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A 3 pc SCALE JET-DRIVEN OUTFLOW FROM SGR A*

F. YUSEF-ZADEH¹, R. ARENDT², H. BUSHOUSE³, W. COTTON⁴, D. HAGGARD¹, M. W. POUND⁵,
 D. A. ROBERTS¹, M. ROYSTER¹, AND M. WARDLE⁶

¹ Department of Physics and Astronomy and Center for Interdisciplinary Research in Astronomy, Northwestern University, Evanston, IL 60208, USA

² CRESST/UMBC/NASA GSFC, Code 665, Greenbelt, MD 20771, USA

³ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

⁴ National Radio Astronomy Observatory, Charlottesville, VA 22903, USA

⁵ Department of Astronomy, University of Maryland, MD 20742, USA

⁶ Department of Physics and Astronomy, Macquarie University, Sydney NSW 2109, Australia

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ABSTRACT

The compact radio source Sgr A* is coincident with a $4 \times 10^6 M_\odot$ black hole at the dynamical center of the Galaxy and is surrounded by dense orbiting ionized and molecular gas. We present high-resolution radio continuum images of the central 3' and report a faint continuous linear structure centered on Sgr A* with a P.A. $\sim 60^\circ$. The extension of this feature appears to be terminated symmetrically by two linearly polarized structures at 8.4 GHz, $\sim 75''$ from Sgr A*. A number of weak blobs of radio emission with X-ray counterparts are detected along the axis of the linear structure. The linear structure is best characterized by a mildly relativistic jet from Sgr A* with an outflow rate $10^{-6} M_\odot \text{ yr}^{-1}$. The near and far sides of the jet are interacting with orbiting ionized and molecular gas over the last 1–3 hundred years and are responsible for a 2'' hole, the “minicavity,” characterized by disturbed kinematics, enhanced Fe II/III line emission, and diffuse X-ray gas. The estimated kinetic luminosity of the outflow is $\sim 1.2 \times 10^{41} \text{ erg s}^{-1}$, so the interaction with the bar may be responsible for the Galactic center X-ray flash inferred to be responsible for much of the fluorescent Fe K α line emission from the inner 100 pc of the Galaxy.

Key words: accretion, accretion disks – black hole physics – Galaxy: center

Online-only material: color figure

1. INTRODUCTION AND OBSERVATIONS

Stellar orbits within 1'' of the compact radio source Sgr A* at the dynamical center of the Galaxy are compelling evidence for a $4 \times 10^6 M_\odot$ black hole (Ghez et al. 2008; Gillessen et al. 2009; Reid & Brunthaler 2004). This compact source is ~ 100 times closer to us than the next nearest example of a supermassive black hole and presents an unparalleled opportunity to study the processes by which gas is captured, accreted, and ejected from black holes. Observations of Sgr A* thus far have revealed no hard evidence for a small-scale jet or an accretion disk, and thus the relative ratio of the accretion and outflow rates is unknown. We have recently reanalyzed archival radio and X-ray continuum and molecular line data that were taken with the Very Large Array (VLA) of the National Radio Astronomy Observatory⁷, *Chandra X-ray Observatory*, and the Combined Array for Research in Millimeter-wave Astronomy (CARMA) observations of the inner few parsec (pc) of Sgr A* to search for interaction sites of a jet with the surrounding material near Sgr A*.

The inner pc of the Galactic center contains diffuse ionized gas, e.g., Sgr A West, which orbits Sgr A* (Lacy et al. 1980; Ferriere 2012). Sgr A West, with its three-arm mini-spiral appearance, consists of the W arm or arc, which is coupled to the Circumnuclear Molecular Ring (CMR), and the E and N arms of ionized gas. With a closest projected distance of ~ 0.1 pc, Sgr A West shows a bright bar of ionized gas, within which a hole or the “minicavity” with a diameter of 2'' is

noted. A chain of circular-shaped radio blob structures links Sgr A* to the “minicavity” by a ridge of emission at 8.4 GHz (Yusef-Zadeh et al. 1990; Wardle & Yusef-Zadeh 1992). The minicavity shows enhanced Fe III line emission, a high electron temperature and is kinematically disturbed, having radial velocities ranging between -150 and -290 km s^{-1} at its edge and a highly blueshifted velocity $\sim -340 \text{ km s}^{-1}$ in the interior (Eckart et al. 1990; Lacy et al. 1991; Lutz et al. 1993; Roberts et al. 1996; Zhao et al. 2009). The kinematic structure may be explained by a shock due to a hot bubble expanding at a velocity of 180 km s^{-1} (Lutz et al. 1993). Here, we present a faint, highly collimated linear structure observed at radio wavelengths which is associated with the ridge of emission linking Sgr A* to the minicavity. We argue that this is a synchrotron emitting jet from Sgr A* and the blobs are sites of dynamical interaction with orbiting gas.

The radio data presented here were taken at 4.85 (6 cm), 8.4 (3.6 cm), 15 (2 cm), 22 (1.3 cm), and 42 (7 mm) GHz using multiple configurations of the VLA. The radio data are self-calibrated in phase to remove atmospheric phase errors as well as properly correcting the time variability of Sgr A* by fitting a point-source model in the visibility plane. The X-ray data derive $\sim 1.4 \times 10^6$ s of archival *Chandra* ACIS-I observations taken between 2000 October 26 and 2011 March 31 which were recalibrated and combined using CIAO 4.4 (CALDB 4.4.8; Fruscione et al. 2006). The merged 0.5–10 keV image has a resolution of $0''.492$ and is normalized at 2.3 keV. The SiO data were obtained with CARMA during the 2009 and 2010 observing seasons in the D and C array configurations. The array consisted of six 10.4 m antennas and nine 6.1 m antennas and the maps were made on a 127-point hexagonal mosaic, Nyquist-sampling the 10.4 m antenna primary beam.

