THE GALACTIC CENTER [+]

K.Y. Lo
Astronomy Department
California Institute of Technology

The center of our Galaxy contains an extremely compact nonthermal radio source. For the first time, elongation in the source structure has been detected. The long axis is nearly aligned with the minor axis of the Galaxy. Recent high resolution observations of the ionized gas within the central 3 parsecs suggest that matter may be falling in towards the center. This has interesting implications on the processes within our Galactic nucleus.

1. INTRODUCTION

At a mere distance of 10 Kpc, the center of our Galaxy can be studied at unsurpassed linear resolution and detail. An example of this is shown in Figure 1: a 1"-resolution λ=6 cm VLA map of Sgr A West, the ionized gas region within 1.5 pc of the center (Lo and Claussen 1983). All the details in the intricate distribution of the ionized gas would subtend only 1" at the distance of M31, the nearest external galaxy with a galactic nucleus.

Besides its proximity, the Galactic Center is interesting because of a variety of phenomena which suggest past and present activities:

(a) Large scale expanding motions in the HI and molecular gas that may suggest past explosions of extraordinary energy (cf Oort 1977);
(b) The extremely compact nonthermal radio source, (e.g. Lo 1982), a possible signature of a massive collapsed object (Rees 1982);
(c) Large velocity dispersion of the ionized gas within the central parsec, indicating the possible existence of massive point mass (Lacy et al 1980);
(d) Time variable e^+e^- annihilation γ-ray line observed towards the center, suggesting a compact source of e^+ (e.g. Lingenfelter and Ramaty 1982);
(e) Very broad ($\Delta V \sim 1500$ Km/s) 2.06μ HeI line, that might indicate mass outflow (Hall et al 1982);
(f) The "spiral-like" pattern of ionized gas within the central 3 pc,

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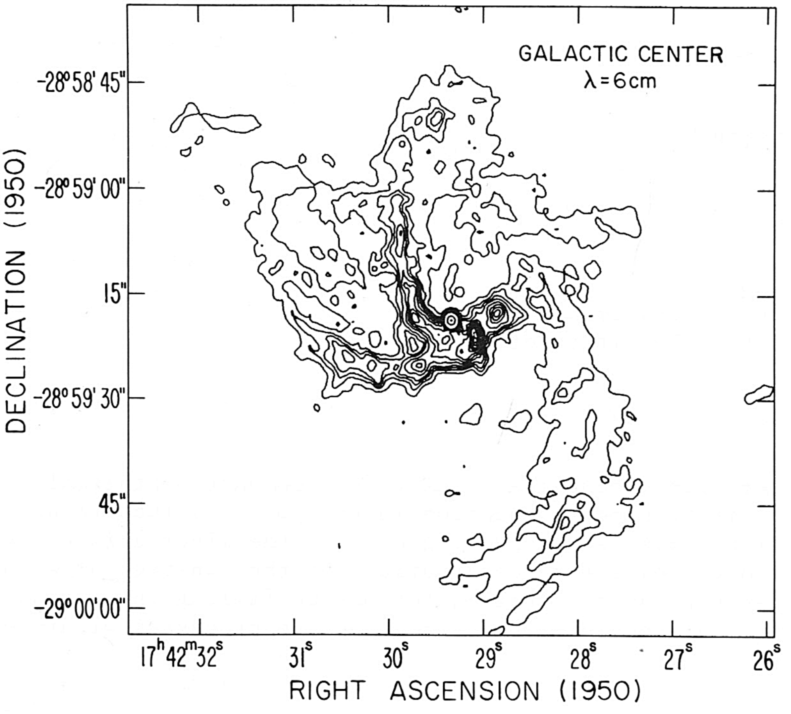

Figure 1
The compact radio source is at the map center.

first noted by Ekers et al (1983).

Radio continuum observations of the Galactic Center have previously been reviewed by Lo (1982). Here, we discuss the recent VLBI results on the compact source and high resolution VLA observations of Sgr A West. We present a new interpretation of the observations of the ionized gas and a model to account for its origin. Finally, we discuss the implications of the observations on the understanding of the Galactic Center.

