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A SHOCKED-JET MODEL OF THE GALACTIC CENTER BRIDGE AND THE RADIO ARC

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ABSTRACT

Based on the recently accumulated observational facts on the radio features in the Galactic center, we propose a shocked-jet model for the radio bridge that connects Sgr A and the radio arc. The bridge is interpreted as a tilted magnetized jet filled with a supersonic and shocked gas ejected from the Galactic nucleus. The jet is largely bent when it encounters an ambient poloidal magnetic field. A magnetic bow shock is formed ahead of the jet at the interaction surface with the ambient magnetic field and is observed as the radio arc. An internal shock wave occurring in the jet is observed as a jump in the gas density on the radio bridge.

Subject headings: galaxies: jets — galaxies: nuclei — galaxies: The Galaxy — magnetic fields — polarization — radio sources: galaxies

I. OBSERVED PROPERTIES

High-resolution radio continuum maps of the Galactic center region have revealed peculiar morphology in the radio arc and the bridge (Yusef-Zadeh, Morris, and Chance 1984). The brightest part of the bridge is composed of complicated filaments of thermal emission (Pauls *et al.* 1976). The northern end of the bridge and the straight radio threads in the arc merge at a right angle. The southern end of the bridge is embedded in the nonthermal halo of Sgr A. The relationship of the thermal bridge to Sgr A is revealed by recent millimeter-wave continuum observations at 43 GHz, at which frequency the nonthermal contamination becomes negligible (Sofue *et al.* 1986).

Figure 1 (Plate L6) shows the 43 GHz map of the Galactic center observed with the Nobeyama 45 m telescope (Sofue *et al.* 1986). The bright part of the bridge does not smoothly reach Sgr A, but has a gap (marked G in Fig. 1). Through this gapped region, several thin, faint filaments run radially from Sgr A toward the bright complex S. The filamentary structure suggests a magnetic field anchored to Sgr A. In fact, a magnetoionic character of the bridge has been indicated by a Faraday effect measurement (Sofue *et al.* 1987). If the magnetic field in the bridge is in an energy equipartition with the turbulent motion of the thermal gas, we have a magnetic strength of the order of 10^2 μG for a gas density of 100 H cm^{-3} and a velocity dispersion of 40 km s^{-1} (Pauls *et al.* 1976).

The density of the gas varies drastically along the bridge. Figure 2 shows a distribution of the radio intensity at 43 GHz along the bridge as a function of the distance Δ from Sgr A West. The gapped region has a low, constant intensity from $\Delta = 0\overset{\circ}{.}04$ to $\Delta = 0\overset{\circ}{.}11$. A sudden jump is seen at $\Delta = 0\overset{\circ}{.}12$, at which the thermal electron density reaches as high as ~ 100 cm^{-3} and, at some points, ~ 400 cm^{-3} (Pauls *et al.* 1976). From the contrast between the radio intensities we can estimate the density contrast between the complex and the gapped region to be greater than a factor of 4. The sudden jump of the gas density may indicate a shock compression by a supersonic flow from the Galactic center region.

The motion of gas in the bridge can be derived from radial velocity and dispersion of the ionized gas by the recombination line measurement (Pauls *et al.* 1976). Figure 3 plots the radial velocity against the Galactic longitude, where the velocity dispersion is indicated by bar length. The radial velocity V lies on an ellipse whose major axis represents a line $V/l = 50$ km $s^{-1}/10'$. The velocity distribution can be attributed to an expanding ring which is rotating around the Galactic center. The radius of the ring is $\sim 10'$ (or 30 pc at a distance of 10 kpc), the rotation velocity is ~ 50 km s^{-1}, and the expansion velocity is ~ 45 km s^{-1}. The total mass of the ionized gas in the bridge is estimated to be 2×10^4 $M_\odot$ from the continuum radio emission, and the total kinetic energy of the expansion is about 4×10^{50} ergs.

The general magnetic field in the central 50 pc of the Galaxy was recently observed to be predominantly perpendicular to the Galactic plane (Sofue *et al.* 1987, Fig. 4) and is shown to be related to the various structures running across the Galactic plane (Yusef-Zadeh, Morris, and Chance 1984; Tsuboi *et al.* 1986; Sofue and Handa 1984). As to the source of the general magnetic field, it has been argued that a vertical component of a global magnetic field in a spiral galaxy is secularly accumulated to the central region and produces a central structure with a strong vertical field (Sofue and Fujimoto 1987).

