THE ASTROPHYSICAL JOURNAL, 521:582–586, 1999 August 20

THE LINEAR POLARIZATION OF SAGITTARIUS A*. I. VLA SPECTROPOLARIMETRY AT 4.8 AND 8.4 GHz

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Received 1999 January 1; accepted 1999 April 1

ABSTRACT

Synchrotron radiation from active galactic nuclei (AGNs) is often highly polarized. We present a search for linear polarization with the Very Large Array (VLA) at 4.8 and 8.4 GHz from the nearest AGN, Sagittarius A*. As a part of this study we used spectropolarimetric data that were sensitive to a rotation measure (RM) as large as 3.5×10^6 rad m^{-2} at 4.8 GHz and 1.5×10^7 rad m^{-2} at 8.4 GHz. The upper limit to the linear polarization of Sgr A* over a broad range of RM is 0.2% at both frequencies. We also present continuum observations with the VLA at 4.8 GHz that give an upper limit of 0.1% for RMs less than 10^4 rad m^{-2}. We conclude that depolarization is unlikely to occur in the Galactic center scattering medium. However, it is possible for depolarization to occur in the accretion region of Sgr A* if the outer scale of turbulence is small enough. We also consider the implications of a very low intrinsic polarization for Sgr A*.

Subject headings: galaxies: active — Galaxy: center — polarization — radio continuum: ISM — scattering

1. INTRODUCTION

The compact nonthermal radio source Sgr A* has long been recognized as a massive black hole candidate. Recent results from stellar proper-motion studies indicate that there is a dark mass of $\sim 2.6 \times 10^6 M_\odot$ enclosed within 0.01 pc (Genzel et al. 1997; Ghez et al. 1998). Very long baseline interferometry studies at millimeter wavelengths have shown that the intrinsic radio source coincident with the dark mass has a size that is less than 1 AU and a brightness temperature greater than 10^9 K (Rogers et al. 1994; Bower & Backer 1998; Lo et al. 1998). Together these points are compelling evidence that Sgr A* is a cyclosynchrotron emitting region surrounding a massive black hole. Nevertheless, specific details of the excitation of high-energy electrons, their distribution, and the accretion of infalling matter onto Sgr A* are unknown (e.g., Falcke, Mannheim, & Biermann 1993; Melia 1994; Narayan et al. 1998; Mahadevan 1998).

Linear polarization stands as one of the few observables of Sgr A* not extensively investigated observationally or theoretically. However, we expect linear polarization to arise from the cyclosynchrotron radiation that is responsible for the radio to millimeter wavelength spectrum. A homogeneous, optically thin, synchrotron source with a uniform magnetic field has a fractional polarization of 70%. Measured fractional polarizations in AGNs are typically a few percent at wavelengths shorter than 6 cm where the compact cores dominate the highly polarized radio lobes in the total flux (e.g., Aller, Aller, & Hughes 1992). However, polarization VLBI images sometimes show regions of significantly enhanced polarization (Brown, Roberts, & Wardle 1994).

The polarization of Sgr A* may prove to be as important a diagnostic of models for the radio to millimeter spectrum as it has been for AGNs. Detection of linear polarization in AGNs has firmly established synchrotron emission as the radiation mechanism. Comparison of the evolution of linear polarization to the evolution of total intensity has provided a strong argument for the existence of shocks in the relativistic jets of AGNs (e.g., Hughes, Aller, & Aller 1985). Detection of similar correlations in polarized and total intensity variations in Sgr A* would be convincing evidence for a jet. Other models may have unique signatures for polarized intensity variations.

Sgr A* is located in a region with strong magnetic fields and high electron density. The image of Sgr A* is significantly scatter-broadened by intervening thermal plasma (e.g., Lo et al. 1998), as are the images of many masers in the Galactic center region (Frail et al. 1994). Furthermore, nonthermal filaments in the Galactic center region show RMs that vary on the arcsecond scale and are as large as 4000 rad m^{-2} (Yusef-Zadeh, Wardle, & Parastaran 1997). Such large RMs can effectively depolarize a signal detected with a large bandwidth.

In § 2, we discuss the effect of large RMs on a polarized signal and our Fourier transform technique for detecting large RMs. In § 3.1, we present VLA continuum observations at 4.8 GHz. In §§ 3.2 and 3.3, we present VLA spectropolarimetric observations at 4.8 and 8.4 GHz. These observations are sensitive to a wide range of RMs. In § 4, we consider other effects of interstellar matter on a polarized signal from Sgr A*. And in § 5, we discuss the consequences of our upper limits for the polarization on models for Sgr A*. In a future paper, we will address millimeter polarization observations of Sgr A*.

