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# High-Resolution 43-GHz Observations of the Galactic Center Arc: Spectral Turn Over of Filaments at High Frequencies

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**Abstract**

High-resolution radio continuum observations at 43 GHz of the G0.18–0.04 region of the radio Arc near the galactic center were made using the Nobeyama Millimeter-wave Array. Straight nonthermal filaments are hardly seen at 43 GHz, which contribute to a small fraction (<10%) of the total Arc brightness, and have a steep spectral index of $\alpha < -0.7$ between 4.7 and 43 GHz. We discuss the implication of this spectral turnover of the nonthermal filaments at high frequencies. The "sickle" feature is clearly seen at 43 GHz and has a flat spectrum, which confirms its thermal characteristics.

**Key words:** Galactic center — Magnetic fields — Radio arc — Radio spectra

## 1. Introduction

The galactic center Arc comprises a bunch of highly aligned vertical magnetic fields (Yusef-Zadeh et al. 1984; Yusef-Zadeh 1986), and shows high linear polarization (Tsuboi et al. 1986; Sofue et al. 1987; Reich 1989). Although the radio emission is nonthermal (synchrotron), its radio spectrum is flat, or even inverted, over a wide range of frequencies from 330 MHz up to 43 GHz (Sofue 1985; Reich et al. 1988; Yusef-Zadeh 1989; Anantharamaiah et al. 1991).

In order to clarify the origin of the filaments, it is important to descriminate the location and epoch of acceleration. In particular, the age of filaments can be obtained by a high-resolution map of the Arc at high frequencies at which the emission might have a spectral turnover. For this purpose, we have performed mapping of the brightest area on the Arc at 43 GHz using the Nobeyama Millimeter-wave Array (NMA). In this region some interaction with ambient thermal matter has been suggested (Serabyn and Güsten 1991), namely in the "sickle" region (= G0.18−0.04).

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## 2. Observations and Data Reduction

The observations were made using the 5-element NMA in the B configuration on 1991 March 1 and 14, and in the C configuration on April 10 and 12. The synthesized beam had a main-lobe HPBW of $15''.3 \times 8''.3$, elongated in the Dec directions at a position angle of $-6^\circ.1$. In order to improve the signal-to-noise ratio in the final map, we convolved the obtained map with a Gaussian beam to a HPBW of $16'' \times 10''$ at a position angle of 0°. The indicated intensity on the final map gives the surface brightness; 1 mJy $(16'' \times 10'')^{-1}$ beam$^{-1}$ corresponds to $2.35 \times 10^{-21}$ W m$^{-2}$Hz$^{-1}$sr$^{-1}$ .

The center position of the field was taken at RA = $17^{\rm h}43^{\rm m}04^{\rm s}.00$ and Dec = $-28^\circ 47' 30''.0$ (epoch 1950). The primary beam is $160''$ (FWHM). Calibrations of the complex visibility and flux were made by observing a nearby radio source, NRAO530, which had flux density of 5.7 Jy, compared to the planet Mars, with an assumed brightness temperature of 200 K. Data acquisition was made with an FX system (a fast-Fourier-transform spectrocorrellator); the data were channel-averaged to provide continuum data. The center frequency was 43.42 GHz and the receiver bandwidth was 320 MHz (1048 channels), while the central 280 MHz (920 channels) were used in the data reduction. Since we observed only one circular polarization, no information concerning linear polarization has been obtained. These data were CLEANed using the AIPS reduction system, and finally smoothed by con-

