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Variable Linear Polarization from Sagittarius A*: Evidence for a Hot Turbulent Accretion Flow

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ABSTRACT

We report the discovery of variability in the linear polarization from the Galactic Center black hole source, Sagittarius A*. New polarimetry obtained with the Berkeley-Illinois-Maryland Association array at a wavelength of 1.3 mm shows a position angle that differs by 28 ± 5 degrees from observations 6 months prior and then remains stable for 15 months. This difference may be due to a change in the source emission region on a scale of 10 Schwarzschild radii or due to a change of 3×10^5 rad m^{-2} in the rotation measure. We consider a change in the source physics unlikely, however, since we see no corresponding change in the total intensity or polarized intensity fraction. On the other hand, turbulence in the accretion region at a radius ~ 10 to $1000 R_s$ could readily account for the magnitude and time scale of the position angle change.

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

1. Introduction

The extreme underluminosity ($\sim 10^{-10}$ times the Eddington luminosity) of Sagittarius A*, the $3 \times 10^6 M_\odot$ black hole in the Galactic Center, is a fundamental puzzle which has inspired many theoretical efforts (e.g., Melia & Falcke 2001, and references therein). Broadly, these can be classified as low accretion rate models and low radiative efficiency models. The recent discovery of linear polarization at wavelengths of 1.3 mm and shorter (Aitken et al. 2000; Bower et al. 2003) has demonstrated that there is a very low accretion rate $\sim 10^{-7}$ M$_\odot$ y^{-1} and that the underluminosity is not solely due to radiatively inefficient accretion. However, the density of gas at the Bondi radius suggests that the accretion rate at large radii is higher by several orders of magnitude (Quataert et al. 1999). This problem is resolved theoretically by the presence of convection, a wind, or an outflow that carries away much of the infalling material before it reaches the black hole (Balbus & Hawley 2002; Proga & Begelman 2003; Igumenshchev et al. 2003). The resulting accretion appears to be turbulent rather than smooth, potentially leading to flux density variations (Goldston et al. 2004).

Millimeter wavelength linear polarimetry has the power to probe the structure and turbulent nature of the accretion medium. Recent measurements with the Very Long Baseline Array have shown that emission at millimeter wavelengths originates very close to the black hole at a radius of ~ 10 Schwarzschild radii (R_s) (Bower et al. 2004). The source of the millimeter and submillimeter emission is either the base of a jet (Yuan et al. 2002) or the inner edge of a hot accretion disk (Liu & Melia 2001). This emission, which is linearly polarized, must then propagate through the magnetized accretion region. The position angle of linear polarization will undergo Faraday rotation in the accretion region. A sufficiently large rotation measure (RM) will cause the linear polarization to disappear when averaged over a given bandwidth. The presence of linear polarization at

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1.3 mm, therefore, indicates a strong upper limit on the RM. This upper limit on the RM provides a constraint on the accretion rate, which is dependent on the radial structure of the magnetic field and density. For most models, however, the range of acceptable accretion rates is on the order of 10^{-7} $M_\odot$ y^{-1} (Quataert & Gruzinov 2000; Beckert & Falcke 2002). Variations in the accretion rate or in the structure of the magnetic field or particle density, potentially as a result of turbulence, will change the RM, leading to a change in position angle with time.

We present here new linear polarimetry of Sgr A* obtained with the Berkeley-Illinois-Maryland Association (BIMA) array at 1.3 mm. In previous observations, we found that the position angle remained constant at 139 ± 4 degrees in four observations in March through May 2002. This position angle was ~ 50 degrees greater than the position angle found with JCMT observations. Our new observations show that the position angle decreased by ~ 30 degrees in the 6 months following the BIMA observations and then remained relatively stable over 15 months. We describe our observations and analysis in §2 and our linear polarization results in §3. We discuss the results and give our conclusions in §4.

