The Astrophysical Journal, 521:L41–L44, 1999 August 10

DISCOVERY OF A NONTHERMAL GALACTIC CENTER FILAMENT (G358.85+0.47) PARALLEL TO THE GALACTIC PLANE

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Received 1999 April 28; accepted 1999 June 10; published 1999 July 6

ABSTRACT

We report the discovery of a new nonthermal filament, G358.85+0.47, the "Pelican," located ∼225 pc in projection from Sagittarius A and oriented parallel to the Galactic plane. VLA continuum observations at 20 cm reveal that this 7′ (17.5 pc) structure bends at its northern extension and is comprised of parallel strands, which are most apparent at its ends. Observations at 6 and 3.6 cm reveal that the Pelican is a synchrotron-emitting source and is strongly linearly polarized over much of its extent. The spectral index of the filament changes from $\alpha_{20/6} = -0.8$ to $\alpha_{6/3.6} = -1.5$. The rotation measures exhibit a smooth gradient, with values ranging from -1000 to 500 rad m^{-2}. The intrinsic magnetic field is well aligned along the length of the filament. Based on these properties, we classify the Pelican as one of the nonthermal filaments unique to the Galactic center. Since these filaments (most of which are oriented perpendicular to the Galactic plane) are believed to trace the overall magnetic field in the inner Galaxy, the Pelican is the first detection of a component of this field *parallel* to the plane. The Pelican may thus mark a transition region of the magnetic field orientation in the inner 1 kpc of the Galaxy.

Subject headings: Galaxy: center — ISM: magnetic fields — radio continuum: ISM

1. INTRODUCTION

The inner hundred parsecs of the Galaxy contain a wealth of unusual radio structures. Prominent among these are unusual linear sources known as the nonthermal filaments (NTFs). The NTFs are typically long (10 pc) and narrow (<0.5 pc) structures with nonthermal spectra and strong linear polarization, indicating synchrotron emission. The intrinsic magnetic field orientation in each NTF is aligned with its long axis. Substructure, in the form of splitting filaments, is observed in nearly every case. In addition, both ionized and molecular gas appear to be associated with almost every NTF (Morris & Serabyn 1996). The most famous of the NTFs, the Radio Arc, is a bundle of filaments that extends for ∼40 pc at $l = 0\overset{\circ}{.}2$, $b = 0\overset{\circ}{.}0$ (Yusef-Zadeh & Morris 1987). Other examples include the Northern and Southern Threads (Morris & Yusef-Zadeh 1985; Anantharamaiah et al. 1991; Lang, Morris, & Echevarria 1999), Sagittarius C (Lizst & Spiker 1995), G359.54+0.18 (Yusef-Zadeh, Wardle, & Parastaran 1997), and the Snake (Gray et al. 1995).

Although it is clear that the NTFs are magnetic in nature, the origin of the relativistic electrons and their mechanism for acceleration remain unclear. Several models of NTF generation have been proposed (see Morris 1996). A common feature of these models is that the NTFs trace the magnetic field in the Galactic center, giving insight to the overall field geometry in this region (Morris 1994). Since the NTFs are all oriented roughly perpendicular to the Galactic plane (within ∼20°), it appears that the magnetic field in this region is poloidal, as opposed to the azimuthal field that traces the spiral arms in most galaxies (Beck et al. 1996). In addition, Yusef-Zadeh & Morris (1987) argue that the field strengths in the NTFs must be of order ∼1 mG, in order to explain the rigid and ordered linear extents of the NTFs in the presence of the extreme turbulence found at the Galactic center.