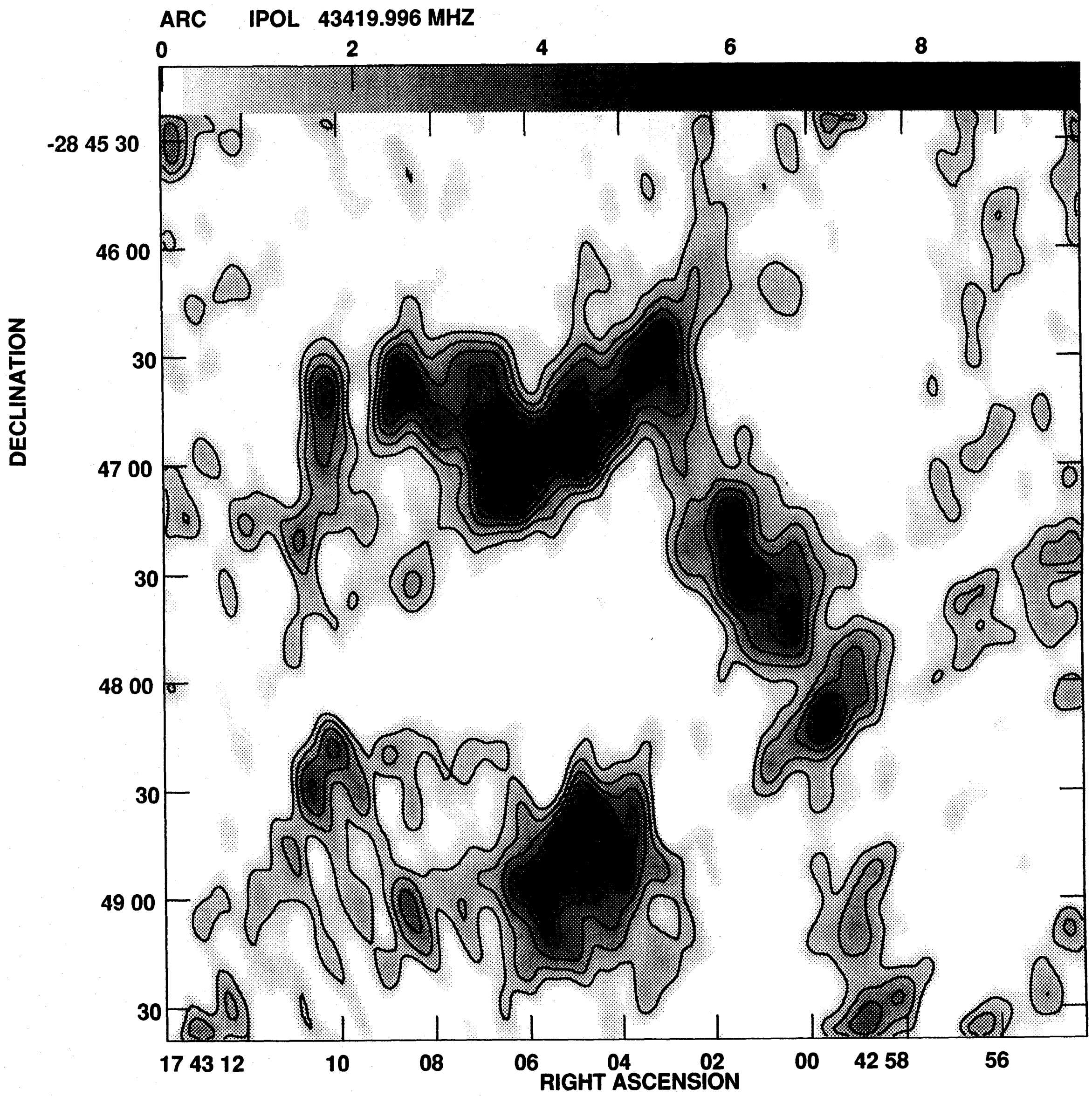


Fig. 1. A 43.42 GHz synthesized map of the G0.18−0.04 region of the radio Arc near the galactic center observed by the Nobeyama mm Array, convolved to a Gaussian beam of HPBW 16″ × 10″. Contours are drawn every 10% of the peak brightness, where the peak brightness is 55 mJy (16″ × 10″)$^{-1}$ beam$^{-1}$ = $1.29 \times 10^{-19}$ W m$^{-2}$Hz$^{-1}$sr$^{-1}$ . No correction for the primary beam attenuation (HPBW 160″) has been applied. True brightness can be estimated by multiplying the indicated values by $2^{\theta/80''}$, with $\theta$ being the distance in arcsec from the map center.

volving with a Gaussian beam, as mentioned above. The rms noise of a flat field in the resultant map is approximately 3.3 mJy (16″ × 10″) beam$^{-1}$.

