A Jet-Injected Bubble from the Galactic Center?— G359.8−0.3

A round, bubble-like object was found near the galactic center on a 10-GHz radio map. The "bubble" is centered on G359.77−0.29, has a diameter of 21′ (49 pc) and is at a projected distance 18′ (42 pc) from Sgr A. Two HII regions and a shell of molecular clouds are apparently associated with this bubble. Nonthermal emission, in spite of the flat radio spectrum, follows from the linear polarization and from a comparison of radio and far infrared intensities. The bubble is located along the extension of a 160-MHz jet emanating from Sgr A. We discuss the implication of such a bubble structure near the galactic center and consider a possible formation mechanism associated with galactic nuclear activity.

Key Words: *activity, galactic center, jet and lobe, magnetic bubble, radio emission*

1. INTRODUCTION

Nuclei of spiral galaxies exhibit various types of ejection phenomena. Some galaxies show bubble-like radio features emerging from their centers. Examples are NGC3079,[1,2] M51[3] and NGC5506.[4] These structures are thought to be ejecta composed of high-energy plasma and magnetic fields originating from the nuclei, although their scales widely range from tens of pc to a few kpc and the energies are from 10^{50} to 10^{54} ergs (see the literature cited above).

The center of our Galaxy exhibits various activities[5] which might be associated with some ejection phenomena: The galactic center lobe[6,7] may be evidence for a large-scale, mild energetic ejection, although it is not clear if it is directly related to the more central

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activity around Sgr A. The radio arc and bridge[8] are interpreted as a manifestation of an energy release by the central activity at Sgr A which ejects one-sided jets.[9] The molecular fan jet at $V_{LSR} = 50$ km s^{-1} [10] is another one-sided jet near the galactic plane.

Closer to the galactic center, two jet-like features are observed, both one-sided and perpendicular to the galactic plane. One is a radio ridge with a steep spectrum observed at low frequencies, 110–160 MHz, which runs from Sgr A-E toward the negative latitudes and is called the low-energy jet.[11,12] Another feature originates in Sgr A-W and extends toward positive latitudes in the form of a parabolic protrusion, which may be a wind streamer emanating from the nucleus.[12,13] If these two features are jets emanating from the galactic center perpendicular to the disk plane, it is expected that they may extend further to higher latitudes.

In this paper we report the detection of a bubble-like object, seen on a 10.5 GHz map, which lies along the extension of the 160-MHz low-energy jet (Section 2). In Section 3 we discuss the implication of such a bubble structure near the galactic center, and consider possible formation mechanisms.

2. G359.8–0.3, A RADIO BUBBLE NEAR THE GALACTIC CENTER

A number of discrete radio sources are found in the central 1° of the Galaxy. Figure 1 shows a distribution of the number of sources counted in every 2° interval of galactic longitude as a function of the longitude for sources with flux density greater than 1 Jy at 5 GHz. The data were taken from the 5 GHz source list.[14,15] From this figure we may conclude that the sources found at $|l| < 1°$ are most likely associated physically with the galactic center.

Among these sources, we noticed a particularly round, bubble-like object, G359.8–0.3, in the radio continuum map at 10.5 GHz, based on observations carried out with the 45-m telescope of the Nobeyama Radio Observatory (see Ref. 16) and in published 2.7 GHz maps.[17]

Figure 2 shows the 10.5 GHz map of this "bubble" at a resolution of 2.′6 after subtracting a large-scale background emission using the background filtering technique.[18] G359.8–0.3 is located close