2. SEARCHING FOR LARGE RMS

In an ionized and magnetized region, right and left circularly polarized waves will have different indices of refrac-

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tion. This leads to a wavelength-dependent delay between circular polarizations that is equivalent to a rotation of the position angle χ of a linearly polarized signal

$$\chi_F = \mathrm{RM}\lambda^2 , \tag{1}$$

where RM is the rotation measure. This rotation of χ is equivalent to a rotation in the two-dimensional Stokes Q and U space.

A linearly polarized signal will be significantly depolarized in an observing bandwidth $\Delta\nu$ if χ rotates by more than 1 rad, or if the RM exceeds

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

If the bandwidth $\Delta\nu$ is split into $n \times \delta\nu$ channels, a search can be made for RMs larger than $\mathrm{RM}_{\mathrm{max}}$. When χ wraps through more than one turn, $n\pi$ ambiguities make it impossible through a linear least-squares fit to detect RMs. Fourier transforming the complex visibility $P = Q + iU$ with respect to λ^2 searches for large RMs without loss of sensitivity. The maximum RM detectable in this scheme can be found by replacing $\Delta\nu$ with $\delta\nu$ in equation (2). In addition to detecting RMs that exceed $\mathrm{RM}_{\mathrm{max}}$, the technique is sensitive to multiple RMs from the same object. A more detailed analysis of this technique can be found in Killeen et al. (1999).

A continuum observation with the VLA at 4.8 GHz with 50 MHz has $\mathrm{RM}_{\mathrm{max}} \approx 10^4$ rad m^{-2}. Splitting the band into 256 channels increases $\mathrm{RM}_{\mathrm{max}}$ by 2 orders of magnitude to 3.5×10^6 rad m^{-2}. The minimum fully sampled RM detectable in a spectropolarimetric data set, $\mathrm{RM}_{\mathrm{min}}$, is approximately equal to $\mathrm{RM}_{\mathrm{max}}$ for a continuum data set with the same total bandwidth.

The RM can be found to better accuracy than $\mathrm{RM}_{\mathrm{min}}$. We estimate the error to be

$$\sigma_{\mathrm{RM}} = \frac{\mathrm{RM}_{\mathrm{min}}}{\mathrm{SNR}} . \tag{3}$$

SNR is the ratio of the peak amplitude in Fourier space to the off-peak rms noise.

3. OBSERVATIONS AND DATA REDUCTION

3.1. *VLA Continuum Polarimetry at 4.8 GHz*

The VLA of the National Radio Astronomy Observatory[5] observed Sgr A* on 1998 April 10 and 18 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. Only baselines longer than 100 kλ were used for Sgr A*. Several nearby calibrator sources, GC 441, W56, and W109, were also observed (Backer & Sramek 1999). All sources were self-calibrated and imaged in Stokes I, Q, and U.

We summarize the measured polarized and total intensities of Sgr A* and the calibrators in Table 1. The rms noise in the Sgr A* map is 74 μJy. Consistency between the results on the 2 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. The maximum RM detectable with this bandwidth is $\sim 10^4$ rad m^{-2}.

3.2. *VLA Spectropolarimetry at 4.8 GHz*

The VLA observed Sgr A* in the A array in a spectropolarimetric mode at 4.8 GHz on 1992 November 27. Observations were carried out in eight consecutively spaced frequency bands of 6.25 MHz each. Each band was divided into 32 separate frequency channels. The bands covered the frequency range from 4832 to 4882 MHz. Five scans of 2.5 minutes apiece on Sgr A* were interleaved with six scans of 2.5 minutes apiece on NRAO 530 in each frequency band. Amplitude, phase, and polarization calibration were performed separately for each band. Polarization calibration was performed with NRAO 530 alone and with NRAO 530 and Sgr A*, producing similar final results. The right − left phase difference was set for each band with an observation of 3C 286.

For each source, the spectral data were time-averaged and exported from AIPS for further processing. A bandpass correction was applied. The complex polarization was then Fourier-transformed with respect to λ^2. Sampling effects were removed through a one-dimensional CLEAN method. The CLEAN method permits a better estimate of the RM peak and of the noise level. The sampling sidelobes are readily visible for 3C 286 and NRAO 530 in Figure 1. Our tests with noise data and with synthetic signals indicate that the CLEAN method does not generate false signals and improves the accuracy of peak determination. Applying CLEAN to the 4.8 GHz NRAO 530 data reduced the noise in the spectrum from 1.6 to 0.26 mJy.