⁷ The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under a cooperative agreement by Associated Universities, Inc.

The spatial resolution and spectral resolution of the final maps are $8''.0 \times 4''.1$ and 6.74 km s^{-1} , respectively, and the 1σ rms noise is 90 mJy beam^{-1} .

2. RESULTS

Figure 1 shows gray-scale 22 and 15 GHz, high dynamic range ($\sim 10^4$) images of the inner $30''$ of Sgr A*. We note a new linear feature in both images running diagonally crossing the bright N and W arms of the mini-spiral, along which several blobs (b, c, d, h1, and h2) are detected. These images best reveal the continuity of the linear feature along a position angle of $\sim 60^\circ$ (E of N) extending symmetrically with respect to Sgr A*. The linear feature to the SW is thicker and brighter than that of the NE by a factor of 1.5–2, respectively. The southern tip of this continuous $30''$ feature appears to cross the W arm and becomes brighter from 0.2 mJy to about 1 mJy at 22 GHz. A bow-shock-like structure is detected at the position where the linear feature crosses the W arm near $\alpha, \delta(J2000) 17^{\text{h}}45^{\text{m}}38^{\text{s}}.9, -29^\circ00'38''$. On the NE of Sgr A*, blob h1 is extended in the direction of the linear feature. Figure 2(a) shows a close-up view of the linear feature at 8.4 GHz within $8'' \times 6''$ of Sgr A* where a ridge of emission is linking blob ϵ to Sgr A*. The ridge of emission is also seen as a linear feature at 42 GHz in Figure 2(b). We note that the weak linear feature at 42 GHz extends for $2''$ pointing toward the brightest segment of the western rim of the minicavity where a cluster of continuum sources coincide with a cluster of young, dusty stars (IRS 13N; Eckart et al. 2012). The morphology of the emission suggests that the linear feature is impacting the minicavity. A “dark radio cloud” labeled in Figure 2(b) is interpreted as an embedded molecular cloud associated with the minicavity, as discussed elsewhere, showing a deficiency of radio continuum emission.

Unlike total intensity, the polarized emission from the region near Sgr A* is not confusion limited. Figure 3(a) shows the detection of linearly polarized contours of emission superimposed on the corresponding total intensity image at 8.4 GHz. The polarized features Sgr A-P1–P4 are placed NE and SW of Sgr A*. The brightest polarized features are aligned along the continuous linear feature, as seen in high-resolution images (cf. Figure 1), with the total projected extent of $\sim 150''$ ($\sim 6 \text{ pc}$). Figure 3(b) shows high-resolution-polarized image of the emission at 8.4 GHz. New polarized sources Sgr A-P1 ($17^{\text{h}}45^{\text{m}}43^{\text{s}}.6, -28^\circ59'22''$), P2 ($17^{\text{h}}45^{\text{m}}43^{\text{s}}.3, -29^\circ00'12''$), and P3 ($17^{\text{h}}45^{\text{m}}43^{\text{s}}.6, -29^\circ00'08''$) located $\sim 75'', 45'',$ and $60''$ NE of Sgr A* and P4 ($17^{\text{h}}45^{\text{m}}34^{\text{s}}.8, -29^\circ01'09''$) lying $75''$ SE of Sgr A*. The brightest polarized feature P1 shows filamentary structure, extending for $\sim 25''$. The lower limit to fractional polarization of P1–P4 at 8.4 GHz are 15%, 5%, 1%–2%, and 8%, respectively. A common characteristic of polarized features Sgr A-P1–P4 is that they are azimuthally extended in the direction perpendicular to the orientation of the linear feature. In addition to the P1–P4 polarized sources, we also notice a weak linearly polarized filament with an extent of $< 1''$ to the south of Sgr A*, labeled P5 in Figure 3(b).

The extension of the linear feature to the NE and SW crosses the concentration of molecular gas associated with the CMR. To examine the possibility that polarized features are physically associated with the molecular ring, Figure 3(c) shows the clumpy distribution of SiO (2–1) emission. The linearly polarized features Sgr A-P1–P4 appear to be spatially correlated with SiO emission, which is known to be an excellent indicator

of shocked molecular gas. Polarized features, in particular, appear to be located at the edge of molecular clumps. P4 appears to be associated with an isolated molecular clump traced by HCN line emission (Christopher et al. 2005). The spectrum of the HCN clump at the position of P4 shows two velocity components at -43 and -120 km s^{-1} .

Although there is no polarized emission detected from Sgr A* at a level of less than 0.1%, we notice weak polarized emission at a level of $50\text{--}100 \mu\text{Jy}$ within the inner few arcseconds of Sgr A*. Figure 3(d) shows contours of 8.4 GHz emission superimposed on diffuse polarized emission with a fractional polarization $\sim 0.5\%$ outside Sgr A*. The diffuse polarized emission is elongated along the axis that links P1 and P4 and the overall electric vector distribution of weak polarized emission outside Sgr A* runs perpendicular to the axis of the elongation. Using the upper limit flux density of $\sim 1 \text{ mJy}$ per $0''.35 \times 0''.2$ beam, the equipartition magnetic fields are 1.6, 1.9, and 5.9 mG for proton to electron ratio of 0, 1, and 100, respectively.