2. VLBI OBSERVATIONS OF THE COMPACT RADIO SOURCE

Observations prior to 1978 were made at $\lambda \geqq 3.6$ cm using the Mark II recording system with sensitivity $\sim$0.1 Jy (5σ). The results have been given by Lo et al. (1981). The principal result was that the measured size scale of the source varies as λ^2 where λ is the observing wavelength This could be explained by either broadening of the intrinsic source size by interstellar scattering (Davies et al. 1976) or the optical depth of thermal electrons within the source (Brown et al. 1978; Lo et al. 1981). In any case, the intrinsic source structure was not known, and the possibility of interstellar scattering implies that the observed source size may only be an upper limit to the intrinsic size.

As both the interstellar scattering and the optical depth of thermal electrons decrease with shorter wavelength, short wavelength observations were emphasized subsequently. This became more practicable with the availability of the ∿5 times more sensitive Mark III recording system (Rogers et al. 1983), and improvements in the receivers. Table I summarizes a series of 2.8 cm (Lo, Backer and Cohen, unpublished) and 1.35 cm (Lo, Backer, Moran, and Cohen, unpublished) observations carried out prior to 1983.

Table I

Wavelength	Date of Observations	Telescopes*
2.8 cm	1980, April	K,G,O
	1981, June	K,G,O
1.35 cm	1981, December	K,G
	1982, June	K,G,O
	1982, December	K,G,O

* K = Haystack 36.5-m telescope, G = NRAO 42-m, O = OVRO 40-m

Success of this series of measurements was severely limited by bad weather at one or more telescopes during the observations. Nevertheless, we obtained the following: At λ= 2.8 cm, the scale size was ∿0.01" which is consistent with the λ^2-extrapolation from longer wavelength. On the other hand, at λ= 1.35 cm, the scale size was >0.003" (the inequality was due to calibration uncertainty), much larger than the extrapolated scattering size. This has important implications because it suggests that at 1.35 cm, we are observing the intrinsic source structure. The 1.35 cm result has been confirmed by measurements of Kellermann and Ekers (private communication).

On May 23, 1983, we carried out a 6-station λ = 3.6 cm observation (Lo, Backer, Cohen, in preparation) using the Mark III system in mode B. While the calibrator source, NRAO 530, was detected on all baselines, the compact radio source in Sgr A was detected only convincingly on the relatively short baselines formed by the NASA 64-m telescope at Goldstone (DSS14), the OVRO 40-m and the Hat Creek 25-m telescopes (HCRK).

The amplitude data (Figure 2) were fitted to two simple models: a symmetric Gaussian brightness distribution and an elliptical Gaussian distribution. The baseline most sensitive to the difference of the two models is DSS14-HCRK (cf Figure 3), because of the relatively large rotation of the baseline.

The better fitting elliptical Gaussian model has the following parameters: the major axis (half-power) diameter is ∿0.015" and an axial ratio of 0.25 with the long axis oriented at a position angle (PA) of 107°. The PA is in agreement with the results of Jauncey et al. (private communica-

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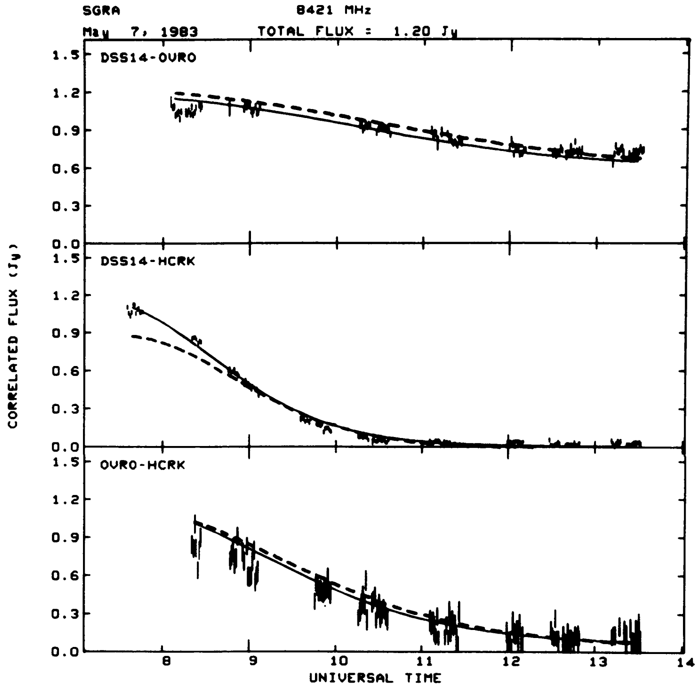

