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The Age of the Galactic Center Arc Determined by its mm-Wave Spectral Cut-Off

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Abstract. High-resolution radio continuum observations at 43 GHz of the Radio Arc near the Galactic Center were made using the Effelsberg 100-m telescope. The straight non-thermal filaments are hardly seen at 43 GHz, while they are clearly seen at 32 GHz and lower frequencies. The spectral index between 32 GHz and 43 GHz of the brightest straight filament is as steep as $\alpha = -1, (S \propto \nu^{\alpha})$, indicating a sharp turnover of the spectrum at these frequencies. Assuming a magnetic field strength of about 1 mG, we estimate the life time of cosmic-ray electrons to be about 4000 years. We conclude that the sharpest non-thermal radio filaments are very short-lived structures. On the other hand, the "sickle" is clearly visible at 43 GHz and has a flat spectrum confirming its thermal characteristics.

1. Introduction

The Galactic Center Arc comprises a bunch of highly aligned vertical magnetic fields, emitting highly polarized synchrotron radio emissions (Yusef-Zadeh et al. 1984, Yusef-Zadeh 1986; Tsuboi et al. 1986; Sofue et al. 1987; Reich 1989). Although the radio emission is clearly non-thermal, its radio spectrum is flat, or even inverted, over a wide range of frequencies from decimeter to millimeter wave ranges (Reich et al. 1988), which implies that the cosmic-ray electrons are young and have a peculiar energy spectrum. A mono-energetic electron spectrum would explain the inverted radio spectrum, while its acceleration mechanism is open to question (e.g., Lesch and Reich 1992, Morris 1996).

In order to clarify the origin of the filaments, it is important to discriminate the location and epoch of acceleration. In particular, the age of the filaments can be obtained by a high-resolution map of the Arc at high frequencies where the emission might have a spectral turnover. In our earlier 43 GHz observations of the bright non-thermal arc crossing the "sickle" region at G0.18–0.04 at 43 GHz using the Nobeyama mm-wave Array (Sofue et al. 1992), we have found that the non-thermal filaments are hardly visible, although the whole Arc is well seen at the lower resolution single-dish map at the same frequency (Sofue et al. 1986). The "sickle" is clearly seen, indicating a flat spectrum for its thermal

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origin (Serabyn and Güsten 1991). The spectral turnover of the non-thermal filaments at 43 GHz suggests that the thin filaments near the "sickle" would be a short-lived feature with a life time of about 4000 years.

In order to perform a more detailed, and better calibrated spectral variation in a wider area of the Arc, we have performed high-resolution, single-dish observations of the Arc in radio continuum at 43 GHz using the Effelsberg 100-m telescope.

2. Observations and Data Reduction

The observations were made using the Effelsberg 100-m telescope on 1998 May 15, 16, 18, and 21 under exceptionally fine weather conditions. We used a HEMT receiver at the center frequency of 43.0 GHz and a bandwidth of 2.8 GHz. Two circular polarizations have been observed, while we use only one channel which had a much lower noise temperature of about 120 K. The beam width was measured to be $20.0''$ using the nearby quasar NRAO 530. The pointing was calibrated by mapping Sgr A*. Including the effect of residual pointing errors of the individual coverages, the effective beam width was $21.5''$ for the final maps. We have mapped the following three regions, each with $6' \times 6'$ area: (1) Centered at RA_{1950}=17h 43m 05s, $\mathrm{Dec}_{1950} = -28°48'00''$, (2) Centered at RA_{1950}=17h 43m 20s, $\mathrm{Dec}_{1950} = -28°51'30''$, (3) Centered close to Sgr A* at RA_{1950}=17h 42m 30s, $\mathrm{Dec}_{1950} = -28°59'25''$.

The mapping was done by a raster-scan mode at orthogonal directions along the right ascension and declination with a scan interval of $10''$. Each of the arc fields (area 1 and 2) was covered 8 times, and the mapping of Sgr A was inserted every two maps. A RMS noise of about 30 mJy per $21.5''$ beam was measured from the final map.

3. Results

The obtained 43 GHz map of the Arc region is shown in the right panel of Figure 1. We also show a 32 GHz map of the same region taken with the same telescope (Lesch and Reich 1992), and a VLA 20 cm map for the same region taken from Yusef-Zadeh et al. (1984). All the maps have been smoothed to a $27''$ beam, what is the 32 GHz original resolution.

