VLBA Imaging at 7 mm and Linear Polarimetric Observations at 6 cm and 3 mm of Sgr A*

Geoffrey C. Bower and Heino Falcke

Max Planck Institut für Radioastronomie, Bonn, Germany

Don Backer and Melvyn Wright

Radio Astronomy Laboratory, UC Berkeley, Berkeley, CA

Abstract. We summarize the results of 7 mm VLBA imaging of Sgr A* and discuss some of the difficulties of accurately constraining the size of Sgr A* with VLBI observations. Our imaging results are fully consistent with the hypothesis that the VLBA image of Sgr A* is a resolved elliptical Gaussian caused by the scattering of an intervening thermal plasma. We show that determination of the minor axis size at 7 mm with the VLBA is very unreliable.

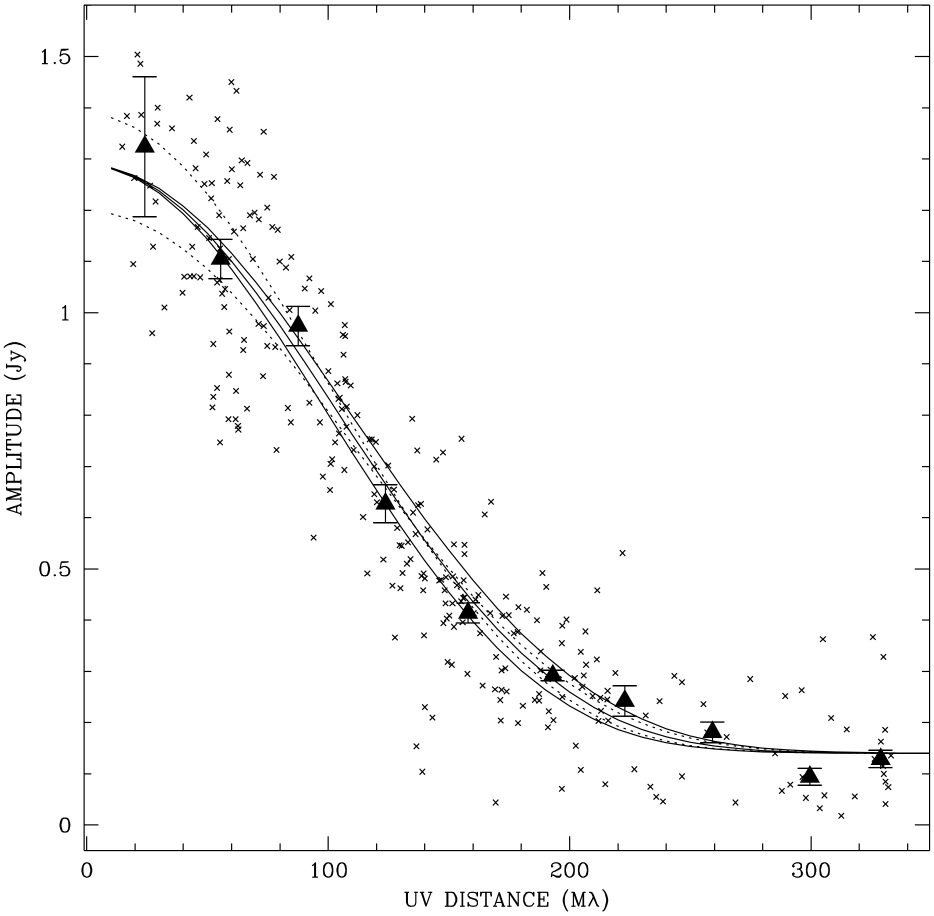
We also present new polarimetric observations from the VLA and from the BIMA array of Sgr A*. At 4.8 GHz, we find an upper limit to the polarization of 0.1%. At 86 GHz, we report a marginal detection of $1 \pm 1\%$ linear polarization. We discuss the effects of interstellar propagation on the linear polarization and consider the significance of very low intrinsic linear polarization in Sgr A*.

