THE ASTROPHYSICAL JOURNAL, 523:L29–L32, 1999 September 20

DETECTION OF CIRCULAR POLARIZATION IN THE GALACTIC CENTER BLACK HOLE CANDIDATE SAGITTARIUS A*

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Received 1999 March 30; accepted 1999 July 19; published 1999 August 17

ABSTRACT

We report here the detection of circular polarization in the Galactic center black hole candidate, Sagittarius A*. The detection was made at 4.8 and 8.4 GHz with the Very Large Array. We find that the fractional circular polarization at 4.8 GHz is $m_c = -0.36 \pm 0.05\%$ and that the spectral index of the circular polarization is $\alpha = -0.6 \pm 0.3$ ($m_c \propto \nu^\alpha$). The systematic error in m_c is less than 0.04% at both frequencies. In light of our recent lower limits on the linear polarization in Sgr A*, this detection is difficult to interpret with standard models. We consider briefly whether scattering mechanisms could produce the observed polarization. Detailed modeling of the source and the scattering medium is necessary. We propose a simple model in which low-energy electrons reduce linear polarization through Faraday depolarization and convert linear polarization into circular polarization. Circular polarization may represent a significant new parameter for studying the obscured centimeter wavelength radio source in Sgr A*.

Subject headings: Galaxy: center — galaxies: active — polarization — radiation mechanisms: nonthermal — scattering

1. INTRODUCTION

The compact radio source in the Galactic center, Sagittarius A*, is the best and closest candidate for a supermassive black hole in the center of a galaxy (Maoz 1998). The source Sgr A* is positionally coincident with a ∼$2.6 \times 10^6\ M_\odot$ dark mass (Genzel et al. 1997; Ghez et al. 1998). Very long baseline interferometry (VLBI) has shown that this source has a scale less than 1 AU and a brightness temperature in excess of 10^9 K (Rogers et al. 1994; Bower & Backer 1998; Lo et al. 1998; Krichbaum et al. 1998). Long-term studies of Sgr A* indicate that the source shows no motion with respect to the center of the Galaxy (Backer & Sramek 1999; Reid et al. 1999). For these reasons, it is inferred that Sgr A* is a supermassive black hole with a synchrotron emission region fed through accretion (Melia 1994; Narayan et al. 1998; Falcke, Mannheim, & Biermann 1993; Mahadevan 1998). In this view, Sgr A* is a weak active galactic nucleus (AGN). However, strong interstellar scattering of the radiation along the line of sight has been shown to broaden the image of Sgr A* at radio through millimeter wavelengths (e.g., Lo et al. 1998; Frail et al. 1994). As a consequence, VLBI observations have not convincingly demonstrated the existence of source structure that would be an important diagnostic of physical processes.

Polarization has proved to be an important tool in the study of AGN. Studies of linear polarization, which is typically on the order of a few percent or less of the total intensity, have confirmed that the emission process is synchrotron radiation and demonstrated that shocks align magnetic fields in a collimated jet, leading to correlated variability in the total and polarized intensity (Hughes, Aller, & Aller 1985; Marscher & Gear 1985). Circular polarization, on the other hand, is less well understood in AGN. Typically, the degree of circular polarization is $m_c < 0.1\%$ with only a few cases where m_c approaches 0.5% (Weiler & de Pater 1983). The degree of circular polarization usually peaks near 1.4 GHz and decreases strongly with increasing frequency.

Recently, VLBI imaging of 3C 279 has found $m_c \simeq 1\%$ in an individual radio component with a fractional linear polarization of 10% (Wardle et al. 1998). The integrated circular polarization, however, is less than 0.5%. The circular polarization is probably produced through the conversion of linear to circular polarization by low-energy electrons in the synchrotron source. This process is also known as repolarization (Pacholczyk 1977).

In recent work we have shown that the linear polarization of Sgr A* from centimeter to millimeter wavelengths is extremely low. Linear polarization was not detected in a spectropolarimetric experiment with an upper limit of 0.2% for rotation measures as large as 10^7 rad m^{-2} at 8.4 GHz (Bower et al. 1999a). More recently, we have found that linear polarization is less than 0.2% at 22 GHz and less than ∼1% at 86 GHz (Bower et al. 1999b). Interstellar depolarization is very unlikely within the parameter space covered by these observations. Given these stringent limits on linear polarization, the presence of circular polarization is not expected. Nevertheless, we have detected circular polarization at a surprisingly high level.

