PROPER MOTIONS OF IONIZED GAS AT THE GALACTIC CENTER: EVIDENCE FOR UNBOUND ORBITING GAS

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

D. A. ROBERTS
National Center for Supercomputing Applications, 1002 West Green Street, Urbana, IL 61801; dougr@ncsa.uiuc.edu

AND

J. BIRETTA
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; biretta@stsci.edu

Received 1997 January 5; accepted 1998 March 13; published 1998 May 6

ABSTRACT

We present radio continuum observations of the spiral-shaped ionized feature (Sgr A West) within the inner parsec of the Galactic center at three epochs spanning 1986 to 1995. The Very Large Array A configuration was used at λ = 2 cm (resolution of 0′′1 × 0′′2). We detect proper motions of a number of features in the northern and eastern arms of Sgr A West including the ionized gas associated with IRS 13 with V(R.A.) = 113 ± 10 and V(dec.) = 150 ± 15 km s⁻¹, IRS 2 with V(R.A.) = 122 ± 11 and V(dec.) = 24 ± 34 km s⁻¹, and the northern arm with V(R.A.) = 126 ± 30 and V(dec.) = −207 ± 58 km s⁻¹. We also report the detection of features having transverse velocities greater than 1000 km s⁻¹, including a head-tail radio structure, the “bullet,” ≈4° northwest of Sgr A* with V(R.A.) = 722 ± 156, V(dec.) = 832 ± 203 km s⁻¹, exceeding the escape velocity at the Galactic center. The proper-motion measurements, when combined with previous H92α radio recombination line data, suggest an unambiguous direction of the flow of ionized gas orbiting the Galactic center. The measured velocity distribution suggests that the ionized gas in the northern arm is not bound to the Galactic center assuming 2.5 × 10⁶ M☉ of dark matter residing at the Galactic center. This implies that the stellar and ionized gas systems are not dynamically coupled, thus supporting a picture in which the gas features in the northern arm and its extensions are the result of an energetic phenomenon that has externally driven a cloud of gas into the Galactic center.

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

1. INTRODUCTION

The ionized gas known as Sagittarius A West (Sgr A West) appears as a three-armed spiral-like structure (north, east, and west arms) that engulfs the inner parsec of the Galaxy where Sgr A*, the compact radio source at or near the dynamical center of the Galaxy, lies (Ekers et al. 1983). These features are surrounded by neutral gas in the circumnuclear disk (CND) rotating with a velocity of about 100 km s⁻¹ at a distance of 2 pc from the Galactic center (e.g., Güsten et al. 1987). The kinematics of ionized gas surrounding Sgr A* show systematic velocities along various components of Sgr A West including the western arc, which has a radial velocity structure that varies regularly between −100 and +100 km s⁻¹ in the north-south direction (e.g., Serabyn et al. 1988; Herbst et al. 1993; Roberts & Goss 1993).

However, the velocity structure of the inner 10⁷, where there is a hole in the distribution of ionized gas which is known as the “minicavity,” becomes increasingly more negative, ≈−350 km s⁻¹ approaching Sgr A* (Yusef-Zadeh, Morris, & Ekers 1990; Roberts, Yusef-Zadeh, & Goss 1996, hereafter RYG).

Recent observations of stellar proper motions show evidence of a 2.5 × 10⁶ M☉ object lying close to the position of Sgr A* (Eckart & Genzel 1996, 1997). The stars orbit randomly around the Galactic center with increasing velocity dispersion around Sgr A*, reflecting the gravitational potential of central mass. The ionized gas, on the other hand, is part of a coherent flow with systematic motion that is decoupled from the stellar orbits. Understanding the kinematics of the system of ionized gas is complicated by its incomplete view of the three-dimensional geometry with respect to Sgr A* as well as by the interaction of orbiting gas with nongravitational forces, such as the winds from the cluster of hot mass-losing stars near the Galactic center. To examine the gas kinematics and the true geometry of the ionized flow, in this Letter we present the results of proper-motion measurements of ionized gas at λ = 2 cm.

2. OBSERVATIONS

Radio continuum observations were carried out with the Very Large Array of the National Radio Astronomy Observatory¹ in 1986.167, 1990.375, and 1995.557 at λ = 2 cm in the A configuration using similar u-v coverage, identical bandwidths of 12.5 MHz, and an identical phase center at R.A. (1950) = 17°42'29.33'' , decl. (1950) = −28°59'17.0''. We have employed a technique in which the variability of Sgr A* is removed on every 10 minute scan to improve the dynamic range of radio continuum images. In order to minimize the difference in calibration errors between three different data sets, the data sets were cross-calibrated against the 1990.375 epoch before the final images were constructed. To measure the two-dimensional transverse velocities with respect to Sgr A*, we generated maximum entropy images and then applied the cross-correlation method of Biretta, Owen, & Cornell (1989). This method, which has been exhaustively tested (Biretta, Zhou, & Owen 1995), determines the fractional pixel position shift between images (pixel size 35 × 35 mas), which maximizes their