1. 7 mm VLBA Imaging of Sgr A*

We summarize previously-published results of 7 mm VLBA imaging of Sgr A* (Bower & Backer 1998). Observations of Sgr A* at 43 GHz were performed on 29 September 1994 with the VLBA. Fringes on Sgr A* were detected to a maximum (u, v)-distance of 250 $M\lambda$. Fringes to the compact calibrator NRAO 530 were detected on all baselines throughout the experiment. Imaging and modeling revealed a single elliptical Gaussian component with a major axis FWHM of 0.762 ± 0.038 mas in a position angle of $77.^\circ0 \pm 7.^\circ4$. The axial ratio was measured to be 0.73 ± 0.10. We show in Figure 1 the visibility amplitudes as a function of (u, v)-distance along with model fits. No secondary structure was detected in the vicinity of Sgr A* to a limit of 35 mJy.

The measured size is fully consistent with the expected major and minor axes predicted by lower frequency observation (Yusef-Zadeh et al. 1994, Lo et al. 1998). However, as Lo et al. note, this result combined with their new result implies a significant deviation in the axial ratio from that expected due to scattering. While this is true, poor North-South resolution and systematic errors in calibration make this claim uncertain and difficult to prove.

Figure 1. Visibility amplitude as a function of *uv* distance for Sgr A*. The solid lines indicate the expectation for a circular Gaussian with a zero baseline flux of 1.28 Jy and FWHM of 0.694, 0.727 and 0.760 mas. The dashed lines indicate the expectation for a circular Gaussian with zero baseline fluxes of 1.38 Jy and 1.18 Jy with FWHM of 0.760 and 0.694 mas, respectively. The noise bias is added in quadrature to the model. The large triangles indicate the median flux in a 35 Mλ bin. The errors indicate the scatter in the data.



1) The North-South resolution of the VLBA is inadequate to resolve the scattering size at 7mm. The extreme southern declination of Sgr A* combined with the northern latitudes of the VLBA produces very poor North-South resolution. In Figure 2 we show the baselines on which we made detections to Sgr A*. The visibilities that contribute predominantly to the minor axis size are limited to three baselines, two of which involve the Brewster station, one of the VLBA's worst millimeter sites. The maximum North-South resolution of $\sim 100M\lambda$ on a single baseline is considerably smaller than the FWHM of the minor axis scattering size $\sim 190M\lambda$. In fact, the size scale of interest — the difference between the scattered and non-scattered minor axis sizes — is more than 10 times smaller than the beam size in that direction.

2) Observations of Sgr A* with the VLBA are performed at very low elevation and are difficult to calibrate. Variable atmospheric opacity due to water vapor in the troposphere makes amplitude calibration particularly difficult at 7 mm. Atmospheric coherence times can be very short and variable, as well. These effects increase as $\sec z$ with increasing zenith angle, z. Further, *a priori* gain curves at low elevation with VLBA antennas are suspect. The Brewster antenna, which provides the two longest North-South baselines on Sgr A*, never gets above 13° elevation. Hence, it is always looking through at least 4.5 atmospheres. Transferring gains from a compact calibrator, J1730-13 or J1924-29, for example, can improve amplitude calibration but a substantial uncertainty remains due to the large difference in contemporaneous elevation. Amplitude self-calibration is not accurate, either, since the density of visibilities in the (u, v) plane is low.

One can consider the combined effect of the lack of resolution and difficulty in amplitude calibration by plotting the amplitudes as a function of the North-South spatial frequency v, after the amplitudes have been corrected for the East-West structure (Figure 3). If the North-South axis were unresolved, the residual amplitude would be unity. The considerable scatter in the data indicates the difficulty in determining the axial ratio accurately. And, as noted above, baselines involving Brewster dominate at large v.

What observations can accurately measure the size of Sgr A* at 7 mm? The use of the Green Bank Telescope with the VLBA will add crucial medium-length North-South baselines to Hancock, Saint Croix, North Liberty and Fort Davis. The Large Millimeter Telescope under construction in Mexico will also add interesting baselines to the Southwestern VLBA stations. Finally, successful adoption of spectral-line calibration methods using the nearby SiO maser VX Sgr will significantly improve calibration.

