The Astrophysical Journal, 560:L123–L126, 2001 October 20

DETECTION OF CIRCULAR POLARIZATION IN M81*

A. Brunthaler,[1,2] G. C. Bower,[3] H. Falcke,[2] and R. R. Mellon[4]

Received 2001 March 30; accepted 2001 September 10; published 2001 September 28

ABSTRACT

We report the detection of circular polarization in the compact radio jet of the nearby spiral galaxy M81 (M81*). The observations were made with the Very Large Array at 4.8 and 8.4 GHz, and circular polarization was detected at both frequencies. We estimate a value of $m_c = 0.54\% \pm 0.06\% \pm 0.07\%$ at 8.4 GHz and $m_c = 0.27\% \pm 0.06\% \pm 0.07\%$ at 4.8 GHz for the fractional circular polarization. The errors are separated into statistical and systematic terms. The spectrum of the circular polarization is possibly inverted, which would be unusual for active galactic nuclei. We also detected no linear polarization in M81* at a level of 0.1%, implying that the source has a very high circular-to-linear polarization ratio as found so far only in Sagittarius A*, the central radio source in our Galaxy. This further supports the idea that M81* is a scaled-up version of Sgr A* and suggests that the polarization properties are intrinsic to the two sources and are not caused by a foreground screen in the Galaxy.

Subject headings: galaxies: active — galaxies: individual (M81) — polarization

1. INTRODUCTION

The nearby spiral galaxy M81 (NGC 3031) is very similar to our own Galaxy in many ways. It resembles the Milky Way in type, size, and mass. It also contains a radio core, M81*, that is most likely associated with a supermassive black hole.

Previous VLBI (Bietenholz et al. 1996), multiwavelength (Ho, Filippenko, & Sargent 1996), and submillimeter observations (Reuter & Lesch 1996) have shown that M81* is very similar to Sagittarius A*, the central radio source in our Galaxy. A comparison of the two radio sources therefore may provide interesting insights in their nature.

Especially for Sgr A*, the nature of the radio emission has been debated for quite some time (see Melia & Falcke 2001 for a review). Either an origin in an accretion flow (Melia 1992; Narayan, Yi, & Mahadevan 1995) or in a jet has been proposed (Falcke, Mannheim, & Biermann 1993; Falcke & Markoff 2000). The jet model, within the context of the jet-disk symbiosis, has also been applied to M81* (Falcke 1996), where it can reproduce the radio flux density and the size of the radio core simply by changing the accretion rate. Indeed, Bietenholz, Bartel, & Rupen (2000) have discovered a one-sided, although very compact, jet in M81*, and they pointed out that in terms of power, jet length, and perhaps accretion rate, M81* is intermediate between radio cores of quasars and Sgr A*.

Recently, Bower, Falcke, & Backer (1999c) detected circular polarization in Sgr A* in the absence of linear polarization (Bower et al. 1999a, 1999d). This was confirmed by Sault & Macquart (1999). This result is surprising, since linear polarization usually exceeds circular by a large factor in active galactic nucleus (AGN) radio jets (Wardle et al. 1998; Rayner, Norris, & Sault 2000). Bower et al. (1999b) proposed that low-energy electrons intrinsic to the source reduce the linear polarization through Faraday depolarization and convert linear polarization into circular polarization (Pacholczyk 1977; Jones & O'Dell 1977). This would provide very important information on the matter content of Sgr A*. On the other hand, it cannot be excluded that the accretion region around Sgr A* contributes to the unusual polarization (Bower et al. 1999a; Quataert & Gruzinov 2000). Less likely, but not fully excluded, is the possibility that the hyperstrong scattering screen could induce the circular polarization through propagation effects (Macquart & Melrose 2000).

Since M81* is not in the direction of the Galactic center and is likely to be observed under a very different inclination angle, observations of this closely related source are independent of the details of the geometry of Sgr A*. Here we report the results of circular and linear polarization observations of M81*, which indicate that indeed M81* and Sgr A* have similar polarization properties.

2. OBSERVATIONS AND RESULTS

We observed M81* with the Very Large Array (VLA) on 2000 April 4 at 8.4 GHz in the C configuration, on 2000 September 27 at 4.8 and 8.4 GHz in the D configuration, and on 2000 November 4 at 4.8 GHz in the A configuration with a bandwidth of 50 MHz in right-circular polarization and left-circular polarization. We used 3C 48 as the primary flux density calibrator, J1044+719 as the secondary calibrator, and J1053+704 as the check source. We went through the cycle J1044+719–M81*–J1053+704–J1044+719–M81*–J1053+704–J1044+719 once for each frequency on 2000 September 27 and twice at 4.8 GHz on 2000 November 4. The observation on 2000 April 4 was part of a polarization survey of 11 low-luminosity AGNs, of which M81 is the closest (Mellon et al. 2000). Here we went through the cycle J1044+719–J1053+704–M81*–J1044+719 five times. A detailed discussion of this survey will be given in an upcoming paper (G. C. Bower, R. R. Mellon, & H. Falcke 2001, in preparation).

