ANOMALOUS MOTION OF IONIZED GAS IN THE SICKLE (G0.18−0.04) NEAR THE GALACTIC CENTER

F. YUSEF-ZADEH
Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208; zadeh@ossenu.astro.nwu.edu

D. A. ROBERTS
National Center for Supercomputing Applications, 405 N. Mathews Avenue, Urbana, IL 61801; dougr@ncsa.illinois.edu

AND

M. WARDLE
Special Research Centre for Theoretical Astrophysics, University of Sydney, NSW 2006, Australia; wardle@physics.usyd.edu.au

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ABSTRACT

We present VLA measurements of H92α radio recombination line emission from the unusual H II region G0.18−0.04, the “Sickle,” with spatial and spectral resolutions of 27′′×24′′ and 14 km s−1, respectively. These observations detected two new kinematic components of ionized gas whose velocities differ greatly from the +25 km s−1 molecular cloud surrounding the Sickle. One component is highly redshifted with a peak velocity of about +150 km s−1, and the other is a blueshifted velocity feature peaking near −35 km s−1. Neither of these high-velocity features have molecular counterparts. The blueshifted feature is forbidden in the sense of Galactic rotation and coincides with the prominent nonthermal filaments crossing the Sickle, thus suggesting that they are physically associated with each other. The results presented here are interpreted in terms of ionized gas being accelerated away from the surface of the cloud associated with the Sickle region, either by the magnetic field associated with the nonthermal filaments or by the stellar winds from the hot helium stars near G0.18−0.04.

Subject headings: galaxies: ISM — Galaxy: center — ISM: individual (Sagittarius A East, Sagittarius A West) — ISM: magnetic fields

1. INTRODUCTION

The unusual source G0.18−0.04, the “Sickle,” is where the nonthermal filaments (NTFs) of the Galactic center are appear to coincide with a thermal source at the Galactic plane (Yusef-Zadeh, Morris, & Chance 1984; Yusef-Zadeh & Morris 1987a). The filaments are long, narrow synchrotron-emitting features tracing organized magnetic fields that run perpendicular to the Galactic plane (Yusef-Zadeh & Morris 1987b). G0.18−0.04 is one of the most interesting regions in the Galactic center because of its potential to provide important clues about the nature of the acceleration of relativistic particles of the NTFs and of the ionization mechanism of thermal gas.

Radio recombination and molecular line studies of G0.18−0.04 detected ionized thermal gas with a sickle-shaped appearance at a velocity near +40 km s−1 delineating the eastern edge of the +25 km s−1 molecular cloud (Yusef-Zadeh, Morris, & van Gorkom 1989; Serabyn & Güsten 1991). G0.18−0.04 is thought to be photoionized by a number of hot helium stars that have been discovered nearby (Moneti, Glass, & Moorwood 1991; Figer, McLean, & Morris 1995; Cotera et al. 1996), and the infrared and radio recombination line ratios are consistent with this picture (Harris et al. 1994; Timmermann et al. 1996; Lang, Goss, & Wood 1997; Simpson et al. 1997).

Interferometric CS observations by Serabyn & Morris (1994) have shown clumps of molecular gas aligned along the NTFs, supporting the suggestion that the NTFs arise through an interaction with a Galactic center molecular cloud with the strong, ambient magnetic field believed to permeate the region (Serabyn & Güsten 1991). In this scenario, the interaction between the magnetic field and the ionized gas at the cloud surface loads energetic particles onto the field lines and the resultant synchrotron emission produces the NTF.

In this Letter we present low spatial and spectral resolution (26′′ and 14 km s−1) observations of G0.18−0.04. The observations complement the detailed high-resolution (6′′ and 8.5 km s−1) H92α observations of Lang et al. (1997) by their increased sensitivity to low surface brightness emission. We report the detection of two extreme low- and high-velocity ionized features in the Sickle at $V_{LSR} = -35$ and +150 km s−1. The low-velocity features are associated with the sites of interaction of the NTFs with the Sickle and further strengthen the connection between the Sickle and the NTFs.