2. Observations and Data Analysis

Polarimetric observations of Sgr A* were obtained on five separate dates at two frequency settings, one centered at 216 GHz and the other at 230 GHz (Table 1). The BIMA array was in C configuration for observations in October 2002 and May 2003 producing a resolution for Sgr A* of approximately 7×3 arcsec. The array was in B configuration for observations in January 2004 producing a resolution of 3×1 arcsec. The observations were performed in a polarization switching mode that gives a full, calibrated measurement of the four Stokes parameters in five minutes (Bower et al. 1999). Observations were 4 to 5 hours in duration centered on transit, placing Sgr A* at a typical elevation of 15 to 21 degrees.

Polarization leakage solutions were obtained from observations of the source 3C 279 at 230 GHz on 13 October 2002 and at 216 GHz on 18 October 2002. The 216 GHz leakage terms are $\sim 10\%$, which is larger than the 230 GHz leakage terms because the quarter-wavelength polarizing grids are optimized for 230 GHz. We determined the position angle of linear polarization for 3C279 to be 27 ± 1 degrees at 216 GHz and 36 ± 1 at 230 GHz. We found that our results for Sgr A* did not vary significantly when we forced the linear polarization for 3C 279 at 216 and 230 GHz to be equal in the process of solving for the polarization leakage terms. Time variations in leakage terms introduce no more than 1% error in the polarization, which corresponds to an error of 6 degrees in the position angle for a source that is 10% polarized (Bower et al. 2003). The leakage terms determined at 230 GHz are similar to those determined previously on 28 February 2002, which were used in Bower et al. (2003). We also found that our results for Sgr A* at 230 GHz did not depend on whether we used the 13 October 2002 or 28 February 2002 leakage terms. For instance, the position angle of the lower sideband (215 GHz) in the 19 May 2003 experiment is identical at 104 ± 5 degrees using either set of leakage terms. We conclude that errors in the leakage terms do not significantly alter our position angle at a level of 10 degrees.

The Sgr A* data were phase self-calibrated and averaged over 5 minute intervals. The appropriate leakage corrections were applied. The flux density in each Stokes parameter was determined from fits in the (u, v) plane to data on baselines longer than 20 $k\lambda$. For the B array experiments, we found similar results using only baselines longer than 40 $k\lambda$. This indicates that our results are not corrupted by polarized dust, confirming measurements and arguments previously published (Bower et al. 2003). We also compared results for the first and second-half of each experiment and found no evidence for variability. In addition, we found no dependence on self-calibration interval.

Results are listed in Table 1. We give the best-fit value for each Stokes parameter in each sideband and for the average of the two sidebands. The fractional polarization and position angle are calculated from Stokes Q and U for each sideband and for the average.

There is an apparent detection of circular polarization in the mean of all experiments $-3 \pm 1\%$. This may result from the failure of the linear approximation for polarization leakage which leads to terms for the circular polarization proportional to DP and $D^2 I$, where D is a typical leakage term,

P is the linear polarization and I is the total intensity. For $D \sim P \sim 10\%$, these terms contribute a false circular polarization $\sim 1\%$, which is comparable to the measured circular polarization. Gain variations may also contribute to a false circular polarization signal.

The range of total intensity flux densities from this paper and from our previous paper is 0.7 to 2.4 Jy, which falls below the 1 to 4 Jy range measured by Zhao et al. (2003) at the same frequency with the Submillimeter Array. The mean in the BIMA data is less by a factor ~ 2. The origin of these differences is uncertain but may be partly due to atmospheric phase decorrelation at the BIMA site. These variations in the flux density will not have an effect on the polarization fraction or position angle because all Stokes parameters are equally affected by the decorrelation.

3. Linear Polarization Results

Sgr A* is clearly detected in linear polarization in all epochs. We show the fractional polarization and the position angle as a function of time in Figures 1 and 2. We also plot the results from Aitken et al. (2000) and Bower et al. (2003) in these Figures.