The range of fully sampled RM is 10^4 rad m^{-2} to 3.5×10^6 rad m^{-2}. The Fourier amplitude for each source is shown in Figure 1, and the results are summarized in Table 2. These images are without bandpass correction and dirty-beam removal. We also calculate and plot the Fourier transform for a distribution of Gaussian noise. Strong peaks at low RM are apparent for both 3C 286 and NRAO 530, as expected. The measured values are consistent with the known RMs of these sources: 1 ± 2 rad m^{-2} for 3C 286 and -63 ± 5 rad m^{-2} for NRAO 530 (Rusk 1988).

No strong peak is apparent for Sgr A* at any RM. The maximum Fourier amplitude for Sgr A* is 0.15% at RM $= 2.1 \times 10^6$ rad m^{-2}. Imaging Sgr A* with and without a RM correction produced a peak polarization of 0.2%. This is equal to the fractional polarization of thermal ionized gas in the vicinity of Sgr A*, indicating that we are limited by residual instrumental polarization.

3.3. *VLA Spectropolarimetry at 8.4 GHz*

The VLA observed Sgr A* in the A array in a spectropolarimetric mode at 8.4 GHz, also on 1992 November 27. Observations were carried out in seven frequency bands of 6.25 MHz each. Each band was divided into 32 separate frequency channels. Five bands covered the frequency range from 8405 to 8437 MHz. Two other bands were centered at 8150 and 8700 MHz. Five scans of 2.5 minutes apiece on Sgr A* were interleaved with six scans of 2.5 minutes apiece on NRAO 530 in each frequency band. Amplitude, phase, and polarization calibration were performed separately for each band. Polarization calibration was performed with

[5] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

TABLE 1

POLARIZED AND TOTAL FLUX FROM CONTINUUM OBSERVATIONS AT 4.8 GHz

Source	Date	I (Jy)	P (mJy)	p (%)	χ (deg)
Sgr A*	1998 Apr 10	0.49	<0.63	<0.13	...
	1998 Apr 18	0.47	<0.34	<0.08	...
1741−038	1998 Apr 10	4.90	10.6	0.22	27
	1998 Apr 18	4.94	15.3	0.31	24
1748−253	1998 Apr 10	0.48	8.4	1.8	−15
	1998 Apr 18	0.48	11.4	2.4	−16
GC 441	1998 Apr 10	0.044	<0.09	<0.20	...
	1998 Apr 18	0.043	<0.12	<0.28	...
W56	1998 Apr 10	0.104	2.2	2.1	−66
	1998 Apr 18	0.104	2.2	2.1	−66
W109	1998 Apr 10	0.098	0.59	0.6	−26
	1998 Apr 18	0.098	0.51	0.5	−17

NRAO 530 alone and with NRAO 530 and Sgr A* together, producing similar final results. The right − left phase difference was set for each band with an observation of 3C 286. The sources W56, 1741−312, GC 441, W109, and 1748−253 were observed for 2 minutes in the three 6.25 MHz bands centered at 8150, 8420, and 8700 MHz. The results for all sources were the same using all frequency bands or only the inner five bands. The same reduction steps were taken for the 8.4 GHz data as for the 4.8 GHz data.

The Fourier amplitudes for all sources are shown in Figures 2 and 3. These images are without bandpass correction and dirty-beam removal. The results are summarized in Table 3. These data are sensitive to $3.5 \times 10^5 < |\mathrm{RM}| < 1.5 \times 10^7$ rad m^{-2}. There are strong detections of linear polarization in 3C 286 and NRAO 530 at RMs consistent with zero. Significant detections were also made for W56, W109, 1741−312, and 1748−253, also at RMs consistent with zero. No polarization was detected in GC 441. The errors in RM for these secondary calibrators are larger owing to the sparser frequency coverage and shorter observing time.

