Concentric Radio Shells around Pistol-Quintuplet Stars in the Galactic Center Arc Region

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Abstract

By filtering out the straight filaments of the Galactic Cente Arc in VLA radio images of Yusef-Zadeh and Morris, we show that numerous concentric radio shells and arcs of radii 5 to 10 pc are coherently surrounding the Pistol and Sickle region. Each shell has a thermal energy of the order of 10^{49} ergs. Several CO-line shells are found toward the radio shells with kinetic energy of the order of 10^{49-50} ergs. We propose a new idea that the concentric shell structure has the common origin: they are expanding fronts from intermittent outflows and/or ionization due to successive star-forming activities near to the Pistol and Quintuplet stars.

1 Introduction

The Galactic Center Arc comprises a bunch of highly aligned magnetic fields vertical to the galactic plane. Various thermal features like Sickle and Bridge are superposed toward the straight Arc (Yusef-Zadeh and Morris 1987a, b). Besides Sickle and Bridge, fainter loops with larger diameters have been known to be apparently superposed on the Arc (Yusef-Zadeh et al. 1987b). However, since the radio emission from the Arc dominates, the fainter radio features have been not investigated in details.

In this paper, we try to enhance concentric radio shell features by applying a filtering technique, which removes straight filaments in the Radio Arc, and show that the enhanced features comprise numerous thermal radio shells. Based on the obtained images, we attempt to propose a new idea that concentric shell structure is produced by a coherent expansion from a common origin near to Pistol and Quintuplet stars. We show that such a coherency is well visualized in our processed images than in the original. We also discuss their physical properties and a possible origin.

2 Filtering Technique and Data

We apply a radial relieving method (Sofue 1993) as well as the pressing method (Sofue and Reich 1979) to the VLA 20 and 6-cm radio data from Yusef-Zadeh and Morris (1987a,b) with angular resolutions of 16 and 2$''$, respectively, which are available in FITS format and are distributed by a CD-ROM (Condon and Wells 1992). We first apply the radial-relieving method with the center at the Sickle (G0.18-0.04), which comprises the following procedure: A radio image is slightly enlarged, e.g. by a factor of 1.05, concentric to a position which is supposed to be the center of a shell to be enhanced. The original map is, then, subtracted from the enlarged map with the center position being coinciding. The difference map gives a relieved residual, enhancing loop-like features concentric to the center position, while other extended features are suppressed. The detail of the method is described in Sofue (1993). We used also the pressing method (Sofue and Reich 1979) in order to subtract the straight filaments in the Arc, which in principle is the same procedure to remove scanning effects from a radio map, except that the scan-direction is assumed to be parallel to the straight filaments. We also used the background-filtering technique (Sofue and Reich 1979) in order to subtract the extended background emission such as due to the Sgr A halo.

Among various features abstracted from the data, we have taken only those features to be real, whose amplitudes are significantly greater (e.g. more than 3 times) than the rms noise of the original image. Here, the rms noise was estimated for emissions from the most quiet region in the original map, including the residual interferometer patterns. The radial relieving has the potential to enhance spurious concentric to the center. In order to confirm that the enhanced features are real, we have cross-checked the result from the three different methods: (a) the radial relieving to enhance shell features, (b) pressing method to remove straight filaments, and (c) background filtering(unsharp masking). The features discussed here are all visible in the three results. They are also confirmed to be visible in the original maps, if their intensities are properly displayed individually.

3 Concentric Multiple Radio Shells

The results are shown in Fig. 1 to 4 in galactic coordinates. Fig. 1 shows the radial-relieved 20-cm image (original data from Yusef-Zadeh and Morris 1987b), Fig. 2 is a pressed image, where the vertical filaments have been removed by the pressing method. and Fig. 3 shows the same, but smoothed to an angular resolution of 20$''$. Numerous loop features are enhanced to be clearly visible in the figures. In Fig. 5 we illustrate the positions of the identified loops in superposition on the original 20-cm VLA map, and name them as GCS (Galactic Center Shells) I to XIII.