Recently, a new wide-field image of the Galactic center at 90 cm was produced by Kassim et al. (1999) based on the VLA data of Anantharamaiah et al. (1991). In a careful examination of this image, a previously unidentified linear feature was discovered ∼$1\overset{\circ}{.}5$ from Sagittarius A (or 225 pc in projection assuming $D_{\rm GC} = 8.0$ kpc; Reid 1993). Close reinspection of the 843 MHz Molonglo Observatory Synthesis Telescope survey image (Gray 1994) confirms the presence of this feature in those data, although the coarse resolution (∼1′) makes it difficult to derive any spectral index information. This feature has now been labeled G358.85+0.47, based on its Galactic coordinates. G358.85+0.47 has a linear structure similar to the NTFs, but it is oriented parallel to the Galactic plane. In contrast, all other NTFs are oriented perpendicular to the Galactic plane. This Letter reports 20, 6, and 3.6 cm observations of G358.85+0.47, in both total intensity and linear polarization. Initial results from 20 cm VLA observations were reported in Anantharamaiah et al. (1999). Here we demonstrate that G358.85+0.47 is properly classified as an NTF, and we discuss the implications of an NTF oriented parallel to the Galactic plane.

2. OBSERVATIONS AND RESULTS

All observations of G358.85+0.47 were made with the VLA using a phase center at $(\alpha, \delta)_{\rm B1950} = 17^{\rm h}37^{\rm m}48\overset{\rm s}{.}7$, $-29°38'17\overset{''}{.}0$. The observing frequencies were 1.365 and 1.435 GHz in the 20 cm band, 4.585 and 4.885 GHz in the 6 cm band, and 8.085 and 8.465 GHz in the 3.6 cm band. The VLA was used in the B array (20 cm), C array (6 cm), and DnC array (3.6 cm), resulting in an approximately equal beam size ($8\overset{''}{.}5 \times 4''$) for all three bands. At each frequency, observations were made in dual-polarization mode with a bandwidth of 50 MHz. Standard Astronomical Imaging Processing System procedures were used for calibration, editing, and imaging of all data; 3C 286 was used in all instances for flux calibration; and NRAO 530 (1733−130) and 1748−253 were used for phase and polarization calibration.

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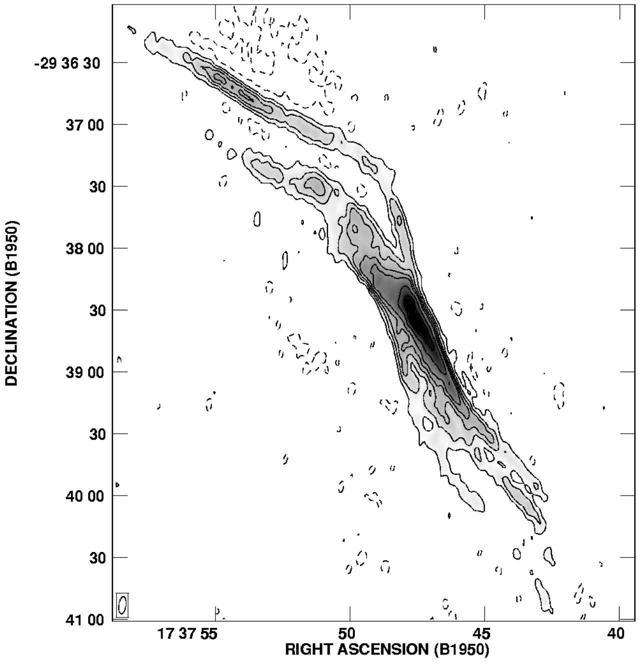

FIG. 1.—The 20 cm continuum image of the Pelican shown in both contours and negative gray scale. The resolution of this image is 8.″43 × 3.″39, P.A. = −7°, and it has been corrected for primary-beam attenuation. The rms noise in this image is 55 μJy beam^{-1}. The contour levels represent −0.2, 0.2, 0.4, 0.6, 0.8, 1, 1.4, 1.8, 2.0, and 2.2 mJy beam^{-1}.

