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150 GHz NOBA Observations of the Galactic Center Arc

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Abstract

We have used the seven-beam 150 GHz bolometer NOBA installed at the Nobeyama 45-m telescope to map the central section of the Galactic Center Arc. In addition, we mapped Sgr A, which shows Sgr A* and the thermal spiral structure. The results agree with previous mm-observations. South of the thermal "sickle" feature (G0.18 − 0.04) we observed three regions of enhanced emission along the Arc, which are located slightly offset relative to the most intense vertical filaments seen at low frequencies. This 150 GHz emission is observed at the apparent interacting areas of dense molecular material with the Arc. Another structure is seen south of the molecular cloud, where the Arc's vertical filaments apparently cross a weak filamentary structure running orthogonally in the direction of Sgr A. The 150 GHz results are unexpected in view of previous 32 GHz and 43 GHz results, which indicate a fading of the Arc towards higher frequencies. Cold dust can be ruled out as the origin of the 150 GHz emission. Synchrotron emission from quasi-monoenergetic electrons or an electron distribution with a low-energy cut-off seems to be compatible with the available data. The coincidence of enhanced emission with regions of interacting molecular gas strongly suggests that high-energy electrons are accelerated in those places where the magnetic field is compressed, and subsequently enter and illuminate the Arc.

Key words: Galaxy: center —magnetic fields —particle acceleration — radio continuum

1. Introduction

The Galactic Center Arc is a unique radio continuum feature located just about 13′ apart from Sgr A*. Morphologically, it consists of numerous thin filaments running approximately perpendicular to the galactic plane, as can be seen at arcsec angular resolution (Yusef-Zadeh et al. 1984). The filaments are embedded in diffuse emission. Its non-thermal nature has been established by missing recombination lines and linear polarization, the amount of which is close to the intrinsic value at high frequencies (Lesch, Reich 1992). Nevertheless, the formation and illumination of the Arc with relativistic particles is not fully understood. Reich et al. (1988) have shown that the Arc's spectrum is slightly inverted and compatible with the existence of a quasi-monoenergetic electron population or an electron spectrum with a low-energy cut-off. Various models have been proposed for the Arc, as reviewed by Morris (1996) and Serabyn (1996). Strong magnetic fields on the order of mG have been proposed for the nearly straight Arc filaments, which are up to 40 pc long. These high magnetic fields are required to resist the pressure of the ambient interstellar medium (Yusef-Zadeh, Morris, 1987). However, such high magnetic fields imply a short synchrotron lifetime of the radiating electrons, and reacceleration might be required. Sofue, Murata, and Reich (1992) have made high resolution 43 GHz observations, and failed to see the thin synchrotron filaments near to the thermal "sickle" feature (G0.18 − 0.04), while lower resolution 43 GHz observations clearly show the diffuse emission from the Arc. This implies a lower magnetic field strength in the diffuse Arc component and, in consequence, a longer lifetime for the electrons. 32 GHz and 43 GHz observations with the Effelsberg 100-m telescope indicate spectral turn-over in this frequency range (Sofue et al. 1999). Sofue et al. (1992, 1999) conclude that the filaments should not be older than about 4000 yr. Tsuboi et al. (1997) found evidence for the Arc interacting with an expanding molecular shell and calculated the resulting ram pressure on the Arc's filaments. They came up with about 5 mG for the magnetic field strength along the Arc's filaments to be in pressure equilibrium, implying an electron lifetime of only a few hundred years. To further study the spectral behaviour of the Arc towards short mm-wavelength we performed 150 GHz observations.