Higher frequency observations are plagued by the same problems of difficult calibration and poor North-South resolution. These are discussed in more detail by Doeleman et al. (1998, these proceedings) and Krichbaum et al. (1998, these proceedings).

2. Linear Polarimetric Observations of Sgr A* at 4.8 and 86 GHz

Linear polarization stands as one of the few observables of Sgr A* not extensively investigated observationally or theoretically. However, we expect that linear polarization should arise from the cyclo-synchrotron radiation that is responsible

Figure 2. Visibility coverage of detections of Sgr A* at 7 mm by Bower & Backer (1998). The starred visibilities are those in which the minor axis dominates the major axis in determination of the visibility amplitude.

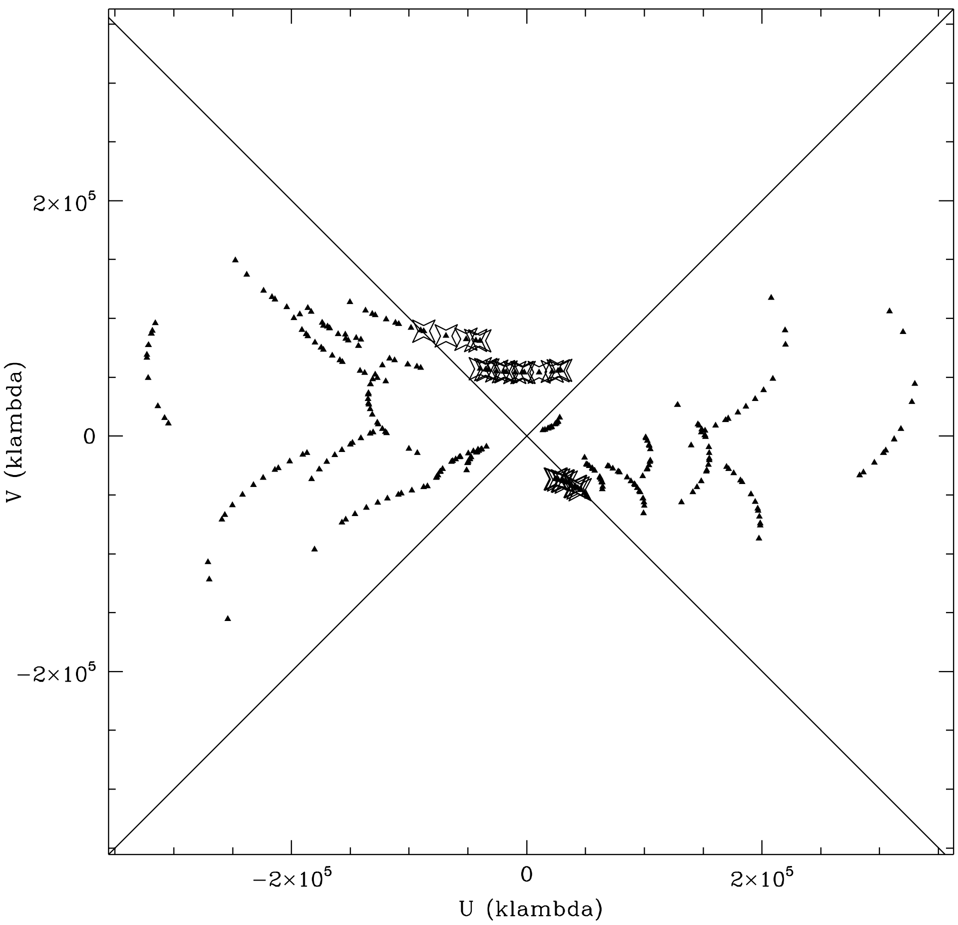
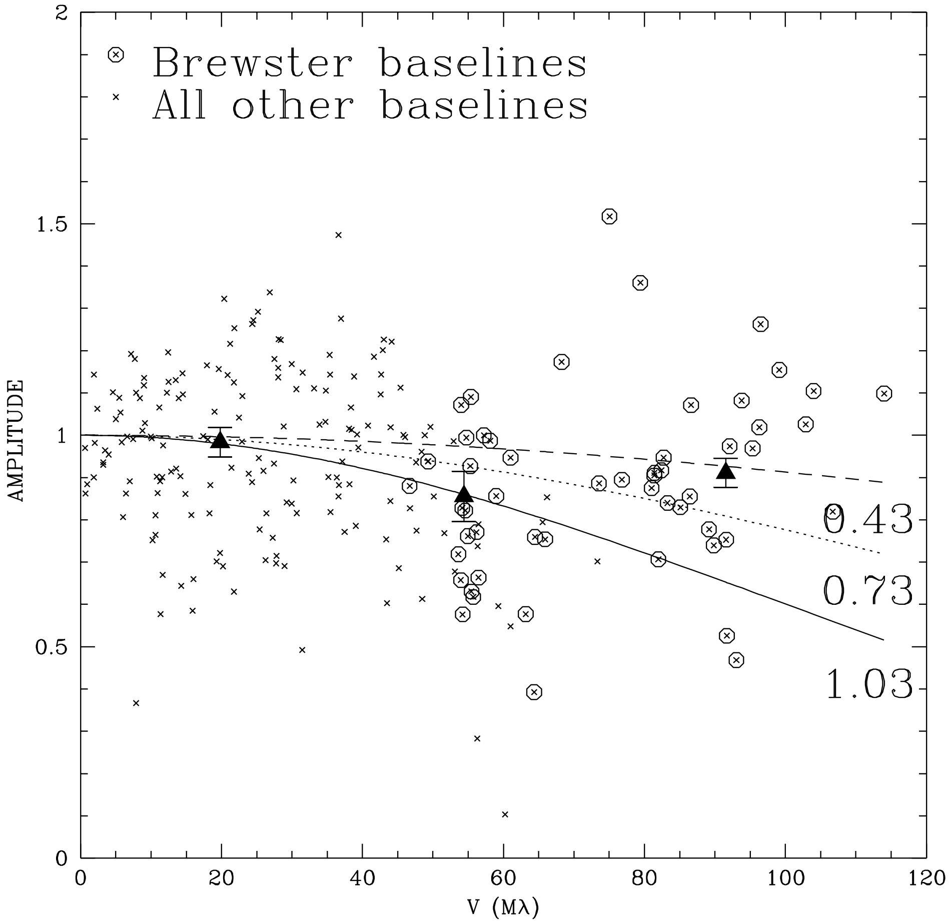