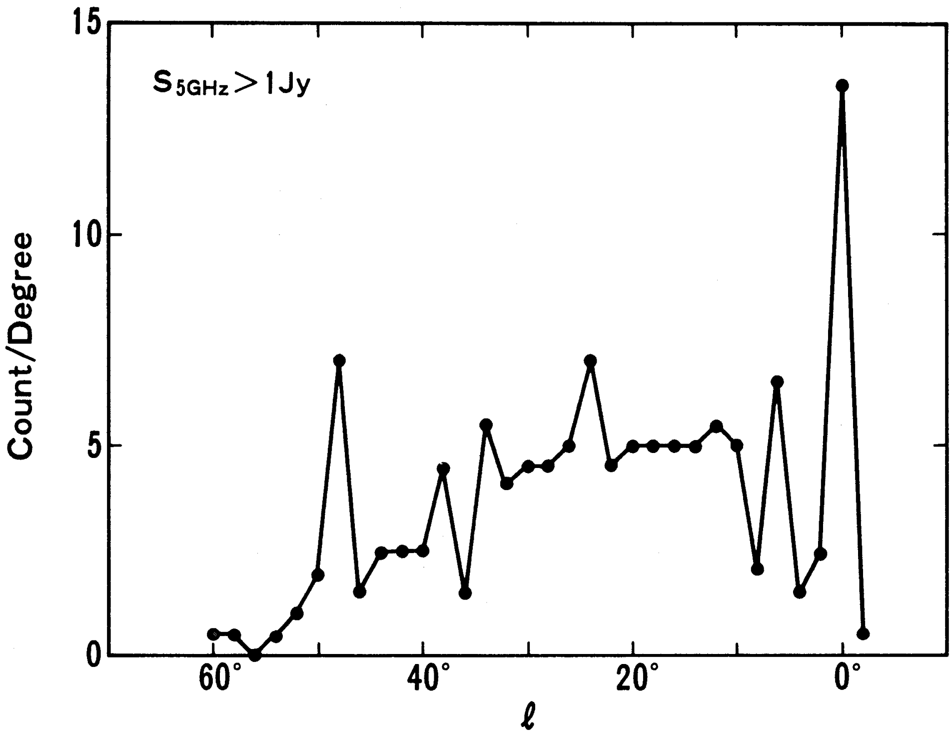

FIGURE 1 The number density of 5-GHz discrete sources stronger than 1 Jy counted per 1° longitude interval plotted as a function of the galactic longitude. The data were taken from Ref. 14. Note the high concentration of sources at $|l| < 1°$, which suggests that the majority of the sources there are most likely associated physically with the galactic center.

to the galactic center at a projected distance of 18′ from Sgr A with the northern part being embedded in the halo of Sgr A and the nuclear disk emission. It is remarkable that the southern boundary of this bubble is sharply cut along a loop which is fitted well with a circle of diameter 21′ centered on G359.77−0.29 (α_{1950} = $17^h43^m.0$, δ_{1950} = −29°16′). More interesting is that this bubble is located just on the extension of the low-frequency (160 MHz) radio ridge with a steep spectrum observed by Yusef-Zadeh *et al.*,[12] although the center does not exactly lie on the ridge axis. The 160-MHz ridge is superimposed on Fig. 2 with thick contour lines.

Two HII regions, G359.65−0.259 and G359.730−0.407, are superposed on the bubble. Recombination line observations of these HII regions show a positive, and therefore "forbidden," LSR velocity at 12 km s^{-1}.[15] Also a high negative (−110 km s^{-1}) velocity