[1]NRO, a branch of the Tokyo Astronomical Observatory, University of Tokyo, is a cosmic observing facility open to outside users.

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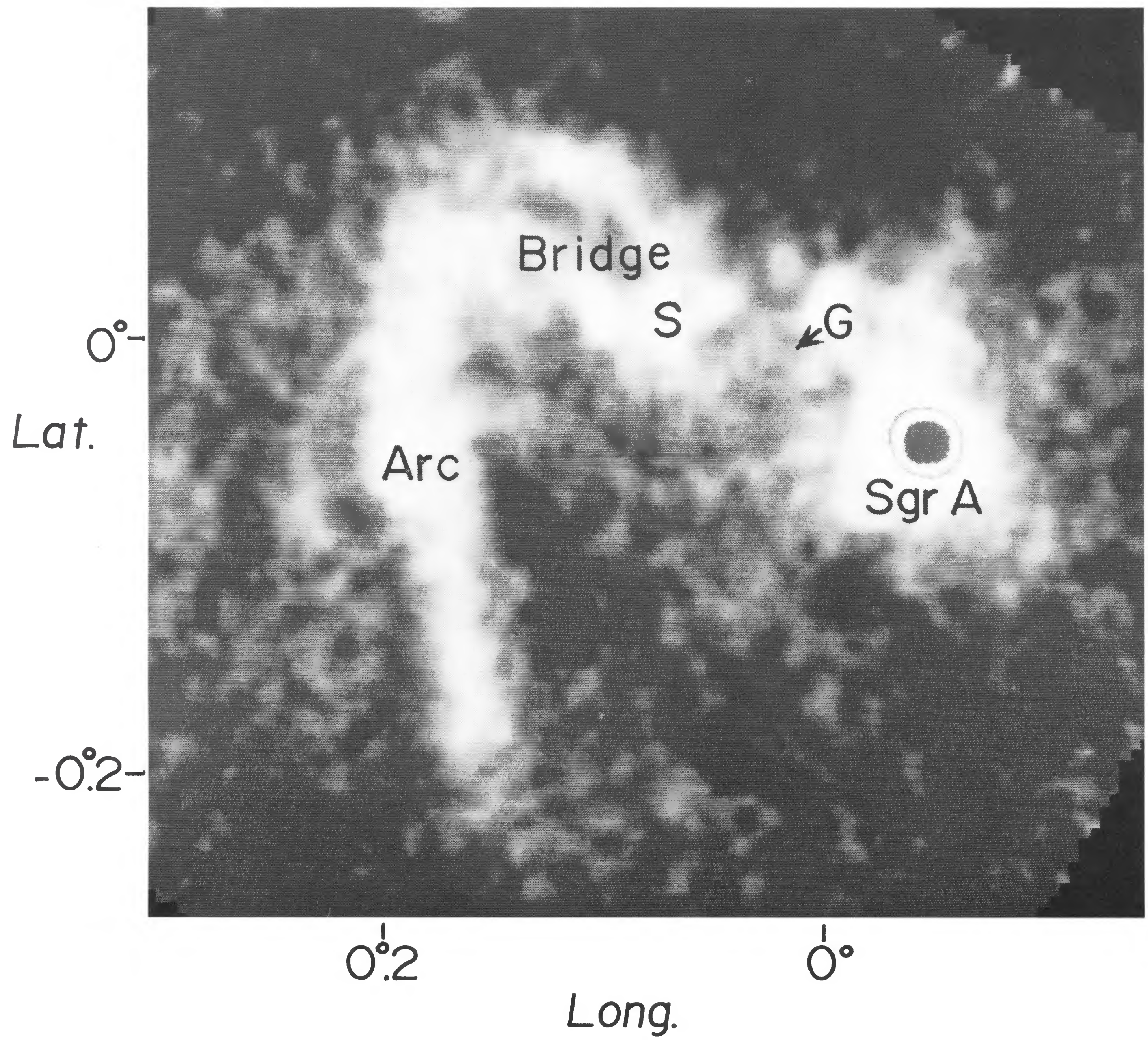

FIG. 1.—A 43 GHz radio continuum map of the Galactic center region obtained with the NRO 45 m telescope. The map has been smoothed to a HPBW of 45″. Arrow G marks the gapped region where are found several thin, faint filaments running radially from Sgr A West, likely representing magnetic lines of force anchored to the Galactic center. Complex S is interpreted as a shock front in a supersonic flow of gas along the bridge.

