THE NATURE, LOCATION AND ENVIRONMENT OF SGRA EAST

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ABSTRACT. We have observed SgrA at 332 MHz (92 cm) with a resolution of 12 arcsec (0.6 pc) using the four configurations of the VLA. These results illustrate the dramatic and almost unique variation of radio spectral index within the central 3-4 arcmin of the galactic center. SgrA East is a non-thermal shell source that could be a supernova remnant or a very low-luminosity example of a radio component associated with the active nucleus of a spiral galaxy. The most dramatic aspect of the new 332 MHz observations is the appearance of the the SgrA West spiral features in absorption against SgrA East. Based on these results, SgrA East is situated behind SgrA West, the center of the galaxy. The halo is in front of or surrounds the former sources. The HII regions to the east of SgrA East ($l = -0\overset{\circ}{.}02$, $b = -0\overset{\circ}{.}07$) are probably associated with the 50 km/s molecular cloud. The 7 arcmin halo (20 pc) has a non-thermal spectrum with turn-over below 1 GHz.

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1. Introduction

The properties and nature of SgrA East have long remained a mystery. For example, Gopal-Krishna and Swarup (1976), Sandquist (1974) and Ekers et al. (1975) have presented images of SgrA East with resolutions of 0.5 to 1 arcmin which suggested a shell structure for this non-thermal source. Jones (1974) and Ekers et al. (1975) have discussed the possibility that SgrA East could well be a supernova remnant (SNR) and was unlikely to be a radio source associated with the nucleus of an active galaxy.

With the advent of Very Large Array (VLA)[1] observations in 1981, it became possible to map SgrA East with resolutions of several arcsec. The B array 20 cm and the C array 6 cm images published by Ekers et al. (1983) showed a clear shell source of size 2.1 x 3.3 arcmin (about 9 pc if a distance of 10 kpc is assumed). SgrA East is the second brightest shell source in the galaxy (after Cas A). If SgrA East is a SNR then it is surpassed in surface brightness only by Cas A and the Crab Nebula. Ekers et al. (1983) and Goss et al. (1983) have discussed the problems of identifying SgrA East with a conventional SNR: (1) the relative location of SgrA East and the nucleus of the galaxy, SgrA West; (2) the size of the SNR and (3) the energy of the SNR.

Mills and Drinkwater (1984) have shown that the thermal component in SgrA becomes increasingly opaque at longer wavelengths, and at 300 cm the source has disappeared completely (LaRosa and Kassim, 1985). Hence the increase in optical depth of the thermal component at low frequencies can be used to constrain the 3-dimensional structure of the Galactic Center. 90-cm observations using the VLA are unique in having sufficient resolution to separate SgrA East from other components in the Galactic Center, and also have sensitivity to extended background emission. In addition, the high brightness temperature of the non-thermal background at low frequencies enables us to detect, in absorption, foreground ionized gas with low emission measures which is too weak to be detected in emission at higher frequencies. A full description and discussion of the results will appear shortly in the Astrophysical Journal (Pedlar, Anantharamaiah, Ekers, Goss, van Gorkom, Schwarz and Zhao, 1989; hereafter Pedlar et al). High resolution 6 and 20 cm observations (1.3 x 2.5 arcsec) are also discussed.

2. THE RESULTS

In this paper, we shall discuss only the central region, which includes SgrA East and West superimposed on a ~7 arcmin halo. This central part of the 90-cm image (12 arcsec resolution), is shown in Fig. 1. Yusef-Zadeh and Morris (1987) have published a 20-cm image with similar resolution (e.g., their Fig. 3).

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[1] The VLA is part of the National Radio Astronomy Observatory which is operated by Associated Universities, Inc. under contract with the National Science Foundation.

