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AN UNAMBIGUOUS DETECTION OF FARADAY ROTATION IN SAGITTARIUS A*

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ABSTRACT

The millimeter/submillimeter wavelength polarization of Sgr A* is known to be variable in both magnitude and position angle on time scales down to a few hours. The unstable polarization has prevented measurements made at different frequencies and different epochs from yielding convincing measurements of Faraday rotation in this source. Here we present observations made with the Submillimeter Array polarimeter at 227 and 343 GHz with sufficient sensitivity to determine the rotation measure at each band without comparing position angles measured at separate epochs. We find the 10-epoch mean rotation measure to be $(-5.6 \pm 0.7) \times 10^5$ rad m^{-2}; the measurements are consistent with a constant value. We conservatively assign a 3σ upper limit of 2×10^5 rad m^{-2} to rotation measure changes, which limits accretion rate fluctuations to 25%. This rotation measure detection limits the accretion rate to less than 2×10^{-7} $M_\odot$ yr^{-1} if the magnetic field is near equipartition, ordered, and largely radial, while a lower limit of 2×10^{-9} $M_\odot$ yr^{-1} holds even for a sub-equipartition, disordered, or toroidal field. The mean intrinsic position angle is $167^\circ \pm 7^\circ$ and we detect variations of 31^{+18}_{-9} degrees. These variations must originate in the submillimeter photosphere, rather than arising from rotation measure changes.

Subject headings: black hole physics – Galaxy: center – polarization – submillimeter – techniques: interferometric

1. INTRODUCTION

The linear polarization of Sgr A* was first detected by Aitken et al. (2000) above 100 GHz, after unsuccessful searches at lower frequencies (e.g. Bower et al. 1999a,b). Subsequent interferometer observations have shown the polarization to vary in position angle (Bower et al. 2005) and fraction (Marrone et al. 2006; hereafter M06), with variability occurring on timescales comparable to those of the previously observed total intensity variations (M06). The variability may be intrinsic to the source or due to propagation effects, but the short timescales suggest processes very close to the black hole are responsible and thus polarization should be a useful tool for the study of Sgr A*.

One aspect of the polarization that has yet to be exploited is its variation with frequency, particularly the frequency-dependent orientation change known as Faraday rotation. The presence of polarization was used immediately after its detection to argue that the infalling plasma must be tenuous and the mass accretion rate low (less than 10^{-6} $M_\odot$ yr^{-1}), because larger accretion rates would depolarize the emission through extreme Faraday rotation gradients (Quataert & Gruzinov 2000a; Agol 2000). Constraints have also been derived through careful examination of the spectrum (e.g. Melia et al. 2000, 2001). However, further progress on determining the accretion rate and its variability has awaited measurement of the Faraday rotation measure (RM), a difficult task because of significant variability of Sgr A* and the diminished effect of rotation at high frequencies. To date there have been three RM determinations from non-simultaneous observations (Bower et al. 2003; M06; Macquart et al. 2006), but none of them is robust. Most recently, Macquart et al. (2006) estimated the RM to be -4.4×10^5 rad m^{-2} from their 83 GHz polarization data and all previous data. However, their analysis allows a much lower RM due to the 180° degeneracy of the polarization position angle (see § 3).

Simultaneous measurements are a much more secure way to determine the RM because they are insensitive to source variability. Such data can be used to measure the RM, the intrinsic polarization direction, and the variability of each. Isolating these changes is crucial to understanding the conditions in the inner accretion flow; the RM can be used to place upper and lower limits on the accretion rate, while variations in the polarization and RM with frequency and time can be used to examine the structure of the flow. The instantaneous frequency coverage of available instruments has not yet been adequate to show Faraday rotation in a single epoch, with the lowest upper limit ($|\mathrm{RM}| \leq 7\times10^5$ rad m^{-2}) from early Submillimeter Array[4] (SMA) 345 GHz polarimetric observations (M06). Here we report SMA measurements of the RM and intrinsic polarization changes of Sgr A*, the first observations to detect the RM with statistical significance and the only measurement made without resorting to comparisons between position angles measured at different epochs. The observations and calibration procedures are detailed in § 2, the RM and the variability of the RM and intrinsic polarization are examined in § 3, and we discuss the implications for the accretion rate and properties of Sgr A* in § 4.