2. OBSERVATIONS

H92α observations of the Sickle were carried out on 1988 July 14 using the D configuration of the Very Large Array of the National Radio Astronomy Observatory. A preliminary account of this observation was described by Yusef-Zadeh et al. (1989). This observation was centered at α(1950) = 17°43′05″, δ(1950) = −28°48′45″.

NRAO 530 and 3C 48 were used as phase and flux density calibrators. Bandpass solutions were obtained using both a 1 hr observation of 3C 84 and the periodic observations of the complex gain calibrator, NRAO 530. The solutions obtained using NRAO 530 were superior to those obtained using 3C 84, because of the fact that they were determined periodically (every 30 minutes) and could track the short timescale variation in the bandpass; thus, the bandpass was corrected using NRAO 530. The correlator was set to observe 32 channels in right-circular polarization with a total bandwidth of 12.5 MHz centered on $V_{LSR} = +60$ km s−1. After on-line Hanning smoothing, the data covered a velocity range of −162 < $V_{LSR}$ < +275 km s−1, with a channel resolution and separation of 14 km s−1. After careful editing of short-spacing visibilities, standard calibration was carried out. In order to emphasize the weak, extended structures, the visibility data were naturally weighted.
Fig. 1.—The gray-scale image in the bottom right-hand corner shows the 8.3 GHz continuum emission from the Sickle region with a spatial resolution of 27'8 × 24'9 (P.A. = 61°). Contour levels for this figure, as well as Figs. 2, 3, and 4, are represented at 20, 80, 140, 200, and 260 mJy beam⁻¹. The three H92α line profiles are obtained at the positions marked in the continuum image. In the profiles, the crosses show the observed spectra, the solid lines show the model fits, and the dotted lines show the residuals.

and tapered at 5 kλ, giving an angular resolution of 27'8 × 24'9 (P.A. = 61°). The continuum channels were fitted and subtracted in the visibility domain using UCLIN in AIPS; the resulting continuum-subtracted data set was imaged. The continuum image was formed by averaging the visibility data in the line-free channels. The typical rms noises for a single line channel and for the continuum are ≈0.55 and 1.58 mJy beam⁻¹, respectively. The negative features near bright sources in the final images are a result of structure in spatial frequencies smaller than those sampled in these observations. The images of integrated line emission and velocity fields were created with the MOMENT program in the MIRIAD software package of the Berkeley-Illinois-Maryland-Association (BIMA). During the moment analysis, the line intensity was used only where the emission was above 2 mJy beam⁻¹ (signal-to-noise ratio [S/N] ≈ 4).

3. RESULTS

The bottom right-hand panel of Figure 1 shows gray-scale and contour representations of the continuum emission from the inner 20 pc of the Sickle feature. The continuum contours show the diagonal southeast-northwest linear feature running perpendicular to the Galactic plane and crossing the Sickle. In high-resolution observations (Yusef-Zadeh & Morris 1987a, 1987b), the linear feature is resolved into a system of narrow and long NTFs. This low-resolution continuum image shows clearly that the system of linear filaments become rather discontinuous and weaker in surface brightness as they cross the Galactic plane and extend to the northwest of the Sickle. The continuum emission associated with the linear feature peaks at a flux density of ≈150 mJy near α(1950) = 17°43′05″, δ(1950) = –28°49′. In high-resolution images, this peak feature appears to be extended to the northern half of the Sickle; this feature is called the “Wake” in the schematic diagram of Yusef-Zadeh & Morris (1987a). The circular-shaped source G0.15−0.05, the “Pistol,” is the brightest continuum feature in Figure 1 located near α(1950) = 17°43′05″, δ(1950) = –28°49′. A north-south feature near the southern half of the Sickle at α(1950) = 17°42′55″, δ(1950) = –28°50′02″ is also noted. The three panels surrounding the continuum image of Figure 1 show three spectra taken toward positions marked as crosses on the continuum image.
The most interesting result is the detection of extended blueshifted ionized gas, which is forbidden in the sense of the Galactic rotation. Figure 2 shows a gray-scale image of the H92α line emission, integrated between $-63$ and $-7$ km s$^{-1}$, overlaid with contours of continuum emission. A typical spectrum of this new feature is shown in position 1 of Figure 1 with an S/N of $\approx 7.6$ and a peak flux density of 4.2 mJy at $\approx -36.0$ km s$^{-1}$. Most of the blueshifted velocity feature is distributed in the diffuse region to the east of the Sickle and to the north of the nonthermal linear feature.