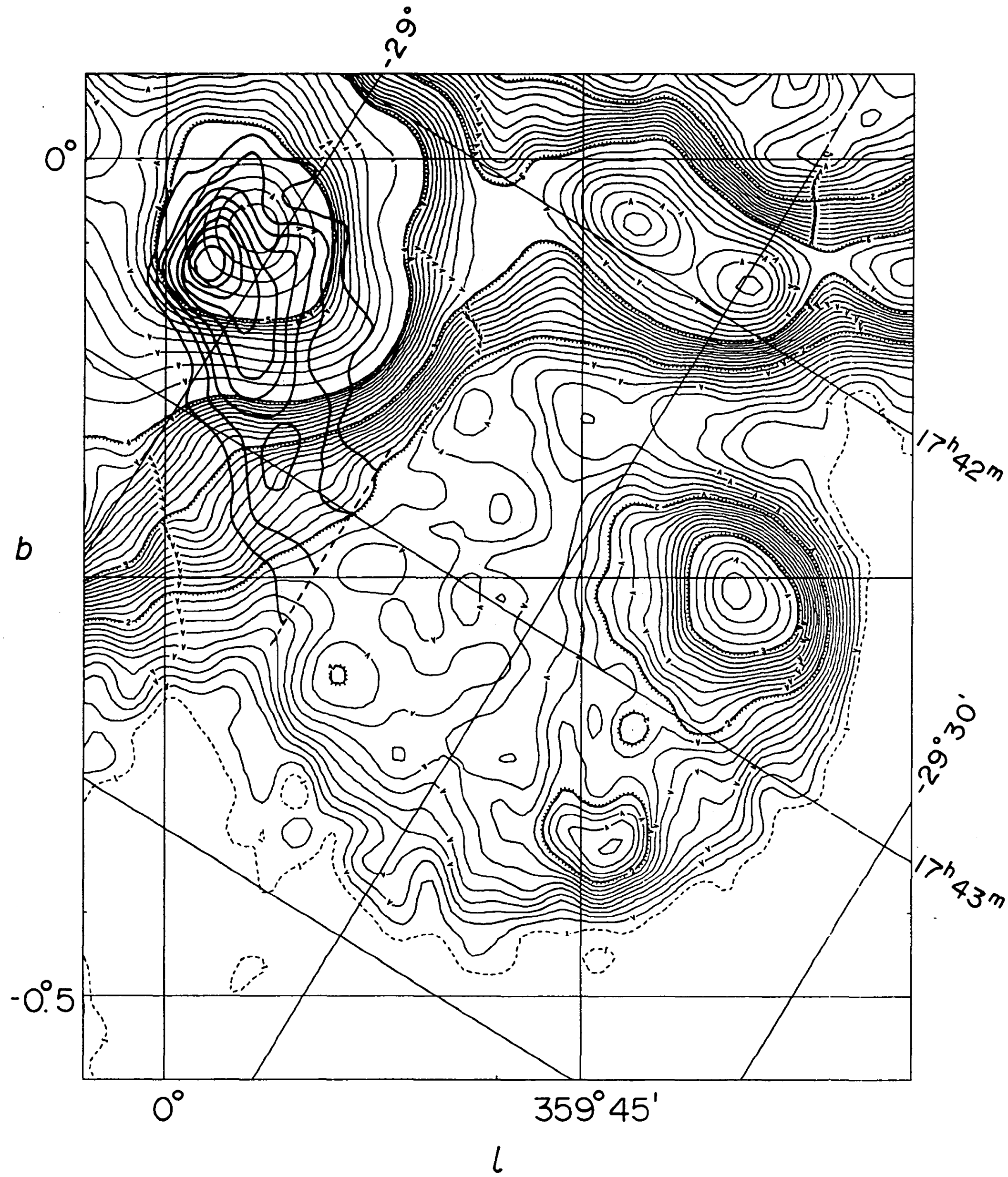

FIGURE 2 A 10.5 GHz radio continuum map of G359.8−0.3 taken with the 45-m telescope at NRO (Ref. 16). A large-scale background emission has been subtracted. As a result of the background filtering, smooth regions around strong sources remain slightly negative and are not drawn in this figure. Hatched contours with labels 1, 2, 3, 4 and 5 represent 0, 0.5, 1, 2 and 10 Jy/beam (2.66′), respectively, and each interval between the hatched contours is equally divided into ten steps. Beyond 10 Jy/beam the contour interval is 9 Jy/beam. The low-frequency jet at 160 MHz emanating from Sgr A-East (Ref. 12) is superimposed with thick contour lines.

absorption line of H_2CO was detected toward G359.65. These velocities indicate that the HII regions are located either near or beyond the galactic center.[15] Radio spectra can be derived by comparing the 10 GHz data with the 5 GHz map having the same angular resolution.[14] The spectra of the two HII regions after subtracting the extended component are $\alpha = 0.0$ and -0.1, respectively, for G359.65 and G359.73, and are reasonable for HII regions.