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2. OBSERVATIONS

The SMA made polarimetric observations of Sgr A* in 2005 June and July. In the ten nights without weather or technical problems there are six (four) tracks in the 230 GHz (345 GHz) band. The 230 GHz observations used a local oscillator (LO) frequency of 226.9 GHz, providing simultaneous measurements of sidebands centered on 221.9 and 231.9 GHz, except for one observation made at LO=225.55 GHz. The higher frequency data use an LO frequency of 343 GHz. The weather was excellent in the usable nights, with a typical zenith opacity at 225 GHz of $0.06 - 0.08$, or $0.19 - 0.27$ when scaled to 343 GHz. All data were obtained with five to seven antennas in the compact configuration ($7 - 70$ meter baselines), resulting in a synthesized beam width of $2''.0\times4''.0$ at 230 GHz and $1''.6\times3''.2$ at 345 GHz on Sgr A*. For the purposes of self-calibration and polarization extraction, baselines shorter than $20k\lambda$ were removed to exclude the extended emission around Sgr A*. Gain calibrators included J1743-038, J1733-130, J1924-292, and Ceres. Very similar polarization results were obtained when the calibrator gains were applied and when Sgr A* was self-calibrated. The flux density scale was derived from observations of planets and their moons, with an expected accuracy of better than 10%. Flux densities in each Stokes parameter were obtained through point-source fits to the visibilities. The observed properties of Sgr A* in all ten epochs are listed in Table 1.

To obtain full polarization information we used the SMA polarimeter (M06; Marrone 2006). Measurement of polarization relies on precise determination of the fractional contamination ("leakage") of each polarization state by the cross-handed polarization. Uncalibrated leakage contaminates the linearly polarized Stokes parameters (Q and U) with I. Leakages were measured each night by observing polarized quasars (3C 279 or 3C 454.3) over a large range of parallactic angle. The leakages are stable, approximately 1% in the upper sideband (USB) for each band, 4% for the 230 GHz lower sideband (LSB), and 2% for the 345 GHz LSB. The r.m.s. leakage variability is 0.3% at 230 GHz and 0.4% at 345 GHz. There are three potential sources of variability: (1) real instrumental polarization changes between nights, (2) finite signal-to-noise ratio, and (3) polarization leakage that is not constant across the sky, resulting in leakage determinations that depend on the hour angle coverage. The first of these may exist but is bounded by the small observed leakage variability. The second is expected to yield variations at the level of 0.1% in the 345 GHz leakages and less at 230 GHz. We know that the third effect is also present, at a level of around 0.2%, due to the fact that cross-polarization introduced skyward of the Nasmyth relay mirror is rotated relative to the feed as a source is tracked in elevation, while the cross-polarization of the wave plate and subsequent optics is fixed. This small additional leakage imprints itself on the polarization of the calibrator and its effect on the leakages derived in calibration (under the assumption of stationary leakage) changes with the elevation coverage of the calibrator. Fortunately, the resulting polarization changes are small. Leakage errors of 0.3%−0.4% contribute 0.2% fractional contamination to the instantaneous polarization, significantly less when averaged over a full track due to the parallactic angle rotation. For Sgr A*, which we measure to be 5%−10% polarized, this results in at most 1° of position angle error. We reduced the Sgr A* data using the average leakages at each frequency instead of the single-night values to confirm this estimate. More importantly for this purpose, the uncorrected instrumental polarization is very nearly constant across the sidebands because properties such as the illumination pattern on the antenna change slowly with frequency. We find the imprint of this additional leakage on the calibrator to be very consistent between sidebands, so although the absolute position angle varies by up to 1°, the inter-sideband difference varies only by $0.1^\circ-0.2^\circ$. We take this as our systematic error for position angle differences, although it is much lower than the thermal noise. Previous SMA 345 GHz observations (M06) do not include enough calibration data to place similar limits on the systematic errors, so we exclude them from the following analysis.

