The Linear Polarization of Sagittarius A* II. VLA and BIMA Polarimetry at 22, 43 and 86 GHz

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ABSTRACT

We present a search for linear polarization at 22 GHz, 43 GHz and 86 GHz from the nearest super massive black hole candidate, Sagittarius A*. We find upper limits to the linear polarization of 0.2%, 0.4% and 1%, respectively. These results strongly support the conclusion of our centimeter wavelength spectro-polarimetry that Sgr A* is not depolarized by the interstellar medium but is in fact intrinsically depolarized.

Subject headings: Galaxy: center — galaxies: active — scattering — polarization

1. Introduction

The compact non-thermal radio source Sgr A* is recognized as one of the most convincing massive black hole candidates (Maoz 1998). 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, Krichbaum *et al.* 1998). Together these points are compelling evidence that Sgr A* is a cyclo-synchrotron 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).

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We have recently demonstrated that Sgr A* is not linearly polarized at a level of 0.2% at 4.8 and 8.4 GHz (Bower *et al.* 1999, hereafter Paper I). This spectro-polarimetric result excludes rotation measures up to 10^7 rad m^{-2}. Interstellar depolarization in the scattering region (Frail *et al.* 1994, Yusef-Zadeh *et al.* 1994, Lazio & Cordes 1998) is unlikely but not completely excluded by these observations. Interstellar depolarization can occur if the scale of turbulent fluctuations in the scattering medium are on the order of 10^{-4} pc. Although this scale is probably too large, it is not fully excluded by observations. The millimeter polarimetry that we describe in this paper directly addresses the significance of interstellar depolarization on these scales.

Our recent detection of circular polarization in Sgr A* gives particular relevance to the question of the level of intrinsic polarization (Bower, Falcke & Backer 1999). Typically, AGN display integrated circular polarization that is an order of magnitude or more less than the integrated linear polarization (Weiler & de Pater 1983). This is not only the consequence of beam dilution. In the case of the VLBI detection of circular polarization in a compact knot in 3C 279, the circular polarization is less than the co-spatial linear polarization by a factor of ~ 10 (Wardle *et al.* 1998). That is, there are no known regions in jets with high circular polarization and low linear polarization. Therefore, the presence of a large circular to linear polarization ratio in Sgr A* is an unsolved and intriguing radiative transfer problem. We discuss later some of the models that may account for this ratio.

In §2 we present VLA[4] and BIMA[5] array polarimetry. There is no detected polarization for Sgr A* at 22, 43 and 86 GHz. In §3 we demonstrate that interstellar depolarization at these frequencies is extremely unlikely. We consider the consequences of an intrinsically unpolarized Sgr A* in §4.

2. Observations and Data Reduction

2.1. VLA Observations at 22 GHz and 43 GHz

We observed Sgr A* on 3 February 1997 at 22 GHz and 43 GHz using the VLA The array was in the BnA configuration. Data were obtained in two 50 MHz wide intermediate frequency (IF) bands at 22.435 and 22.485 GHz, and 43.315 and 43.365 GHz, respectively.

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The 27-element array was divided into two sub-arrays that observed simultaneously at 22 GHz and 43 GHz. The flux density scale was set by assuming standard flux densities for 3C 286. Hourly observations of B1730-130 were used to measure antenna-based gain amplitude fluctuations and to determine the antenna-based polarization leakage terms, following standard practices. Absolute position angle calibration was not possible due to errors in the cross-correlation data for 3C 286. All measured position angles were rotated so that the position angle for B1730-130 was set to 0.

Sgr A* and the compact source B1741-312 were each observed twice an hour for 7 hours. The compact source B1921-293 was observed at 43 GHz once an hour for 4 hours. Total and polarized intensities in each IF band were measured as the best-fit Gaussian in the I and P images (Table 1). The quoted errors are rms errors from the fit. We also report the off-source maximum value in the polarized image, P_{lim} in flux units and p_{lim} as a fraction of the total intensity. A real detection must be more than twice this value to be believable.