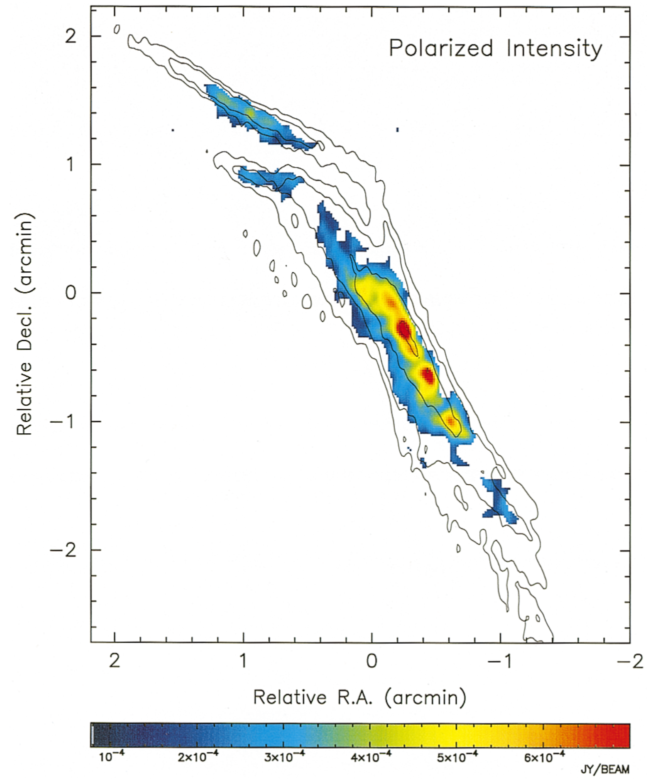

FIG. 2.—Total intensity and polarized emission at 6 cm arising from the Pelican, shown in right ascension and declination units of arcminutes offset from the phase center (α, δ_{B1950} = 17^{h}37^{m}48.^{s}7, −29°38′17.″0). The contours show the total intensity with a resolution of 8.″36 × 3.″54, P.A. = −1°, and an rms noise level of 20 μJy beam^{-1}. The contour levels represent 0.1, 0.2, 0.4, and 0.8 mJy beam^{-1}. The polarized emission is shown in false-color scale with a resolution of 9″ × 5″, in the range of 150–700 μJy beam^{-1}.

2.1. *Morphology of G358.85+0.47, "The Pelican"*

Figure 1 shows the 20 cm continuum image of G358.85+0.47, which appears as a linear feature extending for 7′ (17.5 pc) parallel to the Galactic plane. At a projected distance of 225 pc from Sgr A, this filament is the most distant NTF-like feature from the Galactic center. With the exception of its orientation, the morphological characteristics of G358.85+0.47 are similar to those of other NTFs. G358.85+0.47 is comprised of multiple, parallel filaments, which are most apparent at its ends, and has the appearance of a "pelican" figure, hence the name. Three strands can be distinguished at the southwest (SW) end, and at least two strands are distinguishable at the northeast (NE) extent. One of the strands starts ∼3′ NE of the center of the Pelican and appears to continue through the center, forming the middle SW strand. Similar to other NTFs, the peak emission occurs at the center of the filament. The NE extension of the Pelican has a different orientation by ∼45° from the orientation of the rest of the filament; bendings reminiscent to this have only been observed in one other NTF, the Snake (Gray et al. 1995). Observations of the Pelican at 6 and 3.6 cm reveal that it has essentially the same structure as at 20 cm.