## 3. Results

Figure 1 shows the obtained map convolved with a Gaussian beam of HPBW 16″ × 10″. The contours are drawn at every 10% of the peak flux, or at every $1.29 \times 10^{-20}$ W m$^{-2}$Hz$^{-1}$sr$^{-1}$ = 1.67 rms noise. The map is not corrected for the primary beam attenuation, so that the true brightness can be calculated by multiplying by $2^{\theta/80''}$ the indicated intensity, where $\theta$ is angular distance from the field center (the center of the map). Figure 2 reproduces a 6.4-cm (4.71 GHz) VLA map by Yusef-Zadeh (1986), where the field of view is sufficiently large compared to the indicated field; the intensity scale is therefore almost flat. The features seen near the edges of figure 1 such as that near the bottom-right corner, which have no counter features in the 6 cm map, are distant

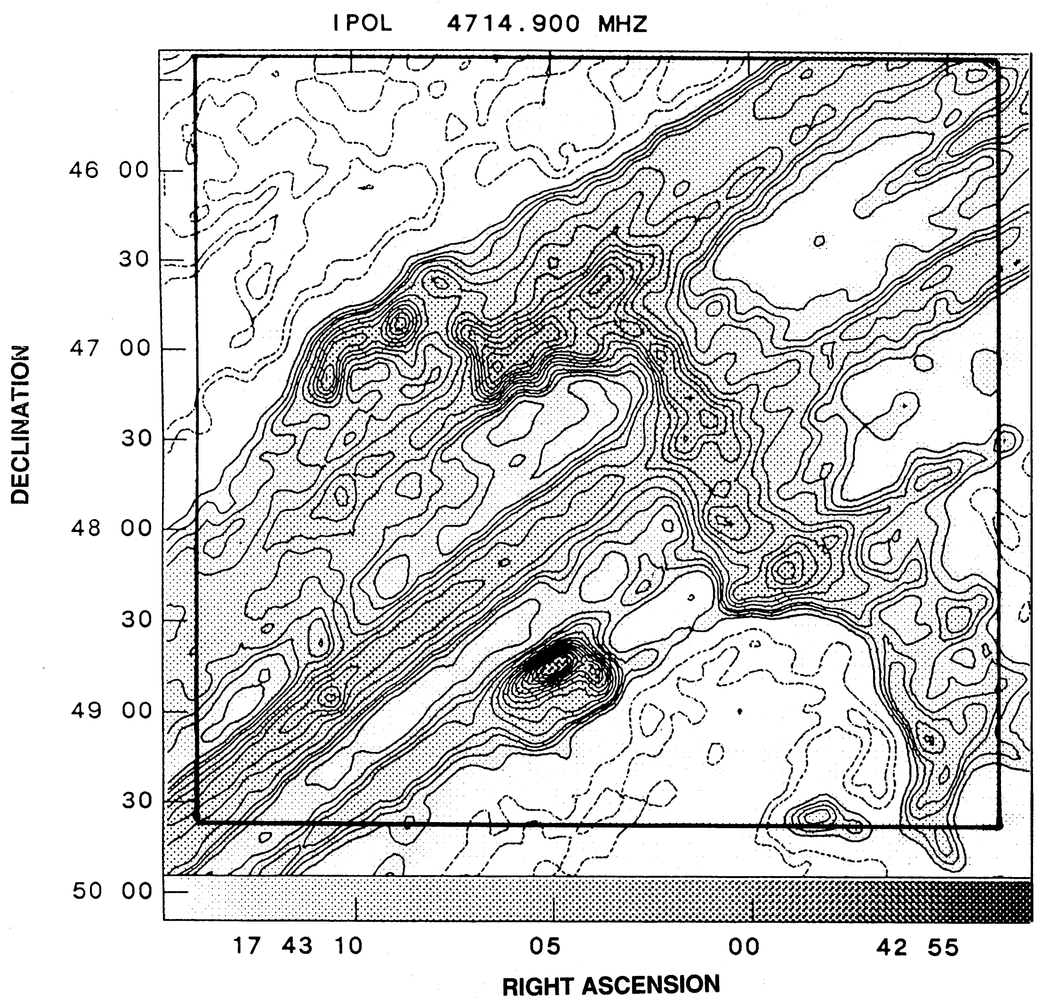


Fig. 2. The 4.71 GHz (6.3 cm) VLA map for the same region as in figure 1 (reproduced from Yusef-Zadeh 1986). The intensity contours are at −5, −2.5, 5, 7.5, 10 15, 20, ... 65 mJy $(7''.1 \times 6''.2)^{-1}$ beam$^{-1}$.

from the field center and may be spurius.