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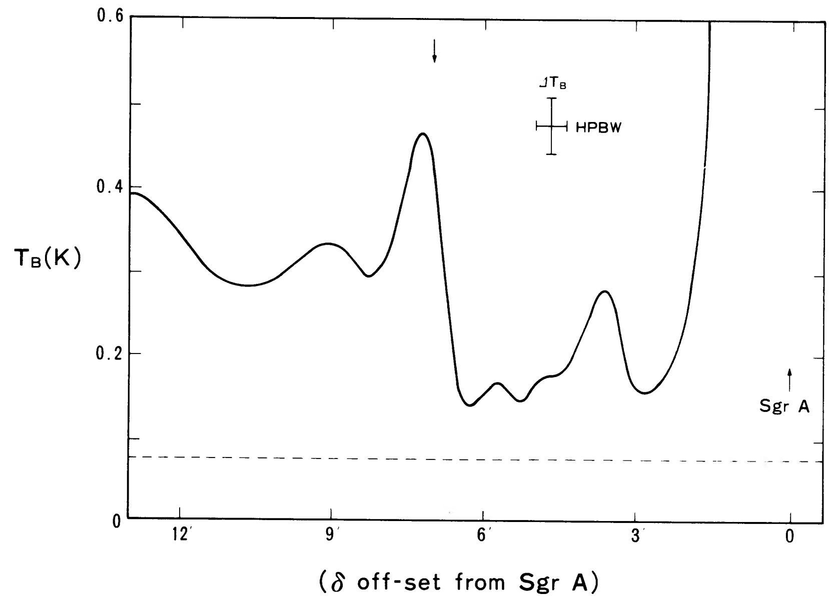

FIG. 2.—Intensity distribution at 43 GHz along the bridge as a function of the distance Δ from Sgr A West. A sudden jump of emission is seen at Δ = 0°12, which is interpreted as a shock front in the jet from the Galactic center.

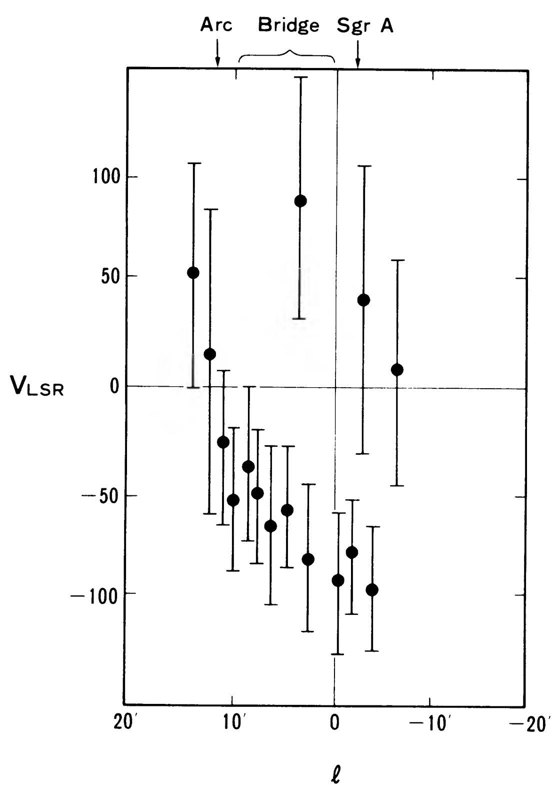

FIG. 3.—Radial velocities of the radio recombination line emission along the bridge as plotted on the *l-V* diagram. The velocities lie on an ellipse, representing an expanding rotating ring. The length of the bars indicates velocity dispersion.

II. A SHOCKED-JET MODEL

Based on the observational facts, we propose the following scenario about the Galactic center bridge and the arc (Fig. 4). The bridge is a trace of a magnetic field anchored to Sgr A with a length of ~ 30 pc. Along the field line is streaming a beamed flow of thermal gas ejected from the nucleus at a supersonic velocity. When the beamed flow, or a jet, encounters the ambient magnetic field in Galactic rotation, the flow is strongly interrupted and largely bent. The radio arc is regarded as a bow shock ahead of the high-velocity flow when it encounters the ambient vertical magnetic field. An internal shock wave occurs in the jet, and the front is observed at the jump of the thermal radio emission in the bridge (S in Fig. 1; Fig. 2). The complex bright part of the bridge is therefore a shock-compressed gas in the subsonic side of the shock front, and the gapped region (G in Fig. 1) is the supersonic side. As the shocked gas is forced to rotate with the ambient matter in Galactic rotation, the observed motion of the bridge (Fig. 3) may partly represent the disk rotation.