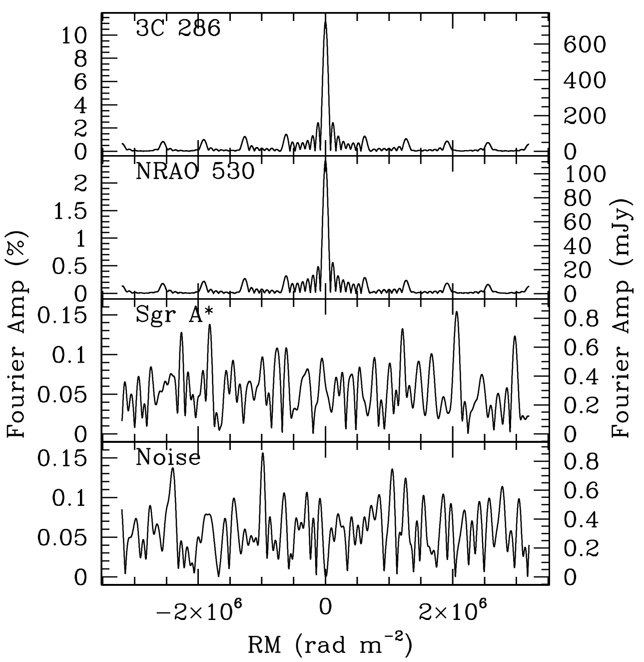

FIG. 1.—Fourier amplitude for 3C 286, NRAO 530, Sgr A*, and a noise data set at 4.8 GHz. The Fourier amplitude is given in mJy and as a fraction of the total flux for each source. The scaling of the Gaussian noise data is set to match that of Sgr A*. The RM is plotted from -3.5×10^6 rad m^{-2} to 3.5×10^6 rad m^{-2}.

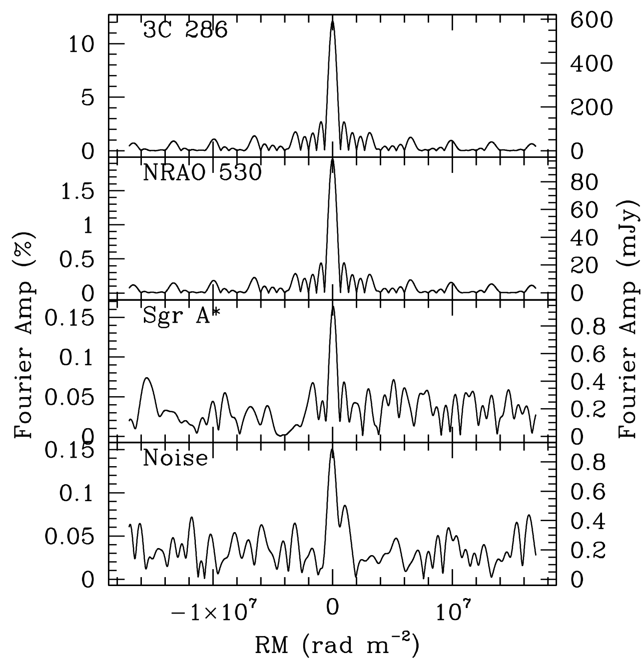

FIG. 2.—Fourier amplitude for 3C 286, NRAO 530, Sgr A*, and a noise data set at 8.4 GHz. The Fourier amplitude is given in mJy and as a fraction of the total flux for each source. The noise data consists of Gaussian noise scaled to the level of Sgr A* and a 0.15% fractional polarization at zero RM. The RM is plotted from -1.5×10^7 rad m^{-2} to 1.5×10^7 rad m^{-2}.

TABLE 2

POLARIZED FLUX AND ROTATION MEASURE FROM SPECTROPOLARIMETRIC OBSERVATIONS AT 4.8 GHz

Source	P (mJy)	p (%)	RM (rad m^{-2})	σ_{RM} (rad m^{-2})
3C 286	727 ± 10	11.2 ± 0.2	-7.3×10^2	2.7×10^2
NRAO 530	106 ± 1	2.4 ± 0.03	-11.9×10^2	2.2×10^2
Sgr A*	<0.8	<0.15	...	...