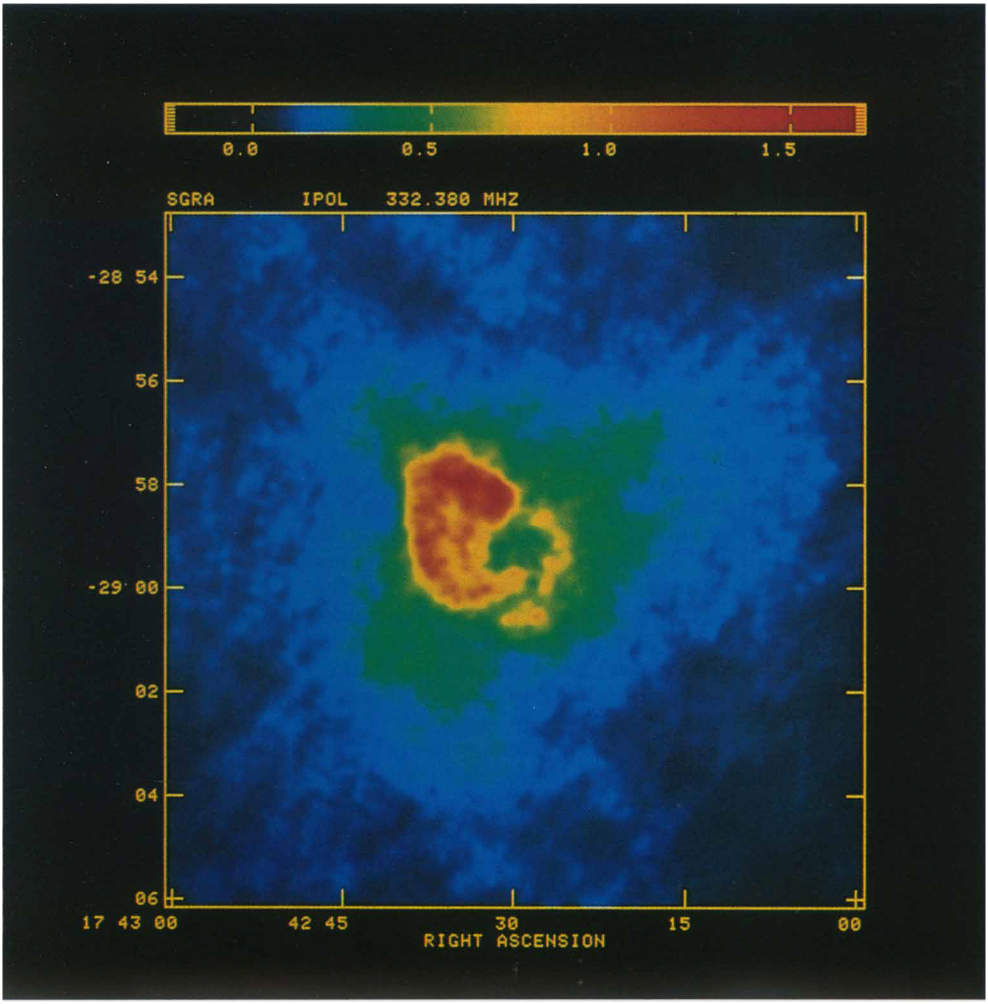

Figure 1. A pseudo-color representation of SgrA and its halo at 90 cm (332 MHz). The angular resolution is 12". The coding of the brightness scale is indicated by the color bar.

2.1. THE 90 CM IMAGE

The brightest feature in the 90-cm image is the 2.1 x 3.3 arcmin shell (PA ~40°) identified with SgrA East. This feature is situated on a roughly triangular-shaped halo with an extent of ~7 arcmin. The eastern edge of the shell is remarkably straight, which may be a consequence of its interaction with the +50 km/s molecular cloud (M-0.02-0.07) as suggested by Goss et al. (1985), Ho et al. (1985) and Mezger et al. (1988). The most striking feature, however, is the deep depression in the brightness on the western side of the shell, which is consistent with free-free absorption of SgrA East by thermal gas associated with SgrA West. The spatial structure of the absorption at 327 MHz in SgrA was first determined by Yusef-Zadeh et al. (1986) based on Culgoora observations.