The fractional polarization is apparently constant with time. The mean polarization fraction determined from these observations is $9.9 \pm 1.4\%$. This is consistent within 2σ of the mean determined from our previous observations of $7.2 \pm 0.6\%$. The mean of all BIMA observations is $7.5 \pm 0.5\%$. If we exclude the last observation from Bower et al. (2003) which appears to be an outlier, then the mean polarization fraction is $8.9 \pm 0.6\%$.

The position angle is not constant with time. The mean position angle from these new observations is 111 ± 3 deg. This differs sharply from the mean of our past observations (March through May 2002) of 139 ± 4 deg, as well as from the Aitken *et al.* 2000 value of 88 ± 3 deg (August 1999).

We find estimates of the RM using the contemporaneous observations covering 215 to 230 GHz. We perform a least squares fit to the position angle as a function of λ^2 for the four frequencies. For the 14 and 17 October 2002 results, we find an RM $0.8 \pm 1.6 \times 10^6$ rad m^{-2}. For the 27 December 2003 and 5 January 2004 results, we find an RM $2.9 \pm 0.9 \times 10^6$ rad m^{-2}. Averaging the Stokes parameters over time, we compute a mean RM that is significant at the 3σ level: 2.4 ± 0.8 rad m^{-2}. If we include a 10 degree systematic error in the position angle at 216 GHz, however, the significance of this result drops to $\sim 1\sigma$. Considering the possibility of additional error originating from the polarization leakage terms, we consider this estimated RM to be an upper limit rather than a detection.

The upper limit to the RM $\sim 2 \times 10^6$ rad m^{-2} is consistent with results determined from previous observations. Relative to previous BIMA observations, these results set an upper limit based on a broader frequency range, 215 to 230 GHz as opposed to 227 to 230 GHz (Bower et al. 2003). The absence of significant bandpass depolarization in JCMT measurements produces a comparable result (Aitken et al. 2000). Together, these results support the conclusion that the mass accretion rate onto Sgr A* has an upper limit of $\sim 10^{-7} M_\odot$ y^{-1}, eliminating ADAF and Bondi-Hoyle models.

The variability in the polarization angle invalidates previous determinations of source physics based on non-contemporaneous measurements. These include the apparent ~ 90 degree position angle jump in the JCMT results (Aitken et al. 2000) as well as RM estimates (Bower et al. 2003). In fact, even our estimated RM from observations separated by 1 week must be viewed as potentially corrupted by variability. These results do suggest that the difference between the JCMT position angle at 220 GHz and previous BIMA results at 230 GHz is due to variability.

4. Discussion

There are two possible interpretations for the time variability of the position angle: a change in the polarization of the source; or, a change in the medium through which the polarization propagates. In the intrinsic polarization scenario, the magnetic field structure from which the polarized radiation originates must undergo a change. This might be due to the propagation of shock in the jet or a change in the orientation of a thin disk. Variability in the centimeter wavelength circular polarization has been interpreted as the result of intrinsic source variations (Beckert & Falcke 2002).

In the propagation scenario, turbulence or clumpiness in the accretion region can change the RM, which then alters the position angle of the linear polarization. The necessary change in the RM is $\Delta\mathrm{RM} \sim 3 \times 10^5$ rad m^{-2}.

Although both scenarios are possible, the apparent stability of the fractional polarization leads us to favor a changing RM as the explanation. Typically, a changing polarization position angle in a jet from a shock is accompanied by a sharp change in the total intensity and polarization fraction (Marscher & Gear 1985). In a disk model for the origin of the linear polarization the polarization fraction in the optically thin limit is highly variable on a time scale of days to weeks while the polarization vector is quite stable (Goldston et al. 2004).