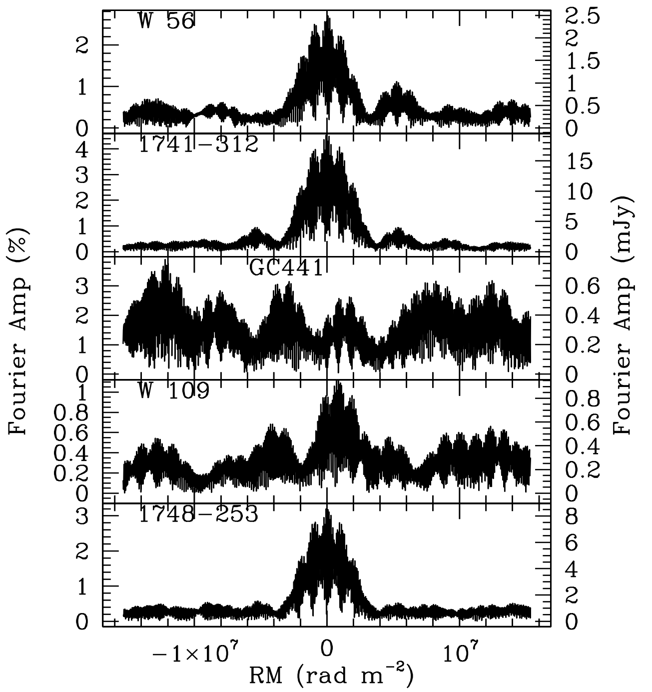

FIG. 3.—Fourier amplitude for W56, 1741−038, GC 441, W109, and 1748−253 at 8.4 GHz. The Fourier amplitude is given in mJy and as a fraction of the total flux for each source. The RM is plotted from -1.5×10^7 rad m^{-2} to 1.5×10^7 rad m^{-2}.

For Sgr A*, we detect a peak in the Fourier spectrum of 0.17% at RM $= 24{,}000 \pm 37{,}000$ rad m^{-2}. Imaging Sgr A* with and without RM corrections, we find a fractional polarization of 0.1%. Off-source fractional polarizations are typically 0.1%, again implying that we are limited by residual instrumental polarization.

We tested noise models to see if we could reproduce a weak signal at nonzero RM. We used an input signal with RM = 0 at 0.15% of the peak intensity of Sgr A* and noise that matched that of Sgr A*. This is the model plotted in Figure 2. The measured RM peak wandered within the error range.

4. INTERSTELLAR PROPAGATION EFFECTS

The interstellar medium may depolarize a linearly polarized radio wave in two ways: significant rotation of the polarization position angle through the observing bandwidth, and differential Faraday rotation along the many paths that contribute to the scatter-broadened image of Sgr A*. We have already addressed the first effect in § 2 and found in § 3 that Sgr A* is not depolarized by RMs less than 1.5×10^7 rad m^{-2}. We now consider the second effect.

The scattering region will depolarize the signal if $\delta\chi_F \approx \pi$. For our observing wavelengths, $\delta \mathrm{RM} = 900$ rad m^{-2} and $\delta \mathrm{RM} = 2400$ rad m^{-2}. Over the scattering size of 50 mas at 4.8 GHz, this corresponds to $\delta \mathrm{RM}/\delta\theta = 18{,}000$ rad m^{-2} arcsec^{-1}.

Observed variations in RM in the GC region are many orders of magnitude below those necessary to depolarize Sgr A*. Observations on the arcsecond to arcminute scale of a nonthermal filament within 1° of Sgr A* find a maximum $\delta \mathrm{RM}/\delta\theta = 250$ rad m^{-2} arcsec^{-1} (Yusef-Zadeh et al. 1997). Extrapolation of the RM structure function to the scattering size implies $\delta \mathrm{RM} \approx 50$ rad m^{-2}. However, these observations are made on a much larger scale than the scattering disk of Sgr A*, and the scattering medium is believed to be inhomogeneous.

Could the more extreme conditions necessary to depolarize Sgr A* exist in the Galactic center scattering region? The RM is expressed as

$$\mathrm{RM} = 0.8 n_e B L \ \mathrm{rad\ m^{-2}} , \tag{4}$$

where n_e is the electron number density in cm^{-3}, B is the magnetic field parallel to the line of sight in μG, and L is the size scale in pc. Since L must be a fraction of the scattering diameter, we find $L \sim 0.1\theta_{\mathrm{SgrA*}} D_{\mathrm{SgrA*}} \sim 10^{-4}$ pc. Yusef-Zadeh et al. (1994) argued that the photoionized skins of molecular clouds in the GC region have a similar length scale, milligauss fields and $n_e \sim 10^4$ cm^{-3}. This matches the depolarization condition if the regions are fully turbulent. However, if the constraints on the outer scale of turbulence derived by Lazio & Cordes (1998) are correct, then $L \sim 10^{-7}$ pc. In this case, the RM condition and pressure balance between the magnetic and thermal components can only be satisfied if $B \sim 10$ mG and $n_e \sim 10^6$ cm^{-3}. These conditions are extreme even for the GC region. The largest magnetic fields as measured for OH masers are on the order of a few milligauss (e.g., Yusef-Zadeh et al. 1996). Ionized densities measured for H II regions on the arcsecond scale ($\lesssim 0.1$ pc) are significantly less than 10^5 cm^{-3} (Mehringer et al. 1993). No depolarization is predicted for the higher temperature and lower density model of Lazio & Cordes (1998) for $B < 1$ G. The conditions necessary to depolarize at 8.4 GHz are even more extreme. We conclude, therefore, that the conditions necessary to depolarize Sgr A* are unlikely to occur in the scattering region.

