Tidal Distortion of the Envelope of an AGB Star IRS 3 near Sgr A*

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Abstract

We present radio and millimeter continuum observations of the Galactic center taken with the Very Large Array (VLA) and ALMA at 44 and 226 GHz, respectively. We detect radio and millimeter emission from IRS 3, lying ∼4.5 NW of Sgr A*, with a spectrum that is consistent with the photospheric emission from an AGB star at the Galactic center. Millimeter images reveal that the envelope of IRS 3, the brightest and most extended 3.8 μm Galactic center stellar source, consists of two semicircular dust shells facing the direction of Sgr A*. The outer circumstellar shell, at a distance of 1.6 × 10^2 au, appears to break up into “fingers” of dust directed toward Sgr A*. These features coincide with molecular CS (5–4) emission and a near-IR extinction cloud distributed between IRS 3 and Sgr A*. The NE–SW asymmetric shapes of the IRS 3 shells seen at 3.8 μm and radio are interpreted as structures that are tidally distorted by Sgr A*. Using the kinematics of CS emission and the proper motion of IRS 3, the tidally distorted outflowing material from the envelope after 5000 yr constrains the distance of IRS 3 to ~0.7 pc in front of or ~0.5 pc behind Sgr A*. This suggests that the mass loss by stars near Sgr A* can supply a reservoir of molecular material near Sgr A*. We also present dark features in radio continuum images coincident with the envelope of IRS 3. These dusty stars provide examples in which high-resolution radio continuum images can identify dust-enshrouded stellar sources embedded in an ionized medium.

Key words: Galaxy: center – Galaxy: nucleus – ISM: clouds – ISM: molecules – ISM: structure – stars: AGB and post-AGB

1. Introduction

The nucleus of our Galaxy hosts a supermassive black hole, Sgr A*, at the dynamical center of the Galaxy. The stellar nuclear cluster surrounding Sgr A* consists of a mixture of an evolved stellar population and a young population of stars at smaller radii. Sgr A* and its neighborhood are subject to intense scrutiny, with the potential for long-lasting impact on our understanding of massive black holes in the nuclei of normal galaxies. Understanding the processes occurring in the immediate environment of the massive black hole provides insight into our own Milky Way’s most massive black hole and presents an unparalleled opportunity to closely study the process by which gas is captured and radiated by supermassive black holes.

Recent OH, CN, CS, HCN, and SiO observations suggest that molecular gas is able to survive within 5″ (0.2 pc) of Sgr A* (Martin et al. 2012; Montero-Castaño et al. 2009; Yusef-Zadeh et al. 2013; Karlsson et al. 2015; Moser et al. 2016). One key question is how this gas finds its way so close to Sgr A*. One possibility is the radial infall of giant molecular clouds toward the Galactic center. Another possibility is that the highly eccentric orbit of compact clouds, such as G2, brings neutral material close to Sgr A* (e.g., Gillessen et al. 2012, 2013). These clouds experience tidal stripping and provide the supply of accreting material onto Sgr A*.

IRS 3 is the brightest and most extended 3.8 μm star in the central parsec of the Galaxy resembling either a young massive star surrounded by dust (Tanner et al. 2005; Viehmann et al. 2005) or a cool dusty star (e.g., Roche & Aitken 1985; Pott et al. 2008). Recent high-resolution 3.8 μm observations identified IRS 3 as a cool AGB star without any associated OH masers. The 3.8 μm emission has two components, a compact and bright source, coincident with the central star with an effective stellar temperature of 3 × 10^3 K, and a dusty shell with a radius of 1″ (or 8000 au) surrounding the central star (Pott et al. 2008).

Here, we present ALMA and VLA observations of the Galactic center and show that the dusty outer shell of IRS 3 located 4.5 NW of Sgr A* (projected distance ∼0.18 pc at the Galactic center distance 8 kpc) is being tidally stretched by Sgr A*. The evidence for tidal distortion of the envelope of IRS 3 implies that dusty, evolved stars with massive envelopes approaching the dynamical center of the Galaxy may supply the fuel for accretion onto Sgr A*.