Figure 3. Visibility amplitude corrected for East-West structure against the North-South spatial frequency v. The lines indicate expected amplitudes for the mean axial ratio and plus and minus three sigma deviations in the axial ratio. Circled visibilities indicate those on a baseline with the Brewster station. These dominate for $v > 60M\lambda$. The triangles indicate median amplitudes in three bins of 40 $M\lambda$ in v.



for the radio and millimeter wavelength spectrum. In active galactic nuclei, the degree of linear polarization is a measure of the order in the magnetic field. Comparing the evolution of linear polarization to the evolution of total intensity provides a strong argument for the existence of shocks in the relativistic jets of AGN (e.g., Hughes, Aller and Aller 1985). Detection of correlated polarized and total intensity variations in Sgr A* would be convincing evidence for a jet model. Uncorrelated variability would indicate that a different mechanism must be responsible for the radio to millimeter spectrum.

2.1. VLA Observations at 4.8 GHz

The VLA observed Sgr A* on 10 and 18 April 1998 in the A array at 4.8 GHz with a bandwidth of 50 MHz. Instrumental calibration was performed with the compact sources 1741-038 and 1748-253. The right-left phase difference was set with observations of 3C 286. Baselines longer than 100 $k\lambda$ were used for Sgr A*.

We summarize the measured polarizations of Sgr A* and several compact calibrators in Table 1. The calibrators GC 441, W56 and W109 belong to the proper motion survey of Backer and Sramek (1998, these proceedings). Consistency between the results on the two days indicates the accuracy of the results. Polarization was reliably detected from all sources but Sgr A* and GC 441. The measured polarization at the position of Sgr A* is 0.1%. This value is equal to the average off source fractional polarization in the map and is, therefore, an upper limit.