GCS I (Sickle), II and III are clearly recognized both on the 20-cm and 6-cm images. The fact that the same loop features are recognized in Fig. 1 to 4, which are obtained by different methods, as well as at different wavelengths, implies that the loops are not an artifact of the reduction procedure. Note, however, that their faintest parts are contaminated by various interferometer patterns, so that we, here, discuss only the global features.

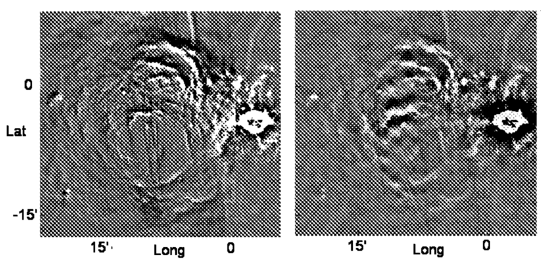

Figure 1: Radial-relieved (left) and pressed (right) images of the Galactic Center Arc region observed with the VLA at 20 cm (1.446 GHz: original data from Yusef-Zadeh and Morris 1987a). Numerous loop features are found.

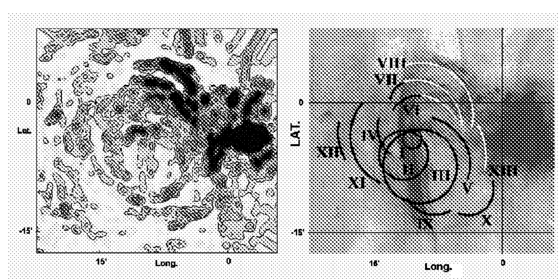

Figure 2: (Left) The same as Fig. 1, but smoothed to a resolution of 20$''$. (Right) Positions of the multiple radio shells (loops) in the Arc region superposed on 20-cm VLA map (Yusef-Zadeh and Morris 1987). GCS (Galactic Center Shells) I to XIII are indicated.

The most pronounced loop, GCS III, is centered on G0.170-0.125 at $(l, b) = (0^\circ.170, -0^\circ.125)$, or $(RA, Dec) = (17h43m12.7s, 28^\circ 50' 50'')$ with a radius of $4'.24$, which comprises an almost perfectly round loop, and is clearly visible in the original (Yusef-Zadeh and Morris 1987). At an assumed distance of the Galactic Center of 8 kpc, this radius corresponds to 9.9 pc. Sickle, which we call GCS I, at G0.192-0.62 with radius $0'.95$ is apparently in touch with GCS III at the north-western inner edge, and the 'Handle' appears to compose a part of this loop.

All the shells (loops and arcs) are approximately concentric to each other with their centers near to Sickle and Pistol. However, they do not necessarily make perfect loops, but sometimes oval and partial. The brightest loops, Shells VI, VII and VIII, are coincident with the thermal filaments in the Radio Bridge, which are also concentric to the other loops. In the southern region, partial loops, Shells IX and X, are found, which are about symmetric to the Thermal Bridge with respect to Sickle. We also find larger shells (XI and XII) at $l \sim 18 - 20'$.

For their round shapes, these loops are most likely tangential views of multiple shells. The shells appear to compose a coherent structure, suggesting multiple expanding spherical fronts concentric to the Pistol/Sickle region. The SW side of the shells is apparently contacting the halo of Sgr A, and is much brighter than the opposite side. On the other hand, the NE side is less bright, and seems to be more easily expanding being weakly deformed. The shells as a whole look like open petals of a lotus bloom with its neck at the Sgr A halo, as in Fig. 2. It is interesting to note that the shells appear to have no clear indication of interaction with the straight nonthermal filaments in the Radio Arc. For example, GCS III, the almost perfectly round shell, is not deformed by the Radio Arc.

4 Discussion

4.1 Properties of Radio Emission

The northern part of Shell III is visible in a 43-GHz map (Sofue et al. 1986). The spectral index of the NE part of the shell inferred from the 43 and 1.4 GHz intensities is about ~ -0.05, consistent with the thermal radio emission from ionized interstellar gas. The typical brightness temperature on the shell is $\sim$ 50 K at 20 cm, which yields an emission measure of $\sim 1.2 \times 10^5$ pc cm^{-6}, if the electron temperature is taken to be $\sim 10^4$ K. Assuming that the thickness of the shell is 0.1 times the radius (0.1×9.9 pc ~ 1 pc), the line of sight depth will be about ~ 4 pc. This yields an electron density of $\sim 1.7 \times 10^2$ cm^{-3}, and a total mass of the ionized hydrogen $\sim 5 \times 10^3 M_\odot$. The thermal energy would be, then, $\sim 1 \times 10^{49}$ ergs.