The measured polarizations for Sgr A* are many times the rms image noise, which is on the order of 0.2 mJy. However, there is a significant contribution from multiplicative errors. These errors principally derive from variations in the polarization leakage terms (Holdaway, Carilli & Owen 1992). The effect of the D-term errors is to scatter a fraction of the total intensity into the polarized intensity map. Typically, at centimeter wavelengths the VLA can achieve a fractional error of $\sim 0.1\%$ (e.g., Bower*et al.* 1999a). The smaller number of antennas and poorer performance of the array at 22 GHz and 43 GHz will lead to larger fractional polarization errors.

Comparing results between IF bands is not a reliable method for determining fractional errors. The dominant sources of D-term errors are common to both antennas. Hence, we see variations between IFs for bright sources that are fully consistent with the thermal noise.

Two factors indicate that the measured polarization for Sgr A* is an upper limit rather than a detection. We show in Figure 1 a 43 GHz image of Sgr A* with polarization vectors overlaid. First, there is large variation in the polarization position angles over the source. This is also true in the 22 GHz images. Second, the sidelobes and noise peaks are polarized at a level comparable to the central source. Off-source peaks in the P maps are as large as the measured polarization. This implies fractional polarization errors of 0.2% and 0.4% at 22 GHz and 43 GHz, respectively.

2.2. BIMA Observations at 86 and 90 GHz

Polarimetric observations of Sgr A* were obtained with the BIMA array (Welch *et al.* 1996) on three dates, 10 March 1998, 14 March 1998 and 19 December 1998. The array was in the A configuration producing projected baselines for Sgr A* in the range 20 to 520 $k\lambda$. Continuum bandwidths were 800 MHz in lower and upper IF sidebands centered at 86.582 GHz and 90.028 GHz. Standard antenna amplitude gains were applied.

Each receiver is sensitive to linear polarization. Quarter-wave plates were installed on all antennas such that the receivers can be switched between linear, right circular (RCP) or left circular (LCP) polarization. One antenna observed linear polarization continuously, while the other antennas were switched between RCP and LCP using a Walsh-function pattern to optimize the visibility coverage in parallel- and cross-hand correlations (Wright 1995, Wright 1996). The data were self-calibrated for both RCP and LCP with respect to the antenna observing linear polarization. Because RCP and LCP is detected with the same receiver in each antenna, there is no phase-offset between the parallel hand visibilities. Hence, the absolute position angle is correctly determined without any further calibration.

For all three observations instrumental leakage was calibrated from observations of strong unresolved sources. The instrumental leakage is stable to about 0.4% rms. This implies that the minimum error in the polarization maps will be 0.4%. If variations in the D-terms are correlated, the error could be over 1% (Holdaway, Carilli & Owen 1992). For the March observations, we used D-term solutions from spectral-line observations of the Orion SiO maser on 28 January 1998 and 25 February 1998 (Rao *et al.* 1998). The average difference per antenna between the Orion maser D-term solutions is 1.3%, implying a minimum error in the polarization of $\sim$ 0.4% if the variations between antennas are uncorrelated. The average difference between the two Orion maser and calibrator D-term solutions is similar. This implies that we are not strongly affected by variations in the D-term solutions over the bandpass. Because solutions were found for a spectral line, they were available only at a single IF frequency. For the 19 December 1998 observations, we used solutions found for 3C 273 observed on 21 November 1998 in the C array. These data showed better agreement between the two IF bands than the solutions found from interleaved observations of B1730-130. A similar level of variation in the D-term solutions was found for these observations.

We summarize the total and polarized intensity in Table 2. The reported errors are estimated from fits to the corrected parallel- and cross-hand visibility data. As is the case with the VLA data, these are underestimates because they do not take into account amplitude calibration and polarization leakage term errors. We estimate the total error by the level of off-source peaks in the polarization maps. These are on the order of 20 mJy, or 1%, for Sgr A*. This is consistent with the results of Rao *et al.* , in which the linear polarization limit is 1.5%. Therefore, we consider the measured polarization for Sgr A* to be an upper limit of 1%.

In Figure 2 we summarize all upper limits to the polarization of Sgr A* from Paper I and from this paper.

3. Interstellar Depolarization

A very large rotation measure (RM) will rotate the position angle of linear polarization through the observing band. However, bandwidth depolarization is unlikely to occur in these observations. The maximum rotation measure detectable in the continuum band of these experiments is 1.3×10^6 rad m^{-2}, 8.4×10^6 rad m^{-2} and 4.8×10^6 rad m^{-2} at 22 GHz, 43 GHz and 86 GHz, respectively. The spectro-polarimetric observations in Paper I would have detected a signal at these RMs if they were present.