We also present new observations indicating multiple shells of dust emission at millimeter extension up to ∼0.1 pc from the central star. We detect diffuse continuum radio emission from the outermost shell of IRS 3, suggesting external photoionization by the central young star cluster, similar to IRS 7. In addition, we show several fingers of dust emission stretched from the outer shell of IRS 3 toward where Sgr A* is located. Finally, dark features coincident with the dusty envelopes of IRS 3 in radio continuum images are noted.

2. Observation and Data Reduction

ALMA and VLA5 observations were carried out as part of a multiwavelength observing campaign to monitor the flux variability of Sgr A*. Here we focus on observations related to IRS 3 and IRS 7 within a few arcseconds of Sgr A*. Observations were obtained on 2016 July 12 and 18.

5 The Karl G. Jansky Very Large Array (VLA) of the National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under a cooperative agreement by Associated Universities, Inc.
The ALMA 230 GHz data consisted of two spectral windows centered on 218.3 and 238.0 GHz, each 1.87 GHz wide. Bandpass and delay calibration was based on J1924–2914. Cross-hand gain calibration was based on Titan and Pallas, which were assumed to be unpolarized, and subsequent calibration averaged the parallel-hand (XX and YY) data sets. The initial amplitude and phase calibration were based on 1744–3116, with an assumed flux density of 0.26 Jy at 234 GHz. Phase self-calibration, followed by amplitude and phase calibration, was applied. The amplitude self-calibration, however, adds uncertainty to the overall amplitude gain calibration. The editing and calibration of the data were carried out using OBIT (Cotton 2008) before all the spectral windows were averaged prior to constructing final images. The July 12 data with a spatial resolution of 0′′.36 × 0′′.25 are presented here.

We also present radio data at 44 and 15 GHz taken with the VLA in its A configuration. The 44 GHz observations were carried out on 2011 July 8–9 and August 31–September 1. We combined all 4 days of observations, resulting in about 25 hr of data, self-calibrated in phase and amplitude before final images were constructed. Details of these narrowband observations are given in Yusef-Zadeh et al. (2013). The 15 GHz observation, which was part of a series of measurements at several frequencies between 1.4 and 44 GHz, was carried out on 2013 March 10. Data reduction and observing setup were identical to those described at 8 GHz in Table 1 of Yusef-Zadeh et al. (2016).

3. Results

3.1. Radio and Millimeter Emission from IRS 3

The top two panels of Figure 1 show 226 GHz images of the central 10′′ × 10′′ of the Galactic center at two different spatial resolutions to reveal millimeter emission from IRS 3 and the newly extended structures. The peak millimeter emission from IRS 3 coincides with a compact point source at 44 GHz (Yusef-Zadeh et al. 2015). Table 1 shows the comparison of radio and millimeter emission from IRS 3 based on data taken on 2016 July 12. Columns of Table 1 give the frequency, the telescope and its configuration, R.A. and decl., the angular distance from Sgr A′ in increasing order, positional accuracy, the spatial resolution, the peak intensity, the spectral index, integrated intensities, and references. The intensities are estimated from background-subtracted 2D Gaussian fits to IRS 3. Table 1 also includes data taken with the VLA in its A-array configuration on 2014 March 9 and February 21 at 34 and 44 GHz, respectively (Yusef-Zadeh et al. 2016). The spectral index α, where the flux density Sν ∝ ν−α, between 44 and 226 GHz and that between 34 and 44 GHz give values of 1.85 ± 1.13 and 1.32 ± 0.32, respectively. Using the peak flux density of IRS 3 at 350 GHz given by Moser et al. (2016), we find that the spectral index is α = 1.17 ± 0.33 between 226 and 350 GHz. Radio emission from the photosphere of an evolved star has a typical spectral index close to α = 1.87 (Matthews et al. 2015), whereas ionized mass-losing stellar winds are characterized to have α ∼ 0.6 (Panagia & Felli 1975). It is clear that radio to millimeter emission from IRS 3 is optically thick and its spectral index within errors is more consistent with the emission from the photosphere of an evolved star than that of ionized stellar winds emanating from young mass-losing stars. Given the large error in α, we cannot rule out the possibility that IRS 3 is a young mass-losing star. However, spectral index measurements of a number of radio stars associated with young massive stars near Sgr A′ do not show a steep optically thick spectrum with a high value of α. In addition, the spatially resolved structure of IRS 3 at 3.8 μm and the extended millimeter emission in its vicinity, as discussed below, are detected only toward IRS 3 in the Galactic center. Thus, we assume that IRS 3 is an evolved AGB star.