The integrated flux of the extended component of the bubble is about 17 Jy at 10 GHz. The spectral index derived for this component between 10 and 5 GHz is about $\alpha \cong 0$. The flat spectrum is consistent with the fact that no emission is seen from the bubble at low frequencies, e.g., at 160 MHz.[11] In spite of its flat spectrum, as is often obtained for nonthermal radio sources near the galactic center,[6,19] significant linear polarization has been detected on the eastern half of the bubble at 10 GHz.[20] Figure 3(a) shows the polarized regions reproduced from Tsuboi *et al.*,[20] where the polarization has been detected above seven to ten sigmas, e.g., the polarization intensity is 50–100 mJy/beam. The polarization including the smooth background emission is about 4–10%.[20] However, if the polarization is associated with the bubble and the background emission is subtracted, the intensity of the extended bubble component alone, 300–400 mJy/beam (Fig. 1), yields a degree of polarization as high as 15–30%.

The nonthermal property of the bubble also follows from a comparison of the radio emission with the far infrared emission[21]: normal HII regions have a FIR-to-radio brightness ratio of $R \sim 1000$, as is actually the case for the two HII regions G359.65 and G359.73, while nonthermal sources have smaller ratio of $R < 500$, as is indeed the case for the southwestern extended part of the bubble which exhibits $R < 500$. Here we defined R as the ratio of the 60 micron brightness from IRAS[22] to the brightness at 2.7 GHz.[17] In Fig. 3(a) we also indicate the regions having small IR-to-radio ratio, which roughly coincide with the polarized regions.

Recent ^{13}CO observations of the galactic center region[23] show the clumpy nature of molecular gas in this region. Among them, at LSR velocity 10–20 km s^{-1}, we find several molecular clouds and a loop (or a hole-like) feature toward the radio continuum