2. Observations and Reduction

We made 150 GHz observations of the Arc and Sgr A in 1999 March, using the Nobeyama 45-m telescope, which is equipped with a sensitive seven-element bolometer array (NOBA) with about 30 GHz bandwidth. It has been described in detail by Kuno et al. (1993). In brief, six feeds are symmetrically arranged around a central feed with a projected distance on the sky of $16''$. The total intensity data are recorded from the central feed and the six differences between the offset feeds and the central feed. The algorithm to restore the total intensity for all seven beams has been described in detail by Kuno (1993), where simulations have proven the reliability of this method. From the measured six differences, a plane was fitted to the differential data. By appropriate integration along all fitted intensity gradients of a single scan, the atmospheric corrected emission for the central beam was restored. With this value the six difference measurements for the offset beams were converted into individual intensities.

At 150 GHz the beam size of the 45-m telescope is a circular Gaussian form of about $12''$ HPBW. An extended error beam is seen when mapping strong sources, which peaks at about -12 dB and decreases to about -22 dB at about $1'$ distance from the source center. Althouygh the error beam needs to be taken into account when the dynamic range exceeds about 16, this does not affect the results for the Arc and marginally the map of Sgr A, which we decided not to clean. Wind pressure on the telescope exceeding about 5 m s^{-1} causes beam broadening; we have regularly observed nearby source, OH 5.89$-$0.39, to check the beam size, the pointing and the atmospheric extinction. Additionally, sky dips have been regularly performed. Useful observations could be made in nights with opacities between 0.06 and 0.15. OH 5.89$-$0.39 also served as a flux-density calibrator, assuming 8.8 Jy. This value is uncertain by about 10%.

Mapping was performed in the equatorial coordinate system by moving the telescope in the right-ascension or declination direction, respectively; accordingly, the bolometer was rotated in such a way that the seven beams simultaneously observe seven rows or columns of a map separated by $5\farcs3$. One observation consisted of several coverages, which were subsequently processed and added to one map. The total integration time for one observation of a $3' \times 3'$ field was about 30 min and that for a $5\farcm5 \times 5\farcm5$ field was about one hour.

We mapped a field of $3' \times 3'$ centered on Sgr A* and two slightly overlapping fields along the Arc of $5\farcm5 \times 5\farcm5$, respectively. The data were reduced with the standard continuum reduction system for observations with the 45-m telescope, which includes restoration algorithm for NOBA observations. This reduction package is incorporated in the IDL image-processing software. The raw data of one observation had been carefully edited before they were added into a map. The relative zero-level was set to both ends of each single scan. The maps were calibrated and pointing corrected. The final combination of maps was made using the NOD2-based reduction package, where in particular the PLAIT program (Emerson, Gräve, 1989) was applied to destripe a set of maps observed at different scanning directions.

Due to varying atmospheric conditions and different wind speeds during the observations, we finally obtained the best result for the Sgr A field by combining maps from five observations. For the northern field of the Arc, five maps were also combined. For the southern field the combination of two maps gave the highest signal-to-noise ratio, which have been observed under quite favourable atmospheric conditions with an opacity of 0.10. However, a wind speed of about 5 m s^{-1} increased the beam width to about $18''$ (HPBW).

3. Results

3.1. Sgr A

We show a 150 GHz contour map of Sgr A in figure 1 at an effective HPBW of about $13\farcs5$. The rms-noise was measured to be about 20 mJy/beam area. We have separated the compact source Sgr A* from the thermal spiral by applying a background-filtering (unsharp-masking) technique (Sofue, Reich, 1979) and measured the flux density of Sgr A* by fitting a two-dimensional elliptical Gaussian profile to the source. At our angular resolution, Sgr A* is confused with the weak thermal sources IRS 2 and IRS 13 (< 200 mJy), as discussed by Falcke et al. (1998). The peak flux density is about 3.6 Jy with an absolute error below 15%. The underlying spiral structure of Sgr A West is optically thin thermal emission. We have compared our map with a 230 GHz map of Zylka and Mezger (1988) observed with the IRAM 30-m telescope (kindly provided by R. Zylka in numerical form). Doing the same unsharp masking operation to separate the thermal spiral from Sgr A*, we measure at $13\farcs5$ angular resolution a 230 GHz flux density of 2.6 Jy. This is in agreement with the 2.5 Jy quoted by Zylka and Mezger (1988) for the original $12''$ beam, although they use a different method to account for the contribution from the thermal spiral structure. The 230 GHz observations are from 1986/1987. The intensity of the thermal spiral structure is almost identical and vanishes when subtracting both maps. Formally, about a 4% difference in intensity was expected for optically thin thermal emission. A slight excess of up to 300 mJy/beam area of the 230 GHz