Data reduction was performed with AIPS. Absolute flux densities were calibrated with the source 3C 48. Then amplitude and phase self-calibration was performed on J1044+719. This

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS 42, Cambridge, MA 02138; abrunthaler@cfa.harvard.edu.

[2] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany; hfalcke@mpifr-bonn.mpg.de.

[3] Radio Astronomy Laboratory, University of California at Berkeley, 601 Campbell Hall, Berkeley, CA 94720.

[4] Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802.

TABLE 1

Total Flux Density I, Circularly Polarized Flux Density P_c, Image rms, and Fractional Circular Polarization m_c at 4.8 GHz

Source	Date	Time on Source (minutes, s)	I (mJy)	P_c (mJy)	rms (mJy)	m_c (%)
J1044+719	2000 Sep 27	3, 20	1443	<0.92	0.34	<0.06 ± 0.02
	2000 Nov 04	5, 17	1503	<0.51	0.15	<0.03 ± 0.01
M81*	2000 Sep 27	5, 3	193.5	0.53	0.11	0.27 ± 0.06 ± 0.07
	2000 Nov 04	12, 8	160.7	0.41	0.07	0.26 ± 0.04 ± 0.06
J1053+704	2000 Sep 27	1, 49	355.1	<0.53	0.17	<0.15 ± 0.05 ± 0.07
	2000 Nov 04	4, 6	362.1	<0.26	0.11	<0.07 ± 0.03 ± 0.06

forces J1044+719 to have zero circular polarization. The amplitude calibration solutions were transferred to M81* and J1053+704. Finally, each source was phase self-calibrated and imaged in Stokes I and V. Flux densities were determined by fitting a beam-sized Gaussian at the image center.

The Stokes parameter V is measured as the difference between the left- and right-handed parallel polarization correlated visibilities. Errors in circular polarization measurements with the VLA have numerous origins: thermal noise, gain errors, beam squint, second-order leakage corrections, unknown calibrator polarization, background noise, and radio frequency interference. The thermal noise is given by the rms in each map, and the values are shown in Table 1. The errors caused by amplitude calibration errors, beam squint, and polarization leakage scale with the source strength, and therefore the fractional circular polarization is a more relevant indicator for the detection of circular polarization. A detailed discussion of these errors is given in Bower et al. (1999c; G. C. Bower, H. Falcke, R. J. Sault, & D. C. Backer 2001, in preparation). We calculated the systematic errors based on the model for VLA circular polarization from G. C. Bower, H. Falcke, R. J. Sault, & D. C. Backer (2001, in preparation). These values are given in Tables 1 and 2.

For the observation on 2000 April 4, 3C 48 was used to calibrate the position angle of linear polarization, and the sources were also imaged in Stokes U and Q to provide linear polarization information.

The results for M81*, the calibrator J1044+719, and the check source J1053+704 are given for 4.8 GHz in Table 1 and for 8.4 GHz in Table 2. The check source J1053+704 showed weak circular polarization at a level of 0.14% on 2000 April 4 at 8.4 GHz. At all other observations, the calibrator source and the check source showed no detectable circular polarization. The upper limits in Tables 1 and 2 were determined by fitting a beam-sized Gaussian at the image center. M81* showed circular polarization in all observations.

We find values of $m_c = 0.27\% \pm 0.06\% \pm 0.07\%$ and $m_c = 0.26\% \pm 0.04\% \pm 0.06\%$ for the fractional circular polarization at 4.8 GHz on 2000 September 27 and 2000 November 4, respectively. At 8.4 GHz, the degree of circular polarization was $m_c = 0.25\% \pm 0.02\% \pm 0.05\%$ on 2000 April 4 and $m_c = 0.54\% \pm 0.06\% \pm 0.07\%$ on 2000 September 27. The errors are separated into statistical and systematic terms. Figure 1 shows the Stokes V map (*contours*) and the total intensity (*gray scale*) of M81* on 2000 September 27 at 8.4 GHz. M81* showed no detectable linear polarization, with an upper limit of 0.1%.

At 4.8 GHz, the measured values for circular polarization in M81* are 5 and 6 times the rms in the image for the observations on 2000 September 27 and November 4, while the upper limits on circular polarization for the check source are only 3 and 2 times the image rms for the two observations. The detection is stronger in the later observation, since the observing time was more than twice as long as in the first observation.

