VARIABLE LINEAR POLARIZATION FROM SAGITTARIUS A*: EVIDENCE OF 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 $28^\circ \pm 5^\circ$ 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 $3 \times 10^5 \text{ rad m}^{-2}$ 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 $\sim 10R_s\sim 1000R_S$ could readily account for the magnitude and timescale of the position angle change.

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

1. INTRODUCTION

The extreme underluminosity (\(~10^{-10}\) times the Eddington luminosity) of Sagittarius A*, the $3 \times 10^6 M_\odot$ black hole in the Galactic center, is a fundamental puzzle that 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 the extreme 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 turbulence is turbulent rather than smooth, potentially leading to flux density variations (Goldston et al. 2005).

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 $\sim 10$ 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 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 of the order of $10^{-7} M_{\odot} \text{ yr}^{-1}$ (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 $139^\circ \pm 4^\circ$ in four observations in 2002 March through May. This position angle was $\sim 50^\circ$ greater than the position angle found with James Clerk Maxwell Telescope (JCMT) observations. Our new observations show that the position angle decreased by $\sim 30^\circ$ 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 2002 October and 2003 May, producing a resolution for Sgr A* of approximately $7'' \times 3''$. The array was in B configuration for observations in 2004 January, producing a resolution of $3'' \times 1''$. The observations were performed in a polarization switching mode that gives a full calibrated measurement of the four Stokes parameters in 5 minutes (Bower et al. 1999). Observations were 4–5 hr in duration centered on transit, placing Sgr A* at a typical elevation of $15^\circ$–$21^\circ$.

Polarization leakage solutions were obtained from observations of the source 3C 279 at 230 GHz on 2002 October 13 and at 216 GHz on 2002 October 18. 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 3C 279 to be $27^\circ \pm 1^\circ$ at 216 GHz and $36^\circ \pm 1^\circ$ 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 $6^\circ$ 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 2002 February 28, 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 2002 October 13 or 2002 February 28 leakage terms. For instance, the position angle of the lower sideband (215 GHz) in the 2003 May 19 experiment is identical at using either set of leakage terms. We conclude that errors in the leakage terms (between 2002 and 2002.5), and results from Aitken et al. (2000) at 220 GHz, did not significantly alter our position angle at a level of 10%.

TABLE 1

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

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, 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 the 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% ± 1%. This may result from the failure of the linear approximation for polarization leakage that leads to terms for the circular polarization proportional to $DP$ and $D^2I$, 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 −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 Letter and from our previous paper is 0.7−2.4 Jy, which falls below the 1−4 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 of −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% ± 1.4%. This is consistent within 2 σ of the mean determined from our previous observations of 7.2% ± 0.6%. The mean of all BIMA observations is 7.5% ± 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% ± 0.6%.

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

We find estimates of the RM using the contemporaneous observations covering 215–230 GHz. We perform a least-squares fit to the position angle as a function of J for the four2 observations covering 215–230 GHz. We perform a least-

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 ΔRM ~ 3 × 10^3 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 timescale of days to weeks, while the polarization vector is quite stable (Goldston et al. 2005).

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 ≳1. This change, however, would be strongly correlated with a change in the polarization fraction. The apparent stability of the polarization fraction over 5 yr with as much as 60° 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 convection-dominated accretion flow models with an accretion rate L ~ 10^7 M☉ yr⁻¹, the electron density is not strongly peaked at the black hole (proportional to r⁻³) and the RM ≲ 3 × 10^3 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 × 10^9 K at a radius of 10Rg and falls off inversely with radius, then the RM is greater than 3 × 10^5 rad m⁻² at radii ≳30Rg. 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 ≳30Rg. On the other hand, in the case of a steeply peaked electron density (proportional to r⁻³) such as that required for the Bondi solution, the RM is dominated by material very close to the black hole.

The timescale of variability is only roughly determined by these observations. We see variability of the polarization angle on a timescale of 180 days followed by stability over 450 days.

4. DISCUSSION

Fig. 2.—Position angle of the linear polarization at 1.3 mm as a function of time. Symbols are the same as in Fig. 1.
We see no change in the polarization fraction on timescales of hours, although our constraint is not very strong. The predicted timescale of a turbulent change in the RM is comparable to the viscous timescale 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 timescales of $10^{-1}$ to $10^3$ days. Our current constraint on the timescale of variability is too poor to determine at what radius the turbulence is taking place.

Higher sensitivity millimeter polarimetry obtained on scales from days to years by the next generation millimeter observatories such as the Combined Array for Research in Millimeter-wave Astronomy, the Submillimeter Array, and the Atacama Large Millimeter Array 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 a 1.3 mm wavelength from Sgr A*. The polarization fraction is steady over several years, while the position angle changes by $\sim30^\circ$--$60^\circ$ on a timescale of months. The magnitude and timescale of the position angle change are consistent with the expectations of turbulence in the accretion region surrounding Sgr A* at radii of $10R_s$--$1000R_s$. 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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