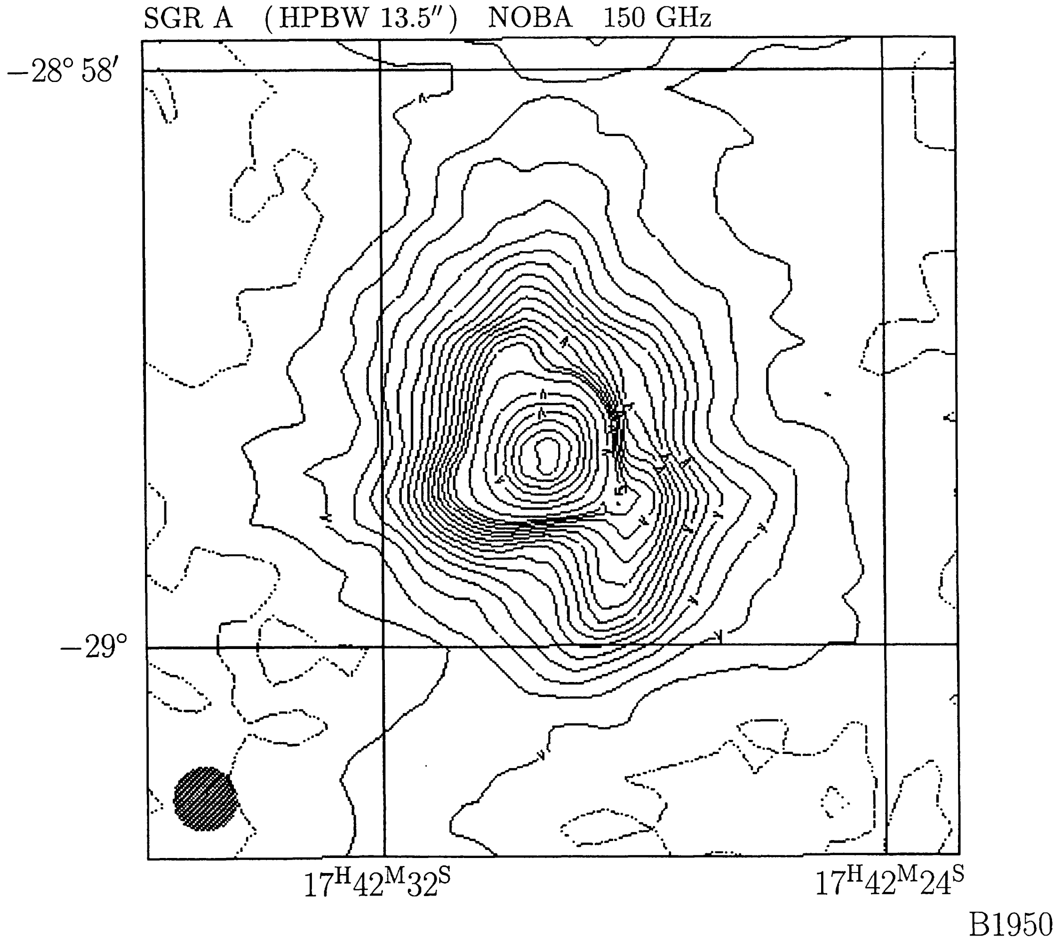

Fig. 1. Total intensity map of Sgr A. The HPBW of 13.″5 is indicated in the lower left corner. Contours run in steps of 100 mJy/beam area up to 1.5 Jy/beam area (labeled contour) and from 1.75 Jy/beam area in steps of 0.5 Jy/beam area. The maximum is at 5.0 Jy/beam area.