Synchrotron self-absorption has also been proposed as the source of wavelength-dependent change in the position angle (Aitken et al. 2000; Agol 2000). A change in the self-absorption frequency would lead to a change in the position angle in the regime where the opacity $\gtrsim 1$. This change, however, would be strongly correlated with a change in the polarization fraction. The apparent stability of the polarization fraction over 5 years with as much as 60 degrees change in position angle argues against this hypothesis.

On the other hand, a change of ΔRM will not lead to a change in the polarization fraction or total intensity. Both the magnitude of ΔRM and the timescale for its change are consistent with model expectations.

The RM as a function of radius from the black hole can be calculated for different models using a knowledge of the radial structure of the electron density, magnetic field and electron temperature along with an assumption of equipartition between kinetic and magnetic energy densities (Bower et al. 1999; Quataert & Gruzinov 2000). For the case of CDAF models with an accretion rate $\lesssim 10^{-7}$ M$_\odot$ y^{-1}, the electron density is not strongly peaked at the black hole ($\propto r^{-1/2}$) and the RM $\lesssim 3\times10^6$ rad m^{-2} at all radii. The actual radius at which the RM peaks is sensitive to the electron temperature distribution. For an electron temperature that peaks at 3×10^{11} K at a radius of $10R_s$ and falls off inversely with radius, then the RM is greater than 3×10^5 rad m^{-2} at radii $\gtrsim 30R_s$. Thus, the change in polarization angle could be due to a change in the electron density and/or magnetic field at any radius of the accretion region $\gtrsim 30R_s$. On the other hand, in the case of a steeply peaked electron density ($\propto r^{-3/2}$) such as that required for the Bondi solution, the RM is dominated by material very close to the black hole.

The time scale of variability is only roughly determined by these observations. We see variability of the polarization angle on a time scale of 180 days followed by stability over 450 days. We see no change in the polarization fraction on time scales of hours, although our constraint is not very strong. The predicted time scale of a turbulent change in the RM is comparable to the viscous time scale at the radius r of the turbulence. Given the range of radii at which turbulent fluctuations could occur, we predict that RM fluctuations could occur on time scales of 10^{-1} to 10^3 days. Our current constraint on the time scale of variability is too poor to determine at what radius the turbulence is taking place.

Higher sensitivity mm λ polarimetry obtained on scales from days to years by the next generation millimeter observatories such as CARMA, the SMA and ALMA will be able to generate a position angle and RM structure function that can be matched to the detailed predictions of models. Observations over a broader range of wavelengths are necessary to clearly discriminate between intrinsic changes and RM changes. Ultimately, these measurements can determine the mode of accretion onto Sgr A*.

5. Summary

We have described new observations of linear polarization at 1.3 mm wavelength from Sgr A*. The polarization fraction is steady over several years while the position angle changes by ~ 30 to 60 degrees on a time scale of months. The magnitude and time scale of the position angle change are consistent with the expectations of turbulence in the accretion region surrounding Sgr A* at radii of 10 to 1000 R_s. This evidence supports the concept that most of the material that begins to accrete onto Sgr A* at the Bondi radius is lost in a wind or outflow before it accretes onto the black hole itself, leaving us with the very low luminosity source that we see.

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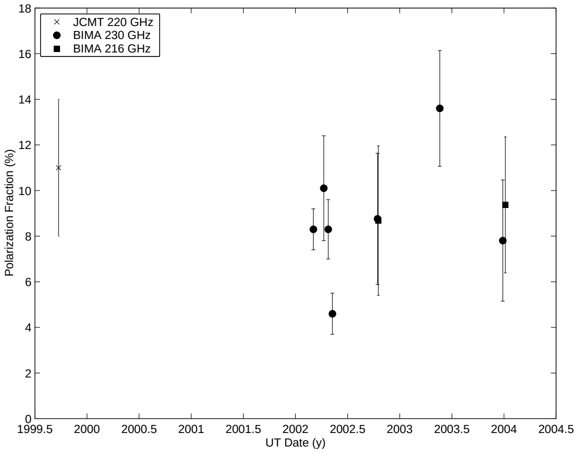

Fig. 1.— Fractional polarization at 1.3 mm as a function of time. We plot our new results at 216 and 230 GHz, results from Bower *et al.* (2003) at 230 GHz (between 2002 and 2002.5) and results from Aitken *et al.* (2000) at 220 GHz.