Figure 2
The lines are the model visibility amplitudes. The dashed line is the symmetric Gaussian model. The models are indistinguishable on the other 2 baselines.

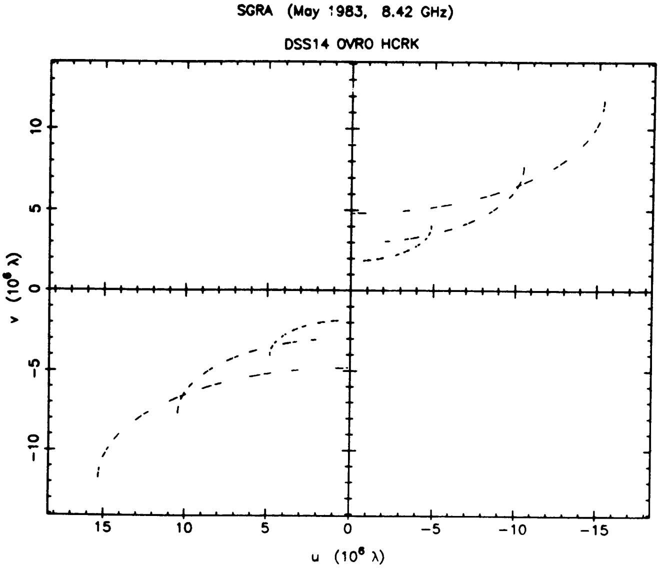

Figure 3
The longest baseline is DSS14-HCRK; the shortest is DSS14-OVRO.

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tion) who used a single N-S baseline in Australia.

The 0.001" core of the compact radio source reported by Kellerman et al. (1977) and Geldzahler et al. (1979) was not detected at an upper limit of 0.01 Jy (6σ).

3. NATURE OF THE COMPACT RADIO SOURCE

The known properties of the compact source is summarized in Table II.

Table II

Scale Size	$\sim 5 \times 10^{14}$ cm
Position Angle of Elongation	$\sim 107°$
Spectral Index	~ 0.2, up to 115 GHz
Radio Luminosity	$\sim 2 \times 10^{34}$ erg/s
Turnover Frequency	$\geqq 115$ GHz
Brightness Temperature	$\sim 4 \times 10^{8}$ K
Flux Variability $\Delta S/S_{min}$	< 1 (1975-1982)
Upper Limit to Mass	$< 5 \times 10^{6}\ M_{\odot}$

They are different from those of any known galactic radio sources associated with stellar objects: pulsars, binary stars, or young supernova remnants (Lo et al. 1981). Rees (1982) suggested that the source could be due to low-level accretion onto a $\sim 10^{6}\ M_{\odot}$ black hole. While the compact radio source has a dimension $\sim 10^{3}$ times the Schwarzschild radius of such a black hole, it has a very modest radio luminosity of $\sim 10\ L_{\odot}$. Based on energetics alone, it is therefore not possible to exclude a stellar object as the underlying energy source.

Hence, the mass of the radio source is a critical parameter to determine.

4. MASS DETERMINATION

The ideal method of mass determination is to observe the distribution of the velocity dispersion of the stars around the radio source. This has to be done at the infrared wavelength because of the large obscuration towards the center. However, attempts at measuring the stellar velocity dispersion have been unsuccessful so far.