emission is seen at the western side of the southern arm, where dust emission from the circum-nuclear-disk shows up (Mezger et al. 1989). The total flux density in the field shown in figure 1 is about 32 Jy, when Sgr A* is excluded. This is larger than the 15 GHz flux density of 22.6 Jy, as measured by Zylka and Mezger (1988) from the VLA-map by Brown and Liszt (1984), which seems to miss some large-scale structure. The 150 GHz flux density measured from Sgr A* in 1999 March is about 0.5 Jy higher than that observed with NOBA in 1997 October (Falcke et al. 1998). However, variability seems possible we note that this excess is within the errors of both measurements.

3.2. The Galactic Center Arc

Our result for the Arc is shown in galactic coordinates in figure 2 at an angular resolution of 21.″5 (HPBW). Both of the observed fields have been combined into a single map, where some zero-level adjustment at the overlapping region was necessary. The rms noise is about a 15 mJy/beam area in the northern field and about 20 mJy/beam area in the southern area, which has less coverage. A gray-scale coded 1.4 GHz VLA-map from Yusef-Zadeh (1986), which we convolved from 10.″7 × 10.″1 to 21.″5 (HPBW), is shown overlaid.

As can be seen in figure 2, the emission at 1.4 GHz and 150 GHz from the thermal "sickle" (G0.18 − 0.04) is quite similar. Differential intensity plots (TT-plots) give an average spectral index of $\alpha = -0.1 \pm 0.05$ ($S \sim \nu^{\alpha}$). Thermal emission is also seen from the small "pistol" feature (l, b = 0.°16,−0.°07). Its peak flux density is about 265 mJy/21.″5 beam at 1.4 GHz and about 170 mJy/21.″5 beam at 150 GHz. A spectral index close to $\alpha = -0.1$ was calculated, as expected for optically thin thermal emission. The strong vertical filament at 1.4 GHz disappeared at 150 GHz,

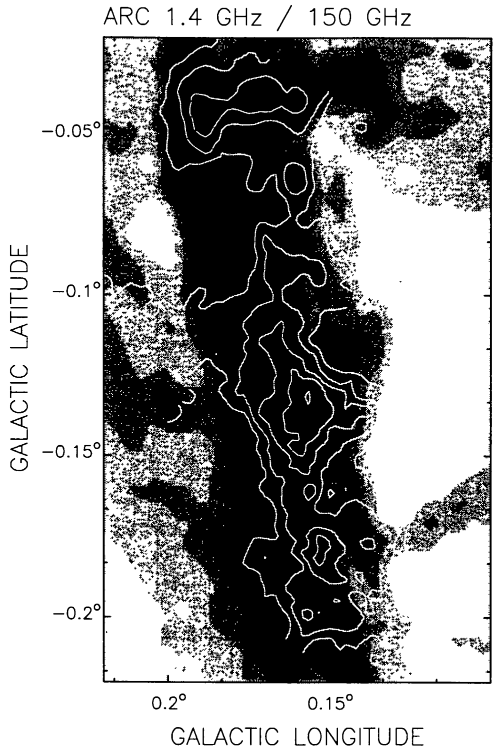

Fig. 2. Galactic Center Arc at 150 GHz. The angular resolution is 21.″5 (HPBW). The contours are 75 mJy/beam area apart. A section of a 1.4 GHz VLA-map (Yusef-Zadeh 1986) is shown gray-scale coded at the same angular resolution.