### 3.1. *Nonthermal Filaments of the Arc*

The VLA nonthermal filaments, which run along the Arc perpendicular to the galactic plane, are hardly recognized on our 43 GHz. Our UV coverage is sensitive enough to any filamentary structures extending in the Arc direction; this can be confirmed from the fact that the elongated thermal features at RA = $17^{\rm h}03^{\rm m}04^{\rm s}$, Dec = $-28°47'$, which are parallel to the nonthermal filaments, are quite visible on the map. We may therefore conclude that the 43-GHz emission from the VLA filaments is below the lowest contour level. The upper limit to the brightness of the filaments near the field center, excluding the sickle, is approximately 6 mJy $(16'' \times 10'')^{-1}$ beam$^{-1}$ = $1.4 \times 10^{-20}$ W m$^{-2}$Hz$^{-1}$sr$^{-1}$ .

On the other hand, the filaments were detected by single-dish observations at the same frequency. The mean brightness of the nonthermal Arc at G0.16−0.14, apart from the sickle, as observed by the 45-m single dish with a HPBW of 38″ at 43 GHz is 280 mK $T_{\rm B} = 1.63 \times 10^{-19}$ W m$^{-2}$Hz$^{-1}$sr$^{-1}$ (Sofue et al. 1986; Reich et al. 1988), and the brightness is almost constant along the Arc. Therefore, this "background" emission must come from extended structures with scale sizes greater than $0'.5$, and may not be detected by the present interferometer observations. The 43-GHz emission from the straight filaments makes less than about 10% of the brightness of the total Arc feature.

The data can be compared with the 4.71 GHz (6.3 cm) VLA data by Yusef-Zadeh (1986), which give a brightness of about 20 mJy $(7''.1 \times 6''.2)^{-1}$ beam$^{-1}$ = $1.7 \times 10^{-19}$ W m$^{-2}$Hz$^{-1}$sr$^{-1}$ for the straight filaments. By convolving with our beam, we obtained approximately 30 mJy $(16'' \times 10'')^{-1}$ beam$^{-1}$ = $7 \times 10^{-20}$ W m$^{-2}$Hz$^{-1}$sr$^{-1}$ at 4.71 GHz. Comparing this

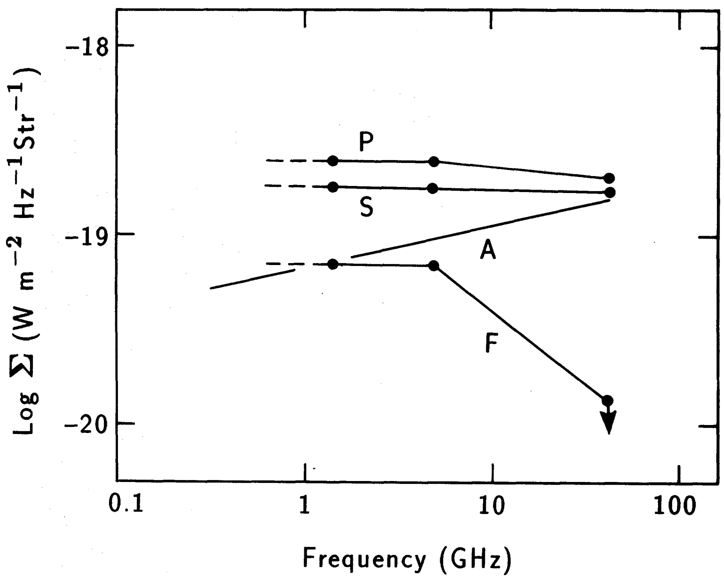


Fig. 3. Spectra between 43.42 and 4.71 GHz for (F) the straight filament near the field center, (S) the brightest part of the sickle G018−0.04, and for (P) the pistol G0.15−0.05. The inverted spectrum for the mean brightness of the radio Arc at G0.16−0.15 (Reich et al. 1988; Anantharamaiah et al. 1991) is also shown (A). The errors are typically ±15% for the 43 GHz data, and about the same for the other data.

value with the upper limit to the 43 GHz brightness, we obtained a spectral index between 4.7 and 43 GHz of the filaments to be $\alpha < -0.7$, where $\Sigma \propto \nu^{\alpha}$. This fact indicates that the straight filaments have nonthermal characteristics of steep spectrum.