2. OBSERVATIONS AND RESULTS

We observed Sgr A* with the Very Large Array (VLA) of the National Radio Astronomy Observatory[5] in its A configuration on 1998 April 10, 18, and 24 at 4.8 and 8.4 GHz with a bandwidth of 50 MHz in two intermediate frequency (IF) bands in both right circular polarization (RCP) and left circular polarization (LCP). At 4.8 GHz, we cycled rapidly between 2.5 minute scans on Sgr A* and the nearby calibrators B1737−294, B1742−283, and B1745−291. Every hour the calibrators B1741−038 and B1748−253 were observed. These observations covered a range of four hours. A similar approach was used at 8.4 GHz over only a single hour. Absolute fluxes

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

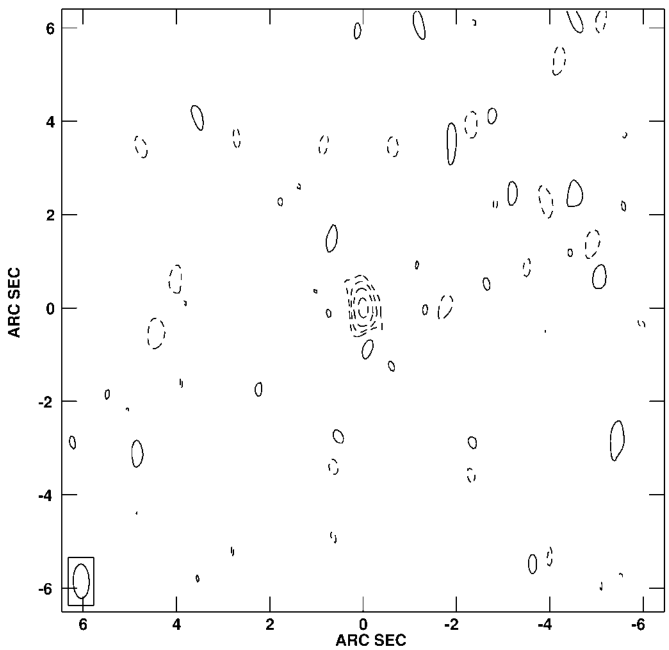

FIG. 1.—Stokes *V* map for Sgr A* on 1998 April 10 at 4.8 GHz. The peak intensity is −1798 μJy beam^{-1}. The noise levels are 68 μJy beam^{-1}. Contour levels are −16, −8, −4, −2, −1, 1, 2, 4, 8, and 16 times 175 μJy beam^{-1}. Negative contours are shown with dashed lines.

were calibrated with the source 3C 286. Time-dependent amplitude calibration of the array was performed through self-calibration of the compact and bright quasar B1741−038. Each source was phase self-calibrated. All presented results were done using baselines greater than 100 kλ in order to resolve out large-scale structure in the Galactic center (e.g., Yusef-Zadeh, Roberts, & Biretta 1998).

Detection of circular polarization with an array with circularly polarized feeds requires careful calibration and is subject to a variety of errors. The requirements are more complex for Sgr A*, which is located in a significantly confused region. Below, we summarize the errors that arise for standard circular polarization measurements and show that they agree with the measured values for the calibrators. Following that, we demonstrate that the background radiation for Sgr A* is not responsible for the measured signal.

The Stokes parameter *V* is formed from the difference of the left- and right-handed parallel polarization correlated visibilities, *LL* and *RR*. This difference is sensitive to amplitude calibration errors. Gain variations with time were measured to be less than ~0.3% for all antennas. Averaged over independent gain measurements at all antennas this implies a calibration error of ~0.02% and ~0.06% at 4.8 and 8.4 GHz, respectively.

Beam squint may also introduce false circular polarization for objects off-axis (Chu & Turrin 1973). Beam squint is due to the slightly displaced RCP and LCP beams in an offset reflector antenna. In the case of the VLA antenna geometry, the offset is 4.6% of the primary beam FWHM (Condon et al. 1998). At 4.8 GHz, this corresponds to 0′.50 within a primary beam of 10′.82. All of our sources were observed on the primary axis with a precision of less than 1″. However, pointing errors for individual antennas can be as large as 10″. This will lead to a false circular polarization of ~0.5% in a single observation on a single antenna. Averaging over multiple observations with the entire array produces a false circular polarization ~0.03%. At 8.4 GHz, the expected false circular polarization is ~0.10%.