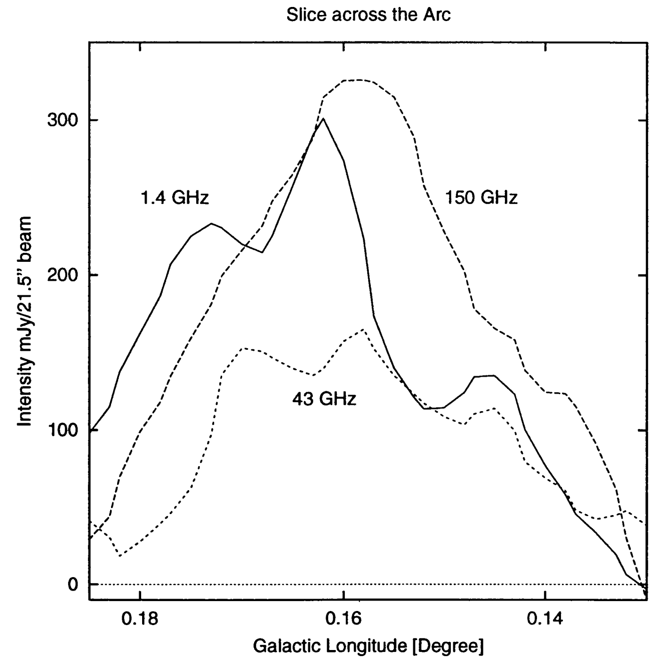

Fig. 3. A 1′ wide slice at $b = -0.^\circ 13$ across the Galactic Center Arc at 1.4 GHz, 43 GHz, and 150 GHz. The angular resolution is 21.″5 (HPBW).

while three distinct emission features are seen near to the filament. Their maxima are slightly shifted to the west and some extended emission runs vertically away from the Arc direction. The peak flux densities are about 200 mJy/21.″5 beam at $l, b = 0.^\circ 27$, $-0.^\circ 09$, 380 mJy/21.″5 beam at $l, b = 0.^\circ 16$, $-0.^\circ 13$ and 300 mJy/21.″5 beam at $l, b = 0.^\circ 15$, $-0.^\circ 18$.

The morphology of the Arc at 150 GHz is also different from the single-dish maps with a comparable angular resolution obtained at 32 GHz (Lesch, Reich 1992), particularly at 43 GHz (Sofue et al. 1999), where the Arc appears as a smooth continuous bar-like structure, which is significantly weaker than the thermal emission visible from the "sickle" area. In contrast, the maximum emission at 150 GHz is in the central section of the Arc.

The distinct 150 GHz emission features along the Arc clearly have an inverted spectrum and are up to a factor of 2 stronger than the emission seen at 43 GHz (Sofue et al. 1999). This corresponds to a spectral index of up to $\alpha = +0.5$, although the error is large. We show a slice across the Arc at the central 150 GHz emission maximum in figure 3. Outside of the distinct emission features the spectrum at the Arc is flat between 43 GHz and 150 GHz. However, we note that the diffuse background emission is known more accurately at 43 GHz due to the Nobeyama Galactic Center survey (Sofue et al. 1986). We do not have similar information on the large-scale structure at 150 GHz at present, and it remains open if the large-scale structure exceeding about 3′ is correctly represented. Therefore, the low-level diffuse emission just south of the "sickle" and close to the "pistol" feature needs to be checked. A more detailed spectral analysis is being prepared.

4. Molecular Gas in an Interaction with the Arc

Figure 4 shows an overlay of the Arc with the Nobeyama CS (J = 1–0) observations by Tsuboi et al. (1997), which clearly shows that enhanced 150 GHz emission is seen in those regions, where the molecular gas approaches the Arc most closely. The CS-data shown in figure 4 are for the velocity range between 15 km s^{-1} and 45 km s^{-1}, where Tsuboi et al. (1997) found strongest morphological evidence for an interaction with the Arc (see their figure 2). The molecular gas has also been traced in the course of line surveys in CO, as discussed by Oka et al. (1997), and has also been seen in $C^{18}O$ and