We consider now whether 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. If we consider the simplest model of spherical infall with $\dot{M} = 10^{-4}\ M_\odot$ yr^{-1} and equipartition between particle, magnetic, and gravitational energy (Melia 1994), then the change δRM over an interval δr at a radius r from Sgr A* is

$$\delta \mathrm{RM} = 1.2 \times 10^{14} r^{-11/4} \delta r \ \mathrm{rad\ m^{-2}} , \tag{5}$$

where we have expressed r and δr in units of the gravitational radius $r_g = 2GM/c^2 = 7.8 \times 10^{11}$ cm for a 2.6×10^6 $M_\odot$ black hole. This relation holds only for $r \gtrsim 10^3$, where

TABLE 3

POLARIZED FLUX AND ROTATION MEASURE FROM SPECTROPOLARIMETRIC OBSERVATIONS AT 8.4 GHz

Source	P (mJy)	p (%)	RM (rad m^{-2})	σ_{RM} (rad m^{-2})
3C 286	592 ± 3	12.1 ± 0.06	4.5×10^2	7.6×10^2
NRAO 530	101 ± 1	2.0 ± 0.02	-3.3×10^3	1.2×10^3
Sgr A*	<1.0	<0.17	…	…
W56	2.7 ± 0.1	2.9 ± 0.1	-8.7×10^4	12.9×10^4
1741−312	20 ± 2	4.7 ± 0.5	6.1×10^4	9.0×10^4
GC 441	<1.1	<5.8	…	…
W109	1.0 ± 0.1	1.1 ± 0.1	4.5×10^5	2.4×10^5
1748−253	8.4 ± 0.4	3.1 ± 0.1	9.0×10^4	10.3×10^4

the temperature falls below 10^9 K. The RM inside this radius is negligible unless there is a separate population of cold electrons. We consider the effect of cold electrons in more detail in the following section. If the scattering screen is at a distance of 100 pc from Sgr A*, then the image will be an average of ray paths over a tangential length scale $l \sim 2 \times 10^{-5} r$. Fluctuations in the RM will depolarize Sgr A* at a given radius if $\delta \mathrm{RM} > 900$ rad m^{-2} and $l > l_0$, where l_0 is the outer scale of turbulence. Assuming $\delta r \sim r$, we find that depolarization will occur only if $l_0 \lesssim 10^{-5}$ pc. Although this scale is much smaller than the outer scale in the local ISM (Armstrong, Rickett, & Spangler 1995), it is a scale that may be pertinent to the dense, energetic environment of the accretion region.

5. AN INTRINSICALLY WEAKLY POLARIZED SGR A*

A polarization fraction less than 1% is uncommon in compact radio sources at wavelengths shorter than 6 cm (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 radio galaxies than quasars or blazars, and it is also more common in compact-double sources or sources with irregular morphologies (Aller et al. 1992). A notable source with a very low polarization fraction (<0.1%) 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. For the case of a spherically symmetric emitting region, an ordered magnetic field may depolarize the source, as well. Alternatively, low-energy electrons in the synchrotron environment of Sgr A* may Faraday depolarize the source. The ADAF model and the Bondi-Hoyle accretion model predict the presence of nonrelativistic electrons in the accretion region.

Observations at millimeter wavelengths may resolve many of the questions raised in this paper. Interstellar effects are reduced such that depolarization in the scattering region is extremely unlikely and depolarization in the accretion region must occur at radii less than 0.01 pc. Furthermore, the synchrotron emission arises from a more compact and presumably more homogeneous region. The source may also have less synchrotron self-absorption at millimeter wavelengths, although this is not required by all models. We will report in a future paper on millimeter polarimetric observations of Sgr A*.

We thank Alok Patnaik for enlightening discussions. H. F. is supported by DFG grant Fa 358/1-1&2.

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