Figure 4(a) shows an 8.4 GHz image of the inner $\sim 45'' \times 30''$ of Sgr A*. The bright central source coincides with Sgr A* surrounded by the three arms of the mini-spiral and the bar of ionized gas within which the “minicavity” lies. Sgr A-a1, a2, b, c, d, and e are identified to the west of Sgr A* crossing the ionized flow associated with the W arm. The ϵ blob, which was originally detected at 15 GHz (Yusef-Zadeh et al. 1990), is the brightest of all the blobs and lies about $1''$ to the west of Sgr A*, followed by two blobs a1 and a2 lying at the western boundary of the minicavity. The Sgr A-blobs f, g, and h are detected to the east of Sgr A* crossing the N arm of Sgr A West. The peak flux density of the blobs a1 and a2 ranges between 0.1 and $0.3 \text{ mJy beam}^{-1}$. Figure 4(b) shows a 22 GHz image displaying diffuse emission lying between the W arm and the minicavity. A weak circular-shaped feature surrounding blobs a1 and a2 with an X-ray counterpart (cf. G359.942-0.045 in Figure 5) is detected with a diameter of $0''.33$. The integrated flux density of the circular-shaped feature which lies immediately adjacent to the minicavity is $\sim 29 \text{ mJy}$ (cf. Figures 5(a) and (b)).

Figures 5(a) and (b) show a 22 GHz VLA and 2–4 keV *Chandra* image of the inner $25'' \times 18''$ of Sgr A*, respectively. One of the new radio features that is revealed in Figure 5(a) is a $\sim 2''$ tear-drop-shaped bubble roughly centered around Sgr A*. This bubble is open on the northern side with a morphology that resembles the shape of the minicavity. Detailed analysis of *Chandra* data suggests that X-ray emission from Sgr A* is spatially extended (Baganoff et al. 2003). However, the coincidence of the extended X-ray emission from Sgr A* with the tear drop suggests that the extended X-ray component is likely produced by the synchrotron jet from Sgr A* or shocked winds by mass-losing stars orbiting Sgr A*, as the ram pressure of the winds pushing the ionized bar away and create a tear-drop cavity.

There are four diffuse and compact X-ray sources that have previously been identified, Sgr A*, IRS 13, G359.945-0.044 (a PWN candidate), and G359.943-0.047 (Baganoff et al. 2003; Wang et al. 2006; Muno et al. 2008), as labeled in Figures 5(a) and (b). There are two faint-extended X-ray sources symmetrically placed with respect to Sgr A*. One is an elongated loop-like structure (labeled NE plume in Figure 5) to the NE of Sgr A* with an extension of $8'' \times 2''$. The SW plume is more difficult to discern because of the bright source IRS 13 and the transient source G359.943-0.047. However, the X-ray source G359.942-0.045, which has a radio counterpart