3. ROTATION MEASURE AND INTRINSIC POLARIZATION

Faraday rotation changes the observed polarization position angle (χ) as a function of frequency according to:

$$\chi(\nu) = \chi_0 + \frac{c^2}{\nu^2}\mathrm{RM}, \tag{1}$$

where χ_0 is the intrinsic position angle. The rotation measure (RM) is proportional to the integral of the electron density and magnetic field component along the line of sight. From the observed LSB and USB position angles we derive a RM and χ_0 for each observation. We plot χ in both sidebands against λ^2 for all ten epochs in Figure 1, along with the average RM and χ_0. The larger errors in Table 1 for 345 GHz band RMs and χ_0s are due to the much smaller inter-sideband difference in λ^2 at the higher frequency; the constraints on these quantities are therefore dominated by the 230 GHz data. The average RM from all 10 epochs is $(-5.6 \pm 0.7) \times 10^5$ rad m^{-2}, while the 230 GHz and 345 GHz points alone yield $(-5.4\pm0.7)\times10^5$ rad m^{-2} and $(-13\pm5)\times10^5$ rad m^{-2}, respectively, consistent within their errors. The ten single-night RM values are consistent with a constant value ($\chi_r^2 = 1.21$, for 9 degrees of freedom). None of the 230 GHz points deviates from the average by more than 1.2 times its measurement error, while the largest deviation at 340 GHz is 2.2σ. We therefore place a conservative upper limit of three times the averaged σ, or 2×10^5 rad m^{-2} on RM variability. This agrees with the small RM fluctuations inferred from the constancy of polarization at 83 GHz (Macquart et al. 2006).

These observations also constrain the intrinsic polarization direction of Sgr A*. The average χ_0 in our ten measurements is $167^\circ \pm 7^\circ$, or $162^\circ \pm 7^\circ$ and $210^\circ \pm 21^\circ$ from 230 and 345 GHz observations, respectively. The χ_0 values vary by more than our measurement errors predict, suggesting intrinsic polarization changes. Assuming a constant χ_0, we obtain $\chi_r^2 = 2.8$ (0.3% probability) using all data points, or $\chi_r^2 = 3.9$ (0.16%) for the 230 GHz points only. The scatter in the full data set suggests an intrinsic χ_0 dispersion of 31^{+18}_{-9} degrees, with very similar results obtained from just the 230 GHz points. It is interesting to note that the mean χ_0 is $\sim80^\circ$ different from the angle observed during IR flares (Eckart et al. 2006; Meyer et al. 2006). A 90° position angle change