We argued in Paper I that the scattering medium will depolarize the source if variations in the RM lead to a phase change of π radians. The required RM variations at 22 GHz, 43 GHz and 86 GHz are 1.8×10^4 rad m^{-2}, 6.4×10^4 rad m^{-2} and 2.7×10^5 rad m^{-2}. The known variations in the RM in the Galactic Center region (Yusef-Zadeh, Wardle & Parastaran 1997) are not sufficient to depolarize Sgr A* at 4.8 GHz and 8.4 GHz (Paper I). Therefore, we must only consider whether the depolarization conditions could arise in the scattering medium around SgrA*.

The angular broadening of images of masers near the Galactic Center and Sgr A* is most likely associated with the ionized skins of molecular clouds. The ionization mechanism is either photo-ionization by hot stars (Yusef-Zadeh *et al.* 1994) or contact with diffuse, hot gas (Lazio & Cordes 1998). There are two relevant length scales for the structure of these scattering screens: the thickness of the ionized skins, $l_{skin} \sim 10^{-4}$ pc which was derived by Yusef-Zadeh *et al.* (1994); and the outer scale of the turbulent spectrum of electron density fluctuations within these skins, $l_0 \sim 10^{-7}$ pc which was derived by Lazio & Cordes (1998). The small outer scale in relation to the skin depth suggests that these layers may contain many independent turbulent cells. The small angular scale of these cells, $l_0/8$ kpc ~ 0.02 mas, means that they can depolarize a linearly polarized signal owing to their random Faraday rotations. The rms RM along independent lines of sight through a single skin will depend on $l_0\sqrt{l_{skin}/l_0}$. This rms will be about some mean if the magnetic field is uniform in the skin or about zero if the field is random. If our line of sight traverses N skins, then the equivalent path length for the rms RM estimation is $L = \sqrt{N l_{skin} l_0}$. This path length is less than 10^{-5} pc for $N < 10$ scattering screens.

The constancy of maser image anisotropy over $\lesssim 10$ arcsec angular scales suggests that the average perpendicular to the line of sight magnetic field imbedded in these skins is uniform over physical scales of $\lesssim 1$ pc (Yusef-Zadeh *et al.* 1999). This scale is a significant fraction of the size of molecular clouds in the Galactic Center region. Hence, the variations on greater scales may be the result of scattering by physically distinct regions. This uniformity then requires the rms RM to be about some mean RM (with contributions from density alone) rather than about zero (with contributions from density and field).

We show now that for L as large as 10^{-4} pc, depolarization in the scattering medium and energy equipartition between the magnetic field and particle energy require that either or both the electron density and magnetic field strength exceed the peak values measured in the Galactic Center region. These two conditions require

$$n_e = 7.3 \times 10^4 \ \mathrm{cm}^{-3} \ \mathrm{RM_4}^{2/3} L_{-4}^{-2/3} T_4^{-1/3} \tag{1}$$

and

$$B = 1.6 \ \mathrm{mG} \ \mathrm{RM_4}^{1/3} L_{-4}^{-1/3} T_4^{1/3}, \tag{2}$$

where RM_4 is the rotation measure in units of 10^4 rad m^{-2}, L_{-4} is the length scale in units of 10^{-4} pc and T_4 is the electron temperature in units of 10^4 K. Mehringer *et al.* (1993) showed that ionized densities in H II regions are significantly less than 10^5 cm^{-3} on arcsecond scales. Magnetic field strengths measured with OH masers in dense molecular regions are on the order of a few milliGauss (Yusef-Zadeh *et al.* 1999).

At 22 GHz and assuming $T_4 = 1$, we find $B \approx 2$ mG and $n_e \approx 10^5$ cm^{-3}, which exceeds the observed upper limit on electron density. At 86 GHz, $B \approx 5$ mG and $n_e \approx 7 \times 10^5$ cm^{-3}. For the case of $L \sim 10^{-7}$ pc, depolarization of the 22 GHz radiation requires $B \approx 15$ mG and $n_e \gtrsim 10^7$ cm^{-3}. The case is much worse at 86 GHz. Increasing the electron temperature does not allow depolarization: it leads to lower electron densities but higher magnetic fields. Therefore, we consider it extremely unlikely that Sgr A* is depolarized by the interstellar medium.