The integrated line emission peaks at $\alpha(1950) = 17^h 43^m 3s.5$, $\delta(1950) = -28^\circ 47' 55''$, coincident with the location of one of the NTFs having the continuum flux density of 83.5 mJy beam$^{-1}$ as it crosses the Sickle. The brightness of the continuum emission from the diagonal linear feature becomes rather weak exactly where the blueshifted ionized feature peaks. High-resolution radio continuum images of this area are dominated by the narrow, nonthermal filaments (Yusef-Zadeh & Morris 1987a). Assuming that the emitting gas for this particular component is in LTE with the line-to-continuum ratio of 5% and an electron temperature of 9800 K (see below), the total ionized mass and the average electron density for the negative velocity feature are estimated to be $\approx 30 M_\odot$ and 150 cm$^{-3}$, respectively. These values are based on assumed model geometries and are uncertain by a factor of 3.

The other peaks in integrated emission at $\alpha(1950) = 17^h 43^m 3.5$, $\delta(1950) = -28^\circ 46' 45''$ and $\alpha(1950) = 17^h 42^m 58'$, $\delta(1950) = -28^\circ 48' 15''$ are generally consistent with the high-resolution observations of Lang et al. (1997), who noted blueshifted velocity features in the region where the $-35$ km s$^{-1}$ feature crosses the northern half of the Sickle (see their L2 and L3 spectra) and at the southern tip of the Sickle (their L8 line profiles). Blueshifted emission is present in the [Ne ii] 12.8 $\mu$m spectrum taken toward the Sickle (see Fig. 6 of Serabyn & Güsten 1991) and possibly in the [O iii] 88 $\mu$m spectrum taken by Timmermann et al. (1996) toward the southernmost peak of the integrated line emission in Figure 2 (see their Fig. 3a).

Figure 3 is a gray-scale representation of the highest redshifted velocity features between $+106$ and $+205$ km s$^{-1}$ with continuum emission contours superposed. Two highly redshifted components are noted in this figure. One is the velocity feature associated with the Pistol located to the south of the linear feature having a peak velocity of $+125$ km s$^{-1}$ (Yusef-Zadeh et al. 1989; Lang et al. 1997). The second component is a new high-velocity redshifted feature distributed close to the peak continuum emission from the linear feature. This feature has a peak velocity of $\approx 150$ km s$^{-1}$ at $\alpha(1950) = 17^h 43^m 10^s.3$, $\delta(1950) = -28^\circ 48' 27''$. Position 2 of Figure 1 presents the spectrum of the peak line emission with a flux density of 5.7 mJy beam$^{-1}$ and a corresponding continuum flux density of 100 mJy beam$^{-1}$. This newly detected ionized feature has the highest radial velocity in the Galactic center region with the exception of Sgr A West. The total ionized mass and the average electron density for this velocity component are estimated to be $\approx 12 M_\odot$ and 170 cm$^{-3}$, respectively.

Figure 4 (Plate L5) shows the velocity distribution of ionized gas ranging between $-100$ and $+190$ with contours of total intensity superposed. Note that the extent of high-velocity redshifted gas beyond $+90$ km s$^{-1}$ is not limited to the Pistol but also to the region to the southern half of the Sickle. The new velocity feature peaks at $\alpha(1950) = 17^h 42^m 55^s.3$, $\delta(1950) = -28^\circ 49' 33''$. The spectrum of this $+92$ km s$^{-1}$ velocity feature with the peak line emission of 7 mJy is observed in position 3 of Figure 1. The total ionized mass and electron density are estimated to be similar to the $+150$ km s$^{-1}$ velocity feature.