TABLE 1
POLARIZATION AND ROTATION MEASURE OF SAGITTARIUS A*

Date	ν (GHz)	I^{a} (Jy)	Q^{a} (mJy)	U^{a} (mJy)	m (%)	χ (deg)	RM (10^5 rad/m^2)	χ_0 (deg)
2005 Jun 4:	...	...	...	...	...	...	-6.7 ± 2.9	215 ± 29
USB ...	230.6	4.00 ± 0.04	100 ± 12	-176 ± 12	5.06 ± 0.29	149.8 ± 1.7		
LSB ...	220.6	3.91 ± 0.03	48 ± 11	-153 ± 11	4.08 ± 0.28	143.7 ± 2.0		
2005 Jun 6:	...	...	...	...	...	...	-23.1 ± 12.6	251 ± 56
USB ...	348.0	4.22 ± 0.04	126 ± 19	-177 ± 20	5.13 ± 0.47	152.7 ± 2.6		
LSB ...	338.0	4.14 ± 0.03	94 ± 16	-214 ± 15	5.62 ± 0.38	146.8 ± 1.9		
2005 Jun 9:	...	...	...	...	...	...	-5.0 ± 1.7	138 ± 17
USB ...	231.9	3.48 ± 0.02	-244 ± 9	-7 ± 8	7.01 ± 0.25	90.8 ± 1.0		
LSB ...	221.9	3.38 ± 0.02	-224 ± 8	28 ± 9	6.68 ± 0.24	86.4 ± 1.1		
2005 Jun 15:	...	...	...	...	...	...	-11.7 ± 13.6	192 ± 60
USB ...	348.0	3.31 ± 0.02	45 ± 16	-166 ± 16	5.18 ± 0.48	142.5 ± 2.7		
LSB ...	338.0	3.32 ± 0.02	29 ± 14	-181 ± 13	5.52 ± 0.41	139.6 ± 2.2		
2005 Jun 16:	...	...	...	...	...	...	-5.4 ± 1.8	174 ± 18
USB ...	231.9	3.94 ± 0.03	-93 ± 9	-196 ± 8	5.50 ± 0.22	122.3 ± 1.1		
LSB ...	221.9	3.79 ± 0.03	-109 ± 8	-157 ± 7	5.05 ± 0.19	117.6 ± 1.1		
2005 Jun 17:	...	...	...	...	...	...	-22.3 ± 7.4	246 ± 33
USB ...	348.0	2.95 ± 0.02	148 ± 14	-228 ± 14	9.21 ± 0.48	151.5 ± 1.5		
LSB ...	338.0	3.02 ± 0.02	109 ± 12	-276 ± 12	9.81 ± 0.41	145.8 ± 1.2		
2005 Jul 20:	...	...	...	...	...	...	-7.5 ± 1.6	209 ± 16
USB ...	231.9	3.82 ± 0.02	15 ± 6	-180 ± 6	4.73 ± 0.17	137.3 ± 1.0		
LSB ...	221.9	3.75 ± 0.02	-25 ± 6	-165 ± 6	4.45 ± 0.15	130.7 ± 1.0		
2005 Jul 21:	...	...	...	...	...	...	$+1.1 \pm 8.2$	154 ± 36
USB ...	348.0	3.87 ± 0.03	240 ± 18	-220 ± 17	8.39 ± 0.46	158.7 ± 1.6		
LSB ...	338.0	3.73 ± 0.03	225 ± 15	-203 ± 15	8.11 ± 0.40	159.0 ± 1.4		
2005 Jul 22:	...	...	...	...	...	...	-3.7 ± 1.8	152 ± 18
USB ...	231.9	3.37 ± 0.02	-91 ± 6	-120 ± 6	4.46 ± 0.18	116.4 ± 1.1		
LSB ...	221.9	3.34 ± 0.02	-105 ± 6	-110 ± 6	4.55 ± 0.17	113.1 ± 1.1		
2005 Jul 30:	...	...	...	...	...	...	-4.8 ± 1.4	133 ± 14
USB ...	231.9	4.16 ± 0.03	-223 ± 7	26 ± 6	5.39 ± 0.16	86.6 ± 0.8		
LSB ...	221.9	4.12 ± 0.03	-193 ± 7	53 ± 6	4.86 ± 0.15	82.4 ± 0.9		

[a] Statistical errors only. Overall flux density scale uncertainty is 10%.

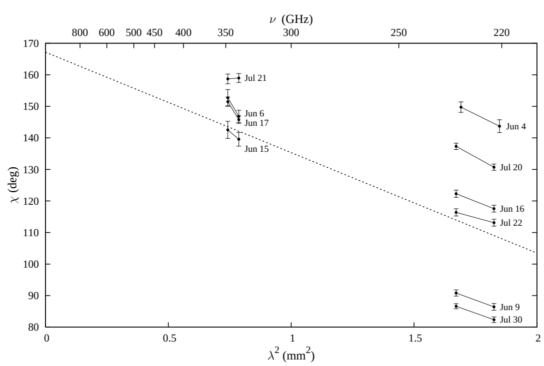

FIG. 1.— The position angles observed in each sideband on each of the ten epochs. The slope between the two sidebands at each epoch is proportional to the RM and the extrapolated intercept at the χ axis is χ_0. The mean RM$-\chi_0$ fit is also plotted. Variability in χ_0 is visible in the 230 GHz points (at right), which show slopes similar to the mean but are widely dispersed in χ.

has been predicted to occur near the spectral peak in theoretical models of the polarization, although the precise flip frequency depends on the details of the models (Agol 2000; Melia et al. 2000). If the IR measurements trace the intrinsic polarization direction at short wavelengths, rather than the possibly random polarization of the transient flare, this would be evidence for such a change above 345 GHz. We do not observe a flip between 230 and 345 GHz.

