-Rayet star. Allen (these proceedings) argues that the central cluster may contain some WR stars and that one might even identify the IRS-16 wind with WR winds. He finds one object with strong near-IR helium emission similar to that of WR winds, but it lies at the southwest rim of the cavity. It may be that the relevant star has yet to be identified.

If we estimate a wind velocity of 300 km s^{-1} from the linewidths in the broad line region centered on IRS-16 and the kinematics of ionized gas along the bar (Lacy *et al.* 1987; Serabyn *et al.* 1988), the expansion time of the mini-cavity is 150 years. In order for the expanding bubble to have entered the snowplow phase, and to have swept up the shell observed at its western edge, the mass-loss rate is inferred to be 3×10^{-3} $M_\odot$ yr^{-1} (Castor *et al.* 1975).

Figure 2a,b: Images of the inner 15″ of Sgr A West at λ2cm are shown with two different contrast levels with a resolution of 0.23″ × 0.12″. These images are based on combining the A, B and C array data sets.



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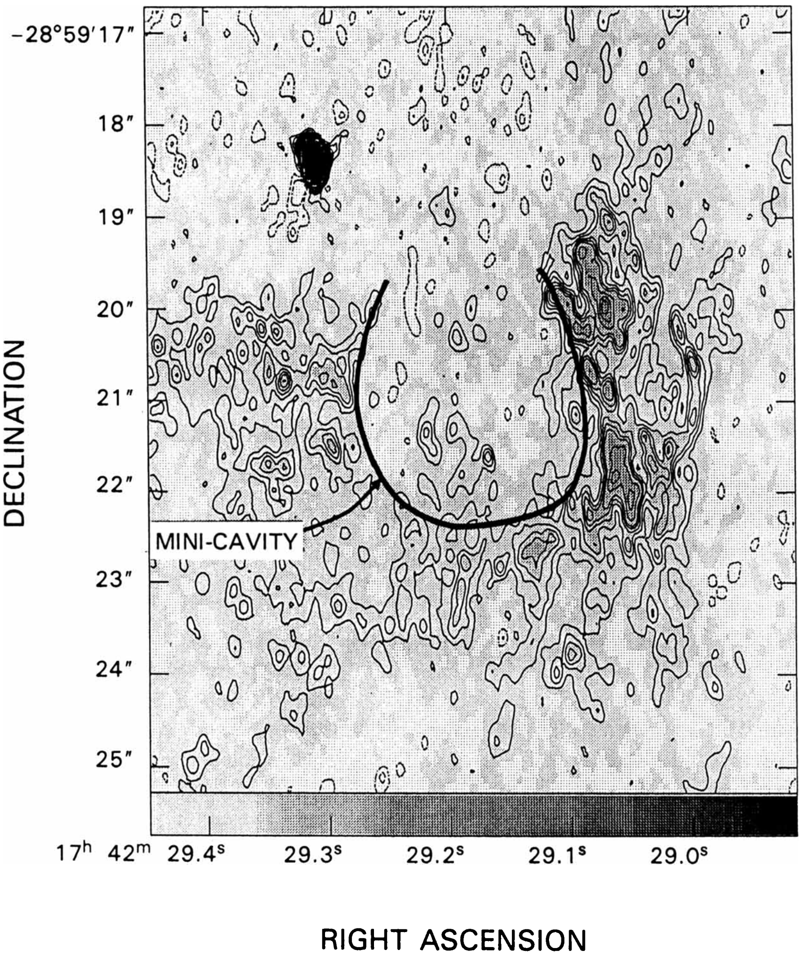

Figure 3: Radio continuum map of the mini-cavity at λ2cm with a resolution of $0.1'' \times 0.2''$. This map is based only on the A-array data. Contour levels are set at -1, -0.5, 0.5, 1, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, 10 mJy/beam area.

Spectral Index Distribution

Figure 4 shows the color display of the distribution of spectral index determined from λ6cm and λ2cm measurements. We note that the eastern arm, appearing in light blue, has a spectral index, α, between ~-0.12 and -0.15, characteristic of free-free emission from optically thin, ionized gas. On the other hand, the positive α