In Fig. 2 we show a greyscale of the 90-cm image (12 arcsec resolution) with the 6-cm image (1.3 x 2.5 arcsec resolution) (from Pedlar et al.) superimposed as contours. The structure of the outer parts of the thermal spiral is evident in the 90- cm absorption feature. The shape of the 90 cm absorption near the center of the spiral does not reflect the 6-cm morphology due to saturation of the free-free absorption at 90 cm. The ~7 arcmin extended region shows considerable structure, and includes a ~1 arcmin feature at α= $17^h42^m40^s$, δ= -29°01′ together with a pronounced depression at the position of the cluster of HII regions to the East of SgrA. Yusef-Zadeh and Morris (1987) separate this extended region into two major components: the SgrA East halo and the NW streamers. This distinction is not clear from our data and we shall make no attempt to determine separate flux densities. We consider 'SrgA' to imply SgrA*, Sgr East and West only, and the 'Sgr A complex' to consist of these three components plus the 7 arc min halo emission. Parts, or all, of this 7 arcmin component are often included in low-resolution flux density measurements of SgrA. By inspection of crosscuts (e.g. Fig. 3), we deduce a background level between 50 and 100 mJy/beam at 90-cm, and, after removing this, measure a total flux density at 90 cm of 370 ± 50Jy within the 10 x 10 arcmin field shown in Fig. 1. The resulting flux densities of SgrA and its halo are given in Table 1. At 6 cm the flux density of only SgrA can be estimated, as the halo is comparable in size to the primary beam.

We have attempted to establish the structure of SgrA East uncontaminated by SgrA West. An existing VLA 2-cm image of SgrA was used; we assume that at this wavelength the emission is almost entirely thermal. This image was appropriately scaled and subtracted from the 6 and 20 cm images shown by Pedlar et al., to give the structure of the non-thermal source SgrA East at 6 and 20 cm.

As Pedlar et al. show, the shell of SgrA East clearly continues across the position of SgrA West. It passes within (~10") of the center of SgrA West. The western shell appears to be brightest at positions coincident with SgrA West. A non-thermal component appears just to the south of SgrA*, and may be a continuation of the shell or a distinct component within SgrA East. The 20-cm flux density in this component is about 5 Jy and it may contribute to the diffuse component of SgrA West discussed by Ekers et al. (1983).

2.2 FREE-FREE ABSORPTION OF SGRA EAST BY THERMAL GAS

At 90 cm, ionized gas at a temperature of 5000K, has an optical depth of unity if the emission measure is $\sim 10^5$ pc cm^{-6}. Based on the determination of the thermal flux density distribution of SgrA West using the existing 2-cm images, SgrA West will have 90-cm optical depth

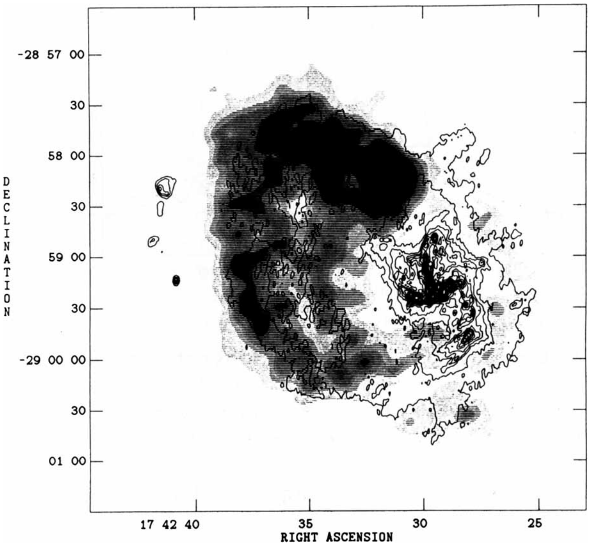

Figure 2. Greyscale of the 90-cm image (12 x 12 arcsec resolution) with the 6-cm image (1.3 x 2.5 arcsec resolution) superimposed as contours. The contours are at 7 mJy/beam intervals until 175 mJy/beam, after which they are every 70 mJy.