4.2 Far-Infrared Shells

GCS III positionally coincides with a far infrared loop at 16-26 μm as observed by the MSX experiment (Shipman et al. 1997). The FIR image shows also many other shells, coincident with the radio shells. The association of the FIR emission may indicate that the shells are predominantly thermal, containing warm dust and probably molecular gas. It is interesting to note that the Arc is not visible in the FIR as well as in the CO line (see below). Therefore, the MSX FIR image looks very similar to the radio image after subtraction of the Arc filaments (e.g. Fig. 1 and 2).

4.3 Molecular Shells

Association of molecular gas has been discussed for thermal features around the Arc (Serabyn and Guesten 1987). In fact, numerous CO-line shells and arcs are found toward the radio shells, whereas no straight CO feature is associated with the Arc. Fig. 6 shows CO-line channel maps at $V_{\rm lsr} = -25$, 25 and 55 km s^{-1}, and a longitude-velocity diagram across $b = -4'$ from Oka et al.'s (1998) ^{12}CO($J = 1 - 0$) survey with the 45-m telescope at a grid spacing of 30". An expanding shell at 55 km s^{-1} has been found by Oka et al., which has a radius and thickness ~ 10 and ~ 4 pc, respectively, as indicated by the arrows. The CO intensity is $\sim 10^2$ K km s^{-1}, yielding a molecular mass of $2 \times 10^4 M_\odot$ for a conversion factor of 1.0×10^{20} H$_2$ [K km s^{-1}]$^{-1}$ (Sofue 1995). The shell is expanding at 25 km s^{-1}, which yields kinetic energy of $\sim 1.4 \times 10^{50}$ ergs, and an age $\sim 4 \times 10^5$ years. Another CO shell is found toward GCS III, which has a radius 10 pc, width 5 pc, systemic and expansion velocities +25 and 30 km s^{-1}, respectively. Its total molecular mass is $\sim 2 \times 10^3 M_\odot$, and kinetic energy $\sim 4 \times 10^{49}$ ergs. Shells V to X and XIII seem to be apparently surrounded by a large CO arc of radius $\sim 10'$ (23 pc) at $V_{\rm lsr} \sim -25$ km s^{-1}.

4.4 X-ray Sources in GCS III

ASCA Galactic Center survey has revealed several bright X-ray sources in the 6.4 keV iron-line have been found with the brightest source in the Sgr B region (Maeda 1998). The second strongest source coincides with the Radio Bridge, where GCS VI, VII and VIII are identified. Most interestingly, the third strongest source, associated with the Arc region, coincides with the center of GCS III, toward the hole in the FIR 16-26 μm emission. An extended continuum X-ray source at 0.7-10 keV is also surrounded by GCS III.

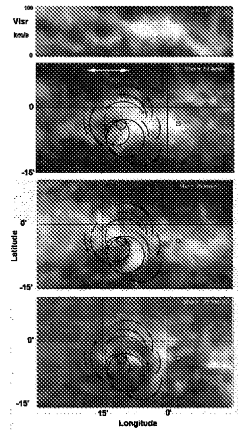

Figure 3: CO-line channel maps at $V_{\rm lsr} = -25$, 25, and 55 km s^{-1}, Showing many molecular shells are found around the radio shells (Oka et al. 1998). The top panel shows a longitude-velocity diagram at $b = -4'$, revealing an expanding feature at 55 km s^{-1}.

4.5 The Origin

The concentric distribution of the radio shells suggests that they have a common origin. Energy comparable to a single supernova or a mass flow from a massive star will be sufficient to cause their expansion as well as to heat up the gas. Star forming activity near to Pistol and the quintuplet stars (Nagata et al. 1996; Figer et al. 1998, 1999) may be related to their origin. Alternatively, the shells might be in an evolved phase of similar nebulae to the Pistol nebula surrounding the supermassive star.

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