Since the flow velocity and density in the subsonic side are about 50 km s^{-1} and 100 cm^{-3}, respectively, and the density jump is more than a factor of 4, the flow velocity and density in the supersonic side are likely greater than 200 km s^{-1} and less than 30 cm^{-3} for the momentum conservation. The magnetic energy in the supersonic side is not necessarily in equipartition with the turbulent energy, or is much less than the kinetic energy of bulk motion of gas. This implies that the supersonic jet is stable against magnetic instability (e.g., Chan and Henriksen 1980), whereas the flow in the subsonic side is no more stable, and the instability results in the complicated morphology. Therefore, although the bridge is considered as a jet, it is already in a decay phase, and a substantial fraction of

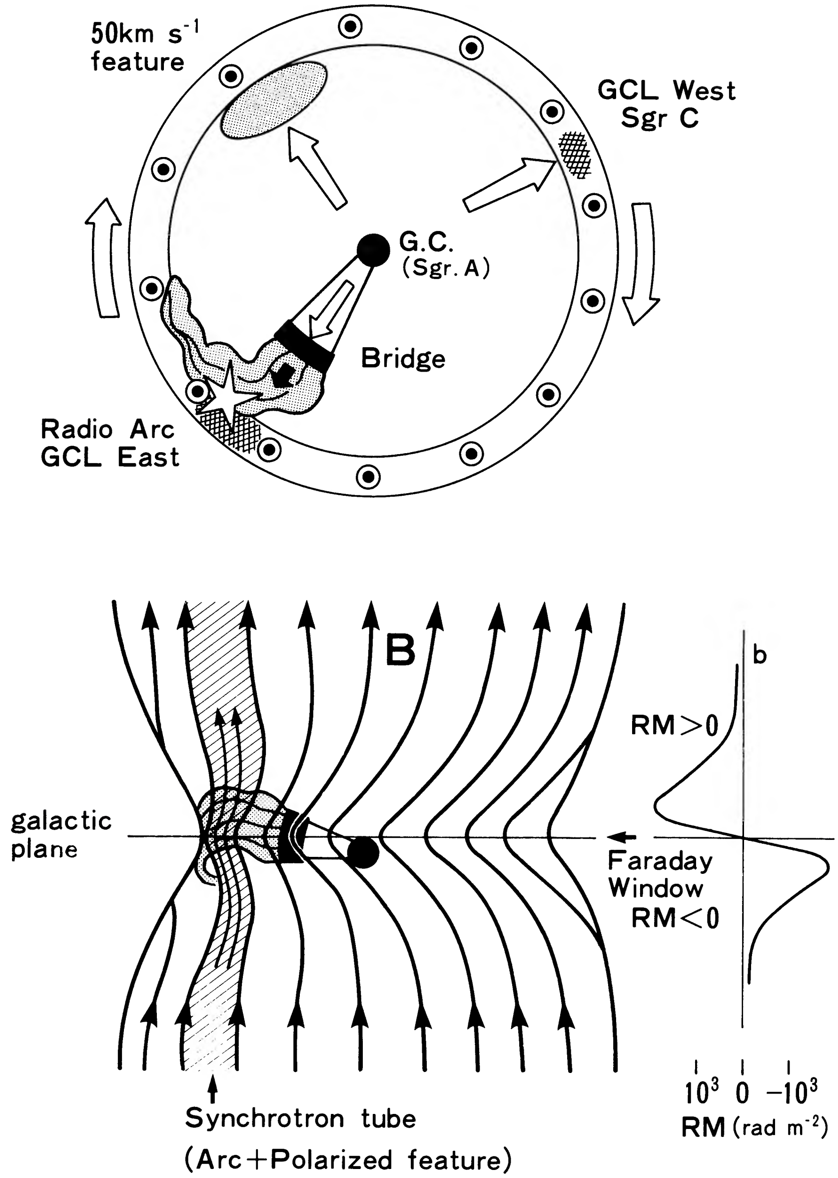

FIG. 4.—Schematic sketch of the shocked-jet model of the radio bridge (a jet from the Galactic center, Sgr A West) and the arc (an interaction surface of the jet with the ambient poloidal field in rotation). The observed rotation measure (rm) variation along the radio arc and its extensions is also sketched.

the jet energy has been converted to the turbulent, thermal, and magnetic energies.