An accurate estimate of the thermal continuum emission from these diffuse ionized features is quite difficult to make in the presence of the nonthermal emission from the NTFs. However, if the ionized gas is assumed to be in LTE and that the abundance of singly ionized helium relative to singly ionized hydrogen ($Y^+$) is 10%, the upper limits to the electron temperature can be estimated. For positions 1, 2, and 3 (see Fig. 1), upper limits to the electron temperatures are estimated to be 9800, 6100, and 2900 K, respectively. The largest uncertainty from these estimates comes from the fact that the...
thermal continuum flux cannot be distinguished from nonthermal continuum. Unlike positions 1 and 2, which are near NTFs, position 3 (the southern half of the Sickle) does not appear to be contaminated by any emission from NTFs; thus, the estimated electron temperature at this position is not an upper limit but, rather, is probably the actual value. This low value of electron temperature is less than that of ionized gas ranging between 4600 and 7000 K in Sgr A West (Roberts & Goss 1993; Yusef-Zadeh, Zhao, & Goss 1995). It should be stated that because of its weak surface brightness and its location, the determination of the electron temperature of this particular velocity component may suffer from the lack of short-spacing data.

4. DISCUSSION

The peaks of blueshifted H2 emission lie exactly on the three bundles of filaments that intersect the Sickle, supporting the notion that there is an interaction between the NTFs and the thermal ionized gas in the Sickle. The results of the observations are generally consistent with the idea that cloud material ionized by UV radiation from hot stars is accelerated from the surface and some of the gas becomes attached to the magnetic filaments and is accelerated to relativistic velocities, where it emits synchrotron radiation (Serabyn & Morris 1994; Timmermann et al. 1996). Indeed, the synchrotron-emitting vertical filaments crossing the Sickle show an intrinsic positive spectral index (Yusef-Zadeh 1989; Anantharamaiah et al. 1991; Tsuibo et al. 1986), which becomes flat or negative toward more negative latitudes away from the Sickle (Pohl, Reich, & Schlickeiser 1992), whereas another group of nonthermal filamentary structures (the “threads”) in the Galactic center region shows steep spectral indices, but they are relatively isolated and do not coincide with any ionized thermal features (Morris & Yusef-Zadeh 1989; Anantharamaiah et al. 1991; Gray 1994). The flat spectrum of the arc may indicate that thermal gas associated with the Sickle is mixed with synchrotron-emitting nonthermal gas associated with the linear filaments (Yusef-Zadeh & Morris 1987a; Anantharamaiah et al. 1991).

Lang et al. (1997) and Timmermann et al. (1996) found a velocity gradient across the Sickle in a direction parallel to the filaments, with the largest (redshifted) velocities toward the west and the smallest (roughly 20 km s\(^{-1}\)) toward the east. The blueshifted gas generally lies to the east of the Sickle, consistent with this velocity gradient. The densest ionized gas is dynamically coupled to the +25 km s\(^{-1}\) molecular cloud, whereas the low-density diffuse features presumably originated at the outer surface of the cloud, where they were accelerated to anomalous velocities. Lang et al. (1997) find an unusually high H115/H2\(\alpha\) ratio, inconsistent with LTE within the Sickle where the NTFs intersect the Sickle. The infrared observations of Simpson et al. (1997) show that the extinction toward the Sickle region is uniform, implying that the Sickle itself lies on the front of the 25 km s\(^{-1}\) cloud and, therefore, that the ionized gas is being accelerated toward us from the surface of the cloud. If the blueshifted gas is being accelerated along the magnetic field aligned with the NTFs, then some of the filaments must be tilted so that the southeast points toward us.

If the magnetic field is responsible for the acceleration, the magnetic pressure must dominate the ram pressure of the blueshifted gas. Adopting an electron density of \(\approx 150 \, \text{cm}^{-3}\) for the \(-35 \, \text{km s}^{-1}\) feature at position 1, a field strength of at least 0.2 mG is required.

Alternatively, the ram pressure from the combined winds of the hot mass-losing stars discovered near the Sickle (Moneti et al. 1991; Figer et al. 1995, 1996; Coteria et al. 1996) may be sufficient to accelerate the gas. The stars’ broad H\(\alpha\) and Br\(\gamma\) emission lines indicate terminal velocities in the range \(V_v = 500–700 \, \text{km s}^{-1}\), similar to the cluster of young stars at the Galactic center (Krabbe et al. 1991). Adopting a distance of 5 pc from the cluster to the Sickle, the required mass loss from hot stars with \(V_v = 700 \, \text{km s}^{-1}\) to accelerate the 30 \(M_\odot\) of ionized gas responsible for the feature at peak 1 from the surface of the Sickle at +25 km s\(^{-1}\) to a velocity of \(-35 \, \text{km s}^{-1}\) over a distance of 2 pc is \(\approx 3 \times 10^{-3} \, \text{M}_\odot \, \text{yr}^{-1}\).