2.2. *Spectral Index*

Based on the integrated fluxes at 90 cm (Kassim et al. 1999) and 20 cm, the spectral index of the Pelican is $\alpha = -0.6$ (where $S_\nu \propto \nu^\alpha$), consistent with synchrotron emission. At 20, 6, and 3.6 cm, where the structure of the Pelican is almost identical, pairwise spectral indices were determined using crosscuts of intensity at several positions along the length of the filament. The spectrum of the Pelican becomes steeper with frequency: $\alpha_{20/6} = -0.8 \pm 0.2$ and $\alpha_{6/3.6} = -1.5 \pm 0.3$, but the spectral index at each frequency pair is constant as a function of position along the filament. Since the beam diameter is essentially equal at each wavelength, the observed steepening in the spectral index is unlikely to be instrumental. An apparent flattening of the spectral index due to free-free absorption at the longer wavelengths can be ruled out by the estimated free-free optical depth at 90 cm. If the actual spectral index is that measured between 6 and 3.6 cm ($\alpha = -1.5$), then in order to produce the observed 20 cm flux density, an optical depth of $\tau_{20\,\mathrm{cm}}$ = 0.9 is required. This implies $\tau_{90\,\mathrm{cm}}$ = 18, which is impossible given that the Pelican was discovered at this wavelength. An alternate explanation is that the observed steepening is due to an intrinsic break in the spectrum. The dramatic steepening at shorter wavelengths may correspond to a very sharp cutoff in the electron energy distribution. A similar steepening of the spectral index has been observed in the Northern Thread, where $\alpha_{20/6} = -0.5$ and $\alpha_{6/2} = -2.0$ (Lang et al. 1999).

2.3. *Polarization*

Observations of the Pelican at 6 and 3.6 cm were the most sensitive to polarization. At 20 cm, if the magnitude of the rotation measure is greater than 500 rad m^{-2}, Faraday rotation across the 50 MHz bandwidth (>90°) will depolarize the polarized emission. A very low level of polarization is detected at 20 cm where the rotation measure values are between −500 and 500 rad m^{-2}, but since it covers such a small portion of the Pelican and has a low signal-to-noise ratio, we rely on the 6 and 3.6 cm data for polarization results. Figure 2 shows the distribution of polarized intensity at 6 cm. The polarized emis-

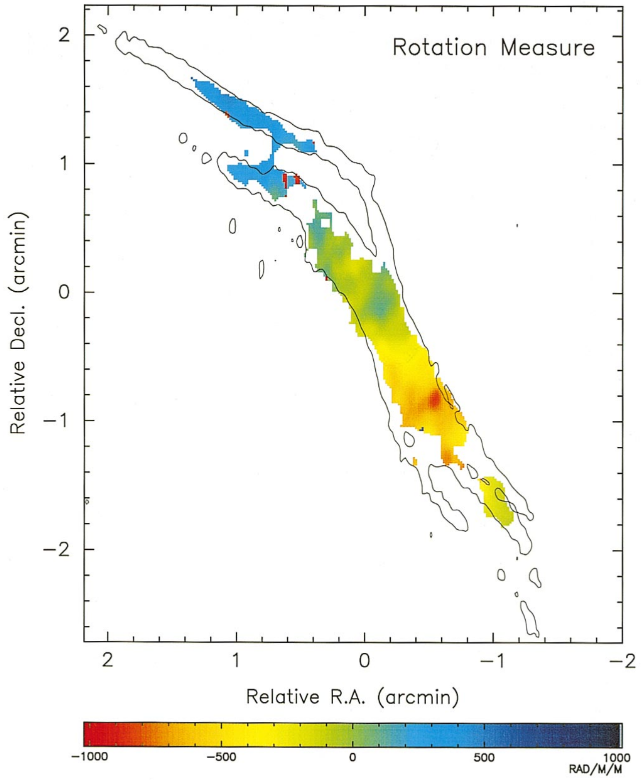

FIG. 3.—The distribution of the RM along the Pelican is shown in false-color scale with units of rad m^{-2}, superposed with the 0.2 mJy beam^{-1} contour of total 20 cm intensity from Fig. 1. The right ascension and declination axes are the same as in Fig. 2.