An independent constraint on the mass of the radio source is its proper motion. If the radio source is massive, no motion is expected, whereas a stellar mass object would have high space motion and thus measurable proper motion. First results of this difficult measurement (Backer and Sramek 1982) are consistent with the secular parallax expected for an object at rest at the Galactic Center.

A third approach is via near infrared spectroscopic observations of the ionized gas within the central parsec. High spatial resolution 12.8μ

[NeII] observations (Lacy et al. 1980) have revealed much about the motion of the ionized gas there. If the motion is due to gravity alone, the velocity dispersion could be used to infer the total mass. Lacy et al. (1980) inferred that there may be $\sim 10^7$ $M_\odot$ of mass within the central parsec, either all in stars, or half in stars and the rest in a central point mass. However, the origin, the motion, the ionization state and the disposal of the gas require explanations (Lacy et al. 1982).

5. RADIO OBSERVATIONS OF THE IONIZED GAS

Ekers et al. (1983) first revealed the "spiral" distribution of the ionized gas in Sgr A West in their large-scale study of Sgr A. Subsequently, Lo and Claussen (1983) obtained a 1" resolution map that adds much detail to the previous maps.

The high resolution map of Sgr A West (Figure 1) shows the following features:

(a) The overall distribution of the ionized gas is dominated by 3 bright "arms" extending north, east and west from the center. By "center" we mean the region immediately surrounding and including the compact radio source.
(b) Features of lower surface brightness are found on the periphery of the distribution. They are the northern continuation of the east arm, an incomplete loop to the north-east of the center, and most prominent of all, the south arm which is apparently joined to the west arm.
(c) The south arm is in fact not connected to the west arm. Where the two arms meet there is a break as well as a large difference in the surface brightness of the arms. Also, there is a large velocity difference between the two arms (cf Lo and Claussen 1983). The south arm continues north, past the west arm, and is most likely connected to the tip of the north arm. Previous interpretation (e.g. Ekers et al. 1983) of the north, west and south arms as forming a "spiral" pattern is no longer compelling.
(d) The compact radio source while not at the peak of the thermal emission, is situated at the centroid of the overall distribution.

6. VELOCITY FIELD OF THE IONIZED GAS

The velocity field of the ionized gas (Figure 4) is given by the [NeII] observations (Lacy et al. 1980). The systematic variation along the north, south and east arms is obvious. Decomposition of the complicated profiles within the central 30" into 3 velocity components makes it possible to identify 3 streams of gas, each corresponding to one of the 3 bright arms (Lo and Claussen 1983). Lines are drawn in Figure 4 to outline the loci of similar velocity. They also suggest the current positions of the gas trajectories which appear to converge to or diverge from the center. Note that the streams do not meet at a single point and the compact radio source is offset ~ 2" (0.1 pc) from the streams.