TABLE 1. Flux density measurements of SgrA (Jy)

Wavelength	SgrA	SgrA Halo	Total	SgrA East[1]
90 cm	114 ± 20	256 ± 60	370 ± 50	
20 cm	240 ± 20	247 ± 35	487 ± 30	222 ± 20
6 cm	88 ± 10	-	-	70 ± 10

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[1] SgrA West contribution extrapolated from 2 cm flux density and subtracted.

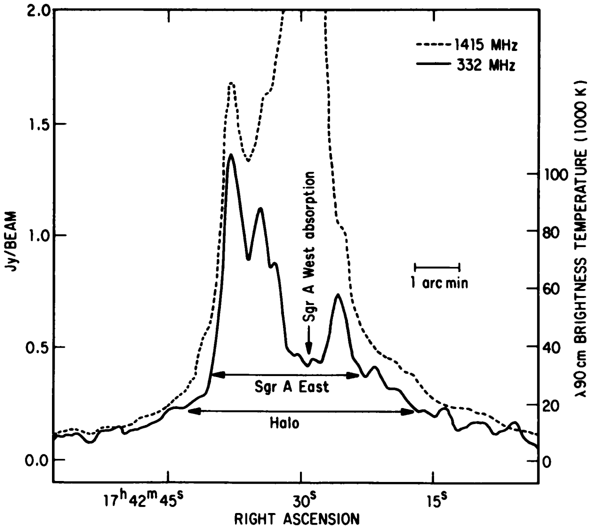

Figure 3. A typical crosscut at constant declination (δ = -28° 59′ 6″) at 90 cm and 20 cm (dotted) illustrating the absorption at the position of SgrA West, and the halo emission. The 20 cm crosscut has been offset for clarity.

>>1 and hence will be effectively opaque to background radiation. The brightness temperature of the 90-cm image varies between 20,000K to 40,000K over the halo, rising to ~120,000K in parts of the SgrA East shell. As can be seen in Fig. 3, at the position of Sgr A West the brightness is depressed. As the depth of the feature is ~80,000K, most of this must be against SgrA East as this is the only source in the field with a high enough brightness temperature. Further, the shell of SgrA East extends behind SgrA West (see Pedlar et al.), providing a strong background against which absorption can occur. The average contribution from the broad galactic background, much of which may be missed by lack of low order spacings, has been estimated by Anantharamaiah and Bhattacharya (1986) to be ~900K, which can be neglected since the rms noise is ~1300K.

The fact that the minimum of the absorption is close to, but not below, the mean level of the halo (see Fig. 3), suggests that most of the 90-cm halo emission is in front of SgrA West. The brightness temperature at the position of SgrA West is ~30,000K, and extends over an area of at least 1 arcmin^2. It appears, therefore, that much of the emission in the direction of SgrA West must have a non-thermal origin. As the thermal component in most of SgrA West is essentially opaque at

90 cm, the most likely source of this non-thermal emission, given the approximate agreement in brightness temperatures, is the 7 arcmin halo.