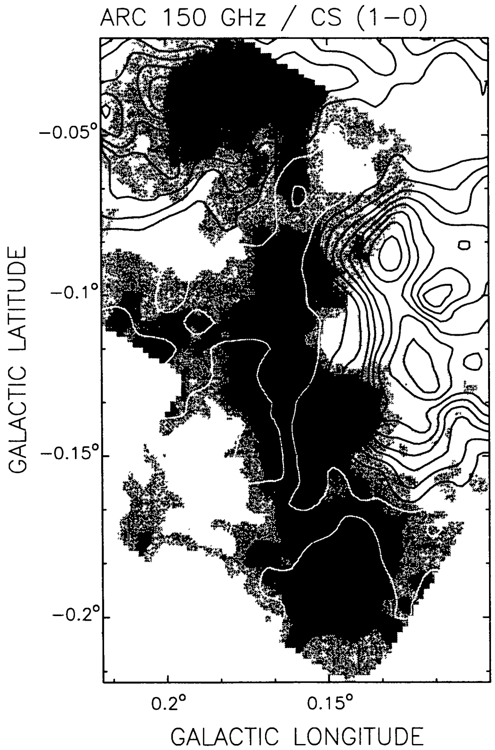

Fig. 4. Arc at 150 GHz (HPBW = 21."5) is shown greyscale coded with contours of the CS (J = 1–0) emission (HPBW = 34″) as observed by Tsuboi et al. (1997) overlaid. The velocity range is from 15 km s^{-1} to 45 km s^{-1}.

HNCO by Lindquist et al. (1996).

The enhanced emission seen at l, b = 0.°15, −0.°18 does not seem to coincide well with intense CS-emission from interacting molecular gas. In this area the vertical Arc structure is seen to cross other weak structures, which run almost perpendicular to the Arc towards Sgr A. This is clearly visible at 1.4 GHz (figure 2). These features, which are much fainter than the emission from the Arc, are seen on all sensitive large-scale observations of the Galactic Center region, but have not been studied in detail. The spectrum appears to be flat. Polarization is missing and it is likely that it is thermal. We note that these structures run along the southern boundary of the molecular cloud (figure 4), although their relation is presently unclear. The crossing of these features and their possible interaction with the Arc has already been discussed by Benford (1988), where a current running in a closed circle across the Arc, the filamentary structures, and the Sgr A region was suggested.

5. On the Nature of the 150 GHz Emission

The present observations show enhanced emission regions with an inverted spectrum between 43 GHz and 150 GHz. This enhanced emission is observed at the apparent interacting regions of dense molecular gas with the Arc, and thus supports the idea that molecular clouds compress the poloidal large scale magnetic field in the Galactic Center to a field strength of up to a few mG. Particle acceleration will take place in these regions of interaction. However, 150 GHz is a high frequency, where cold dust emission might show up; this possible contribution needs to be clarified before considering other possibilities. Although it seems quite unlikely that the interaction process leeds to enhanced cold dust emission, this needs to be checked by comparing with higher frequency data. In this frequency range optically thin emission from cold dust should scale with about ν^4. The IRAM 230 GHz survey by Zylka and Mezger (Mezger et al. 1996, figure 21) does not show any significant emission along the Arc. The weak patchy structure seen in this area does not exceed about 100 mJy/11″ beam. This corresponds to an emission of less than 400 mJy/21."5 beam and is in agreement with the slightly inverted spectrum between 43 GHz and 150 GHz. The low 230 GHz emission definitely rules out emission from cold dust, where we expect an increase by about a factor of 5 between 150 GHz and 230 GHz. We have also checked the IRAS 100 μm and 60 μm low-resolution maps for this region, which show a depression in intensity along the Arc (see the IRAS 60 μm map shown by Reich et al. 1987). Moreover, a higher-resolution FIR map at 16–26 μm from the MSX experiments (Shipman et al. 1997) shows no signature of dust emission at the 150 GHz peak, but the peak appears to be located rather at the center of a hole of dust emission. To summarize, available data rule out a significant contribution from cold dust to the observed 150 GHz emission.