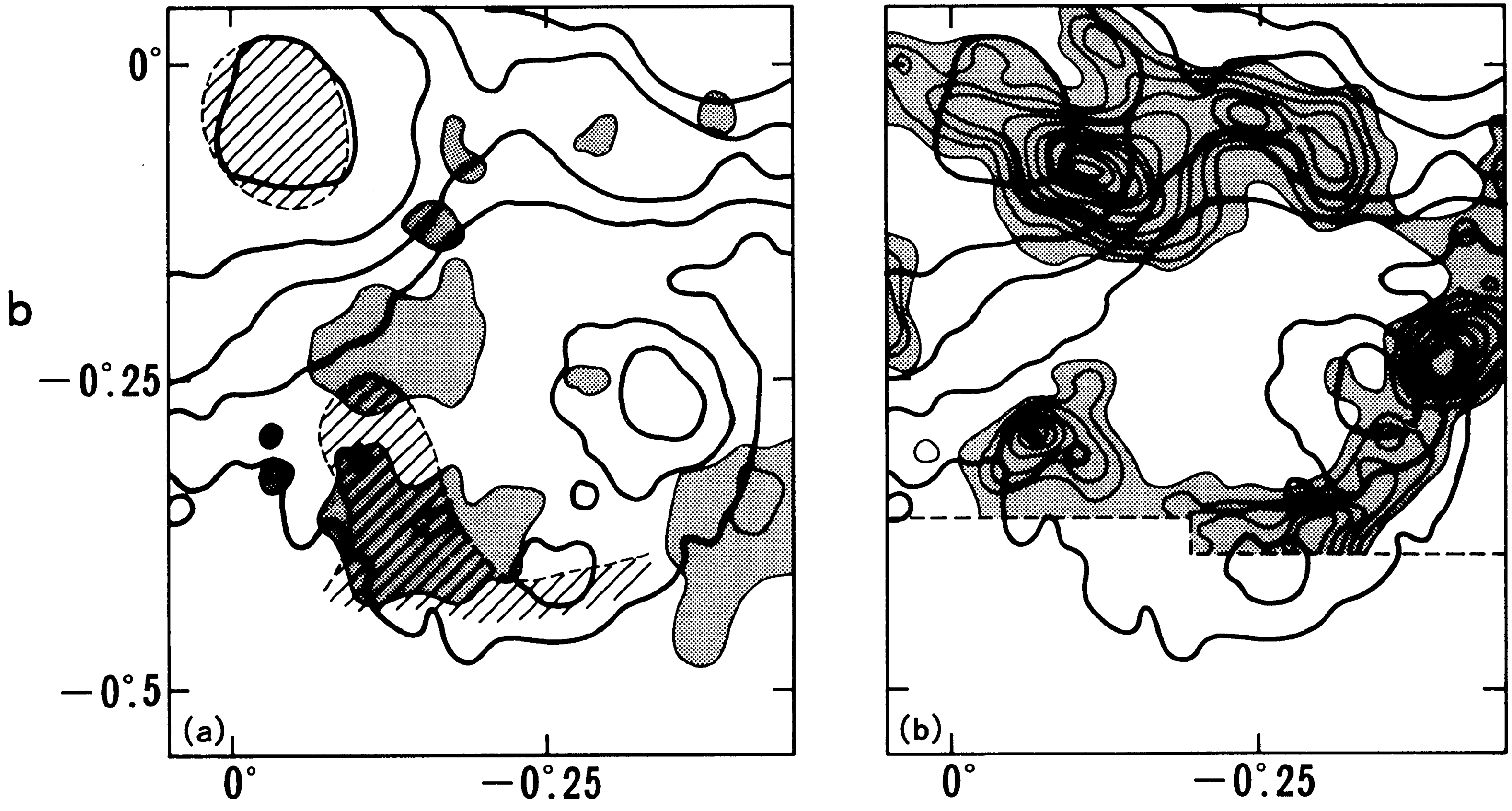

FIGURE 3 (a) Linearly polarized regions at 3 cm (shadowed) (Ref. 20) and nonthermal regions showing small IR-to-radio ratio (hatched) (Ref. 21) superimposed on the radio continuum map of the bubble. (b) ^{13}CO line-intensity distribution at V_{LSR} = 10–20 km s^{-1} (Ref. 23) superimposed on the radio continuum.

bubble. The center of the loop is located at $(l,b) = (-0.25°, -0.25°)$, and the diameter is about 0.4°. The loop roughly follows the edge of the continuum bubble but slightly shifted toward the north by 0.05°. Figure 3(b) shows the positional relationship of the CO loop and the bubble. The HII regions G359.65 and G359.73 are associated with CO clumps at $V_{LSR} = 16\ \mathrm{km\ s^{-1}}$. The molecular hydrogen mass along the loop is roughly $10^5\ M_\odot$ if it is at a distance of 8 kpc.

3. DISCUSSION

Among the enigmatic radio features near the galactic center, G359.8–0.3 is a particularly round object with partly nonthermal characteristics. Physical association of the bubble with the galactic center, with the HII regions, or with the CO loop is still an open question, because many of the objects seen toward the galactic center in general may lie along the line of sight.

As a possible origin of this bubble structure we may envision the following possibilities.

(1) An extended HII region or a stellar wind shell (bubble) associated with intense HII regions and molecular clouds. The proximity on the sky to the galactic center and the low-energy jet may then be by a chance coincidence along the line of sight. The nonthermal characteristics of the southwestern part is then also due to contamination of the foreground and background nonthermal emission of the galactic plane. (2) A shell-type supernova remnant along the line of sight, which has a peculiar emission mechanism for its flat radio spectrum. The association of the HII regions and molecular clouds may be an interesting subject to be discussed in this case. (3) A bubble which was produced by some energetic activity of the galactic center, like a jet or an ejection of magnetic flux.