The absorption at 90 cm has been estimated using the 20 and 6-cm images from which the thermal emission has been removed. The free-free optical depth is calculated assuming that all of the absorbing medium is in front of the 90-cm emission. As expected, most of the SgrA West region shows high optical depth ($\tau > 4$), implying an emission measure of at least 5 10^5 pc cm^{-6}. This distribution is superimposed on an extended background optical depth of 1.5-2, which corresponds to an extended thermal component undetected by the 2-cm measurements (Pedlar et al.). The region with optical depth ($\tau > 3$) appears to be larger than the 6-cm image of SgrA West, and implies that the thermal 'spiral' is embedded in a halo of ionized gas with an emission measure of ~2 10^5 pc cm^{-6} and an extent of 1.5'. Using a simple, uniform density (N_e ~200 cm^{-3}) spherical model for the ionized gas, we estimate this component to contain ~500 $M_\odot$ of ionized gas. This component would have a flux density of ~3 Jy at 6 cm and 20 cm and may, together with the ~5 Jy non-thermal component discussed earlier, be part of the diffuse component of SgrA West referred to by Ekers et al. (1983).

The north and south 'spiral arms' of SgrA West are clearly visible (Fig. 1) where they cross the shell of SgrA East and can be traced further than is evident in emission on the 6-cm contour image shown in Fig. 2, although this extension is faintly visible on the 6-cm greyscale plots of Yusef-Zadeh and Morris (1987). Using crosscuts we estimate the increase in optical depth at the positions of the arms to be ~1, indicating an emission measure of ~10^5 pc cm^{-6}. The 90-cm brightness temperatures at the positions of the spiral features are 40,000K, although as the 12 arcsec beam does not fully resolve these, they should be considered upper limits, and the corresponding optical depths and emission measures, lower limits.

There is no evidence that either of these features is seen in absorption against the ~7 arcmin halo at 90 cm. If SgrA West is in front of the halo, then it may be that the arms terminate shortly after crossing the shell of SgrA East, otherwise an optical depth of 0.5 would be detectable against the halo. The 20/6 cm spectral index image shown by Pedlar et al. suggests that thermal emission, possibly associated with a continuation of the northern arm of SgrA West, is present to the northwest and yet does not show up as absorption against the halo.

Apart from SgrA West and its arms, the optical depth distribution across the rest of SgrA East shows no strong variations. Most of the source shows an optical depth between 1.5 and 2.5, with the higher values in the southern part of the shell. This distribution could be due to a foreground HII region with an emission measure of ~2 x 10^5 pc cm^{-6}, or may be associated with the thermal component in the 7 arcmin halo (see Pedlar et al.).

2.3 HII REGION COMPLEX G-0.02-0.07

The four compact HII regions to the east of SgrA East at $l = -0\overset{\circ}{.}02$, b =

-0°07 were discovered by Ekers et al. (1983) and discussed in detail by Goss et al. (1985). The 14.7-GHz continuum image of this complex is shown in Fig. 4 (from Goss et al., 1985). This region is 1.5 pc to the east of the SgrA East shell source. The H76 alpha recombination lines were observed with velocities in the range 43 to 52 km s^{-1}. The implied LTE electron temperatures are in the range 6000 - 7000K with line widths in the range 23 to 36 km s^{-1}. These HII regions are only a few percent of the luminosity of the Sgr B2 complex. Each of the four components could be excited by a single 07 to 09 star; the four sources are typical compact HII regions.

The H76α velocities agree to within ~10 km s^{-1} with the CO velocities of the prominent 50 km s^{-1} molecular cloud M-0.02-0.07. In addition, Yusef-Zadeh, Telesco and Dreher (this volume) find a 10 micron peak near the compact HII component A. There is a slight shift between the radio and IR positions and the IR excess of 34 suggests that the exciting star is cooler than an 07 star. Yusef-Zadeh and Morris (1987) have discussed an alternative model for these HII regions which involves ionization caused by the supernova explosion which created SgrA East.