On the other hand, the mean brightness of the larger-scale emission averaged over a wider Arc region at 6 cm is about $1.2 \times 10^{-19}$ W $m^{-2}Hz^{-1}sr^{-1}$, which leads to a flat or rather inverted spectral index of $\alpha = +0.2$ for the Arc (Reich et al. 1988). Therefore, the 4.7 GHz VLA straight filaments make a significant fraction (70%) of the mean brightness of the Arc. This is in contrast to the contribution by the filaments at 43.4 GHz, which is less than about 10%.

### *3.2. G0.18−0.04 (The "Sickle")*

The "sickle" is clearly seen as a loop-like association of clumpy features at 43 GHz (figures 1 and 2), and coincide well with the 6-cm VLA features (figure 3). However, its "handle" seen at 6 cm, a feature extending toward the bottom-right corner of figure 2, is hardly seen at 43 GHz, which suggests that this part might be due to its nonthermal property, although this is not conclusive for its distance from the map center. The brightest part of the sickle's blade has a brightness of about 70 mJy $(16'' \times 10'')^{-1}$ $\mathrm{beam}^{-1} = 1.7 \times 10^{-19}$ W $m^{-2}Hz^{-1}sr^{-1}$ after a primary beam correction. The brightness of this part at 4.71 GHz, after subtracting the contribution from the straight filaments, is about $1.8 \times 10^{-19}$ W $m^{-2}Hz^{-1}sr^{-1}$. Hence, the spectral index between 4.71 and 43.42 GHz toward the brightest point of the sickle can be determined to be $\alpha = -0.1$. A similar spectrum is obtained for most part of the sickle. The flat spectral index is consistent with the thermal characteristics, as indicated by the detection of the H109$\alpha$ recombination line toward the sickle (Pauls et al. 1976).

### *3.3. G0.15-0.05 (The "Pistol")*

The "Pistol"-like feature is also clearly seen at 43 GHz. The peak brightness of G0.15–0.05 is about 80 mJy $(16'' \times 10'')^{-1}$ $\mathrm{beam}^{-1} = 1.9 \times 10^{-19}$ W $m^{-2}Hz^{-1}sr^{-1}$, and its total flux is $\sim 0.5$ Jy, after correction for primary beam truncation. This can be compared to the 4.7 GHz VLA brightness convolved to the same beam, $2.7 \times 10^{-19}$ W $m^{-2}Hz^{-1}sr^{-1}$, and total flux of 0.5 Jy (Yusef-Zadeh and Morris 1987). The brightness at 1.45 GHz after convolution to our beam is $2.3 \times 10^{-19}$ W $m^{-2}Hz^{-1}sr^{-1}$, and total flux of $\sim$0.5 Jy (Yusef-Zadeh 1986). This gives a brightness spectral index of $\alpha = -0.1$ between 43 and 4.7 GHz and a flat spectrum between 4.7 and 1.4 GHz. The spectrum of the total flux is also flat.

### *3.4. Contribution from Molecular Lines*

Since our frequency band includes some molecular line emissions, like the CS line, we should estimate here their contribution. The strongest CS ($J = 1-0$) line has a peak brightness of about 2 K toward RA = $17^{h}43^{m}05^{s}$, Dec = $-29°46'$ (Tsuboi 1988; Serabyn and Güsten 1991).

Since the line width is about 10 km $s^{-1}$ , or 1.4 MHz, its averaged brightness within our bandwidth, 280 MHz, is approximately 10 mK. This is less than that of the noise level of figure 1, which is 14 mK. Contributions from the other lines should be much smaller; even the integrated contribution from all the lines in our band should be less than the lowest contour level. In fact we have observed no structures toward the above-mentioned position in figure 1. Moreover, the line emissions are much smaller in the other regions, apart from the above mentioned position. We may, therefore, safely assume that the contribution from molecular lines to our map is much smaller than the lowest contour level.

## 4. Summary and Discussion

The NMA high-resolution map at 43 GHz of the radio Arc near the galactic center has revealed the thermal complexes G0.18−0.04 (the sickle-like association) and G0.15−0.05 (the pistol). The sickle has a flat spectrum characteristic of thermal emission, consistent with the previous observations. The pistol also has a flat spectrum between 1.4 and 43 GHz, and is consistent with the previous observations at lower frequencies.