These electron densities correspond more closely to what we expect from a sub-parsec accretion flow onto Sgr A* (Melia 1994, Melia & Coker 1999, Quataert, Narayan & Reid 1999). As Melia and Coker show, densities in excess of 10^5 cm^{-3} appear at radii less than ~ 0.01 pc. We demonstrated in Paper I that this can easily lead to very high RMs and that depolarization will occur if the accretion region is sufficiently turbulent. However, the detailed character of the accretion region is not well-known. The geometry, volume filling factor and degree of turbulence are poorly constrained.

4. An Intrinsically Weakly Polarized Sgr A*

The degree of linear polarization in AGN typically rises with frequency. Aller, Aller & Hughes (1992) showed that in their flux-limited sample $\sim 40\%$ of AGN have polarization fractions less than 1% at 4.8 GHz while $\sim 10\%$ of the same sample have polarization fractions less than 1% at 14.5 GHz. All sources in the sample have detected polarization fractions greater than 0.2% at 14.5 GHz. This includes 3C 84 which has an average polarization fraction at 4.8 GHz of $0.03 \pm 0.01\%$. A polarization increase with frequency can be explained by the high RMs present in some radio cores (Taylor 1998), the increased prominence of shocked regions and the decreased synchrotron opacity (Stevens, Robson & Holland 1996). We note that a flux-limited sample of this kind is biased towards powerful, beamed sources which may have different polarization properties than weaker unbeamed sources. The polarization properties of these weaker sources are not well-studied due to their low flux densities. There is no high-frequency polarization study of a volume-limited sample for weaker sources. However, Rudnick, Jones & Fiedler (1986) did observe a sample of "weak" cores with flat spectra. They found that even at 15 GHz many of these sources were unpolarized at a level of $\sim 1\%$.

The absence of linear polarization in Sgr A* from 4.8 GHz to 86 GHz can be explained with the presence of thermal electrons or with significant magnetic field cancellation. The thermal electrons may be outside the emission region (in the accretion flow, as discussed above, but not in the scattering medium) or may be coincident with the emission region. This latter case is appealing because it may be able to account for the presence of circular polarization through the conversion of linear polarization to circular polarization (Bower, Falcke & Backer 1999, Pacholczyk 1977, Jones & O'Dell 1977).

Magnetic field cancellation could occur as the result of a tangled field or a circularly symmetric field orientation. The former is typically assumed to depolarize radio jets. This requires for Sgr A* that the emission region consist of $(70/0.2)^2 \approx 10^5$ independent B-field cells. The latter case may arise if the emission originates in a quasi-spherical inflow (e.g., an ADAF model). Magnetic field cancellation is an unlikely depolarization mechanism if the circular polarization is intrinsic to the source (e.g., Wilson & Weiler 1997). However, if the circular polarization arises from interstellar propagation effects (Macquart & Melrose 1999), then magnetic field cancellation is a possible explanation. In this case, the absence of linear polarization argues against a strong shock origin for the total flux variability in Sgr A* (Wright & Backer 1993, Falcke 1999). Total flux variability in AGN comes about from the presence of shocks which order the magnetic field and accelerate particles in the relativistic jet leading to linearly polarized emission (Marscher & Gear 1985).

We have shown here that Sgr A* is not linearly polarized to the current limits of instrumental sensitivity at 22, 43 and 86 GHz. The possibility is remote that Sgr A* is externally depolarized. However, the linear and circular polarizations are unique to Sgr A*. Explaining that relationship may reveal significant details for the emission region and environment of Sgr A*.