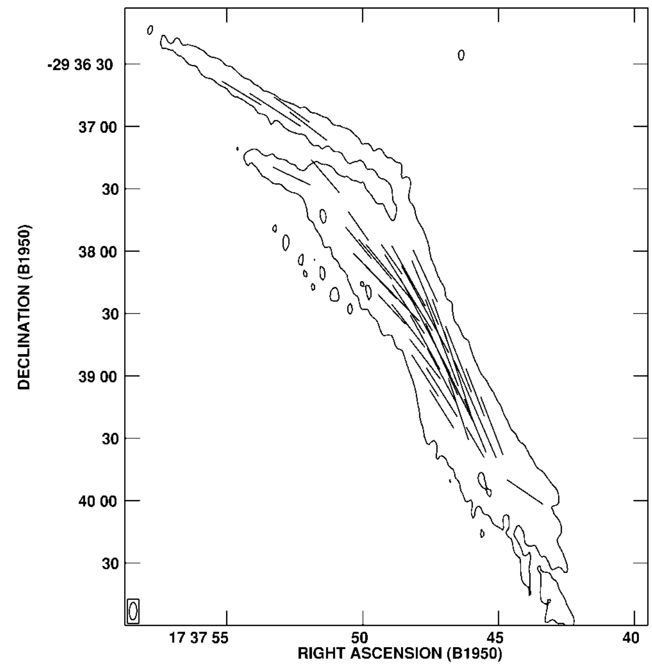

FIG. 4.—The vectors representing the intrinsic orientation of the magnetic field in the Pelican are shown superposed on the 0.2 mJy beam^{-1} contour of 6 cm continuum emission from Fig. 2.

sion is concentrated along a central ridge of the Pelican, where several peaks of polarized emission are obvious, and extends over more than half the length of the filament. Polarized emission also arises from the NE extension of the Pelican. Crosscuts of the polarized and total intensity at several positions along the filament length were compared. At 6 cm, fractional polarizations are typically 50%–60%, whereas at 3.6 cm, the fractional polarization is 60%–75%. Faraday rotation may cause the 6 cm fractional polarization to be slightly lower than at 3.6 cm, since the magnitude of Faraday rotation is proportional to λ^2. The fractional polarization in the Pelican is higher and more coherent across the filament than in other NTFs (Gray et al. 1995; Yusef-Zadeh et al. 1997; Lang et al. 1999). Since the fractional polarizations are near the theoretical limit for synchrotron emission (75%), there does not appear to be any significant depolarization toward the Pelican. At 6 and 3.6 cm, bandwidth depolarization is insignificant for $\Delta\nu = 50$ MHz. Also, beam depolarization cannot be a significant effect since we find that the intrinsic magnetic field is highly ordered (see below).

2.4. *Rotation Measure and Intrinsic Magnetic Field Orientation*

Using the polarization angles at the four observed frequencies (4.585, 4.885, 8.085, and 8.465 GHz), we can solve for the Faraday rotation toward the Pelican. Figure 3 shows the rotation measure (RM) distribution, with RM values in the range of -1000 to 500 rad m^{-2}. Errors were estimated using fits of the rotation angle to λ^2 and are in the range of ± 10 rad m^{-2}. There is a strong gradient of RM across the Pelican: at the NE extent, RM $=$ 500 rad m^{-2}, at the center, RM $=$ 0 rad m^{-2}, and at the SW end, RM $= -500$ rad m^{-2}. The RM values toward the Pelican are less than those toward the other NTFs, where rotation measures are typically 2000–5000 rad m^{-2} (Gray et al. 1995; Yusef-Zadeh et al. 1997; Lang et al. 1999). The sign reversal of the RM toward the center of the Pelican has also not been observed toward any of the other NTFs. Both the high fractional polarization and the λ^2 dependence of the rotation angle indicate that internal Faraday rotation is not occurring in the Pelican. Therefore, the sign reversal in the RM implies that the magnetic field along the line of sight to the Pelican must undergo a sign reversal in the intervening medium.

Figure 4 shows the orientation of the intrinsic magnetic field in the Pelican, after correction for Faraday rotation. The magnetic field is remarkably well aligned along the entire extent of the filament, showing that the structure is indeed dominated by the magnetic field. Therefore, the highest equipartition magnetic field value obtained for the Pelican in its narrow NE extension, ~70 μG, is a lower limit. At the center of the Pelican, the orientation of the field is parallel to the filament and to the Galactic plane; in the NE extension, where the filament bends by ~45°, the field orientation also changes by ~45°. The magnetic field orientation in both strands of the NE region of the Pelican bends as the filament does, thus demonstrating that the magnetic field also dominates the substructure of the filament. Figure 4 therefore illustrates the first detection of a large-scale magnetic field in the Galactic center region that is oriented differently from the known magnetic structures.