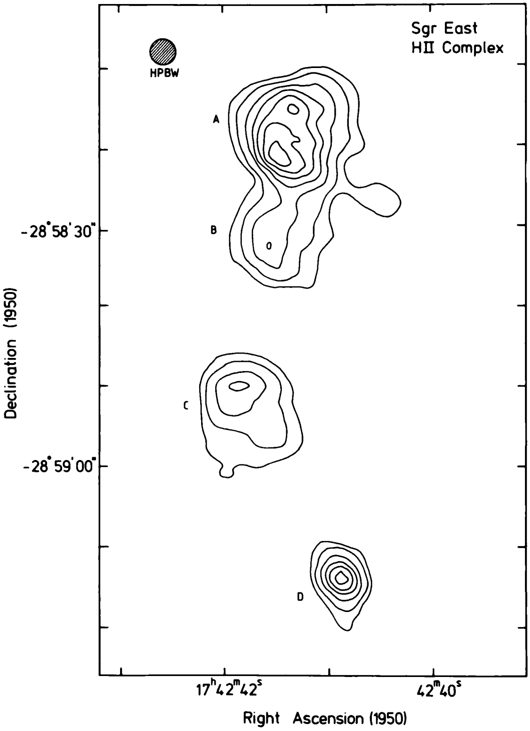

Figure 4. Continuum image of the HII cluster at l= -0°02, b =-0°07 at 14.7 GHz as observed with the VLA (beam of 3.6 x 3.0 arcsec, $\alpha x \delta$. The contours are 5, 10, 20, 30, 40, 50 and 60 mJy/beam.

Goss et al. (1985) have discussed the question of the relationship between the possible SNR SgrA East and the HII cluster at G-0.02-0.07. SgrA East could well be a SNR which occurred in the 50 km s^{-1} molecular cloud. However, as Goss et al. point out, "... this model gives no explanation of the close association between the western rim of SgrA East and the structure at the center of the Galaxy."

3. DISCUSSION

There seems little doubt that SgrA West and SgrA* are the center of activity in our Galaxy. The 90-cm observations show conclusively that SgrA East is on the far side of the center, although from other constraints (e.g., Gusten and Downes, 1980) it must still be within 100 pc of the nucleus. It is also interesting to note that, after removing the thermal emission, the brightest part of the shell of SgrA East is at the position of SgrA West. This observation could indicate that the two components are physically related. This possibility is also suggested by the similarity between the shape of the linear N-S feature (Fig. 1) and the boundary of the ionized gas associated with SgrA West. Both the N-S feature and the western edge of SgrA East and West coincide with enhanced molecular emission as if both components were colliding with the same molecular clouds; a possible physical association is suggested. It appears that SgrA East is situated towards the far side of the halo if we are to account for its 90-cm turnover by free-free absorption by the thermal component in the halo.

In Fig. 5a we show a possible configuration of the components within SgrA, where SgrA West has been assumed to be at the center of the halo. It has been suggested (e.g. Yusef-Zadeh and Morris, 1987) that the halo is a secondary manifestation of the supernova explosion which produced SgrA East, and may represent leakage of cosmic ray electrons throughout the shell of SgrA East. If our deduction from optical depth considerations that the halo is largely in front of SgrA East is correct, then such leakage must be preferentially on the near side of SgrA East. Such a configuration may be a consequence of SgrA East being bounded by giant molecular clouds on the far side, as in the picture suggested by Goss et al. (1985) and Mezger et al. (1988 and this volume). The displacement of the center of SgrA East from SgrA West could suggest that the structure is elongated at an angle of 10 to 20 degrees from the line of sight from the Galactic Center to the Sun. If SgrA East is embedded within the halo, then SgrA West must be situated close to the center of the halo not only in the plane of the sky, but also along the line of sight. We could then speculate that the relativistic electrons in the halo originated in SgrA*.

