Polarization in Sagittarius A*

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Abstract

We summarize the current state of polarization observations of Sagittarius A*, the compact radio source and supermassive black hole candidate in the Galactic Center. These observations are providing new tools for understanding accretion disks, jets and their environments. Linear polarization observations have shown that Sgr A* is unpolarized at frequencies as high as 86 GHz. However, recent single-dish observations indicate that Sgr A* may have strong linear polarization at frequencies higher than 150 GHz. Circular polarization, which was recently discovered in Sgr A*, is detectable to frequencies as high as 43 GHz. It is strongly variable on a 10-day timescale, with the degree of variability increasing with frequency. At low frequencies, fractional circular polarization is stable over nearly 20 years. We discuss some of the possible models for the origin of the circular polarization.

Introduction

Polarization observations have been very successful in the study of active galactic nuclei (AGN). Linear polarization (LP) observations have demonstrated conclusively that synchrotron emission is the dominant mechanism in jets, that magnetic fields are present in jets, and that shocks propagate in jets leading to variability in the total and polarized intensity. Circular polarization (CP) observations, while producing less clear cut conclusions so far, have the potential for illuminating new physics. For example, on the basis of CP observations Wardle et al. (1998) have recently claimed that jets are not primarily hadronic but leptonic.

With the success of polarization observations in AGN in mind, we set out to determine the polarization characteristics of Sagittarius A*, the supermassive black hole candidate and compact radio source in the Galactic Center. Polarization observations offer the possibility to break the theoretical deadlock that exists over the nature of Sgr A*. Both advection dominated accretion flow (ADAF) models (e.g., Özel, Psaltis & Narayan 2000) and accretion-disk-powered-jet models (Falcke & Biermann 1999) can account for the spectrum from centimeter wavelengths to the X-ray, while meeting the size constraints imposed by very long baseline interferometry.

Observational methods are limited by the high galactic extinction and the hyperstrong interstellar scattering screen in the Galactic Center. Polarization observations have the potential to see through the scattering screen and determine intrinsic source characteristics. Now, new observational results are leading to new opportunities for understanding of Sgr A*.

Linear Polarization

Sgr A* has been known to show no LP since not long after its discovery (Balick & Brown 1974). However, this result had not been quantified and it was often assumed that the interstellar scattering screen depolarized the intrinsic source through beam or bandwidth depolarization. Recently, with VLA and BIMA observations, we confirmed the low LP and showed that interstellar depolarization is unimportant (Bower et al. 1999ab). We summarize in Figure 1 our continuum measurements of LP in Sgr A*. Note that the increasing value of the upper limits with frequency is a measure of the increasing difficulty of these observations.

Both bandwidth and beam depolarization are Faraday effects. The dense, magnetized plasma of the interstellar scattering screen is a potential source of these effects. Observed rotation measures (RMs) in the GC are on the order of 10^3 rad m^{-2} (Yusef-Zadeh, Wardle & Parastaran 1997) but they could potentially reach $10^4 - 10^5$ rad m^{-2} (Bower et al. 1999a). High frequency polarimetry and spectro-polarimetry are useful techniques for avoiding these effects. The first relies on the decreasing strength of the effects with frequency. The second removes the effect of large RMs through a Fourier transform method.

In the case of bandwidth depolarization, a large RM rotates the LP position angle through $\gtrsim \pi$ rad in the observing band. High frequency continuum polarimetry and spectro-polarimetry rule this effect out in Sgr A*. The RM must exceed 8×10^6 rad m^{-2} in order to depolarize any intrinsic LP at 43 GHz in the 50 MHz bandwidth of the VLA. VLA spectro-polarimetry at 4.8 and 8.4 GHz also place a lower limit of $\sim 10^7$ rad m^{-2} to an RM that depolarizes intrinsic LP.

Beam depolarization occurs when different paths of the scatter broadened image experience different RMs. This places stricter limits on the RM than bandwidth depolarization, if the scale of turbulence is sufficiently small. RM variations greater than 3×10^5 rad m^{-2} are necessary to depolarize the signal at 86 GHz. These are disallowed, however, by the known conditions of the scattering medium.

Very recently, Aitken et al. (2000) reported that with SCUBA observations at the JCMT they have detected LP in Sgr A* at frequencies greater than 150 GHz. These results are complicated by the large primary beam of the JCMT ($34''$ at 150 GHz) and the presence of strong free-free emission and polarized dust emission. Removing these effects, Aitken et al. find 10^{+9}_{-4}% LP at 150 GHz. This result requires confirmation with a millimeter/submillimeter interferometer. If true, they are a significant and challenging addition to our understanding of the polarization properties of Sgr A*.

The very sharp rise in LP from 86 to 150 GHz may be due to Faraday effects in the accretion region (Bower et al. 1999a). Quataert and Gruzinov (2000) have demonstrated that a high frequency detection of LP can distinguish between disparate models for Sgr A*. ADAF inflows have high electron and magnetic field densities leading to bandwidth depolarization at radii $r \lesssim 10^4 r_g$ even at frequencies greater than 100 GHz. The high frequency detection by Aitken et al. implies that the electron density and accretion rate must be much lower than in the standard ADAF case.