This measurement represents the first reliable determination of the RM of Sgr A*, and the only measurement made from simultaneous observations at multiple frequencies and therefore able to isolate source polarization changes. Macquart et al. (2006) derived a RM of -4.4×10^5 rad m^{-2} from the average χ at four frequencies over the last several years. However, their interpretation requires a 180° unwrapping of the 83 GHz position angle and the non-wrapped position angle is not strongly excluded. They report a χ_r^2 of 2.1 for 3 degrees of freedom (10% probability) for the non-wrapped fit (RM$=-1.9 \times 10^5$ rad m^{-2}). Furthermore, this χ_r^2 relies on their poorly measured USB polarization (just two of five measurements detect polarization at 3σ) and the standard error of the mean of just two measurements at 216 GHz in order to provide additional degrees of freedom. Discarding the former and using the 230 GHz variability to estimate the 216 GHz variability increases the probability of the non-wrapped position angle to 26%.

4. DISCUSSION

The RM we observe is too large to be produced by material beyond the accretion radius of Sgr A* (approximately 1″ or 0.04 pc). Using the density determined by Baganoff et al. (2003), the RM in the dense inner 10″ is just 8×10^3 rad m^{-2} assuming a 1 mG ambient field. RMs determined in nearby sources are as large as 70% of this estimate (e.g. Yusef-Zadeh & Morris 1987).

The RM can be used to determine the accretion rate ($\dot{M}$) at small radii around Sgr A* if assumptions are made about the nature of the accretion flow. The procedure is outlined in M06 and assumes a power-law radial density profile ($n \propto r^{-\beta}$) and an ordered, radial, equipartition-strength magnetic field. Our RM detection places upper limits that are 15% lower than those in their Figure 4. The important parameter for determining the upper limit is $r_{\rm in}$, the radius at which electrons become relativistic and their RM contribution begins to be suppressed (Quataert & Gruzinov 2000a). In general, shallow density profiles approaching that of the convection-dominated accretion flow ($\beta \to 1/2$; Narayan et al. 2000; Quataert & Gruzinov 2000b) yield hotter central temperatures and thus larger $r_{\rm in}$ (Quataert 2003), while steep profiles ($\beta \to 3/2$), as in Bondi-like or advection-dominated accretion flows (ADAF; Narayan & Yi 1995) are marginally relativistic to small radii and may have $r_{\rm in}$ of a few $r_{\rm S}$. Simulations (e.g. Hawley & Balbus 2002; Igumenshchev et al. 2003; Pen et al. 2003) favor $\beta \leq 1$. Those with published temperature profiles show $r_{\rm in}$ between 30 and 100 Schwarzschild radii ($r_{\rm S}$), yielding upper limits for $\dot{M}$ of 2×10^{-7} to 5×10^{-8} $M_\odot$ yr^{-1}.

