BIMA Observations of Linear Polarization in Sagittarius A* at 112 GHz

Geoffrey C. Bower[1,2], Melvyn C.H. Wright[2], Heino Falcke[3], Donald C. Backer[2]

ABSTRACT

We report here BIMA array observations of linear polarization in Sagittarius A*, the compact radio source in the Galactic Center. These observations had a resolution of $20'' \times 5''$ oriented North-South. We do not detect linear or circular polarization at a level of 1.8% (1-σ) at 112 GHz. This puts a new constraint on models that show a sharp change in linear polarization fraction at 100 GHz.

Subject headings: Galaxy: center — galaxies: active — polarization — radiation mechanisms: non-thermal — scattering

1. Introduction

The evidence that Sagittarius A* is associated with a supermassive black hole in the Galactic Center has been reviewed recently in Maoz (1998) and Backer & Sramek (1999). However, significant details of the accretion and emission region are not understood. In particular, it is not known whether the emission originates in an inflow or an outflow and whether the emission mechanism is synchrotron or gyrosynchrotron (e.g., Melia 1994; Özel et al. 2000; Falcke & Markoff 2000).

Polarization is an important diagnostic of Sgr A*. The source exhibits no linear polarization at frequencies less than 86 GHz (Bower et al. 1999a,c). Interstellar depolarization has been eliminated as an effect by this high frequency result and by 4.8 and 8.4 GHz spectropolarimetry. Recently, Aitken et al. (2000) have claimed detection of high levels of linear polarization in Sgr A* at millimeter and submillimeter wavelengths. Their JCMT/SCUBA observations at 150 GHz indicate $p = 12^{+9}_{-4}\%$ and increasing values at higher frequencies. The low resolution of these observations ($33.5''$) required substantial corrections to the observed total intensity and polarized fluxes due to dust and free-free emission in order to determine the polarization of Sgr A*. The implied sharp rise in polarization has significant implications for models of the emission region (Quataert & Gruzinov 2000; Agol 2000; Melia et al. 2000).

We have also pursued circular polarization observations of Sgr A* (Bower et al. 1999b, 2001). These results indicate that the circular polarization is variable and that it exceeds the linear polarization at frequencies as high as 15 GHz and possibly higher. Any complete model of the emission region must account for both linear and circular polarization.

We present here BIMA array observations of linear and circular polarization in Sgr A* at 112 and 115 GHz. These interferometric observations have a resolution of $20'' \times 5''$, which is an order of magnitude less than those of Aitken etal. We detect no linear or circular polarization at a level of 1%.

2. Observations and Results

We used the BIMA array in its C array configuration on 13 May 2000 to observe Sgr A* and on 12 May and 6 June 2000 to observe the polarization calibrators 3C 273 and 3C 279. Observations were

[1]National Radio Astronomy Observatory, P.O. Box O, 1003 Lopezville, Socorro, NM 87801; gbower@nrao.edu

[2]Astronomy Department & Radio Astronomy Laboratory, University of California, Berkeley, CA 94720; gbower,mwright,dbacker@astro.berkeley.edu

[3]Max Planck Institut für Radioastronomie, Auf dem Hügel 69, D 53121 Bonn Germany; hfalcke@mpifr-bonn.mpg.de

made in two sidebands with central frequencies of 111.8 and 115.3 GHz and bandwidths of 800 MHz each.

We observed in the polarization switching mode previously described in Bower et al. (1999c). A single antenna was kept in linear polarization while other antennas switched between right (RCP) and left (LCP) circular polarization. Self-calibration of parallel-hand visibilities was performed with respect to the reference antenna in linear polarization. The compact and highly polarized source 3C 279 was used as a polarization leakage calibrator on 12 May and 6 June. Observations were 3.5 and 4.5 h in duration on the two dates, respectively. We plot the lower sideband polarization leakage solutions in Figure 1. The rms difference between these solutions is 1.3%. This indicates a maximum 1-σ systematic error of 0.4% for polarization results. Previous measurements of linear polarization with BIMA have achieved similar limits (e.g., Bower et al. 1999c; Rao et al. 1998).