1 The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under a cooperative agreement by Associated Universities, Inc.
cross-correlation. Uncertainties on the velocities were estimated by extracting 20 noise images from a CLEANed image in regions beyond the inner 60° of the Galactic center, adding these to the maximum entropy method (MEM) images, and repeating the cross-correlations; position uncertainties and hence velocity uncertainties were determined from the dispersion in the results for these 20 noise images. The rms noises of 1986, 1990, and 1995 images are 0.13, 0.104, and 0.16 mJy beam⁻¹, respectively.

Sgr A* serves as an excellent reference point because of its small proper motion \([V(\text{R.A.}) = -13 \pm 13, V(\text{decl.}) = -11 \pm 9 \text{ km s}^{-1}; \text{Bac}k\text{er} 1996]\) and is likely to be directly associated with the compact, massive object. The above technique was applied to two bright radio continuum sources surrounding IRS 13 and IRS 10 continuum sources. The uncertainties from our data for the east-west and north-south components of motion are 10 and 33 km s⁻¹, respectively. At the distance of 8 kpc, a shift of 1 mas yr⁻¹ corresponds to about 39 km s⁻¹. The velocity uncertainty in the radial direction is much smaller than in transverse directions. The effect of the aberration was too small to be of importance.

3. RESULTS

Figure 1a (Plate L11) shows the pseudocolor representation of the continuum image at the resolution of 0.01 × 0.02 resolution superposed on the pseudocolor representation of the radial velocity distribution of H92α recombination line emission with spectral and spatial resolutions of 14 km s⁻¹ and 0.75 × 1.2 (RYS), respectively. The vectors drawn from the center of each box show the orientation of the transverse velocities, and their lengths represent their magnitude. The regions with the highest signal-to-noise ratio (greater than 10) averaged roughly over 1.5 arcsec² are shown as boxes 6 and 10 in Table 1, where the continuum emission is strongest. The plots in Figure 2 show the change in \(\alpha\) and \(\delta\) of the IRS 13 (box 6) source as a function of three epochs. Proper motions were determined by a least-squares fit to the data in which the position values were weighted by their uncertainties.

The western half of the minicavity is represented by boxes 6, 8, 10, and 11, in which the prominent clusters of hot stars, IRS 13 and IRS 2, are embedded within extended ionized gas. From \([\text{Ne II}]\) and H92α line observations, the ionized gas in this region shows high radial velocities of \(\approx -300\) km s⁻¹. The transverse velocities vary from 24 to 150 km s⁻¹, which are much less than their radial velocity components. The filamentary ionized structure connecting the IRS 13 and IRS 2 (box 11) features also shows transverse velocities directed toward the northwest.

The eastern half of the minicavity is represented by boxes 1, 2, and 5. Box 4 corresponds to the radio blob \(\zeta\) (Yusef-Zadeh et al. 1990; Zhao et al. 1991), which lies near the center of the minicavity. Again, all of the features to the east and near the center of the minicavity appear to have transverse velocities not reported. The angular distance of the center of each box with respect to Sgr A* is shown in radial, \(\alpha\), and \(\delta\) directions in columns (2), (3), and (4), respectively. The total measured velocities and the upper limits to the corresponding escape velocities of ionized gas (determined using the projected distance \(r\) from Sgr A* with a mass of 2.5 × 10⁶ \(M_\odot\)) are shown in the last two columns.

Figure 1b shows contours of the \(\lambda = 2\) cm continuum image from A-array observations at 0.01 × 0.02 resolution superposed on the pseudocolor representation of the radial velocity distribution of H92α recombination line emission with spectral and spatial resolutions of 14 km s⁻¹ and 0.75 × 1.2 (RYS), respectively. The vectors drawn from the center of each box show the orientation of the transverse velocities, and their lengths represent their magnitude. The regions with the highest signal-to-noise ratio (greater than 10) averaged roughly over 1.5 arcsec² are shown as boxes 6 and 10 in Table 1, where the continuum emission is strongest. The plots in Figure 2 show the change in \(\alpha\) and \(\delta\) of the IRS 13 (box 6) source as a function of three epochs. Proper motions were determined by a least-squares fit to the data in which the position values were weighted by their uncertainties.
predominantly directed to the west, with the exception of the anomalous velocity feature in box 1, which has transverse velocities exceeding 1000 km s\(^{-1}\). The trend of westerly transverse motion of the ionized gas is also seen along the northern and eastern arms (boxes 3, 12, 15, 16, 17, 18, and 19).