Second-order polarization leakage effects may produce false circular polarization as well. For an array such as the VLA with polarization leakage terms on the order of 1%, weakly linearly polarized sources will produce false circular polarization on the order of a few times 0.01%. We performed our analysis with and without polarization leakage correction and found no difference in the results.

Finally, false circular polarization may appear through interference. We analyzed each of the 12 2.5 minute scans for Sgr A* at 4.8 GHz in the 1998 April 10 data independently and found no dependence on time in Stokes *V*. The typical rms image noise in each scan was 375 μJy beam^{-1}, or 0.07%. Assuming that the circular polarization did not change, we find $\chi^2 = 13.0$ for 11 degrees of freedom. Interference may also have a frequency dependence. We measured Stokes *V* for the separate IF bands for Sgr A* at 4.8 GHz in the April 10 data to be −0.43% and −0.29%, which is consistent with no frequency dependence for the error determined below.

Adding in quadrature errors from amplitude calibration, beam squint and polarization leakage gives total errors for a measurement corresponding to a single day of ~0.05% and ~0.12% at 4.8 and 8.4 GHz, respectively. We estimate the error in the average measurements to be 0.03% and 0.07%. These values are very similar to the values observed for the calibrator sources. We estimate the error in the mean for Sgr A* from the variance of the three measurements to be 0.05% and 0.06% at the two frequencies, respectively. These estimates are very close to the error determined above, which suggests that we are accounting for most sources of error. However, we now detail additional sources of error and how we eliminate them independently.

Sgr A* may have additional errors because of the presence of significant extended and compact structure in the Galactic center region. We eliminate the effect of this structure on the correlated visibilities by comparing the given results with those obtained using all baselines, only baselines greater than 300 kλ, and only baselines less than 300 kλ. We find at 4.8 GHz for 1998 April 10 m_c = −0.36%, −0.34%, and −0.37%, respectively.

A source in the beam sidelobes could also introduce a false signal if it is circularly polarized or if the sidelobe response is circularly polarized. The signature of this effect would include time dependence and possibly frequency dependence as the sidelobe swept over the source. But we have demonstrated that these effects do not exist at our sensitivity levels.

Finally, nonlinear response of the detectors to the extended structure will introduce a systematic offset in circular polarization between the amplitude calibrator and Sgr A*. The detector response is linear to better than 1%. The shift in system temperature between the calibrator and Sgr A* is from 25 to 35 K at 4.8 GHz, implying a systematic error of $\lesssim$0.3% per antenna per polarization. Averaging over both polarizations and all antennas, one expects a systematic offset of unknown sign in Stokes *V* due to the background radiation of $\lesssim$0.04%. The magnitude of this effect at 8.4 GHz is also $\lesssim$0.04%.

We show in Figure 1 the Stokes *V* image of Sgr A* at 4.8 GHz from 1998 April 10. The peak at −1.8 mJy is more than 20 times the noise level of 68 μJy beam^{-1}. For the same epoch, the calibrator B1748−253 has a peak flux of 262 μJy in a map with a noise level of 58 μJy beam^{-1}. The total intensities of Sgr A* and B1748−253 are 0.525 and 0.488 Jy at the time of detection, respectively.

We summarize in Table 1 the total and circularly polarized intensities for all sources at 4.8 and 8.4 GHz in our experiment. At 4.8 GHz, the calibrators all have mean circular polarizations