Although the former two possibilities are equally likely and cannot be excluded, we here consider the third model in more detail, because the out-of-plane bubble (loop) structure near the galactic center seems of particular interest owing to its potential implication for the physical processes related to activity of the galactic nucleus.[4,24] Moreover, the apparent proximity to Sgr A strongly suggests its physical connection.

If we adopt a distance of 8 kpc to the bubble, its diameter is about 49 pc and the projected distance from Sgr A is 42 pc. The bubble is located on an extension of the slightly curving 160-MHz ridge emanating from Sgr A-E. Yusef-Zadeh[8] suggests that the 160-MHz ridge is a low-energy, one-sided jet ejected from the galactic center almost perpendicular to the galactic plane, being confined by the dense ambient matter. Since a poloidal magnetic field dominates in the central region,[25] the jet is also likely to be accelerated by a twisted-magnetic-jet model with the existence of a rotating disk near the nucleus.[26] Besides this object, several one-sided asymmetric ejection phenomena have been suggested (e.g., Refs. 10, 7, and 9), and seem to be common in the galactic center region.

If the ridge is a manifestation of an energy release from the galactic center, i.e., if it is really a jet, the energy may either have been thrown off toward the halo after penetrating the galactic disk, or be still accumulating somewhere in the disk, blocked by the disk matter. Since the energy is low and internal pressure is not strong enough to blow off the ambient dense matter,[8] it is more likely that the latter is the case. That is, the jet encounters the ambient gas and magnetic field after penetrating the disk for some 30 pc. In the case that the jet is accelerated by the magnetic twist mechanism, a stagnation at the top of the jet gives rise to an umbrella-like shape of magnetic flux. This may mimic the observed morphology of the jet and bubble.

The energy transferred by the jet may be partly used to accelerate high energy particles having flatter (younger) spectra in the bubble through the encounter with the ambient magnetic field. However, there remains the question as to why the spectral index can be so different between the bubble (flat) and the jet (steep). If the radio emission of the bubble is due to synchrotron radiation and equipartition between the magnetic and cosmic ray energies is assumed, the nonthermal energy involved within the bubble is estimated to be of the order of $E_{nth} \sim 10^{49}$ ergs, corresponding to a magnetic field strength $B \sim 10^{-5}$ G and total luminosity $L \sim 10^{34}$ ergs s^{-1}. The radiation decay time of the bubble is then $t \sim E/L \sim 3 \times 10^7$ yrs.

The high-energy plasma produced by the jet injection will then cause an expansion of the interstellar medium, compressing the surrounding gas and magnetic field, and will result in a round, bubble shape. The expanding motion may be of the order of local Alfvén velocity. If the ambient gas density is about 20 m_H cm^{-3} [27] and the magnetic field strength is $\sim 10^{-5}$ G, the Alfvén velocity is a few tens of km s^{-1}. Then the time scale of the expansion of the bubble is 10^{6-7} years. As the ambient matter involves dense molecular gas, a compression by the bubble expansion may enhance star formation there in some 10^6 years. This could account for the presence of the compact HII regions and molecular shell (loop).

The "jet-and-bubble (lobe)" morphology associated with a compact source near the jet axis (HII region G359.73) reminds us of extragalactic jets and lobes like Cyg A and Her A (e.g., Refs. 28 and 29). The present jet-bubble structure in the galactic center might be a miniature of those in huge extragalactic jets. We might also suppose that the bubble could be a less energetic case mimicking the large-scale magnetic bubbles emerging from nuclei of spiral galaxies like NGC3079[1] and the unusual radio loop emerging from the nucleus of the Seyfert galaxy NGC5506.[4]

Heyvaerts *et al.*[24] recently proposed a magnetic loop model for structure and activity in the galactic center. They showed that a loop of magnetic flux is formed via the Parker-type[30] inflation from a central rotating compact torus (ring) with a strong magnetic field. A detached loop from the torus may then inflate and expand into the space high above the galactic plane. We note that the present bubble (loop) mimics this loop, and could alternatively be accounted for by such a model, although we need explanation of the other associated features.

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