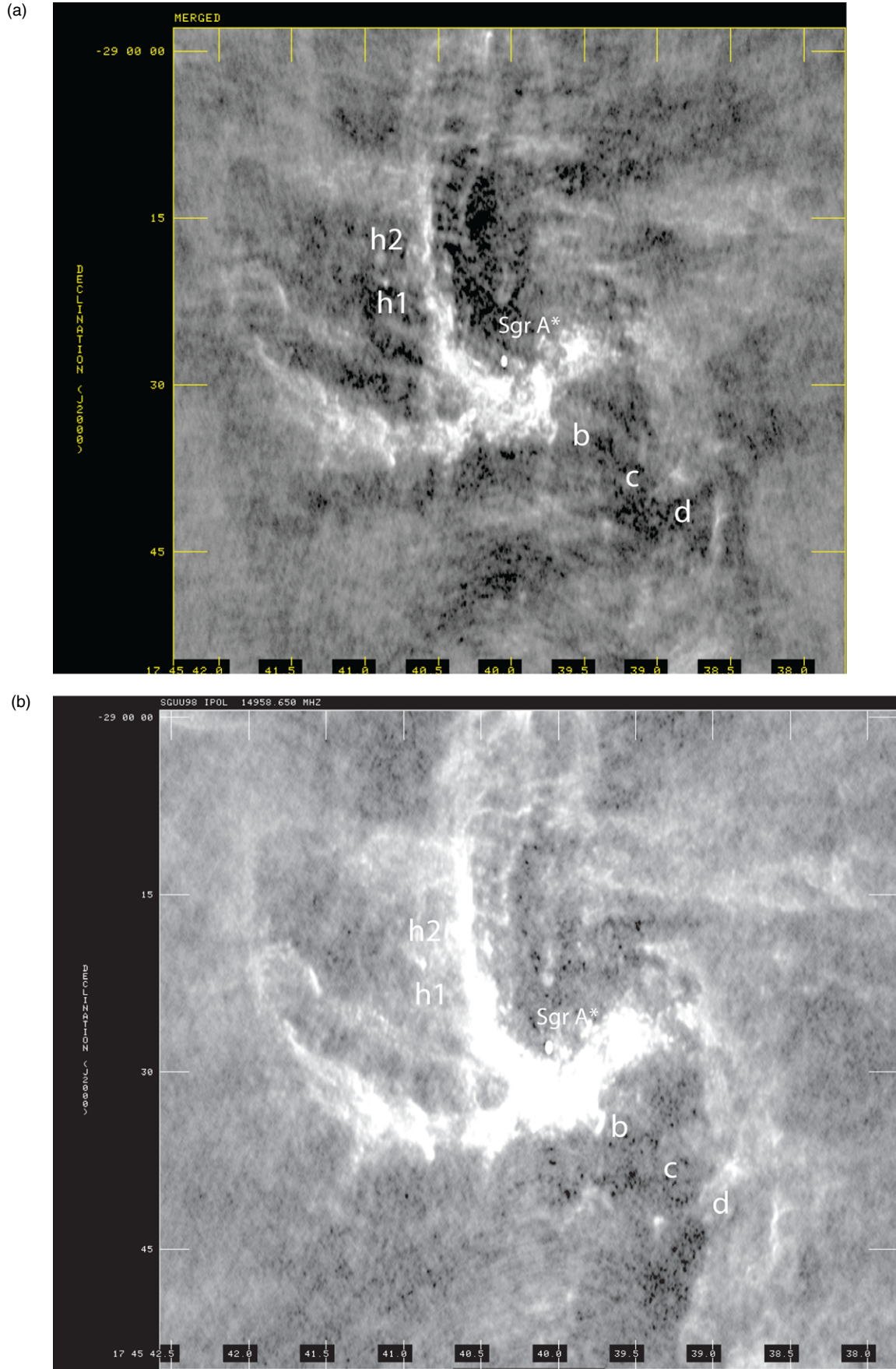


Figure 1. (a) and (b) 22 and 15 GHz VLA images constructed by combining A and B array data with resolutions of $0''.36 \times 0''.18$ (P.A. = 2°) and $0''.36 \times 0''.20$ (P.A. = -0.6°), and rms noises of 1.5×10^{-4} and 9×10^{-5} mJy beam $^{-1}$, respectively.