Absorption mechanisms in the Galactic Center have been looked at by Lesch et al. (1988). Their calculations show that neither synchrotron self-absorption nor thermal absorption of optically thin synchrotron emission is able to explain the inverted Arc spectrum up to 43 GHz (Reich et al. 1988). The size of the emitting region is by some orders of magnitude too large, so that synchrotron self-absorption becomes relevant. This is even more extreme for the case of the 150 GHz emitting regions. The same holds for thermal absorption, where Lesch et al. (1988) showed that the required column densities are several orders of magnitude too large to invert the spectrum of the Arc. The 150 GHz emission, which we observe, requires even larger column densities.

A decomposition of the spectrum of the Arc by Reich et al. (1988) results in $\alpha = +0.3$ for the filaments and a diffuse flat spectrum component with $\alpha = -0.2$. High-resolution VLA-observations by Anantharamiah et al. (1991) have confirmed the inverted $\alpha = +0.3$ spectrum for the filaments. Such an inverted spectrum is expected to originate from a quasi-monoenergetic electron distribution or an electron distribution with a low-energy cutoff. The emission visible at 150 GHz has a similar spectrum as the Arc shows at lower frequencies; thus, a similar electron distribution is required. However, physically, the 150 GHz emission is separated from the filaments as can be seen from figure 2. It seems likely that the interacting regions between the molecular cloud and the Arc are the acceleration region for the electrons, which subsequently enter the Arc and its filaments. The Arc's filaments are most intense in this area and have about the same electron spectrum. The evolution of the inverted radio spectrum away from the point of injection, up to about 400 pc out of the galactic plane, was discussed by Pohl et al. (1992). With increasing distance from the injection point the intensity decreases and the spectrum steepens.

6. Origin and Lifetime of the 150 GHz Emission.

Tsuboi et al. (1997) calculated a magnetic field strength of about 5 mG to keep the Arc in pressure equilibrium with the massive expanding molecular shell, which is partly shown in figure 4. This shell has a diameter of about 7.5 pc and is centered at $l, b = 0^\circ\!.11$, $-0^\circ\!.11$. Its density is about $n(\mathrm{H_2}) = 6 \times 10^4$ cm^{-3} and the expansion velocity is 20 km s^{-1}. The shell rotates with about 5 km s^{-1}.

As already calculated by Tsuboi et al. (1997) a magnetic field of 5 mG results in a synchrotron lifetime for 0.9 GeV electrons of about 400 yr. Assuming that 150 GHz is close to the maximum frequency $\nu_{\max}$ of the emission, a critical frequency of $\nu_c = 450$ GHz ($\nu_{\max} = 0.3\ \nu_c$) results. With ν_c [MHz] $= 16.08 \cdot 10^6\ B_\perp$ [G] E^2 [GeV] we calculate an energy of $E \sim 2.4$ GeV ($\gamma = 4600$) for the electrons in the 150 GHz emission regions. The lifetime of the electrons reduces, because of $t_{1/2} = (119.7\ B_\perp^2$ [G] E [GeV]$)^{-1}$, to about 140 yr. Taking the radius of the strongest 150 GHz emission region at $l, b = 0^\circ\!.16$, $-0^\circ\!.13$ to about $1'\!.5$ or 3.7 pc (for a Galactic Center distance of 8.5 kpc), the electrons need a drift velocity of about 0.08 c to cross the region within their lifetime. Pohl et al. (1992) calculated from modelling the synchrotron emission of the entire Arc structure a bulk velocity of about 0.1 c. In this model a magnetic field strength for the Arc's filaments of 1 mG was assumed, where the accelerated electrons are injected. The drift velocity is close to the minimum velocity required here. Therefore we conclude that a magnetic field strength of 5 mG exceeds the maximum field strength to allow accelerated particles to escape the region of acceleration and to enter the Arc.