Table 1. Polarized and Total Flux at 4.8 GHz

Source	Date	I (Jy)	P (mJy)	p (%)	χ (deg)
Sgr A*	10 Apr	0.49	< 0.63	< 0.13	...
	18 Apr	0.47	< 0.34	< 0.08	...
1741-038	10 Apr	4.90	10.6	0.22	27
	18 Apr	4.94	15.3	0.31	24
1748-253	10 Apr	0.48	8.4	1.8	-15
	18 Apr	0.48	11.4	2.4	-16
GC441	10 Apr	0.044	< 0.09	< 0.20	...
	18 Apr	0.043	< 0.12	< 0.28	...
W56	10 Apr	0.104	2.2	2.1	-66
	18 Apr	0.104	2.2	2.1	-66
W109	10 Apr	0.098	0.59	0.6	-26
	18 Apr	0.098	0.51	0.5	-17

2.2. BIMA Observations at 86 GHz

Observations of Sgr A* with the BIMA array were conducted on 10 and 14 March 1998 at 86 GHz with a bandwidth of 800 MHz. The BIMA array was configured in its A array with baselines from 20 to 540 $k\lambda$. Nine antennas were switched systematically between right and left circular polarization throughout the 5 hour track. A single antenna observed linear polarization constantly. This permitted phase self-calibration for each 10 sec averaging interval. Amplitude calibration was performed with *a priori* gain information. Phase calibration was done with interleaved scans of NRAO 530.

Instrumental polarization calibration was performed in several ways, producing similar results. D-term solutions were obtained from the calibrator NRAO 530 on 14 March, from Sgr A* itself on both days and from observations of the SiO maser in Orion on 28 January 1998 and 25 February 1998. A comparison of these D-terms shows that the instrumental polarization is stable over two months to a level of 0.3% (Figure 4).