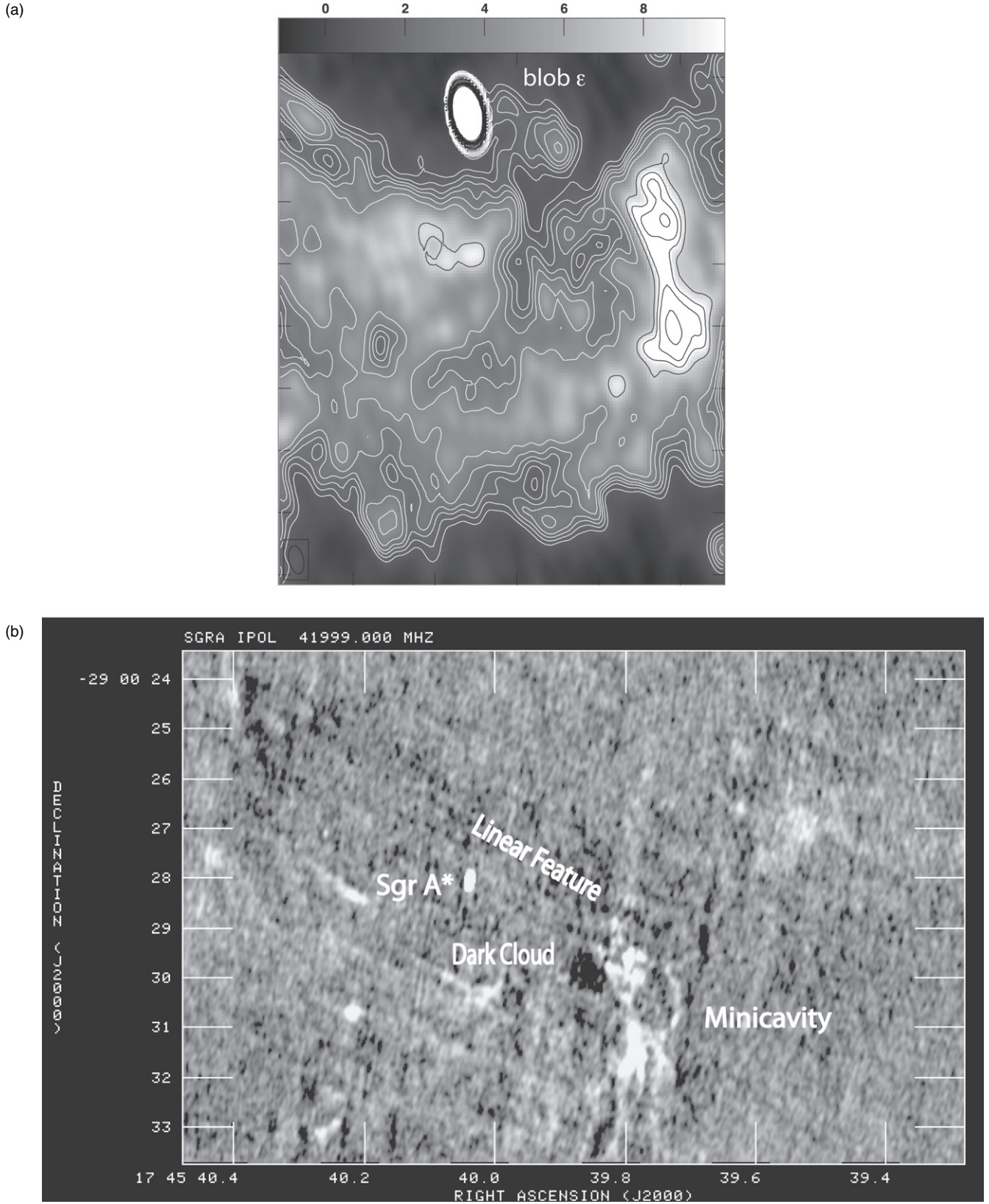


Figure 2. (a) Contours of emission with a resolution of $0''.46 \times 0''.23$ (P.A. = -12°) at 8.4 GHz $-1.2, 1.2, 1.6, 2, 2.4, 3, 4, 6, 8, 10, 12, 16, 20, \dots, 40$, and 50 mJy beam^{-1} . (b) 42 GHz image with a resolution $0''.16 \times 0''.08$ (P.A. = 0°).

(blob b in Figures 1 and 5), appears to be a part of the SW plume. The two extended plume-like features lie along the axis in which the continuous linear structure is detected at radio wavelengths. There are also weak X-ray features noted in the

immediate vicinity of the N arm, G359.947-0.047 in Figure 5(b), along the same axis as the linear radio feature. The X-ray emission adjacent to the N arm provides a strong evidence that an energetic event is responsible for X-ray emission.

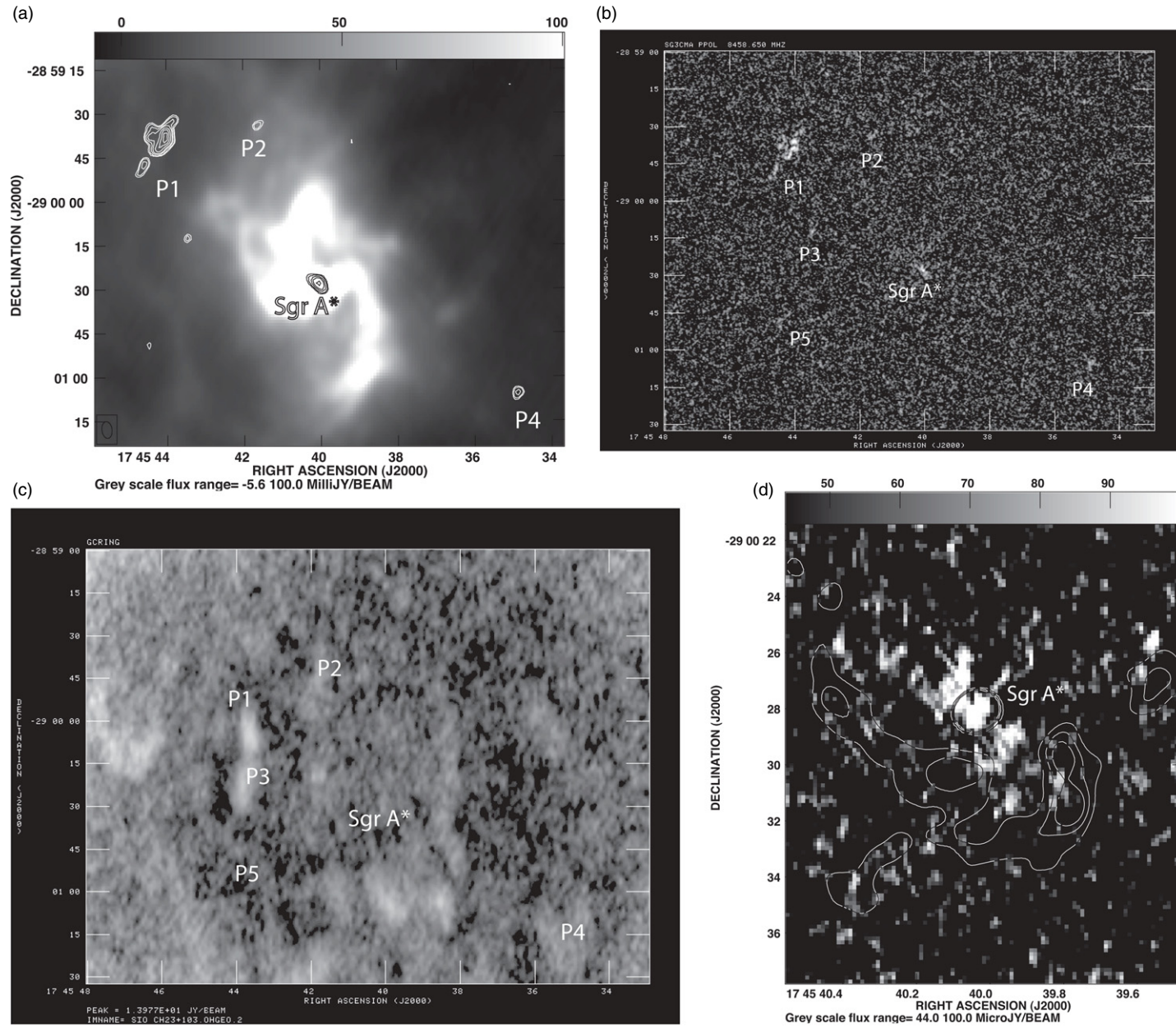


Figure 3. (a) Contours of 8.4 GHz polarized emission with a resolution of $10'' \times 10''$ with levels set at $(3.5, 4, 5, 6, 8, 10, 12) \times 50 \mu\text{Jy beam}^{-1}$ on a gray-scale intensity image with a resolution of $5''.8 \times 3''.5$ (P.A. = 7°). (b) A gray-scale 8.4 GHz polarized intensity at 8.4 GHz with a resolution of $0''.93 \times 0''.51$ (P.A. = -7°). (c) A gray-scale distribution of SiO(2-1) emission from the CMR integrated between velocities -121.6 and 148 km s^{-1} . (d) Contours of 8.4 GHz intensity of the minicavity with levels set at 20, 30, and 40 mJy beam $^{-1}$ superimposed on polarized intensity from Sgr A* and its immediate vicinity. The resolution is the same as (b).