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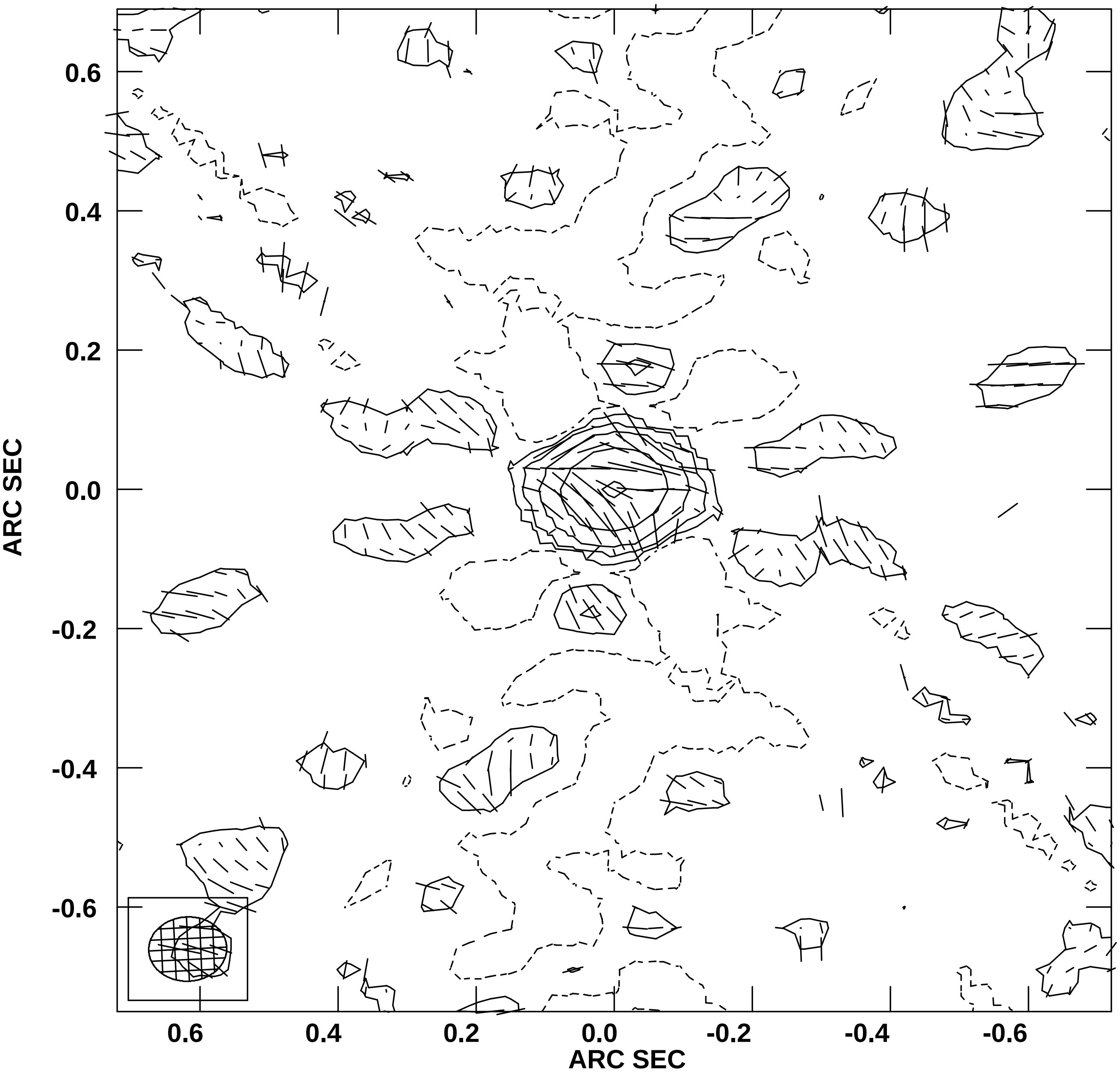

Fig. 1.— A total intensity image of Sgr A* with polarization contours overlaid from IF 1 at 43 GHz. The scatter in the polarization vectors over the compact source and the strength of the off-source polarization indicate that the polarization peak is an upper limit. The total intensity contours are -1%, 1%, 3%, 10%, 30% and 90% of the peak intensity. A polarization vector one arcsecond long represents a polarized intensity of 33.3 mJy/beam. The synthesized beam is shown in the lower left corner.