Figure 1b also displays an anomalous high-velocity feature in Sgr A West. This source, called the “bullet,” as seen in box 9, lies about 4° northwest of Sgr A* and shows a total transverse velocity of 1100 km s\(^{-1}\), which is much greater than the upper limit to the escape velocity of 373 km s\(^{-1}\) at its projected distance from Sgr A* (see Table 1). The low-resolution H\(\alpha\) measurements of this region (Roberts & Goss 1993), which were obtained using a limited velocity coverage (−200 km s\(^{-1}\) < \(V_{LSR}\) < +200 km s\(^{-1}\)), show extended line emission with radial velocities of about −36 km s\(^{-1}\), which is not likely associated with the bullet. The peak flux density at \(\lambda = 1.2\) cm is \(\approx 2.5\) mJy within a beam of \(0\text{\arcmin}31 \times 0\text{\arcmin}22\). Assuming that the bullet is an optically thin thermal source at the temperature of 10\(^{4}\) K, the electron density would be \(3.6 \times 10^4\) cm\(^{-3}\), which is similar to typical electron densities of blobs (Wardle & Yusef-Zadeh 1992). The mass of the bullet would be \(8 \times 10^{-4}\) \(M_\odot\) assuming a spherical size of radius \(6 \times 10^{-3}\) pc.

The proper-motion velocity of the bullet derived from the image correlation technique is large enough that the positions of the peak are displaced by a significant fraction of the synthesized beam on the plane of the sky between the various epochs. The velocity determined from measuring the displacement of the peak agrees with that determined by the correlation method. Figure 3 shows the transverse motion of the peak emission in the three different epochs superposed on a gray-scale image of the bullet (including the tail) from the 1990 observations. The most recent image (1995) shows the peak to be at the position of the head of the source, with the tail pointing roughly toward the head in the earlier observations. The images shown in Figure 3 provide confidence in the results obtained from two completely different techniques of proper-motion measurements.

4. DISCUSSION

By combining the transverse and radial velocities, we are able to unambiguously determine the direction of ionized flow at the Galactic center. The predominant component of the motion in the plane of the sky is from east to west for most of the measured features, with the exception of few places at which the velocity of ionized gas is anomalously large. It appears that the flow of ionized gas in the northern arm (box 12) originates in the northeast with redshifted velocities in the orbital plane. The ionized gas then follows an orbital trajectory to the southwest as it crosses the plane of the sky and passes by Sgr A* before the ionized gas moves to the northwest.

One idea that has been suggested to explain the origin of the minicavity and its unusual characteristics (e.g., Lutz, Krabbe, & Genzel 1993; Melia, Coker, & Yosef-Zadeh 1996) is the collision of fast-moving blobs with the orbiting ionized gas. The blobs are hypothesized to be formed as a result of high-velocity winds of the IRS 16 cluster escaping from but focused by the gravitational potential of Sgr A*. This focusing mechanism allows the diffuse outflowing materials to collide with each other and form dense blobs of ionized gas leaving the gravitational potential of Sgr A* (Wardle & Yusef-Zadeh 1992). The anomalous high-velocity features seen in boxes 1, 4, 8, and 9 are consistent with the outflow picture. In particular, the bullet is clearly escaping from the gravitational potential of the Galactic center region even when the mass of the stellar cluster is included. In this model, however, it is not expected
that a tail would be produced behind the fast-moving blobs. The existence of a bow shock or X-ray-emitting gas associated with the head of the bullet would favor a model in which these fast-moving features are ejected by mass-losing stellar sources. Further observations of the bullet are needed to understand its origin.

The comparison between the measured total velocities and the upper limits to the escape velocities at projected distance \( r \) from the center of each box to Sgr A* (Table 1) suggests that the upper limits to the escape velocities at projected distance \( r \) from the center. If we use the projected distance as \( 45 \) kpc for the origin. The global velocity field which may also be unbound to the Galactic center. If we use the projected distance as \( 45^\circ \) of the actual distance, almost all of the measured velocities are greater than the escape velocities listed in Table 1. The mass within the inner \( 10^\circ-20^\circ \) is assumed to be dominated by a compact source centered on Sgr A* having a mass of \( 2.5 \times 10^6 M_\odot \) as measured recently from stellar proper-motion measurements (Eckart & Genzel 1997). The escape velocity estimates may not be applicable at large distances where the mass of the evolved stellar cluster becomes important. From the comparison of the three-dimensional stellar and ionized gas motions, it appears that these two systems are not dynamically coupled in the inner \( 20^\circ \) of the Galactic center.