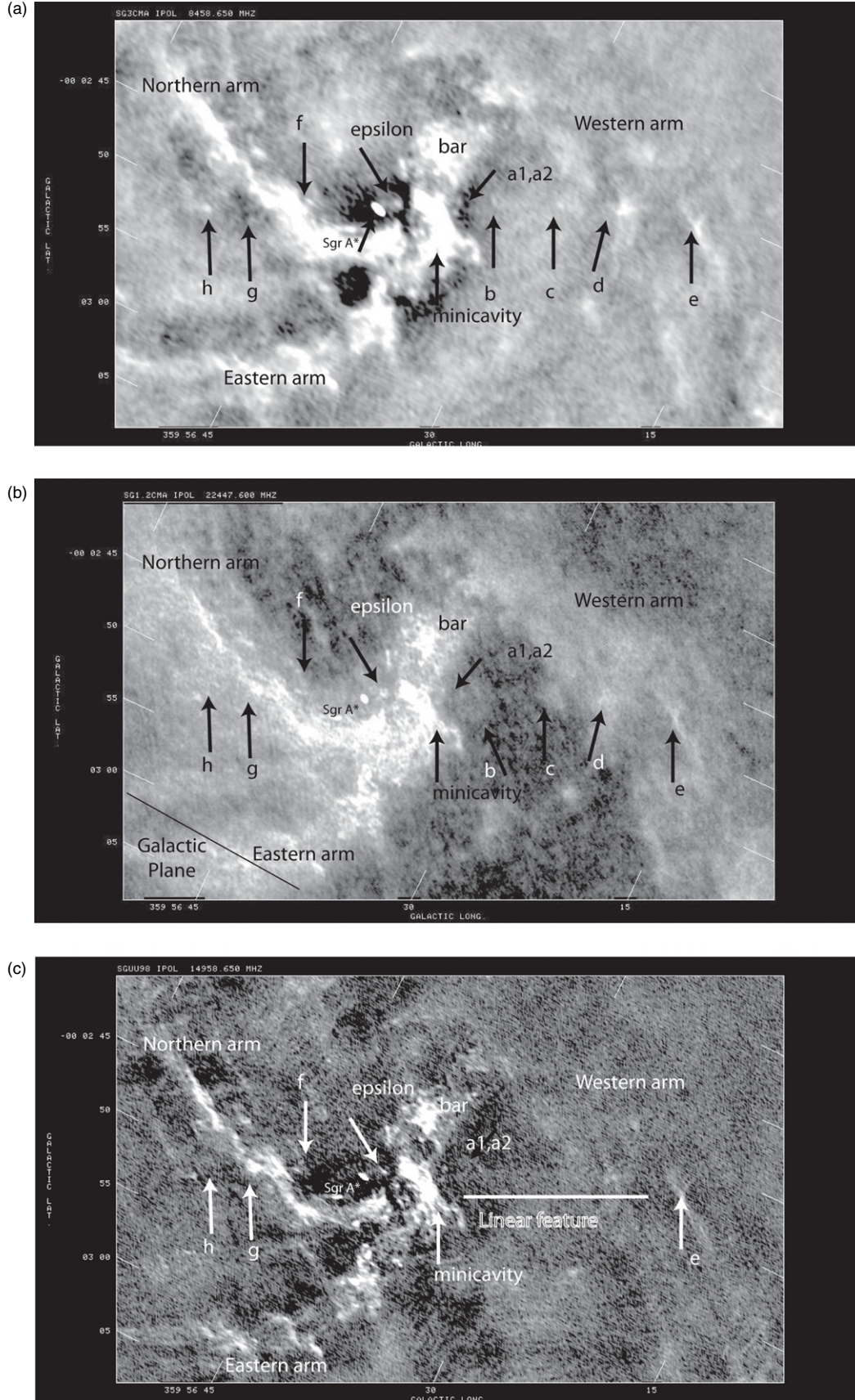


Figure 4. All images are rotated by $\sim 28^\circ$ with respect to the Galactic plane in order to place the linear feature along the horizontal axis. (a) A gray-scale total intensity image of the inner $30'' \times 45''$ of Sgr A* at 8.4 GHz based on combining A-array configuration data sets taken on 1991 August 15 and 1990 May 30. The spatial resolution is $0''.46 \times 0''.23$ (P.A. = 12°). (b) Similar to (a) except at 23 GHz based on combining A, C, and B-array data taken on 1990 May 30, 1986 December 28, and 1987 November 27, respectively. The resolution of the image is $0''.24 \times 0''.17$ (P.A. = $1^\circ 58'$). (c) Similar to (a) except at 15 GHz based on A-array data taken on 1998 April 30. The resolution is $0''.2 \times 0''.1$ (P.A. = $-0^\circ 23'$).