TABLE 1
CIRCULARLY POLARIZED FLUX AT 4.8 AND 8.4 GHz

Source	Date (1998)	4.8 GHz I (Jy)	4.8 GHz P_c (mJy)	4.8 GHz m_c (%)	8.4 GHz I (Jy)	8.4 GHz P_c (mJy)	8.4 GHz m_c (%)
Sgr A*	Apr 10	0.525	−1.8	−0.34	0.590	−1.9	−0.32
	Apr 18	0.494	−1.5	−0.30	0.555	−0.87	−0.16
	Apr 24	0.611	−2.6	−0.42	0.738	−2.1	−0.29
	Average	0.543	−1.97	−0.36	0.628	−1.62	−0.26
B1748−253	Apr 10	0.488	0.26	0.05	0.278	−0.23	−0.09
	Apr 18	0.481	0.31	0.06	0.277	0.27	0.10
	Apr 24	0.491	−0.25	−0.05	0.276	0.27	0.10
	Average	0.487	0.11	0.02	0.277	0.10	0.04
B1737−294	Apr 10	0.046	0.05	0.11	0.030	0.15	0.68
	Apr 18	0.045	0.06	0.13	0.030	−0.13	−0.43
	Apr 24	0.046	0.07	0.15	0.029	0.10	−0.34
	Average	0.046	0.06	0.13	0.030	0.04	0.13
B1742−283	Apr 10	0.108	−0.04	−0.04	0.138	0.40	0.30
	Apr 18	0.105	0.08	0.07	0.136	0.27	0.20
	Apr 24	0.108	−0.05	−0.05	0.135	0.15	0.11
	Average	0.107	−0.00	−0.00	0.136	0.27	0.20
B1745−291	Apr 10	0.101	−0.13	−0.13	0.096	0.14	0.15
	Apr 18	0.099	0.08	0.08	0.096	0.18	0.19
	Apr 24	0.101	0.12	0.11	0.095	0.16	0.17
	Average	0.100	0.02	0.02	0.096	0.16	0.17
B1730−130	Apr 10	...	...	...	5.782	−1.7	−0.03
	Apr 18	...	...	...	5.618	6.7	0.12
	Apr 24	...	...	...	5.467	8.1	0.15
	Average	...	...	...	5.622	4.37	0.08

less than 0.02% with the exception of B1737−294, which is dominated by the thermal noise of ∼60 μJy. The detection of circular polarization in Sgr A* is very certain at 4.8 GHz. At 8.4 GHz, the greater thermal noise and the less accurate calibration make the detection of circular polarization for Sgr A* in each observation less certain. However, the average result firmly demonstrates detection. The average circular polarization flux is 16 times that of B1748−253.

We find $m_c = -0.36 \pm 0.05\%$ and $m_c = -0.26 \pm 0.06\%$ at 4.8 and 8.4 GHz, respectively. The errors are estimated from the variance of the three separate measurements for each frequency. These errors set an upper limit to the variability as well. The average spectral index of the fractional circular polarization is $\alpha = -0.6 \pm 0.3$ for $m_c \propto \nu^{\alpha}$. The error in α is less than that expected from the errors in m_c. This is due to the fact that variations in m_c between epochs appear to be due to systematic errors that are common to both frequencies.

3. MECHANISMS FOR THE PRODUCTION OF CIRCULAR POLARIZATION

While the detection of circular polarization for Sgr A* is in itself an unexpected result, two additional properties set this source apart from other radio cores and make the result difficult to understand: the fact that circular polarization exceeds linear by more than a factor of 2 and the flatness of the circularly polarized spectrum.

We have established previously that the interstellar scattering does not depolarize any intrinsic linearly polarized emission from Sgr A* (Bower et al. 1999a, 1999b). However, the subparsec accretion region of Sgr A* may have very large rotation measures (Bower et al. 1999a). This region may depolarize an intrinsic linearly polarized signal without interfering with the circularly polarized radiation. Detailed modeling of the accretion region may be able to address these issues (e.g., Melia & Coker 1999).

We consider now whether the circular polarization is produced not in the source, but in the intervening scattering screen. A birefringent scattering medium may produce scintillating circular polarization from an unpolarized background source. This effect has been studied in detail (Macquart & Melrose 1999). This requires a scattering region with a fluctuating rotation measure gradient. Such a mechanism is appealing due to the strong scattering medium and the strong observed gradients in RM in the GC region (Yusef-Zadeh, Wardle, & Parastaran 1997). The fact that the scattered image of Sgr A* itself is anisotropic might also indicate an anisotropic scattering medium. However, the diffractive effect has $\alpha = -4$ or steeper, which is not consistent with the measured spectral index. Further calculations of this relatively unexplored issue should show whether such a scattering model could nevertheless be made consistent with the observations.