Note that the assumptions of the M06 formalism, which were taken from previous related works (e.g. Melia 1992; Quataert & Gruzinov 2000a), are not constrained by existing observations. In particular, the assumption of equipartition-strength fields cannot be justified observationally, although simulations may show a tendency to reach equipartition fractions of a few percent (Igumenshchev et al. 2003). Magnetic fields that are a fraction ϵ of the equipartition strength will raise the accretion rate limits by $\epsilon^{-2/3}$ (a factor of 10 for $\epsilon = 3\%$). The assumption of a non-reversed field is also potentially suspect. The direction of position angle change with frequency, and thus the sign of the RM, appears unchanged since the Aitken et al. (2000) measurements in 1999. This is not natural for a turbulent accretion flow, except along special lines of sight (e.g., the axial region in model A of Igumenshchev et al. 2003). Ruszkowski & Begelman (2002) suggested that the stability of the sign of circular polarization (CP) noted by Bower et al. (2002) could be explained by Faraday conversion of linear to circular polarization in a highly reversed field with a small directional bias. The bias field (B_b) naturally creates stability in the CP and RM signs if $B_b \gg B_{rms}/\sqrt{N}$, where B_{rms} is the random field and N the number of reversals. In this limit the integrated product of the electron density and parallel magnetic field, without regard to field reversals, would be large, as would the accretion rate, but the net RM would be small and originate in the bias field. The turbulent jet model of Beckert & Falcke (2002) also uses a random field with a small bias to produce stability. If these models are correct the accretion rate upper limits derived from our RM detection would no longer hold.

Our RM also allows us to place lower limits on the accretion rate; these are not subject to the above caveats since the uncertainties act to raise the minimum accretion rate. If we take $r_{\rm in}$ to be around $10 r_{\rm S}$ or $3 r_{\rm S}$ (smaller $r_{\rm in}$ yields smaller lower limits, so this is conservative for hot flows), we find that $\dot{M}$ must be greater than $1-2 \times 10^{-8}$ $M_\odot$ yr^{-1} or $2-4 \times 10^{-9}$ $M_\odot$ yr^{-1}, respectively. If the field is toroidal, reversed, or sub-equipartition, these lower limits are raised and may pose problems for very low-$\dot{M}$ models. Using the RM-$\dot{M}^{3/2}$ scaling derived in M06, the observed limit on RM variability (35%) limits accretion rate variability to 25% over two months.

Our detection of significant variability in χ_0 is the first clear separation of the effects of a variable RM and variable intrinsic polarization; disentangling these effects requires multi-frequency observations. In the optically thin limit χ_0 represents the intrinsic polarization direction of Sgr A* at all frequencies and χ variations should follow χ_0 variations, with RM fluctuations potentially contributing a frequency-dependent component to the χ dispersion. However, comparing all previous measurements near 230 and 345 GHz (employing our RM to translate all observations to a single frequency), we find a dispersion of 22° in 16 observations at 230 GHz and just 8° in 11 epochs at 345 GHz (Aitken et al. 2000; Bower et al. 2003, 2005; M06; this work). Although these two dispersions scale by approximately ν^{-2}, consistent with RM fluctuations of approximately 2×10^5 rad m^{-2}, we consider this explanation unlikely. From equation (1), the proportionality between RM and χ fluctuations should be λ^2 if RM changes are responsible for χ changes, with an increasing RM (less negative) expected for increasing χ. In fact our 230 GHz data show the opposite trend, with the least negative RM values occurring on the days with the smallest χ. The best-fit slope of the RM$-\chi_{230}$ relation is $(-3.4 \pm 3.6) \times 10^3$ rad m^{-2} deg^{-1}, different from the expected slope of $+10 \times 10^3$ rad m^{-2} deg^{-1} by 4σ. Similar analysis is inconclusive in the 345 GHz data, which are less sensitive to RM. This confirms that we are seeing intrinsic polarization changes rather than RM fluctuations. Moreover, the necessary RM changes would yield variability of 150° at 83 GHz, much larger than the 8° observed by Macquart et al. (2006). The emission from Sgr A* appears to be optically thick below $300-400$ GHz (Marrone et al., in prep) so χ_0 may vary with frequency, contrary to the expectation at low optical depth. The observed spectrum of position angle variability between 83 and 345 GHz most likely represents differences in the stability of the magnetic field orientation (manifested as χ_0) at the photospheres at these frequencies. If the Faraday screen is located at much larger radii than the submillimeter emission region, its variations are likely to be slower than those of the intrinsic polarization; this allows the intrinsic changes to be isolated from putative RM fluctuations by examining short timescales, even without better knowledge of the RM stability.

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