These leakage solutions were applied to the phase-self-calibrated data for Sgr A* and other calibrators. The calibrated visibilities were imaged and deconvolved in all four Stokes parameters. Baseline lengths ranged from 10 to 80 m. This produced a resolution of $20'' \times 5''$ in position angle -3.4° for Sgr A*. We tabulate the total intensity and polarized fluxes in the images Table 1. These fluxes were measured through the fitting of Gaussians at the phase-center of the images. Errors in linear and circular polarization are the 1-σ statistical error.

Differences in the polarization between epochs for some sources may be due to real source variability. Compact, flat-spectrum sources are known to show significant changes in their total and polarized flux density on timescales less than 2 months (Marscher et al. 1999).

The results at 112 GHz are clearly more reliable than those at 115 GHz. For Sgr A*, the higher frequency flux is ~ 0.5 times the flux at 112 GHz and the polarization measurement error is higher by a factor of ~ 4. Similar effects are seen for the other sources. This is the result of increased atmospheric opacity from the 118 GHz O_2 line. System temperatures at 115 GHz were roughly twice those at 112 GHz, as predicted for model atmospheres (e.g., Liebe 1989). The increased system temperature leads to lower SNR in self-calibration of the antenna phases, and thus decorrelation. The decorrelation is enhanced for Sgr A* due its low declination. Therefore, while the polarization results at the two frequencies are consistent, the more accurate results are at 112 GHz.

Decorrelation is unlikely to play a large effect at 112 GHz. The short baseline flux that we measure for Sgr A* at 112 GHz is roughly equal to the peak flux in the JCMT maps at 150 GHz with $33.5''$ resolution. Furthermore, analysis of J1733-130 and the other calibrators indicates that there is less than 25% decorrelation on the longest baselines with no dependence on source declination.

Confusion of thermal emission from Sgr A West may increase the measured total intensity of Sgr A*. This confusion is likely to be small with respect to the total intensity of Sgr A*. This is in part because the good East-West resolution separates Sgr A* from the North-South arm of the minispiral. There is some component of emission in the East-West arm, or bar, of the minispiral, however. We can estimate a maximum confusion flux from the well-sampled 3.6 cm VLA continuum image of Sgr A West of Roberts & Goss (1993). Convolving this image with a $20'' \times 5''$ beam we find a total flux at the map center of 5.4 Jy. The actual flux of Sgr A* in this map is 0.7 Jy, implying an excess flux of 4.7 Jy. Extrapolating with a power law index appropriate to free-free emission ($S \propto \nu^{-0.1}$), we expect 3.6 Jy of additional flux in the central beam. Clearly, much of this flux is absent in our image. This is in part a result of the less complete (u, v)-coverage of our observations, especially on short-baselines. Extended flux is not usually preserved in images made from incompletely-sampled visibility data (e.g., Cornwell et al. 1999). This flux can be seen in the (u, v)-distance plot on baselines shorter than 10 $k\lambda$ (Figure 2).

A more direct comparison comes from an analysis of the visibility amplitudes as a function of (u, v)-distance and a comparision with higher resolution results at lower frequencies (Bower et al. 1999c,b, 2001). These show that flux in the visibility range of 20 to 35 $k\lambda$ is an excellent estimator of the total flux over a broad range of frequencies. In VLA A-array observations of Sgr A* at 8.4 GHz, the mean flux between 20 and 35 $k\lambda$ is

0.78 ± 0.13 Jy, which is very close to the true flux of 0.75 ± 0.02 Jy determined on baselines longer than 100 $k\lambda$. At 43 GHz, VLA A-array fluxes in the same two (u, v) distance ranges are 0.92 ± 0.16 Jy and 0.99 ± 0.02 Jy, respectively. And at 86 GHz, BIMA fluxes are 2.27 ± 0.47 Jy and 2.40 ± 0.02 Jy, respectively. This effect is due to the averaging of flux from arcsecond-scale structure that beats with the flux from Sgr A*. Apparently, and as expected, it is independent of frequency, specific (u, v)-coverage and the flux of Sgr A*.