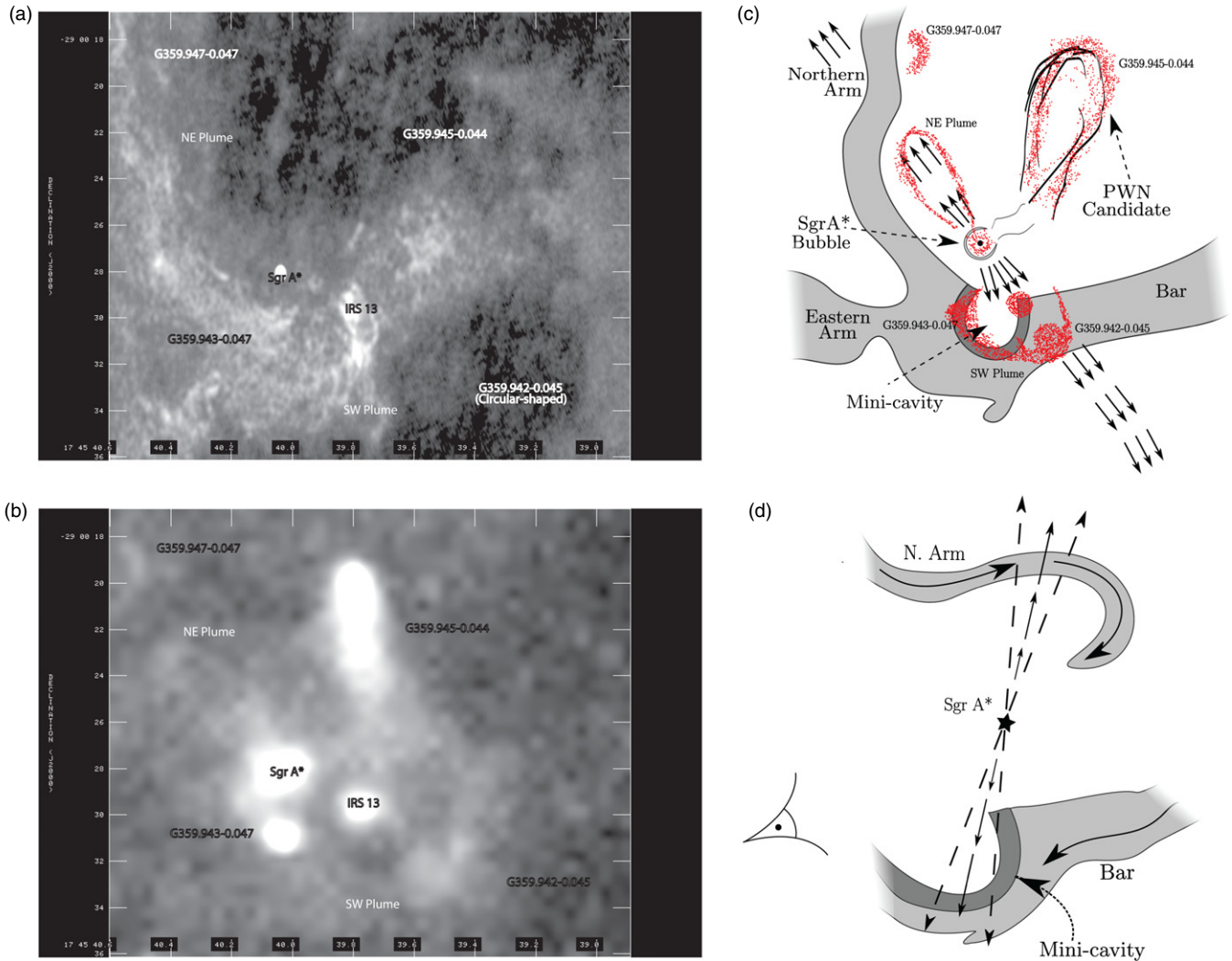


Figure 5. (a) A radio continuum image of Sgr A* at 22.3 GHz with a spatial resolution of $\sim 0''.24 \times 0''.17$ (P.A. = $1^\circ 6$). The data are taken in the A-array configuration on 1990 May 30, 1987 November 27, combined with the C-array configuration on 1986 December 28. (b) The same region as (a) but showing X-ray emission between 0.5 and 10 keV at a resolution of $0''.49$. (c) A schematic diagram showing bright radio and X-ray features in gray and red, respectively, and a model of a narrow two-sided jet from Sgr A*. (d) A schematic diagram of a model showing the near- and far-side components of the symmetrical jet running into the ionized bar and the N arm which are assumed to be located in the front and the back side of Sgr A*, respectively.

(A color version of this figure is available in the online journal.)

3. DISCUSSION

Our high-resolution radio and X-ray continuum images show new structural details within 5 pc of Sgr A*. We detect a chain of faint blobs which are distributed along a continuous linear feature. The linear feature continues beyond the ionized arms of Sgr A West, extending to about $75''$ (3 pc) away from Sgr A* before it is terminated by extended linearly polarized features. The orientation of the collimated feature is consistent with the proper motion and cometary morphology of dust features as well as the bow shock structure of Fe II line emission leading to the idea of an outflow from young massive stars or from Sgr A* (Lutz et al. 1993; Müzic et al. 2007). The collimated feature could be produced by the winds of massive young stars associated with the clockwise rotating stellar disk (Paumard et al. 2006). However, it is not clear how to collimate the outflowing winds. Numerical simulations of wind–wind collisions incorporating the dynamics of stars in the central cluster do not show any evidence of collimated structure (Cuadra et al. 2008). Thus, it is more likely that Sgr A* itself

is responsible for the origin of the collimated feature and the acceleration of particles to high energies.