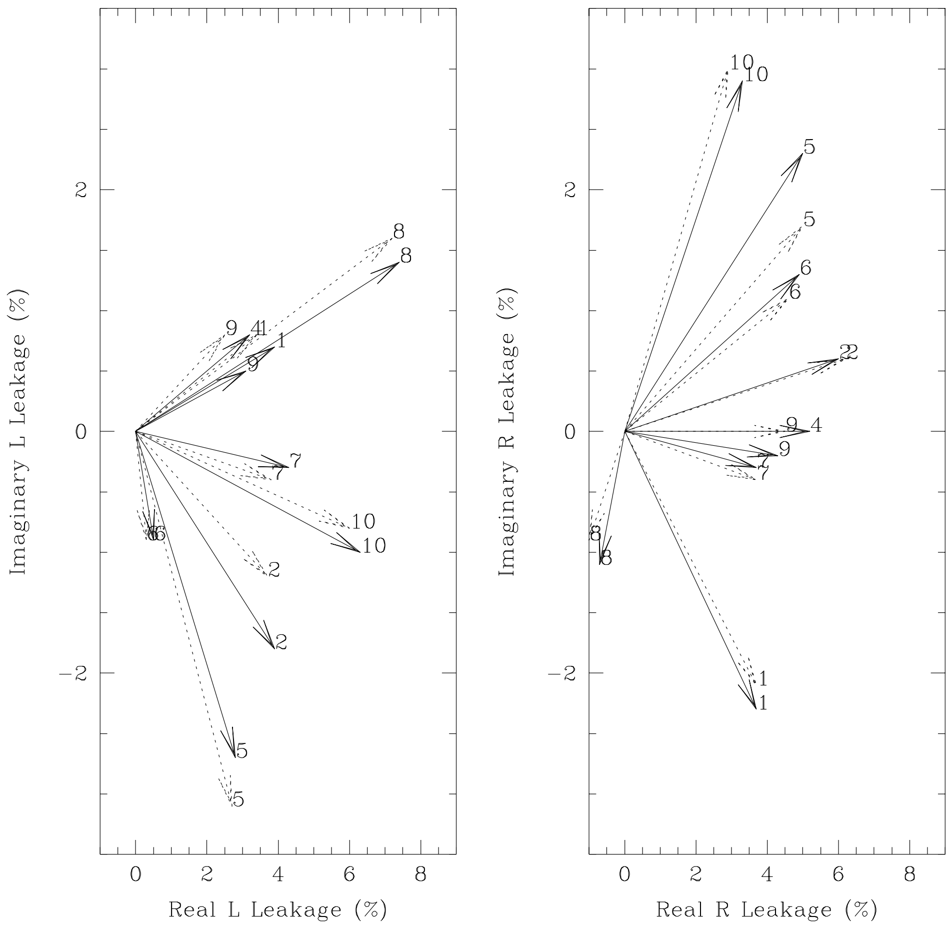


Figure 4. D-terms for all antennas determined from SiO maser observations on 25 Feb 98 (solid lines) and 28 Jan 98 (dashed lines). The terms differ by 0.3% on average.

We tabulate the measured polarization on Sgr A* and other sources in Table 2. The results for Sgr A* are marginally consistent with each other and a fractional polarization of $1 \pm 1\%(3\sigma)$.

We note that our observations occurred within days of the peak of the millimeter flare reported by Tsuboi, Miyazaki and Tsutsumi (1998, these proceedings). Our mean flux $S_{86} = 1.5 \pm 0.2$ Jy is lower than but marginally consistent with the peak flux of 2.4 ± 0.4 Jy reported by these authors.

Table 2. Polarized and Total Flux at 86 GHz

Source	Date	I (Jy)	P (mJy)	p (%)	χ (deg)
Sgr A*	10 Mar	1.72 ± 0.075	22 ± 6	1.3 ± 0.3	-41 ± 8
	14 Mar	1.37 ± 0.097	7 ± 10	0.5 ± 0.7	16 ± 41
3C273	10 Mar	24.7 ± 1.1	756 ± 36	3.1 ± 0.1	-1 ± 1
	14 Mar	23.9 ± 1.7	802 ± 96	3.3 ± 0.3	0 ± 3
3C454.3	10 Mar	5.33 ± 0.37	34 ± 11	0.6 ± 0.2	43 ± 10
	14 Mar	4.93 ± 0.13	21 ± 12	0.4 ± 0.2	-41 ± 16
1733-130	14 Mar	2.82 ± 0.010	66 ± 3	2.3 ± 0.1	-42 ± 1

2.3. Interstellar Propagation Effects

The interstellar medium may depolarize a polarized radio wave in two ways: differential Faraday rotation along the many paths that contribute to the scatter-broadened image of Sgr A*; and, significant rotation of the polarization position angle through the observing bandwidth. We consider each of these separately.

The Faraday rotation is

$$\chi_F = \mathrm{RM}\ \lambda^2,$$

where RM is the rotation measure in rad m^{-2} and λ is the wavelength in meters. The scattering region will depolarize the signal if $\delta\chi_F \approx \pi$. Such variations may occur over multiple turbulent cells in a scattering screen each of which will have a different RM. For $\lambda = 6$ cm, $\delta\mathrm{RM} = 900$ rad m^{-2} (at $\lambda = 3$ mm, $\delta\mathrm{RM} = 3 \times 10^5$ rad m^{-2}). Over the scattering size of 50 mas at 6 cm, this corresponds to $\delta\mathrm{RM}/\delta\theta = 18000$ rad m^{-2}arcsec^{-1}. Observations on the arcsecond to arcminute scale of a nonthermal filament within 1 degree of Sgr A* find a maximum $\delta\mathrm{RM}/\delta\theta = 250$ rad m^{-2}arcsec^{-1} (Yusef-Zadeh, Wardle & Parastaran 1997). Extrapolating their RM structure function to the scattering size implies $\delta\mathrm{RM} \approx 50$ rad m^{-2} These values are well below those necessary to depolarize Sgr A*.