3.2. Asymmetric Shells and Fingers of Dust Emission

ALMA images reveal extended emission from IRS 3, which includes four new substructures at millimeter wavelength. The new millimeter substructures are faint, but we detect them in both epochs of our millimeter observations. First, we detect millimeter emission from a shell of dust closest to the central star. The second panel of Figure 1 shows this narrow layer of dust separated from the central peak, facing south toward Sgr A′. The typical flux density of this layer of dust is 100 μJy per 0′′.49 × 0′′.38 beam (PA ∼ −75°). Comparison between the top three panels of Figure 1 shows that the innermost millimeter dust shell traces the southern edge of the dusty and cool AGB star at 3.8 μm. The dark dashed lines closest to the central star outline the boundary of the dust shell at millimeter emission in the top two panels of Figure 1. The dashed white line outlines schematically the northern and southern boundaries of the equivalent width (EW) extended envelope in 3.8 μm (see the third panel of Figure 1). Second, a thick layer with a dearth of emission is sandwiched between the inner circumstellar shell, lying within 1″ of the central star, and an outer shell, about 2″/5 from the peak millimeter emission. The intensity in this dark layer ranges from 100 to ~400 μJy across the two millimeter shells. We also note that the southern segment of IRS 7 in the top two panels of Figure 1 shows a similar dark feature. The outer dark dashed lines drawn in Figure 1 trace the outer shell of IRS 3. The two shells and the dark layer of IRS 3 face Sgr A′ with similar curvature, suggesting that these shells are concentric and are associated with the central AGB star. We also note weak 15 GHz continuum emission from the outer shell of IRS 3, as shown in the bottom panel of Figure 1. The mean intensity of the 15 GHz emission is 0.1 mJy per 0″.2 × 0″.1 beam. Third, the outer millimeter shell is irregular in its appearance and reveals a number of “fingers” of dust emission in the top two panels of Figure 1. These fingers extend for about 2″ toward Sgr A′ with a position angle of ~120°–160°.

Figure 2(a) shows a 226 GHz grayscale close-up of the dark layer, the central millimeter peak emission from the photosphere of IRS 3, and the inner and outer circumstellar shells of IRS 3. The peak emission appears to be extended in the NE–SW direction and is similar to that seen in the 3.8 μm with a PA ∼ 65° and angular size of ~3″, as seen in the third panel of Figure 1. The extended emission to the south of IRS 3 coincides with CS (5–4) emission and spots of compact SiO (6–4) emission with radial velocities between 20 and 100 km s^{-1} within a 6″ × 4″ region to the south of IRS 3 (Moser et al. 2016). The extinction map based on near-IR observations, as shown in Figure 2(b), also reveals a cloud of extinction with an excess of ~0.5 mag with respect to its surroundings at 2 μm (Schödel et al. 2010), coincident with the CS (5–4) emission. Figure 2(c) shows a close-up view of IRS 3 at millimeter emission, where contours of 226 GHz emission are superimposed on a 3.8 μm grayscale image. This relatively low
resolution millimeter image shows elongation of IRS 3 in the EW direction similar to that seen in Figure 1(c). Figure 2(d) shows a schematic diagram of the new millimeter substructures.