In our observation on 2000 September 27, the measured value for circular polarization in M81* at 8.4 GHz is 10 times the rms in the image for the observation on 2000 September 27, while the upper limit on circular polarization for the check source is 4 times the rms. On 2000 April 4, we detected circular polarization in both M81* and the check source at a level of 10 times the image rms, but the fractional circular polarization is a factor of 2 higher in M81*.

If the detections would have been caused by calibration errors, beam squint, polarization leakage, or unknown calibrator polarization, fractional circular polarization should have been detected in the check source with the same value.

3. DISCUSSION

The mechanism for the production of circular polarization in AGNs is still not known with absolute certainty, and several mechanisms have been proposed. An important new parameter, which has been largely ignored so far, is the circular-to-linear polarization ratio $R_{\rm CL} = m_c/m_l$. For powerful blazars one typically has $R_{\rm CL} \ll 1$ (Homan & Wardle 1999) for the cores of jets. In the radio cores of very low power AGNs, M81* and Sgr A*, we now find $R_{\rm CL} \gg 1$ with limits on the linear polarization that are very low.

TABLE 2

Total Flux Density I, Circularly Polarized Flux Density P_c, Image rms, and Fractional Circular Polarization m_c at 8.4 GHz

Source	Date	Time on Source (minutes, s)	I (mJy)	P_c (mJy)	rms (mJy)	m_c (%)
J1044+719	2000 Apr 04	12, 8	1542	<0.02	0.03	<0.001 ± 0.002
	2000 Sep 27	3, 28	1316	<0.60	0.28	<0.05 ± 0.02
M81*	2000 Apr 04	4, 59	263.6	0.66	0.06	0.25 ± 0.02 ± 0.05
	2000 Sep 27	5, 3	193.6	1.05	0.11	0.54 ± 0.06 ± 0.07
J1053+704	2000 Apr 04	10, 1	467.7	0.66	0.07	0.14 ± 0.01 ± 0.05
	2000 Sep 27	2, 4	405.0	<0.68	0.19	<0.17 ± 0.05 ± 0.07

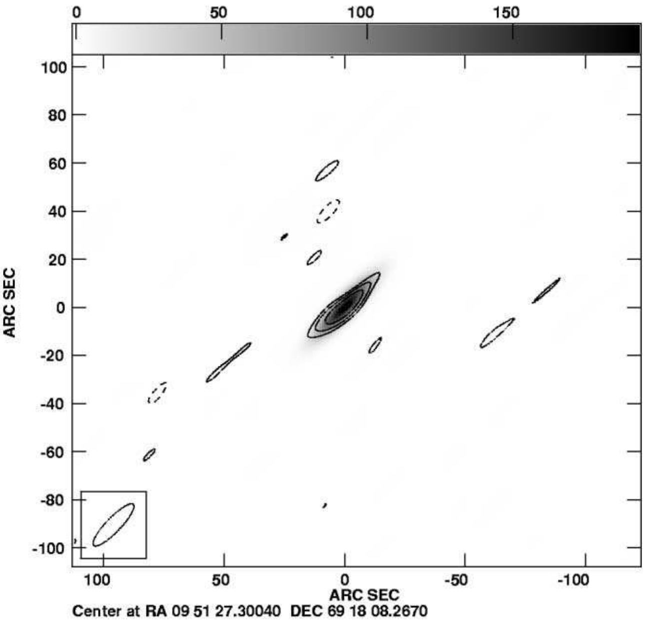

FIG. 1.—Stokes V (*contours*) and total intensity (*gray scale*) map for M81 on 2000 September 27 at 8.4 GHz. The rms noise of the Stokes V map is 0.11 mJy beam^{-1}. The contours are $0.3 \times (-1, 1, 1.414, 2, 2.828, 4, 5.657)$ mJy, and the peak flux density is 0.89 mJy beam^{-1}.

This first raises the question of how to reduce the linear polarization to such undetectable levels. Already Bower et al. (1999b, 1999d) suggested that Faraday depolarization in the interstellar medium, and specifically the scattering medium in the Galactic center, could not be responsible for this. Our finding of a high $R_{\rm CL} = m_c/m_l$ in M81*, which is not scatter broadened, confirms this notion. This also suggests that the birefringent screen proposed by Macquart & Melrose (2000) is not applicable here. On the other hand, depolarization by a hot, geometrically thick accretion flow (Agol 2000; Quataert & Gruzinov 2000) is not excluded but also does not yet explain the presence of circular polarization.

A viable mechanism could be Faraday conversion (Pacholczyk 1977; Jones & O'Dell 1977) of linear polarization to circular polarization caused by the lowest energy relativistic electrons. Bower et al. (1999c) proposed a simple model for Sgr A* in which low-energy electrons reduce linear polarization through Faraday depolarization and convert linear polarization into circular polarization. Conversion also affects the spectral properties of circular polarization and may lead to a variety of spectral indices, including inverted spectra (Jones & O'Dell 1977). In inhomogeneous sources, conversion can produce relatively high fractional circular polarization (Jones 1988).