The time the expanding molecular shell needs to cross the emission area is on the order of 2×10^5 yr, about two or three orders of magnitude larger than the synchrotron lifetime of the 150 GHz emitting electrons or the Arc's filaments. The crossing time is larger or similar to the lifetime of the entire Arc structure. Therefore, the Arc appears as a short-living structure, just supplied with freshly accelerated electrons at the surface of the molecular cloud, and might disappear or be deformed when the molecular cloud has crossed. In that case, the assumption of pressure equilibrium is no longer needed, and smaller magnetic fields with longer electron lifetimes will result. Using the above equation we obtain for a magnetic field strength of 1 (0.3) mG a lifetime of 1500 (10^4) yr. However, in the case of weaker magnetic fields the acceleration process has to be more efficient, since higher electron energies are required to radiate at 150 GHz. For a field strength of 1 (0.3) mG electrons with energies of 5.4 (10) GeV [$\gamma = 10^4$ ($1.9 \cdot 10^4$)] are needed.

Various mechanisms to accelerate high-energy electrons showing up in the Arc have been discussed, as reviewed by Morris (1996) or Serabyn (1996). Shock acceleration or magnetic reconnection seem to be the most likely processes. Both mechanisms are able to result in a quasi-monoenergetic electron distribution. Schlickeiser (1984) has shown that a monoenergetic electron distribution by shock acceleration is provided, if the particle escape time is much longer than the acceleration time. Magnetic reconnection gives about the same energy for all runaway electrons. This process converts the magnetic field energy into particle energy, and thus reduces the magnetic field strength. However, the efficiency of magnetic reconnection is just up to 10%, which seems too be too low to reduce the magnetic field strength substantially. Magnetic reconnection is a local process, where magnetic fields of opposite directions merge. The electric field strength and the length of the merging magnetic fields determine the energy of the accelerated runaway electrons (Lesch, Reich 1992). In this case the efficiency depends very much on the details of the interaction as well as the clumpiness of the molecular material, its degree of ionization and its magnetic field strength. The molecular clumps encounter and compress the magnetic field traced by the diffuse emission which surrounds the filaments of the Arc. Its strength was estimated to be on the order of 0.1 mG (Reich 1990).

Lesch and Reich (1992) calculated a maximum Lorentz factor of $\gamma_{\max} \sim 4 \cdot 10^4\ [B/1\ \mathrm{mG}]^4$ in the case of magnetic reconnection and reasonable assumptions for the thermal electrons and the movement of the molecular cloud in the Arc region. Because $\gamma_{\max}$ could be too low for a magnetic field strength substantially below 1 mG to account for the observed 150 GHz emission, we conclude that a 1mG field seems to be a good estimate for both requirements;

a long enough lifetime and a high enough electron energy.

7. Summary

150 GHz observations with the bolometer array NOBA installed at the Nobeyama 45-m telescope resulted in maps at 13.″5 angular resolution for Sgr A and at 21.″5 for a large section of the Galactic Center Arc. We measured the peak flux density for Sgr A* of 3.6 Jy in 1999 March. This confirms previous measurements of an excess emission of Sgr A* above 100 GHz (Falcke et al. 1998). The integrated flux density of the mini-spiral underlying Sgr A* was measured to be 32 Jy, and its thermal nature has been confirmed. We observed intense emission features associated with the Galactic Center Arc, but slightly shifted towards the west from its most intense filaments. The spectrum of the emission is inverted relative to 43 GHz and compatible with an origin from quasi-monoenergetic electrons or an electron spectrum with a low energy cut-off, but not with optically thin emission from cold dust. The 150 GHz emission coincides with areas with apparent interaction of the Arc's magnetic field and dense molecular gas exists. An estimated magnetic field strength of about 5 mG in order to keep the Arc in pressure equilibrium results in problems with the synchrotron lifetime of the radiating electrons seen at 150 GHz. However, the time the molecular material needs to cross the emitting regions is much larger than the synchrotron lifetime of the Arc's filaments or the 150 GHz emitting electrons, and the assumption of pressure equilibrium might not be valid. A lower magnetic field strength requires a larger electron energy to be emitted at 150 GHz. Using previous estimates for magnetic reconnection as a possible acceleration mechanism, a magnetic field strength of about 1 mG seems to be most likely.

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