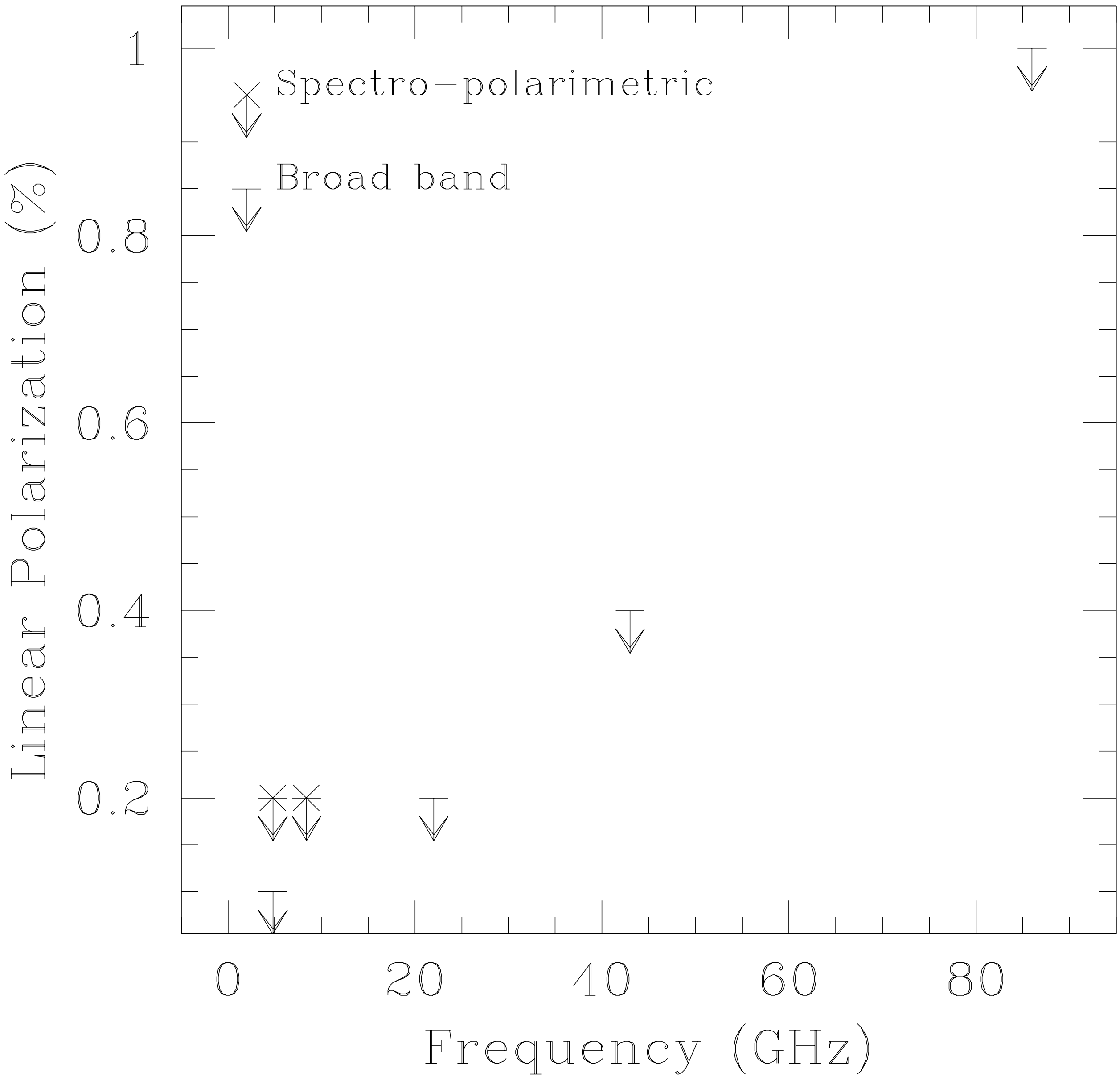

Fig. 2.— Upper limits to the linear polarization of Sgr A*. Broad band observations are indicated with an arrow. Spectro-polarimetric observations are indicated with an arrow and a cross.