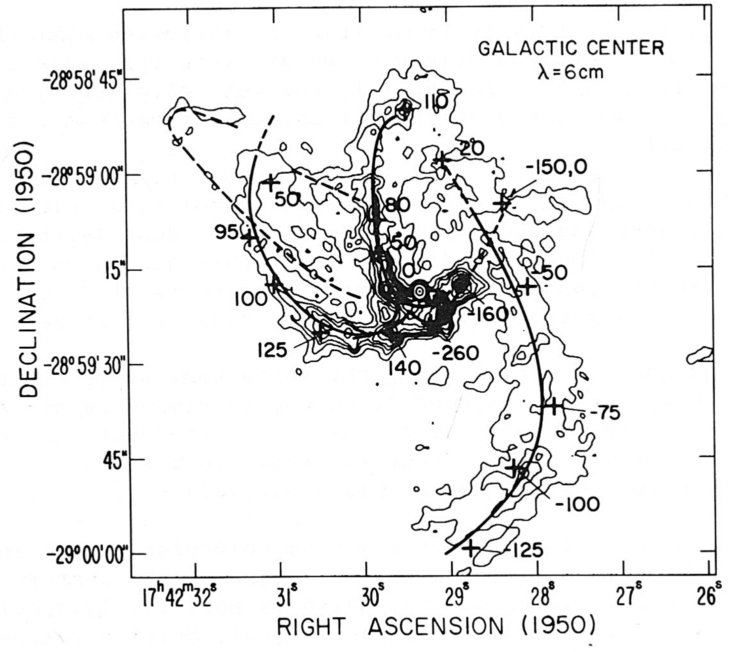

Figure 4

The numbers next to the crosses are the radial velocities (Km/s) of the [NeII] emission measured at those points.

There exists some symmetry in the velocity field: the north and south arms have velocities of opposite sign, which is also true for the velocities of the east and west arms. However, for the north and south arms, the magnitude of the velocity decreases towards the center, while for the east and west arms, the maximum velocity is observed near the center. This suggests that the north and south arms could be part of a rotating "ring" about the center whereas the east and west arms could not be part of the same structure.

7. PROPOSED MODEL OF THE IONIZED GAS

The morphology of the ionized gas is a transient phenomenon since the dynamic time scale is $\sim 10^4$ years. It must be the result of systematic motion- a combination of rotation, ejection and infall (cf Ekers et al. 1983).

Precessing twin-beam ejection such as that proposed by Brown (1982) cannot explain the complicated morphology. To account for the 3 bright arms, 3 precessing nozzles operating simultaneously in 3 independent directions

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are required. Blandford (private communication) suggested that the streams result from ionized gas driven outwards along the field lines of a spinning magnetized object. In general, however, ejection by a single object cannot explain why the 3 streams of gas do not meet at a single point near the center.

Ekers et al. (1983) suggested tidal distortion of molecular clouds as one of several possible explanations. Since we can now identify the 3 streams of gas near the center, the tidal distortion picture has become more attractive. The Roche density of the central parsec is $\sim 10^8$ cm^{-3}, much higher than the ionized gas density, making the tidal effect very strong.

The gas moves from north to south along the south arm, which orbits about the center, and is probably connected to the north arm which spirals in towards the center. The east and west arms are independent streams falling towards the center along paths roughly normal to the plane of orbit of the south and north arms (cf Lo and Claussen 1983).

The gas must originate as low angular momentum molecular clouds in the vicinity of Sgr A West. As it falls within 1.5 pc of the center, it is ionized by the central ionizing source, which is most likely a collection of O,B stars (Lacy et al. 1982). A single central ionizing source is not excluded, however.

8. IMPLICATIONS

The central issue here is whether the compact radio source is the signature of a massive collapsed object. The supporting evidence is compelling, but circumstantial. Based on energetics alone, we cannot exclude a stellar object. The latest VLBI results indicate that the compact radio source is elongated in a direction nearly parallel to the rotation axis of the Galaxy (PA = 122°). If the alignment has a physical origin, then it would be hard to argue that the compact source is simply a peculiar stellar radio source within the central star cluster. Thus, it is even more urgent now to obtain a detailed VLBI map of the compact radio source.

The compact radio source may be dependent on its environments. Recent high resolution observations have led to a clearer picture of the spatial distribution and kinematics of the ionized gas within the central few parsecs. This is important since it may be possible to use the morphology and the velocity field of the ionized gas to probe the central mass disbribution and check the existence of a central point mass.

The most natural explanation of the ionized gas in Sgr A West is that it is tidally distorted molecular gas falling in towards the center. The transient nature of the ionized gas, however, implies that the processes within the Galactic Center may not occur under steady-state conditions. Thus, variability of the activities with time is indicated, especially if the central luminosity is dependent on the accretion of interstellar matter.

If the proposed infall is verified, then we have for the first time direct observational evidence of infall of matter towards the center of a galaxy. Accretion of interstellar matter by a central black hole has been proposed as the energy source for much of the activities seen in quasars, radio galaxies and Seyfert nuclei. In the center of our Galaxy, we may be witnessing directly the path of accretion.

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