For our 112 GHz data the flux density is 0.85 ± 0.04 Jy in the range 20 to 35 $k\lambda$. The consistency with the lower frequency data sets is shown in Figure 2. This implies a free-free contribution to the flux measured at the position of Sgr A* to be ~ 0.5 Jy. The 1-σ upper limit for the polarization of Sgr A* is 1.8%.

3. Discussion

These results indicate that the linear polarization of Sgr A* at 112 GHz is not detected at a level of 1.8%. This is consistent with previously-made lower frequency observations (Bower et al. 1999a,c). We can reject the hypothesis of constant linear polarization fraction at a weighted mean of 3.5% between 112 and 150 GHz: our measurement combined with the JCMT/SCUBA result gives $\chi^2_\nu = 5.4$. Thus, a very steep rise in linear polarization fraction is necessary to reconcile the two measurements. As both Quataert & Gruzinov (2000) and Agol (2000) have shown, very specific conditions are necessary in the source and in the accretion environment to produce such a steep rise.

Variability of the linear polarization signal is a potential explanation for the discrepancy. Zhao et al. (2001) have recently demonstrated 106-day periodic variations in the total intensity of Sgr A* at 15 and 22 GHz. The strength of the variation does increase with frequency, suggesting that there may be substantial variation at frequencies above 100 GHz. However, the number of epochs of polarization monitoring indicate that this is an unlikely cause. We observed in total four separate epochs at 86 and 112 GHz without detection. The flux varied by a factor of two between these observations with no apparent change in the linear polarization. Such variations in the total flux have been observed previously at high frequencies (Wright & Backer 1993; Tsuboi et al. 1999). Additionally, Aitken et al. (2000) claim detection at different frequencies in two widely separated epochs. Interestingly, these two epochs are roughly at the same phase of the 106-day period. If variability were confirmed as the source of the discrepancy, then the relationship between total intensity and polarized intensity variations would be a very important diagnostic for Sgr A*.

We also present measurements of the circular polarization of these sources. Circular polarization is not detected in any source. For Sgr A*, the rms uncertainty in the polarization is 1.7%. The high degree of order in the magnetic field necessary to produce linear polarization fractions greater than 10% will also lead to a higher fractional circular polarization in a synchrotron or gyrosynchrotron source. Thus, the absence of circular polarization also suggests that the linear polarization limit is robust. The circular polarization is known to be variable with an inverted spectrum at frequencies as high as 15 GHz (Bower et al. 2001).

An absence of linear polarization at high frequencies has several possible explanations. One, a dense accretion region as expected by both jet and ADAF models will likely depolarize a linearly polarized signal. The low accretion rate model of Quataert & Gruzinov (2000) is not required. Two, the emission region may have a strongly tangled magnetic field. Three, the emission is not synchrotron or there is a large number of low energy electrons in the source that depolarize the emission.

Higher frequency interferometric observations are crucial to resolve the apparent disagreement between these results and those of Aitken et al. (2000). Beyond that, connection of linear and circular polarization properties with each other and with total intensity variability stands as an important observational and theoretical goal for our understanding of Sgr A*.