Table 1. Polarized and Total Flux from VLA Continuum Observations at 22 GHz and 43 GHz

Source	IF	I (Jy)	P (mJy)	P_{lim} (mJy)	p (%)	p_{lim} (%)	χ (deg)
			22 GHz				
B1730-130	1	11.342 ± 0.072	301.0 ± 2.3	21.5	2.65 ± 0.02	0.19	...
	2	11.748 ± 0.064	281.4 ± 2.4	26.7	2.40 ± 0.02	0.23	...
B1741-312	1	0.663 ± 0.001	29.8 ± 1.0	2.9	4.49 ± 0.15	0.44	-35.9 ± 1.3
	2	0.668 ± 0.001	28.2 ± 0.5	3.0	4.22 ± 0.08	0.45	-38.9 ± 0.7
Sgr A*	1	1.053 ± 0.001	2.0 ± 0.5	2.1	0.20 ± 0.05	0.20	-34.4 ± 10.1
	2	1.061 ± 0.001	1.7 ± 0.5	2.2	0.16 ± 0.05	0.21	-12.3 ± 11.9
			43 GHz				
B1730-130	1	11.512 ± 0.004	227.0 ± 3.2	9.5	1.96 ± 0.03	0.08	...
	2	11.482 ± 0.004	219.5 ± 4.5	11.3	1.91 ± 0.04	0.10	...
B1741-312	1	0.476 ± 0.002	28.6 ± 1.2	3.5	6.01 ± 0.25	0.74	9.4 ± 1.7
	2	0.479 ± 0.002	29.3 ± 1.5	3.1	6.12 ± 0.31	0.65	7.0 ± 2.1
B1921-293	1	14.154 ± 0.032	115.6 ± 12.4	12.2	0.82 ± 0.09	0.09	10.2 ± 4.3
	2	14.161 ± 0.032	89.6 ± 15.3	17.9	0.63 ± 0.11	0.13	8.2 ± 6.9
Sgr A*	1	1.074 ± 0.001	3.4 ± 0.9	2.6	0.32 ± 0.08	0.24	-29.3 ± 10.7
	2	1.073 ± 0.001	3.7 ± 0.8	2.5	0.34 ± 0.08	0.23	91.7 ± 8.8

Table 2. Polarized and Total Flux from BIMA Continuum Observations at 86 GHz

Source	IF	I (Jy)	P (mJy)	P_{lim} (mJy)	p (%)	p_{lim} (%)	χ (deg)
			10 March 1998				
3C273	1	25.250 ± 0.340	742.8 ± 13.2	39.3	2.94 ± 0.05	0.15	-2.1 ± 0.5
3C454.3	1	5.564 ± 0.095	47.8 ± 6.4	28.3	0.86 ± 0.11	0.51	40.9 ± 3.8
Sgr A*	1	1.715 ± 0.053	17.3 ± 3.2	23.1	1.01 ± 0.18	1.35	-32.6 ± 7.5
			14 March 1998				
3C273	1	23.180 ± 0.368	726.3 ± 2.7	44.0	3.13 ± 0.01	0.19	-3.5 ± 0.1
3C454.3	1	4.816 ± 0.105	39.1 ± 13.8	37.8	0.81 ± 0.29	0.78	50.5 ± 10.1
B1730-130	1	2.824 ± 0.020	71.3 ± 1.2	67.4	2.53 ± 0.04	2.39	50.8 ± 0.5
Sgr A*	1	1.352 ± 0.065	9.5 ± 7.0	35.6	0.70 ± 0.52	2.63	-12.1 ± 29.9
			19 December 1998				
3C273	1	18.400 ± 0.045	1166.1 ± 4.7	94.1	6.34 ± 0.03	0.51	-38.5 ± 0.1
	2	18.250 ± 0.083	1136.2 ± 7.0	75.3	6.23 ± 0.04	0.41	-38.5 ± 0.2
3C454.3	1	5.828 ± 0.119	291.7 ± 10.4	34.3	5.00 ± 0.18	0.59	-85.2 ± 1.0
	2	5.646 ± 0.069	338.7 ± 19.2	30.4	6.00 ± 0.34	0.54	-84.8 ± 1.6
B1730-130	1	2.841 ± 0.001	77.5 ± 21.1	33.8	2.73 ± 0.74	1.19	10.8 ± 7.8
	2	2.754 ± 0.002	85.5 ± 7.7	34.0	3.11 ± 0.28	1.23	14.9 ± 2.6
Sgr A*	1	2.374 ± 0.016	22.8 ± 5.7	20.9	0.96 ± 0.24	0.88	26.5 ± 10.1
	2	2.422 ± 0.018	22.9 ± 3.6	19.6	0.95 ± 0.15	0.81	-39.1 ± 6.4