What mechanism produces such a one-sided jet largely tilted from the Galactic rotation axis? It has been shown that a sporadic accretion of slightly off-plane gas clouds onto a central massive object with a poloidal magnetic field causes highly-tilted, one-sided sporadic ejections of matter in random directions (Fujimoto and Sofue 1987). The magnetized gas flow in the bridge, which has a large angle to the rotation axis of the Galaxy, may be just one case of such a one-sided jet from the nucleus. Another ejection which occurred further in the past in a roughly opposite direction to the bridge may have excited the VLA filament in Sgr C at $l = 359^\circ.4$ (Liszt 1984) and is located at the root of the western side of the Galactic center lobe (Sofue and Handa 1984; Sofue 1985). A giant molecular fan jet at $V_{\rm lsr} = 50$ km s^{-1} has been observed on the eastern side of Sgr A (Fukui *et al.* 1977) and is thought to be a similar, but more energetic, one-sided jet (see Fig. 4, *top*).

The interaction surface of the bent magnetic jet (the bridge) and the ambient poloidal magnetic field is likely highly turbulent. In fact, the velocity dispersion near the radio arc is as high as $\sigma = 50$–70 km s^{-1} (Fig. 3), about twice that on the bridge where $\sigma = 30$–40 km s^{-1}. Cosmic rays may be accelerated there in a manner similar to that of a bow shock at a contact point of an extragalactic plasma jet with the intergalactic magnetic field (Blandford and Rees 1974). The accelerated high-energy electrons emit synchrotron radiation along the arc. The electrons further propagate along the field lines toward the high latitudes, yielding nonthermal features above and below the Galactic plane. Such a leakage of high-energy particles along certain lines of the poloidal field may explain why the polarized synchrotron emission is found only along a local tube or the "synchrotron tube" but not on the whole poloidal field (Fig. 4) (Seiradakis *et al.* 1985; Tsuboi *et al.* 1986).

III. ENERGETICS

We discuss the energetics required for the excitation of the synchrotron tube through a dissipation of magnetic energy at the interaction surface where the field lines in the bridge contact the ambient poloidal field at a right angle. As is well known (e.g., Shivamoggi 1985), the micro and a macro annihilation of magnetic fields is enhanced through the compression of two nonparallel magnetic fields. The nonthermal energy released at the contact region is not anything but the kinetic energy of the jet. For a turbulent magnetic diffusion the dissipation time scale is of the order of $t_d \approx d_1^2/l\ \sigma$, where d_1 is the thickness of the contact layer, l is the turbulent eddy size, thought to be comparable to d_1, and σ is the turbulent velocity or the velocity dispersion. If we take $d_1 \approx l \approx 5$ pc and $\sigma \approx 60$ km s^{-1}, then we have $t_d \approx 10^5$ yr. This time scale is short enough compared to the rotation period of a 30 pc radius circle around the Galactic center at a rotation velocity ~ 50 km s^{-1}, $t_{\rm rot} \approx 4 \times 10^6$ yr. This means that only a small azimuthal section, ~ 3% of the circle or a width, $d_2 \approx 5$ pc, of the ambient poloidal field, is illuminated by the cosmic rays that produce the synchrotron tube. The released energy is about $d_1^2 d_2 B^2/8\pi \approx 10^{48}$ ergs, where we took $B \approx 100\ \mu$G both for the magnetic fields in the bridge and for the ambient poloidal field. Then the dissipation rate of the magnetic energy at the interaction surface (the arc) is $L_m \approx 10^{48}$ ergs/10^5 yr $\approx 4 \times 10^{35}$ ergs s^{-1}. This rate is large enough to supply the radio luminosity of the radio arc and the eastern ridge of the Galactic center lobe (Sofue 1985), $L_{\rm radio} \approx 10^{35}$ ergs s^{-1}. The kinetic and magnetic energies in the bridge originally come from the kinetic energy of the jet flow. The energy amount, $\sim 10^{51}$ ergs, is easily accounted for if a small fraction of gravitational energy of a gas cloud, say $10^{-4}\ M_\odot$, near the central black hole is released as a jet.

Finally, we mention that the magnetic annihilation may actually destroy the magnetic flux near the contact surface and causes the complicated structures in the bridge. This may result in an injection of thermal gas of the bridge into the ambient magnetic field. This may explain the enhancement of thermal emission on some points on the arc (Pauls *et al.* 1976) and the high depolarization of the polarized emission at the merging point of the bridge and the arc (Yusef-Zadeh 1986). The ambient large-scale field, on the other hand, is little affected by the annihilation of the small fraction of magnetic flux and keeps its straight structure.

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