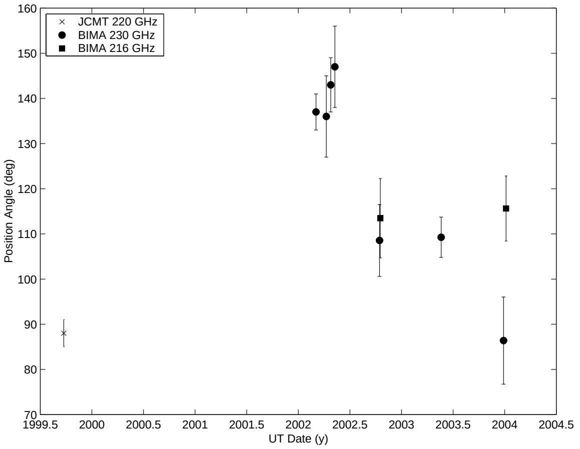

Fig. 2.— Position angle of the linear polarization at 1.3 mm as a function of time. Symbols are the same as in Figure 1.

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Table 1

Polarized and Total Flux Density of Sgr A* at 1.3 mm

Date	ν (GHz)	I (Jy)	Q (mJy)	U (mJy)	V (mJy)	p (%)	χ (deg)
14 OCT 2002	227.7	1.12 ± 0.04	-69 ± 39	-57 ± 39	-3 ± 39	8.0 ± 3.5	110 ± 13
...	230.5	1.17 ± 0.04	-91 ± 40	-64 ± 40	-32 ± 40	9.5 ± 3.4	108 ± 10
...	229.1	1.14 ± 0.03	-80 ± 28	-60 ± 28	-17 ± 28	8.8 ± 2.9	109 ± 8
17 OCT 2002	215.0	0.69 ± 0.03	-8 ± 26	-65 ± 26	-36 ± 26	9.5 ± 3.8	131 ± 11
...	217.8	0.71 ± 0.03	-74 ± 26	-24 ± 26	-47 ± 26	11.0 ± 3.7	99 ± 10
...	216.4	0.70 ± 0.02	-42 ± 19	-45 ± 19	-42 ± 19	8.7 ± 3.3	113 ± 9
19 MAY 2003	227.7	1.25 ± 0.04	-180 ± 37	-96 ± 37	-22 ± 37	16.3 ± 2.9	104 ± 5
...	230.5	1.20 ± 0.04	-78 ± 38	-113 ± 38	-27 ± 38	11.5 ± 3.2	118 ± 8
...	229.1	1.23 ± 0.03	-131 ± 26	-104 ± 26	-24 ± 26	13.6 ± 2.5	109 ± 4
27 DEC 2003	227.7	0.89 ± 0.03	-90 ± 32	-15 ± 32	-9 ± 32	10.2 ± 3.6	95 ± 10
...	230.5	0.84 ± 0.03	-43 ± 34	34 ± 34	16 ± 34	6.4 ± 4.0	71 ± 18
...	229.1	0.87 ± 0.02	-67 ± 23	9 ± 23	3 ± 23	7.8 ± 2.7	86 ± 10
05 JAN 2004	215.0	1.50 ± 0.05	-92 ± 50	-136 ± 50	-82 ± 50	10.9 ± 3.4	118 ± 9
...	217.8	1.53 ± 0.05	-86 ± 50	-86 ± 50	-89 ± 50	7.9 ± 3.3	112 ± 12
...	216.4	1.52 ± 0.04	-89 ± 36	-111 ± 36	-85 ± 36	9.4 ± 3.0	116 ± 7