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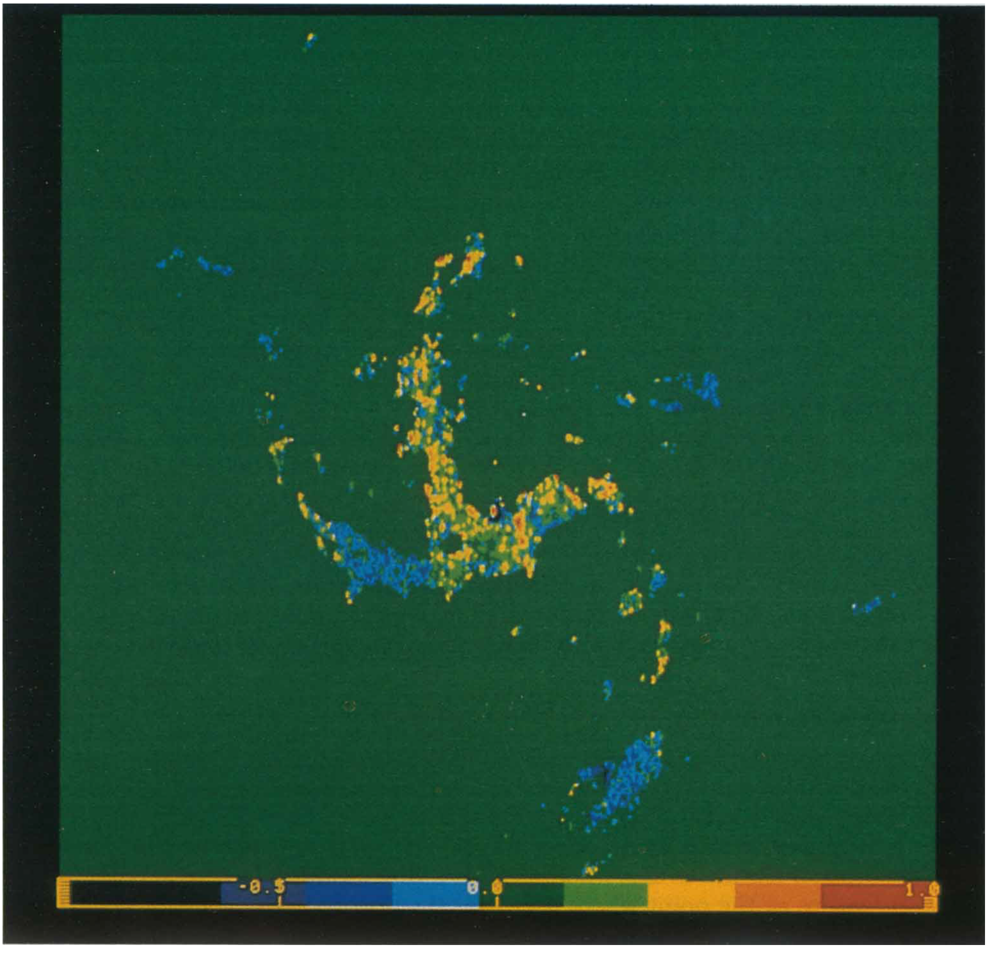

Figure 4: The color radiograph of the spectral index distribution of Sgr A West determined from the $\lambda 6$ and 2cm images. The values of the spectral indices are shown in the key at bottom.

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noted along the northern arm and the bar indicates higher opacity along these features. The fact that the bar and the northern arm have very similar spectral indices is consistent with the hypothesis that these two components of Sgr A West are part of a unified structure. This hypothesis stems from the continuous velocity structure of [NeII] between IRS-1 and IRS-2, which are positioned along the northern arm and the bar, respectively (Serabyn *et al.* 1988).

Large discontinuities in the distribution of α along the arms of Sgr A West are caused by a number of isolated thermal structures which cross the arms of Sgr A West, in projection. For example, we note a large gradient in α near the extreme western portion of the eastern arm. The positive value of α is associated with a feature which appears to connect IRS-1 in the northern arm and IRS-9 in the eastern arm. The [NeII] measurements show a large change in the velocity of ionized gas at these positions (Lacy *et al.* 1987).

The spectral index and surface brightness distributions of Sgr A West, based on the λ6 and 2cm measurements, indicate that the electron temperature along the bar and the arms of Sgr A West are similar, i.e., $\sim 10^4$K. The positive spectral index along the bar can easily be accounted for by a higher emission measure along the bar than that along the arms of Sgr A West without introducing a higher electron temperature, as claimed by some authors. The electron temperature is derived from $T_e = T_b(1\text{-}\exp(-\tau))$ where τ is the opacity which is derived from the comparison of the λ6 and 2cm measurements with the *a priori* assumption that the optically thin ionized gas has $\alpha \sim$-0.1. The uniform electron temperature of $\sim 10^4$K throughout Sgr A West is consistent with Brγ line emission detected from the bar as well as the rest of the nebulosity associated with Sgr A West (Depoy *et al.*, these proceedings; Forrest *et al.* 1987).

Absorption Feature

A filamentary absorption feature is seen at λ2 and 6cm running roughly parallel to the northern arm about 5$''$ to the west. This indicates that a dense, cool plasma is present near Sgr A West, but the presence of a bright radio rim on the absorption feature indicates that it is externally ionized. Pictorial evidence for the presence of the absorption feature is also inferred from a discontinuity in a weakly emitting east-west feature at the point where it crosses the northern arm – $\delta = -28°59'04''$. The surface brightness of this feature changes by at least a factor of 3 at λ2cm corresponding to an optical depth, τ, of $\geq$1. Thus, $ET_e^{-1.33} \geq 3.6 \times 10^3$, where E is the emission measure and T_e is the electron temperature.

Sinuous Feature

At high resolution, the northern arm of Sgr A West is manifested as a sinuous structure with a wavelength of 0.4 pc. Possible causes for the the sinuous structure include: 1) a Rayleigh-Taylor instability caused at the interface between two fluids, 2) a Kelvin-Helmholtz instability occuring as a result of the interaction between the flow of matter along the northern arm and the high-velocity wind emanating from the vicinity of IRS16, or 3) the presence of a dynamically important helical magnetic field threading the northern arm; the appearance of a braiding near IRS-1 and IRS-10 supports the view that the magnetic field lines play a role in shaping the structure of ionized gas, in particular, the sinuous structure. The far-IR polarization from the cool dust particles of the circum-nuclear ring (Werner, these proceedings) plus polarized mid-IR emission from hot dust particles in Sgr A West (Aitken, these proceedings) suggest that the ionized gas along the arms of Sgr A West is strongly influenced by the magnetic field lines. We therefore, prefer the latter hypothesis.

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