An alternative configuration for the SgrA complex is shown in Fig. 5b, as our data cannot rule out the possibility that the halo is a spatially separate component, which may be in front of both SgrA East and West. If we consider the halo as a separate object, then its non-thermal spectrum, together with its relativistic energy of 5×10^{50} ergs and size of ~20 pc could suggest that it was an evolved supernova remnant, of which SgrA East may be either a younger example, or one which has occurred in a much denser environment (Goss et al. 1983, Ekers et al. 1983). Several other components of the SgrA complex could possibly be supernova remnants such as the ring to the S-E. It should be pointed out, however, that there are many structures which are unique to the Galactic Center, such as the threads. Although there is little evidence of shell type structures in the halo, such ordered structures might be expected to be disrupted by the violent environment close to the Galactic Center, once the pressure within the remnant is roughly equal to the ambient pressure.

Supernova explosions would be a natural consequence of the on-going star formation at the Galactic Center. However a somewhat more speculative possibility is that SgrA East and the halo are two non-thermal components which have originated from the active nucleus. This would then suggest similarities with Seyfert type activity in the

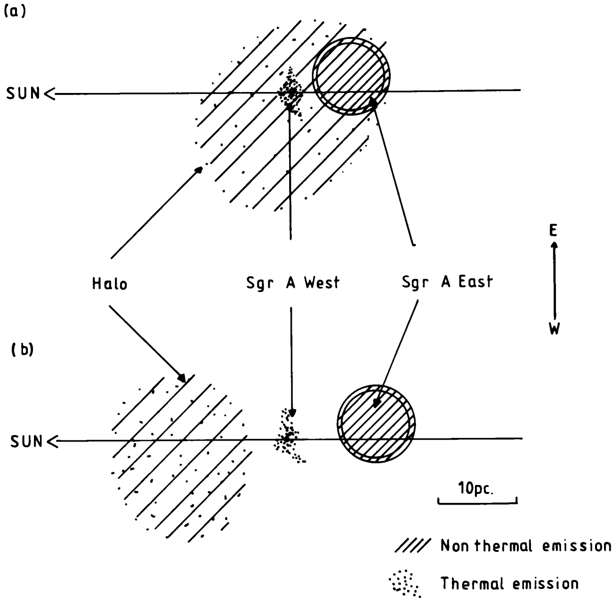

Figure 5. Two possible configurations for the structure of radio emission in the SgrA complex. As discussed in the text our observations demonstrate conclusively that SgrA East is behind SgrA West. Pedlar et al. 1989 show that the absorption across SgrA East is consistent with a location of this component at the far side of the halo. The overall elongation of the structure is not constrained by our measurements: the three components could be in close contact, as in (a); or well separated, as in (b). The offset of 3 pc between the centres of SgrA East and West may be produced by inclining the above structures to the line of sight.

nuclei of spiral galaxies and thought to originate in a central engine. Many of these have associated radio emission which appears to originate in collimated ejection from the nucleus, which rarely seems to align with the rotation axis of the spiral (e.g. Booler et al. 1982). Evidence for such collimated ejection is seen in the compact, non-thermal radio components which straddle the optical nucleus (Ulvestad and Wilson 1984, Unger et al. 1986). The origin of these components is unclear as their energy in relativistic particles/magnetic fields range from 10^{51} - 10^{55} ergs. These high energies and their collimation would appear to rule out conventional SNRs. This type of phenomena also appears in normal spirals such as M51 (Ford et al. 1985), although this can often only be detected with the highest available sensitivity. The lower limit of $\sim 10^{51}$ ergs for these components (Unger et al. 1986) is largely due to instrumental sensitivity and an object such as SgrA East or the halo would be undetectable if situated in a galactic nucleus beyond a few Mpc. It is of interest to note if SgrA East were to be the remnant of a supernova which had exploded directly into a Giant Molecular Cloud then an event of at least 4 x 10^{52} ergs in total energy would be required to produce the observed radio emission, although this can be reduced if the supernova progenitor excavates a cavity with a strong stellar wind (Mezger et al. 1988).

At this stage it is unclear to us whether SgrA East represents the high energy end of a distribution of SNR, or one of the lower energy examples of the class of radio components which appear common in the active nuclei of spiral galaxies.

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