Alternatively, we can ask whether the conversion mechanism or intrinsic synchrotron circular polarization could be at work in Sgr A* (Pacholczyk 1977; Jones & O'Dell 1977). Here, the main problem is the low level of linear polarization. Magnetic field reversals would reduce linear polarization, but most likely would affect circular polarization in the same way (Wilson & Weiler 1997). However, one important factor in the relative level of linear to circular polarization is the electron energy distribution, since low-energy electrons (with Lorentz factors less than 100) can lead to Faraday-depolarization of linear and/or conversion of linear to circular polarization.

As model calculations show (Jones & O'Dell 1977, Fig. 1) circular polarization of a radio component peaks near the self-absorption frequency $\nu_{\rm ssa}$, where linear polarization drops to a minimum. In typical radio core components the strongest contribution to linear polarization therefore comes from the optically thin power-law part of its spectrum. However, in Sgr A* such a power law is most likely absent or already ends at a frequency $\nu_{\rm max} \sim \nu_{\rm ssa}$, as indicated by the steep high-frequency cutoff in its spectrum toward the infrared (Serabyn et al. 1997; Falcke et al. 1998).

Such a situation has not yet been considered in synchrotron propagation calculations involving conversion. However, it may result in a high m_c-to-m_l ratio if $\nu_{\rm max} \sim \nu_{\rm ssa}$ is true for the electrons that produce the low-frequency spectrum. For example, Jones & O'Dell show that for a power law of electron energies with characteristic frequencies $\nu_{\rm min}$ extending at least a factor 30 below $\nu_{\rm ssa}$, circular polarization around $\nu_{\rm ssa}$ can exceed m_l. With the absence of any higher frequency emission, linear polarization could be quenched. On the other hand, a narrow distribution with $\nu_{\rm min} \sim \nu_{\rm ssa} \sim \nu_{\rm max}$ would again lead to significant linear polarization even at the self-absorption frequency (Jones & Hardee 1979).

We consider here a simple synchrotron model of Sgr A*, where the flux density at 5 GHz is produced in a spherical component by a flat electron distribution with a power-law index of $p = 1$ ranging over electron energies that correspond to the characteristic frequencies $\nu_{\rm max} = \nu_{\rm ssa} = 5$ GHz and $\nu_{\rm min} = \nu_{\rm max}/30$. This model corresponds to a single zone of a complete inhomogeneous model (e.g., Blandford & Königl 1979). The low- and high-energy electrons are fully mixed. Assuming equipartition, we find a magnetic field of 0.4 G and a maximum electron Lorentz factor of 60. The electron distribution chosen here has an equal number of low- and high-energy electrons per logarithmic interval. According to Pacholczyk (1977, eq. [3.152]), such a power law will contain enough low-energy electrons near $\gamma_{\rm min}$ to produce the observed circular polarization through repolarization. Intrinsic circular polarization could be as important as conversion in this model. The intrinsic synchrotron circular polarization is given by $m_c = 3\%(B/{\rm G})^{1/2}(\nu/{\rm GHz})^{-1/2} = 0.9\%$, assuming an angle of 60° between the magnetic field and the line of sight (Legg & Westfold 1968). However, field reversals and optical depth effects will decrease that number.

The polarization properties of models (e.g., ADAF and Bondi-Hoyle) that produce gyrosynchrotron emission with low-temperature electrons are largely unexplored (Narayan et al. 1998; Melia 1994). However, Ramaty (1969) did show that circular polarization may dominate linear polarization in some simple gyrosynchrotron sources.

Obviously, a more self-consistent treatment of these problems is required. The circular and linear polarization spectrum will depend on the electron distribution and the temperature and magnetic field stratification in the source. Nevertheless, it seems as if a highly self-absorbed source with a low high-energy cutoff and a modest amount of low-energy electrons might explain the observed properties of Sgr A*.

Observationally, the most crucial steps are the measurement of the circularly polarized spectrum over a broader frequency range and its variability characteristics.

This discovery opens a significant new parameter space for the study of the nearest supermassive black hole candidate and its environment. This is especially important at centimeter wavelengths where the morphological structure of Sgr A* will remain concealed forever due to strong scattering. In concert with other radio and millimeter wavelength techniques, we may be closer to decoding the complex picture of Sgr A*.

We thank A. G. Pacholczyk, M. Rees, J. Wardle, F. Melia, R. Perley, and R. Beck for many useful discussions.

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