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Table 1

Polarized Flux of All Sources

Source	Date	ν (GHz)	I (Jy)	σ_I (Jy)	p (%)	σ_p (%)	χ (deg)	σ_χ (deg)	V (%)	σ_V (%)
3C 273	May12	112	6.665	0.008	3.18	0.12	-44.9	1.1	0.33	0.12
		115	5.316	0.010	3.25	0.19	-46.4	1.7	0.24	0.19
	Jun06	112	6.737	0.011	2.69	0.17	-26.8	1.8	-0.38	0.17
		115	5.359	0.015	3.15	0.28	-30.2	2.6	-0.42	0.28
3C 279	May12	112	19.080	0.007	11.33	0.03	61.3	0.1	0.07	0.03
		115	15.630	0.009	11.40	0.06	62.1	0.1	0.08	0.06
	Jun06	112	15.380	0.006	14.12	0.04	58.8	0.1	0.40	0.40
		115	12.520	0.009	14.23	0.07	58.4	0.1	0.40	0.07
3C 454.3	May13	112	5.390	0.014	1.97	0.26	-80.2	3.8	-0.15	0.26
		115	4.341	0.019	0.96	0.45	-74.6	13.3	-0.85	0.45
	Jun06	112	4.733	0.014	1.37	0.30	-65.9	6.2	-0.26	0.30
		115	3.921	0.019	1.50	0.50	-89.1	9.5	-1.06	0.50
J1733-130	May13	112	1.719	0.018	6.14	1.06	-6.3	4.9	1.36	1.06
		115	0.968	0.027	8.45	2.82	-15.4	9.6	4.57	2.82
	Jun06	112	1.622	0.022	4.64	1.33	-6.1	8.2	0.96	1.33
		115	1.266	0.032	7.02	2.56	25.7	10.4	-6.62	2.56
Sgr A*	May13	112	1.412	0.015	1.16	1.09	75.2	26.8	0.19	1.09
		115	0.735	0.030	2.79	4.13	-31.6	42.5	0.04	4.13

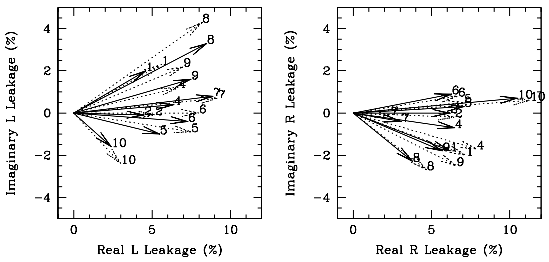

Fig. 1.— The leakage terms for each antenna in the BIMA array at 112 GHz determined by observations of 3C 279 on 12 May 2000 (solid line) and 6 June 2000 (dotted line).

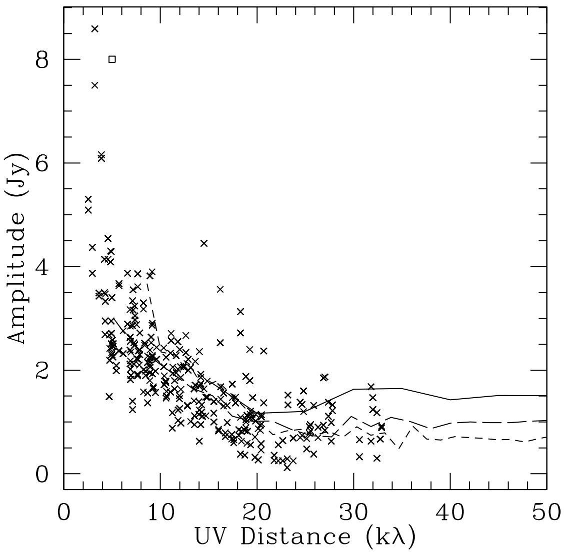

Fig. 2.— The calibrated total intensity amplitude in Jy for Sgr A* at 112 GHz as a function of projected baseline length. The short-dashed, long-dashed and solid lines indicate mean visibility amplitudes from previous 8.4, 43 and 86 GHz observations with high resolution, respectively. The measured fluxes were 0.75 ± 0.02 Jy, 0.99 ± 0.02 Jy and 2.40 ± 0.02 Jy, respectively. Note that mean flux in the 20 to 35 $k\lambda$ range is a good estimator of the long baseline flux. The 86 GHz results were plotted with 1 Jy subtracted.