From a comparison of our data with the published maps at lower frequencies, we may discuss the spectral characteristics of the nonthermal filaments as follows: The filaments are hardly seen in our 43 GHz map. The 43-GHz contribution to the Arc brightness is less than 10%, and the spectrum of the filaments is as steep as $\alpha < -0.7$. In contrast, the filaments at lower frequencies comprise a significant part of the mean brightness (~70% at 4.7 GHz). The filaments are still visible on a 15-GHz VLA map by Inoue et al. (1989). Moreover, the nonthermal VLA filaments are known to have a flat spectral index between 1.4 and 4.7 GHz, where $\alpha$ ranges between −0.2 and +0.1 (Yusef-Zadeh 1989). Hence, we may conclude that the nonthermal filaments in the Arc have a spectral turn over between 4.7 and 43 GHz, probably between 15 and 43 GHz, although the published 15 GHz map has no flux density scale.

On the other hand, it is known that the entire Arc structure, as observed with single dishes, has a flat, or rather inverted, spectrum (Reich et al. 1988). These facts indicate that high-energy cosmic-ray electrons emitting at 43 GHz are not well concentrated in the filaments, but are widely spread over the entire Arc area, while the lower-energy electrons which emit at lower frequencies (6 cm) are more concentrated in the filaments. These facts may also give some constraints on the lifetimes of the filamentary structures, as follows.

The magnetic field strength in the filaments is estimated to be about 1 mG (Yusef-Zadeh et al. 1984). Energy of synchrotron electrons which emit at 43 GHz in this magnetic field are approximately $E \sim \sqrt{\frac{2\pi m^3 c^5 \nu}{eB}} \sim$ 2 GeV. The lifetime of an electron of this energy is then $\tau \sim \frac{3m^4c^7}{2e^4B^2E} \sim 4 \times 10^3$ yr. Here, $\nu$, $m$, $e$, $E$, $B$ and $c$ are the frequency, electrons mass, electric charge, energy, magnetic field strength, and light velocity, respectively. The Larmor radius of such electrons is of the order of $r \sim E/(eB) \sim 10^5$ km $\sim 10^{-9}$ pc, small enough compared to the thickness of a VLA filament of about an arcsec $\sim 3 \times 10^{-2}$ pc. Hence, it is safely assumed that the electrons are well localized in the filaments, and cannot escape across the field lines. High-energy electrons emitting 4.7 GHz radiation have typical energies of 0.6 GeV; their lifetime is about $1.3 \times 10^4$ yr, and their Larmor radius is still smaller.

The magnetic field in inter-filament regions, which is the space surrounding the filaments, of the Arc must be weaker than in the filaments: here we simply assume an order of magnitude weaker field, $B \sim 0.1$ mG. The energies of electrons emitting at the same frequencies are three-times greater than those for 1 mG, 6 GeV and 1 GeV at 43 and 4.7 GHz, respectively. However, their lifetimes are 30-times longer than those in the filaments: $\tau \sim 1.2 \times 10^5$ yr for 43-GHz electrons and $\sim 4 \times 10^5$ yr for 4.7 GHz. The Larmor radii are an order of magnitude larger than those in the filaments, but sufficiently small compared to the scale of the Arc extent.

It is known that the radio spectrum is nearly flat everywhere in a wide area (a few hundred pc) of the galactic center region (Sofue 1985; Anantharamaiah et al. 1991). This indicates that the "background" electrons emit flat spectrum radiation. If a magnetic flux tube is locally compressed, such as due to some shocked interaction with ejected matter from the nucleus (Sofue and Fujimoto 1987; Yusef-Zadeh and Morris 1987), energetic electrons within such an amplified magnetic tube must decay much faster than the ambient regions, and the high-energy part may show a spectral turnover. In this model the filaments which we discussed above must have appeared (been compressed) during a period earlier than $4 \times 10^3$ yr ago and later than $10^4$ yr ago. Namely, we may consider that the nonthermal filaments in the Arc are transient magnetic tubes, the lifetimes of which are several thousand years. In this context, we point out the similarity to the "threads" near the galactic center, which are considered to be thin magnetic tubes which also have a steep spectrum ( Anantharamaiah et al. 1991), even though the lifetime of the threads may be much longer, as is indicated by their steep spectra at lower frequencies.

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