We account for the origin of the new features in terms of a mildly relativistic jet symmetrically emanating from Sgr A*. The jet interacts with the orbiting gas, forms the structure of the minicavity, compresses, and shocks the gas producing X-ray and radio emitting blobs of emission. The brightest polarized features are symmetrically placed at a projected distance of ~ 3 pc from Sgr A* and are consistent with the jet picture. The lack of polarized emission at 8.4 GHz from the inner pc is due to depolarization by dense ionized gas.

The near- and far-side components of the symmetrical jet run into the ionized bar and the N arm which are assumed to be located in the front and the back side of Sgr A*, respectively. In this picture, the ionized bar and the N arm are two independent ionized features orbiting Sgr A* (Zhao et al. 2009). The ram pressure of the near-side component of the jet disturbs the ionized bar and produces the high negative velocity at the western edge of the minicavity. The change in the velocity of the gas is about 100 km s^{-1} between the E and W boundaries of

the minicavity. The blueshifted gas associated with the bar gets more blueshifted at the interaction site. Similarly, the far-side component of the jet punches through the N arm and causes a sinusoidal pattern along the clockwise motion of the N arm. If we assume that the jet is mildly relativistic, it can punch through the 10^5 cm^{-3} gas of the bar. However, if the jet missed the bar originally and then the bar is currently sweeping around it, the jet can survive deflection and the interaction might create the minicavity.

The mass outflow rate in the jet should be somewhat less than the accretion rate onto Sgr A*, which is estimated to be a few times $10^{-5} M_{\odot} \text{ yr}^{-1}$ (e.g., Cuadra et al. 2008). We adopt a nominal mass outflow rate of $10^{-6} M_{\odot} \text{ yr}^{-1}$, a Lorentz factor $\gamma \sim 3$, and a cross-section equivalent to a diameter of $1''$. Then the momentum transfer rate $\dot{M}\gamma v = 0.3 \gamma M_{\odot} \text{ yr}^{-1} \text{ km s}^{-1}$, sufficient to drive a $270\gamma^{0.5} \text{ km s}^{-1}$ shock into the 10^5 cm^{-3} molecular gas associated with the bar. The interaction of this gas with the jet may then be responsible for the minicavity, which exhibits a velocity disturbance of $100\text{--}200 \text{ km s}^{-1}$ (Roberts et al. 1996), suggesting an age of approximately 100–300 years for this interaction. The gas would be shock heated to about 3 million K, with a cooling time of only a few years, and the X-ray luminosity of the cooling gas is of order the kinetic luminosity of the jet. If the interaction only lasted for 1–2 decades, it would have produced the X-ray flash thought to be responsible for much of the fluorescent 6.4 keV Fe K α line emission within 100 pc of the Sgr A* (Sunyaev & Churazov 1998; Koyama et al. 2009). In addition, the interaction of the jet compresses the gas in the mini cavity, and may trigger star formation in the gas rich environment of Sgr A*, as evidenced by a cluster of young massive stars.

The jet continues crossing the W and N arms and eventually interacts with the molecular ring where linearly polarized emission is detected. The wider thickness and higher surface brightness of the jet to the SW compared to that of NE are consistent with a higher density of material distributed in the dense ionized bar. The jet drives shocks into gas clouds, producing blobs of X-ray emitting gas, and shocked molecular H₂ and SiO emission, enhancing the iron abundance in the gas phase, generating a low dust to gas ratio in the minicavity, and disturbing the kinematics of orbiting ionized gas.

The collimation of the outflowing material from Sgr A* along a jet axis is generally considered to be due to an accretion disk. The axis of the jet outflow from Sgr A* is estimated to be 60° . This position angle of large-scale jet differs by $30^\circ\text{--}60^\circ$ from the constraints placed by Very Long Baseline Array measurements (Markoff et al. 2007). However, the analysis of near-IR polarization infers the spin axis of Sgr A* to be quite similar to the PA of the detected jet features (Zamaninasab et al. 2011). Notably the orientation of the jet, indicated by dashed line in schematic diagrams of Figures 5(c) and (d), runs perpendicular to the principal axis of the clockwise stellar disk (Paumard et al. 2006). This alignment may be a coincidence or possibly due to the accretion processes that still continue in

forming young low-mass stars or due to the ionized winds of stars in the clockwise stellar disk. If the latter, Sgr A* is retaining the memory of in situ star formation activity in its vicinity. Almost all models of the steady component of the emission from Sgr A* predict an accretion disk, a jet, and/or an outflow. Present observations support jet models for Sgr A* (e.g., Falcke & Markoff 2000; Das et al. 2009; Becker et al. 2011).

In summary, we have presented evidence for a faint pc scale linear feature arising from Sgr A* that interacts with ionized and molecular material orbiting Sgr A*. An important implication of a jet/outflow is that a disk is needed to collimate the outflowing materials. Given that the VLA is a linear array, deconvolution errors may result linear structures along the symmetric beam pattern with the beam being strongest in the NS direction for southern sources. Our images do not show any evidence of symmetric “cross” pattern. However, future observations with nonlinear arrays, such as ALMA, should confirm the reality of polarized jet associated with Sgr A*, as reported here.

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