3.3. Radio Dark Dusty Stars

Radio continuum images show dark features toward the envelopes of IRS 3 and IRS 7, reminiscent of radio dark clouds (RDCs) that appear in radio continuum images of Galactic center sources (Yusef-Zadeh 2012). Radio dark clouds in continuum images with high dynamic images provide imprints of molecular and dust clouds that are embedded in a bath of ionizing radiation. In regions where thermal radio continuum emission is depressed along the line of sight through a molecular cloud, the cloud appears as a dark feature in radio continuum images. This depression can also be produced by swept-up gas of an outflow within an ionized medium.

Figure 3 presents the dark features associated with IRS 3 at 44 GHz and 3.8 μm. The locations of three dark features are drawn as ellipses. The one to the east coincides with the region surrounding the northern arm of the minispiral. The dark features to the southwest and northwest lie in the vicinity of the IRS 13N complex (Muzic et al. 2008) and IRS 3, respectively. The feature close to IRS 3 traces roughly the shells noted in Figures 1 and 2.

A close-up and high-resolution view of the region around IRS 3 and IRS 7 is presented in the top and bottom panels of Figure 4 at 44 GHz and 3.8 μm, respectively. A faint radio source that coincides with the central star of IRS 3 (see Table 1) is labeled. We note an extended and elongated dark feature to the southwest of IRS 3. This dark feature, drawn as white dashed lines, covers the inner shell and the dark layer detected at millimeter emission, as described above. We also note another dark feature in the immediate vicinity of IRS 7. Both these dark features extend to the outer envelope of the dusty stars IRS 3 and IRS 7 and terminate where strong and weak ionized gas is detected, respectively.

Dark features in radio continuum images could result from interferometric errors due to the incomplete sampling of the uv plane (Yusef-Zadeh 2012). However, we detected these dark features in several high-frequency images using the VLA in different array configurations. In addition, the dark features correlate with a reservoir of molecular gas in the region between IRS 3, IRS 7, and Sgr A* (Moser et al. 2016). The expected correlation of molecular line emission surrounding IRS 3 and radio dark clouds is consistent with that noted toward radio dark clouds and molecular clouds (Yusef-Zadeh 2012). Furthermore, dark clouds correlate with excess near-IR extinction (Schödel et al. 2010). The CS (5–4) line emission and an extinction excess in near-IR (Schödel et al. 2009; Moser et al. 2016) coincide with radio dark dusty star IRS 3 and its extension to the southeast. The third dark feature to the northeast, however, shows no molecular or extinction counterparts. This feature and the one surrounding the inner 2″ of Sgr A* coincide with dust cavities.

4. Discussion

4.1. Tidal Distortion of the Circumstellar Shells of IRS 3

The most interesting result of this study is the discovery of asymmetric millimeter dust shells centered on IRS 3 and facing Sgr A*. The shells exhibit a wavy pattern with wavelength

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**Figure 1.** Top panel: grayscale millimeter image of the inner 10″ × 10″ of the Galactic center at 226 GHz with a resolution of 0″49 × 0″38 (PA = −75°) taken with ALMA. Second panel: similar to the top panel, except with a resolution of 0″44 × 0″34 (PA = −70°). Third panel: similar region to that of the top panel at 3.8 μm taken with the VLT (S. Gillessen 2017, private communication). Bottom panel: radio image of the same region shown in the top panel at 15 GHz at a resolution of 0″24 × 0″11 (PA = 5°8) taken with the VLA on 2014 March 10.
### Table 1
Parameters of 2D Gaussian Fits to IRS 3