The effect of a strong gravitational potential due to the large concentration of dark matter near Sgr A* is manifested as high-velocity gradients of over 600 km s\(^{-1}\) pc\(^{-1}\). However, the existence of ionized gas in an unbound orbit is inconsistent with the notion that the ionized gas in the northern arm is a tidally stretched infalling feature (e.g., Serabyn et al. 1988). Additionally, the present proper-motion data do not support the interpretation that the northern arm is a segment of a one-armed spiral pattern induced as a result of an instability in the rotating disk (e.g., Lacy, Achtermann, & Serabyn 1991). A significant variation in the velocity distribution of ionized gas along the northern arm is not consistent with small variations expected from Keplerian motion, thus supporting the notion that the northern arm is a material feature. We believe that the high velocity of ionized gas on an unbound orbit supports a scenario in which an energetic phenomenon outside the inner few parsecs of the Galactic center accelerates a cloud to pass by the Galactic center, which then collides with the CND and results in the loss of angular momentum of the material in the CND (Serabyn et al. 1988). There is evidence of disturbed neutral gas and shocked molecular gas based on OH 1720 MHz maser emission at the interface of the extension of the northern and eastern arms of Sgr A West and a “gap” in the CND (Yusef-Zadeh et al. 1996; Jackson et al. 1993). In this picture, the northern and eastern arms delineate the edges of the intruding cloud photoionized by the UV radiation field at the Galactic center (Jackson et al. 1993). The neutral gas in the gap of the CND is interpreted to be the site of collision with a cloudlet pushed into the Galactic center, possibly by the energetic explosion of Sgr A East. Future modeling of the three-dimensional motion of ionized gas should constrain the inclination of the orbital plane of the ionized gas with respect to the orbital plane of the CND and examine the possibility that the CND is the origin of the northern and eastern arms.

The work of F. Y.-Z. was supported in part by NASA grant NAGW-2518. D. R. acknowledges support from the NSF grant AST94-19227. We thank Mark Wardle for useful discussion.

REFERENCES

Backer, D. C. 1996, in IAU Symp. 169, Unsolved Problems of the Milky Way, ed. L. Blitz & P. Teuben (Dordrecht: Kluwer), 193

Biretta, J., Owen, F., & Cornwell, T. 1989, ApJ, 342, 128

Biretta, J., Zhou, F., & Owen, F. 1995, ApJ, 447, 582

Eckart, A., & Genzel, R. 1996, Nature, 383, 415

———. 1997, MNRAS, 284, 576

Ekers, R. D., van Gorkom, J. H., Schwartz, U. J., & Goss, W. M. 1983, A&A, 122, 143

Güsten, R., Genzel, R., Wright, M. C. H., Jaffe, D. T., Stutzki, J., & Harris, A. I. 1987, ApJ, 318, 124

Herbst, T. M., Beckwith, S. V. M., Forrest, W. J., & Pipher, J. L. 1993, AJ, 105, 956

Jackson, J. M., Geis, N., Genzel, R., Harris, A. I., Madden, S., Poglitsch, A., Stacey, G. J., & Townes, C. H. 1993, ApJ, 402, 173

Lacy, J. H., Achtermann, J. M., & Serabyn, E. 1991, ApJ, 380, L71

Lutz, D., Krabbe, A., & Genzel, R. 1993, ApJ, 418, 244

Melia, F., Coker, R. F., & Yusef-Zadeh, F. 1996, ApJ, 460, L33

Roberts, D., & Goss, W. M. 1993, ApJS, 86, 133

Roberts, D., Yusef-Zadeh, F., & Goss, W. M. 1996, ApJ, 459, 627

Serabyn, E., Lacy, J. H., Townes, C. H., & Bharat, R. 1988, ApJ, 326, 171

Wardle, M., & Yusef-Zadeh, F. 1992, Nature, 357, 308

Yusef-Zadeh, F., Morris, M., & Ekers, R. D. 1990, Nature, 348, 45

Yusef-Zadeh, F., Roberts, D. A., Goss, W. M., Frail, D., & Green, A. 1996, ApJ, 466, L25

Zhao, J.-H., Goss, W. M., Lo, K. Y., & Ekers, R. D. 1991, Nature, 354, 46
Fig. 1.—Left: Pseudocolor image of the $\lambda = 2$ cm continuum from the 1990 epoch data with a resolution of 0\'
1 $\times$ 0\'2 and a rms noise of 0.104 mJy beam$^{-1}$. The boxes (see Table 1), except box 21, are regions in which proper-motion measurements have been carried out with a greater than 3 $\sigma$ level detection in at least one direction. Right: $H_2$ velocity distribution with spectral and spatial resolutions of 14 km s$^{-1}$ and 0.75 $\times$ 1.2 presented in pseudocolor with contours of the $\lambda = 2$ cm continuum image superposed. The length and direction of the vectors represent the transverse velocity in each box. The velocity and uncertainty of each vector are presented in cols. (6) and (7) of Table 1.

YUSEF-ZADEH, ROBERTS, & BIRETTA (see 499, L160)