Do the conditions exist to depolarize Sgr A* in the scattering screen? The RM is

$$\mathrm{RM} = 0.8 n_e B L \text{ rad m}^{-2},$$

where n_e is the electron number density in cm^{-3}, B is the magnetic field in μG and L is the size scale in pc. In the thin screen approximation L must be a fraction of the scattering diameter θ_{SgrA*}. We find $L \sim 0.1\theta_{SgrA*}D_{SgrA*} \sim$

10^{-4} pc. This implies $n_e B \sim 10^7$ μG cm^{-3}. This condition is matched by that found by Yusef-Zadeh et al. (1994) for the ionized skins of molecular clouds in the Galactic Center. However, the high temperature and low density model of Lazio & Cordes (1998) predicts no depolarization of Sgr A* for $B < 1$ G.

Finally, depolarization may occur in the accretion region of Sgr A* where the electron density and magnetic field strength are large but the length scale is smaller. In the model of Melia (1994) inside a radius of 0.01 pc, $B \gtrsim 100$ mG and $n_e \gtrsim 10^4$ cm^{-3} for an accretion rate of $10^{-4} M_\odot\ y^{-1}$. The ADAF model requires similar conditions (Narayan *et al.* 1998). Whether the extreme conditions in the accretion region can cause a significant δRM depends critically on the scale of turbulence.

We now consider the effect of Faraday rotation on a polarized signal measured over a specific bandwidth. Differentiating χ_F permits us to write the maximum observable rotation measure as a function of bandwidth $\Delta\nu$ and observing frequency

$$\mathrm{RM}_{\max} \approx \frac{1}{2}\frac{1}{\lambda^2}\frac{\nu}{\Delta\nu}.$$

For the observing bandwidths of 50 MHz and 800 MHz at 4.8 GHz and 86 GHz, we find maximum rotation measures of 10^4 rad m^{-2} and 10^7 rad m^{-2}, respectively. The detection of rotation measures in the Galactic Center as large as a few thousand suggests that the low frequency result may in fact be limited by a very high rotation measure (e.g., Yusef-Zadeh, Wardle & Parastaran, 1997). We are currently studying spectro-polarimetric observations of the continuum radiation from Sgr A* at 4.8 and 8.4 GHz in search of linear polarization with extremely high rotation measures (up to 10^7 rad m^{-2}). A preliminary result from this study is that an extreme RM does not depolarize Sgr A*.

It is not yet certain whether interstellar propagation effects can depolarize Sgr A*. Known RM variations are insufficient to depolarize Sgr A*. However, at least one model for the scattering medium of Sgr A* does include the necessary conditions. We now consider the hypothesis of an intrinsically weakly polarized Sgr A*.

2.4. Discussion

The centimeter and millimeter wavelength polarization studies probe different regions of Sgr A*. Spectral studies of Sgr A* (e.g., Falcke et al. 1998) reveal that there may be significantly different sources at centimeter and millimeter wavelengths which may have different polarization structures. A higher fractional polarization at 86 GHz may be the result of observing at lower opacity and over a smaller, more homogeneous region. The polarization of AGN are greater and more variable at millimeter than at centimeter wavelengths (e.g., Nartallo *et al.* 1998).

A polarization fraction less than 1% is uncommon in compact radio sources at centimeter wavelengths (Aller, Aller & Hughes 1992). However, optically thick quasar cores observed with VLBI are frequently weakly polarized (Cawthorne et al. 1993). Such cores may be analogous to the radio source in Sgr A*, which, due to its low power, may not produce the strong shocks in the jet that are the source for higher polarization regions in quasars. Weak polarization is more common in galaxies than quasars or blazars and it is also more common in compact-double sources or sources with irregular morphologies (Aller, Aller & Hughes 1992). A notable source with a very low polarization fraction is the radio galaxy 3C 84, which has a very irregular morphology. If the radio to millimeter spectrum of Sgr A* does arise in a jet, the low power of this jet or environmental effects in the Galactic Center region may limit the magnetic field order. Alternatively, low energy electrons in the synchrotron environment of Sgr A* may depolarize the source.

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