3.1. Non-thermal Filaments

The VLA non-thermal filaments are well recognized in the 32 GHz map. However, the bright filaments seen at lower frequencies hardly recognized in our 43 GHz map. This can be more clearly seen by comparing the 5 GHz VLA map (taken from Yusef-Zadeh 1986) and the 43 GHz map from Nobeyama mm-Array (NMA: Sofue et al. 1992) as shown in Figure 2. This fact indicates that the spectrum of the brightest filament is nearly flat between 1.4 GHz and 32 GHz, while it turns to drop steeply between 32 GHz and 43 GHz. Namely, the filament has a steep spectral cutoff at ~ 40 GHz. This is also clearly recognized by comparing the intensity ratio maps between 1.4 GHz and 32 GHz and 32 GHz to 43 GHz, respectively, in Figure 3.

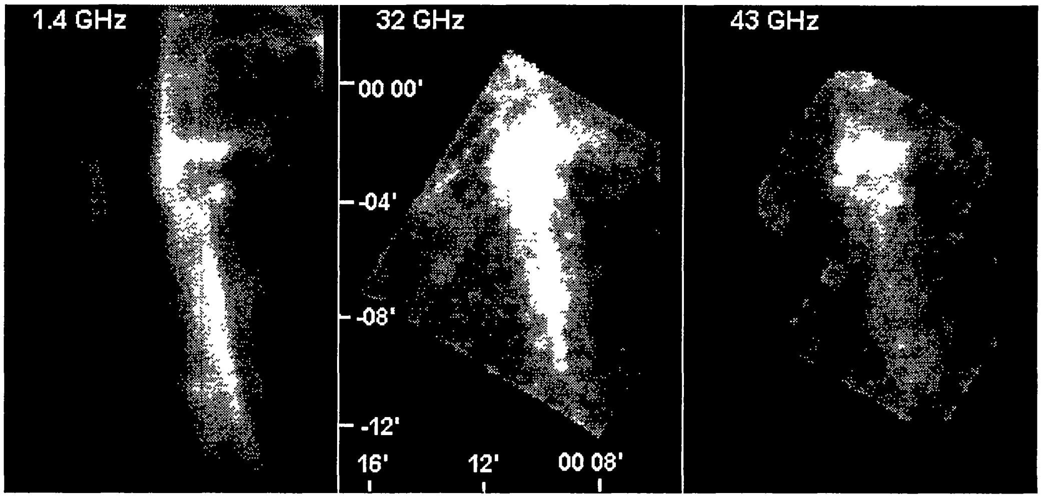

Fig. 1. (a) 1.4 GHz VLA map of the Radio Arc convolved to a beam of 27″ (Yusef-Zadeh et al. 1984)(left). (b) 32 GHz map observed with the 100-m telescope at the original resolution of 27″ (middle). (c) 43 GHz map observed with the 100-m telescope, convolved to 27″ (right). [Coordinates are (l, b). The map centers are at $(l, b) = (00°10', -00°06')$.

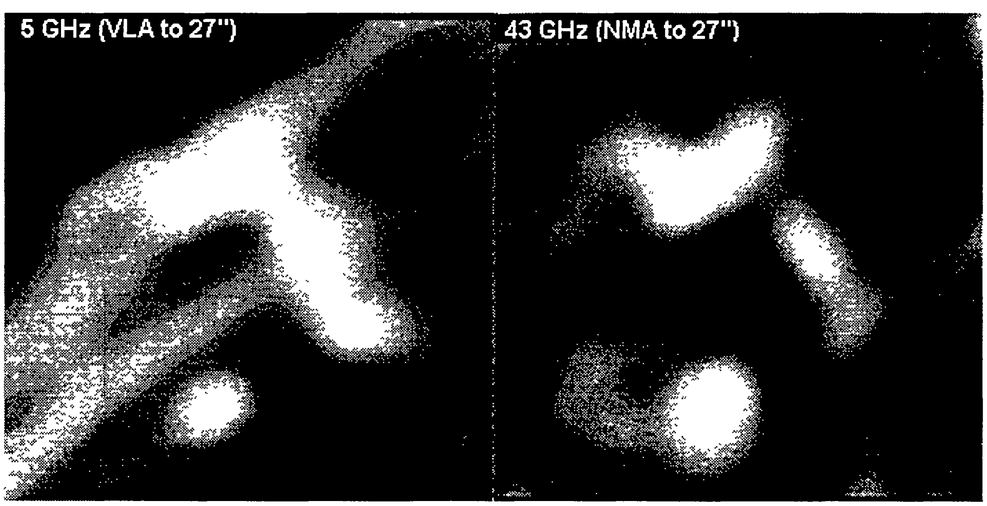

Fig. 2. (a) 5 GHz VLA map of the Radio Arc convolved to a beam of 27″ (Yusef-Zadeh 1986)(left). (b) 43 GHz map observed with the NMA convolved to a 27″ beam (right). [Coordinates are (Ra, Dec).]