A ram pressure of this magnitude is also capable of accelerating the redshifted gas, for which the physical relationship with the NTFs is less clear. The gas at position 2 lies well away from the Sickle H\(\alpha\) region, between the two northernmost bundles of filaments that pass through the Sickle. A small continuum feature is present at this position in the 5 GHz image of Yusef-Zadeh & Morris (1987a) and the 8.3 GHz image of Lang et al. (1997). The southeastern end of the Sickle (near position 3) also does not appear to be associated with any NTFs. The kinetic energy of the features are roughly \(3 \times 10^{40}\) and \(10^{48}\) ergs, respectively.

Measurements of the field strength and the total stellar mass loss rate in this region would be useful in discriminating between these mechanisms for accelerating the anomalous-moving clouds.

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REFERENCES

Anantharamaiah, K. R., Pedlar, A., Ekers, R. D., & Goss, W. M. 1992, MNRAS, 249, 262
Coteria, A. S., Erickson, E. F., Cogan, S. W. J., Simpson, J. P., Allen, D. A., & Burton, M. J. 1996, ApJ, 461, 750
Figer, D. F., McLean, I. S., & Morris, M. 1995, ApJ, 447, L29
Figer, D. F., Morris, M., & McLean, I. S. 1996, in ASP Conf. Ser. 102, The Galactic Center, ed. R. Griedel (San Francisco: ASP), 263
Gray, A. D. 1994, Ph.D. thesis, Univ. Sydney, Australia
Harris, A. I., Krenz, T., Genzel, R., Krabbe, A., & Lutz, D. 1994, The Nuclei of Normal Galaxies: Lessons from the Galactic Center, ed. R. Genzel & A. Harris (Dordrecht: Kluwer), 233
Krabbe, A., Genzel, R., Dapprich, S., & Rotacice, V. 1991, ApJ, 382, L19
Lang, C. C., Goss, W. M., & Wood, D. O. S. 1997, ApJ, 474, 275
Moneti, A., Glass, I. S., & Moorwood, A. F. M. 1991, Mem. Soc. Astron. Italiana, 62, 755
Morris, M., & Yusef-Zadeh, F. 1989, ApJ, 343, 703
Pohl, M., Reich, W., & Schlickeiser, R. 1992, A&A, 262, 441
Roberts, D. A., & Goss, W. M. 1993, ApJS, 86, 133
Serabyn, E., & Güsten, R. 1991, A&A, 184, 133
Serabyn, E., & Morris, M. 1994, ApJ, 424, L91
Simpson, J. P., Colgan, S. W. J., Coteria, A. S., Erickson, E. F., Haas, M. R., Morris, M., & Rubin, R. H. 1997, ApJ, 487, 689
Timmermann, R., Genzel, R., Poglitsch, A., Lutz, D., Madden, S. C., Nikola, T., Geis, N., & Townes, C. H. 1996, ApJ, 466, 242
Tsuibo, M., Inoue, M., Handa, T., Tabara, H., Kato, T., Sofue, Y., & Kafiu, N. 1986, AJ, 92, 818
Yusef-Zadeh, F. 1989, IAU Symp. 136, The Center of the Galaxy, ed. M. Morris (Dordrecht: Kluwer), 275
Yusef-Zadeh, F. & Morris, M. 1987a, AJ, 94, 1178
Yusef-Zadeh, F. & Morris, M. 1987b, ApJ, 322, 721
Yusef-Zadeh, F., Morris, M., & Chance, D. 1984, Nature, 310, 557
Yusef-Zadeh, F., Zhao, J.-H., & Goss, W. M. 1995, ApJ, 442, 646

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Fig. 4.—A pseudocolor representation of the velocity distribution of ionized gas covering the entire range between −100 and +190 km s$^{-1}$. The overlaid contours show the 8.3 GHz continuum emission in the Sickle region.

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