3. DISCUSSION

There is no doubt that the Pelican should be classified as a member of the unusual class of Galactic center NTFs, despite its orientation parallel to the Galactic plane. Its morphology, spectral index, fractional polarization, and the alignment of the magnetic field along its length are all very consistent with the known properties of the NTFs. The multiple parallel strands in the Pelican are reminiscent of the filaments in the Radio Arc (Yusef-Zadeh & Morris 1987), where more than a dozen strands run along the length of the Radio Arc and appear to bifurcate into multiple, parallel strands. In the case of the Pelican, the filamentation manifests itself on a smaller scale, and there are fewer strands. The concentration of brightness toward the center of the Pelican, and the wispy nature of the strands of filamentation toward its end, can be compared with the structure in Sgr C, G359.54+0.18, and G359.8+0.2, which also show bright centers and diffuse subfilamentation at their ends (Anantharamaiah et al. 1991; Lizst & Spiker 1995; Yusef-Zadeh et al. 1997; Lang et al. 1999).

Many of the well-studied NTF systems have associated ionized and molecular gas, and there seems to be evidence for interaction between them (Serabyn & Güsten 1991; Serabyn & Morris 1994; Uchida et al. 1996; Staghun et al. 1998). Such associations have in fact been used to construct models for the generation of NTFs through the interaction of the strong and ordered large-scale magnetic field (traced by NTFs) with the magnetic field that is tied to the partially ionized molecular gas. Where these field systems intersect, magnetic field reconnection has been invoked to accelerate the electrons along the field lines, thereby illuminating the NTFs (Serabyn & Morris 1994). The Pelican does not appear to be associated with any ionized region, and any association with molecular material remains to be investigated. The relative isolation of the Pelican could thus prove to be an interesting counterexample to the known NTFs and may constrain existing models for NTF generation.

Since the NTFs are the main probe of the large-scale magnetic field at the Galactic center, their structure and orientation are crucial for understanding the magnetic field geometry in this region. Morris (1994) points out that the gentle curvature of several of the NTFs is suggestive of a dipolar field that diverges above and below the plane. The 45° bend in the northern filamentary strands of the Pelican may establish a link between the magnetic field orientation that it traces and the perpendicular component that the other NTFs define. Indeed, there may be a transition region occurring at ∼200 pc from the Galactic center, inside of which the magnetic field appears to be vertical and highly ordered. The Pelican demonstrates that the magnetic field in the inner regions of the Galaxy has a more complicated structure than the apparently simple vertical dipolar field, which is suggested by the known NTFs.

4. SUMMARY

We report the discovery of a new filamentary feature, G358.85+0.47, located ∼225 pc in projection from the Galactic center. Based on its appearance, we refer to it as the Pelican. Multifrequency VLA observations show that the Pelican can be properly classified as a Galactic center NTF. The Pelican has a nonthermal spectrum and is strongly linearly polarized, similar to other NTFs. The unique feature of the Pelican is its orientation, parallel to the Galactic plane, in contrast to the rest of the NTFs, which are oriented perpendicular to the plane. After correction for Faraday rotation, the intrinsic magnetic field of the Pelican is remarkably well aligned along its length. The north strand of the Pelican bends by ∼45° from the orientation of the rest of the filament, and the orientation of the intrinsic magnetic field follows this bend. Since the NTFs are believed to trace the overall magnetic field configuration in the inner few hundred parsecs of the Galaxy, the detection of the Pelican makes it the first component of the large-scale magnetic field found in the inner Galaxy to be parallel to the Galactic plane.

The Very Large Array (VLA) is a facility of the National Science Foundation, operated under a cooperative agreement with the Associated Universities, Inc. Basic research in radio astronomy at the Naval Research Lab is supported by the office of Naval Research.

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