Of course, synchrotron radiation has a small intrinsic component of circular polarization (Legg & Westfold 1968), which can play an important role. However, this intrinsic circular polarization will be reduced by field reversals and optical depth effects. Finally, gyro-synchrotron emission can also lead to high circular polarization with an inverted spectrum and low linear polarization (Ramaty 1969). All the latter mechanisms are to some degree related and require that M81* and Sgr A* both contain a rather large number of low-energy electrons. A more detailed discussion of this issue will be presented in an upcoming paper by T. Beckert et al. (2001, in preparation).

4. SUMMARY AND CONCLUSION

We have presented VLA observations of M81* at 4.8 and 8.4 GHz, and circular polarization was clearly detected at both frequencies with a possible flat-to-inverted spectrum at a level of 0.25%–0.5%.

In most AGNs, the fractional circular polarization typically 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. Surprisingly, the fractional circular polarization in M81* is higher at 8.4 GHz than at 4.8 GHz for our observation on 2000 September 27. The value at 4.8 GHz showed no variation between two epochs separated by six weeks despite a change in total intensity.

We also found that M81* shows less than 0.1% linear polarization, thus making M81* the second low-luminosity AGN radio core, after Sgr A*, with a circular-to-linear polarization $R_{\rm CL} \gg 1$. This confirms that both sources may be of similar nature and similar models may apply. It also strongly suggests that the polarization properties are indeed intrinsic to the two sources and are not caused by the Galactic scattering screen. In this respect, it is important that M81* was resolved into a jetlike structure by VLBI, indicating that jets indeed can produce an $R_{\rm CL}$ as high as observed here and in Sgr A*.

Since the basic mechanisms to explain circular polarization involve low-energy electrons, one will need to consider their origin and their effects on the spectrum in future models. This will provide one with an important new constraint for the sub-Eddington accretion onto supermassive black holes. Even if the radio emission is produced in a jet, the composition and temperature of this plasma should reflect the plasma properties of the accretion flow very close to the black hole.

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

REFERENCES

Agol, E. 2000, ApJ, 538, L121
Bietenholz, M. F., et al. 1996, ApJ, 457, 604
Bietenholz, M. F., Bartel, N., & Rupen, M. P. 2000, ApJ, 532, 895
Bower, G. C., Backer, D. C., Zhao, J.-M., Goss, M., & Falcke, H. 1999a, ApJ, 521, 582
———. 1999b, ApJ, 521, 582
Bower, G. C., Falcke, H., & Backer, D. C. 1999c, ApJ, 523, L29
Bower, G. C., Wright, M. C. H., Backer, D. C., & Falcke, H. 1999d, ApJ, 527, 851
Falcke, H. 1996, ApJ, 464, L67
Falcke, H., Mannheim, K., & Biermann, P. L. 1993, A&A, 278, L1
Falcke, H., & Markoff, S. 2000, A&A, 362, 113
Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1996, ApJ, 462, 183
Homan, D. C., & Wardle, J. F. C. 1999, AJ, 118, 1942
Jones, T. W. 1988, ApJ, 332, 678
Jones, T. W., & O'Dell, S. L. 1977, ApJ, 214, 522
Legg, M. P. C., & Westfold, K. C. 1968, ApJ, 154, 499
Macquart, J.-P., & Melrose, D. B. 2000, ApJ, 545, 798
Melia, F. 1992, ApJ, 387, L25
Melia, F., & Falcke, H. 2001, ARA&A, 39, 309
Mellon, R. R., Bower, G. C., Brunthaler, A., & Falcke, H. 2000, AAS Meeting, 197, 39.02
Narayan, R., Yi, I., & Mahadevan, R. 1995, Nature, 374, 623
Pacholczyk, A. G. 1977, Radio Galaxies: Radiation Transfer, Dynamics, Stability, and Evolution of a Synchrotron Plasmon (Oxford: Pergamon)
Quataert, E., & Gruzinov, A. 2000, ApJ, 545, 842

Ramaty, R. 1969, ApJ, 158, 753
Rayner, D. P., Norris, R. P., & Sault, R. J. 2000, MNRAS, 319, 484
Reuter, H.-P., & Lesch, H. 1996, A&A, 310, L5
Sault, R. J., & Macquart, J.-P. 1999, ApJ, 526, L85
Wardle, J. F. C., Homan, D. C., Ojha, R., & Roberts, D. 1998, Nature, 395, 457
Weiler, K. W., & de Pater, I. 1983, ApJS, 52, 293