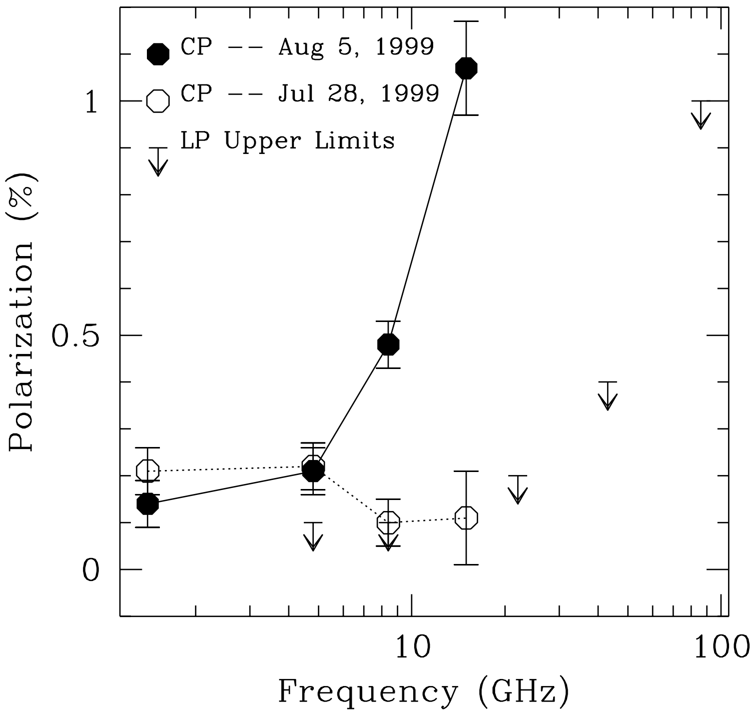

Figure 1: Linear and circular polarization in Sgr A* from 1.4 to 86 GHz. The down arrows indicate upper limits for linear polarization measurements. The open octagons are CP measurements from the VLA on July 28, 1999. The filled octagons are measurements from the VLA on August 5, 1999. The sign of CP has been flipped in this figure. Not shown is the $10^{+9}_{-4}\%$ detection of LP at 150 GHz by Aitken et al.

Circular Polarization

In the course of discovering that Sgr A* shows no LP at centimeter wavelengths, we discovered serendipitously that Sgr A* has strong CP (Bower, Falcke &

Backer 1999c). This is surprising in light of the strong limits on linear polarization. AGN typically have LP-to-CP ratios $\gg 1$ (Weiler & de Pater 1983). But for Sgr A* at 4.8 GHz, the fractional CP is $\sim -0.3\%$, which is at least 3 times the level of LP. We have since followed up with monitoring campaigns using the VLA and the ATCA and an analysis of data from the VLA archives covering 18 years. CP measurements with the VLA are technically difficult; confirmation with ATCA observations (Sault & Macquart 1999) and at multiple frequencies over many epochs with the VLA has been crucial.

The VLA archive data clearly indicates that the CP flux at 4.8 GHz is stable at $-0.31 \pm 0.13\%$ over 18 years, despite a factor of two change in total intensity. CP at 8.4 GHz is also apparently stable at $-0.27 \pm 0.10\%$ over 10 years. However, short-term variability around the mean value is apparent. In fact, the CP flux changes significantly on timescales as short as a few days. In Figure 1, we show the spectrum of CP from 1.4 to 15 GHz on two dates separated by a week. In this short interval, the CP has increased dramatically at frequencies greater than 5 GHz. This flare in fractional CP is coincident with a 30% flare in total intensity (Bower, Falcke, Sault & Backer 2000).

In general, the degree of CP variability increases sharply with frequency. Recently, after several epochs without detection, we have detected strong CP with an inverted spectrum at 22 and 43 GHz using the VLA. The analysis of this new result is not yet complete but the preliminary result suggests that the CP spectrum rises during flares into the millimeter regime.

Interpretation of the CP results is not yet certain. The variability suggests a two component model that includes a steep-spectrum quiescent phase and frequent inverted-spectrum flares. Under this scenario there are two distinct origins for the CP, originating in the low and high frequency components of Sgr A*. In jet models, these are more and less compact regions, respectively. In ADAF models, the high/low frequency component originates from non-relativistic/relativistic electrons in the flow.

Gyrosynchrotron radiation is a natural model for the high frequency component of the CP. It originates from non-relativistic electrons in a strong field and produces low LP-to-CP ratios. However, this is certainly not the only possible model. Synchrotron radiation can produce low LP-to-CP ratios under certain conditions. This can include the effects of linear-to-circular conversion, which is believed to be active in 3C 279 (Wardle et al. 1998). Finally, birefringent scattering, in which a magnetized region scatters LCP and RCP differentially in angle, could play role if the natural steep spectrum that it produces can be accounted for. Any model must explain the low LP-to-CP ratio, the inverted spectrum of CP and the nature of the variability. Detailed modeling of the source is probably necessary.

Outstanding observational issues for the CP in Sgr A* are the relationship between CP and total intensity fluctuations; determining the turnover frequency of CP flares; and observing potential structural changes on the AU scale that are related to CP variability.

In the future, CP and LP measurements could be very important tools for understanding accretion flows, jets and their environments. Nearby low luminosity AGN, which are often associated with ADAF systems, are the first targets for these studies. However, before that we must ground our understanding of these behaviors in the best studied and most well-known AGN, Sgr A*.

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