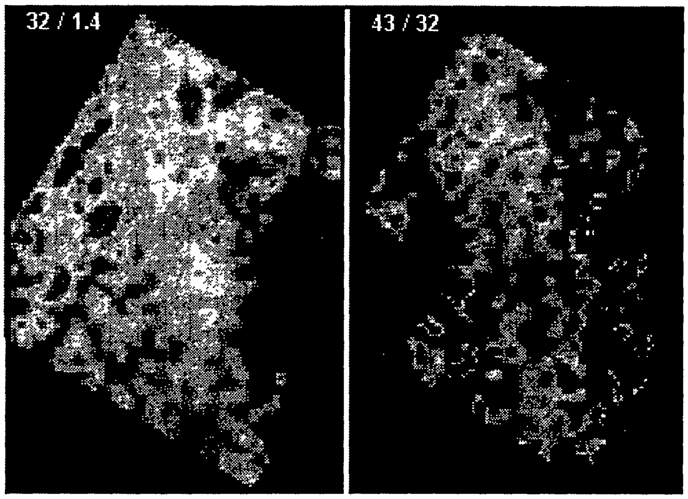

Fig. 3. (a) Intensity ratio of the 32 GHz to 1.4 GHz maps (left) for the same region in Fig. 1. (b)The same but 43 GHz to 32 GHz maps (right).

3.2. The "Sickle" and "Pistol"

The "sickle" is clearly seen as a loose association of clumps at 5 GHz, 32 GHz and 43 GHz, having flat spectra, corresponding to their thermal characteristics. The "Pistol" is also clearly seen at 43 GHz. It appears to be brighter at 43 GHz than at 32 GHz and 1.4 GHz, suggesting an inverted spectrum above 32 GHz. The "Pistol" might have more than one component or is partly optically thick.

4. Discussion

The straight Arc-filaments are hardly seen in our 43 GHz map. They have a sharp spectral turnover between 32 GHz and 43 GHz. This has been already found in a filament near the "Sickle" in our 43 GHz interferometer observations (Sofue et al. 1992). On the other hand, it is known that the entire Arc structure, when observed at low resolution with single dish telescopes, has a flat, or rather inverted, spectrum (Reich et al. 1988). This indicates that high-energy cosmic-ray electrons emitting at 43 GHz in the filaments have already decayed away, while they are widely spread in the entire Arc region. On the other hand, lower-energy electrons, which emit at lower frequencies (32 GHz and 1.4 GHz), are still alive and confined in the filaments. These facts give constraints on the epoch of the acceleration of cosmic-ray electrons in the filaments.

The magnetic field strength in the filaments is of the order of 1 mG (e.g., Yusef-Zadeh et al. 1984). The energy of synchrotron electrons which emit at 43 GHz in such a magnetic field is approximately

$$E \sim \sqrt{\frac{2\pi m^3 c^5 \nu}{eB}} \sim 2 \text{ GeV}.$$

The lifetime of an electron of this energy is then

$$\tau \sim \frac{3m^4c^7}{2e^4B^2E} \sim 4 \times 10^3 \text{ years.}$$

Here, ν, m, e, E, B and c are the frequency, electrons mass, electric charge, energy, magnetic field strength, and light velocity, respectively. Thus, the nonthermal filaments in the Arc would be magnetic tubes, temporarily illuminated by high-energy electron fluxes, whose acceleration would have taken place about 4000 years ago. The Larmor radius of such electrons is small enough compared to the thickness of a filament resolved with the VLA. Hence, the electrons are localized in the filaments, and cannot escape across the field lines.

We point out the similarity of the filaments to the "threads", which, however, have steep spectra (Anantharamaiah et al. 1991; Lang 1999). The threads may be magnetic tubes, which were illuminated by high-energy electrons accelerated earlier than the Arc electrons. The high-energy electrons have decayed meanwhile and the spectrum has steepened.

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