| Freq.  | Telescope | R.A. (J2000) | Decl. (J2000) | Sgr A* Pos. | Offset Accuracy (mas) | Peak Intensity (mJy beam$^{-1}$) | Spectral Index ($\alpha$) | Integrated Flux (mJy) |
|--------|-----------|--------------|---------------|-------------|------------------------|-------------------------------|-------------------------|----------------------|
| 44.5   | VLA(B)    | 39.8614      | 24.2147       | 4.50        | 50.24                  | 0.109 ± 0.052                 | 0.121 ± 0.096           |                      |
| 226    | ALMA      | 39.8644      | 24.2573       | 4.44        | 101.29                 | 0.841 ± 0.021                 | 1.215 ± 0.400           |                      |
| 350    | ALMA      | 39.8644      | 24.2573       | 4.44        | 490 × 410              | 1.4 ± 0.2                     | 1.22 ± 0.38             |                      |
| 34.5   | VLA(A)    | 39.8619      | 24.2522       | 4.47        | 10.93                  | 85 × 42 (−5.3)                | 0.081 ± 0.012           | 0.108 ± 0.025         |
| 44.5   | VLA(A)    | 39.8624      | 24.2520       | 4.46        | 7.55                   | 74 × 34 (−4.0)                | 0.132 ± 0.034           | 0.111 ± 0.052         |

**Notes.**

* $\alpha$ between 44.5 and 226 GHz.
* $\alpha$ between 226 and 350 GHz.
* Moser et al. (2016).

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**Figure 2.** Top left: contours of 226 GHz emission from the inner $2''\times 3''$ of IRS 3 are set at $(-0.5, 0.5, 1, 2, 3, 4, 6, 8, 10, 15, 20, 25, and 30) \times 55.5$ μJy beam$^{-1}$ with a resolution of $0''49 \times 0''38$ (PA $\sim 74^\circ$) and with a grayscale range between $-0.79$ and $0.5$ mJy beam$^{-1}$. Top right: similar to the top left panel, except that it is an extinction map with contours set at $2.5, 2.55, 2.6, 2.65, 2.7, 2.75, 2.8, 2.85, 2.9, 2.95, 3, 3.025, 3.050 \times 1.1$ mag at K band (Schödel et al. 2009). The grayscale range is between $2.650$ and $2.950$ mag. Bottom left: contours of 226 GHz emission with a resolution of $0''59 \times 0''47$ (PA $\sim 82.5^\circ$) are superimposed on a 3.8 μm image of IRS 3 with levels set at $(-12, -10, -8, -6, -4, -3, -2, -1, -0.5, 0.5, 1, 2, 3, 4, 6, 8, 10, 12) \times 55.5$ mJy beam$^{-1}$. Given that this image is weighted to show extended features, emitting features are depressed by the negative bowls, due to the lack of short spacings. Bottom right: schematic diagram showing the new millimeter substructures between IRS 3 and Sgr A*.
∼0′.25–0′.5 along the shell. In addition, the outermost shell of IRS 3 is broken up into fingers of millimeter emission, pointing toward Sgr A∗. The fingers of dust emission appear to coincide with a region where CS (5–4) emission is concentrated (see Figure 6 of Moser et al. 2016). We first estimate the mass of gas associated with the CS (5–4) emission and show that it could arise from the envelope of IRS 3. The emission extends over a ∼6′′ × 4′′ region with velocities between about 40 and 80 km s⁻¹ (Moser et al. 2016). We used the online version of RADEX⁶ (Van der Tak et al. 2007) to estimate the density and column of the emitting molecular gas. Adopting a kinetic temperature of 300 K, consistent with the proximity to hot stars in the central parsec, and a 40 km s⁻¹ FHWM, the observed radiation temperature can be produced by a medium in which the product of hydrogen number density and line-of-sight CS column »´n₁₀HCS cm⁻³ as long as »´n₁₀H ≈ 3 × 10⁵ cm⁻³. Under these conditions the line is subthermally excited and optically thin. We assume that the CS abundance relative to H is »´xCS = 5 × 10⁻⁷, consistent with observations of carbon stars (Woods et al. 2003), and assume that the depth of the source along the line of sight, L, is 0.2 pc, consistent with the angle subtended by the CS emission on the sky. Then noting that »´n₁₀H N₁₀CS = »´xCS n₁₀H² L, we find »´n₁₀H ≈ 6 × 10³ cm⁻³. This implies an uncomfortably large envelope mass »´Menv ≈ 1.4 M☉ unless the IRS 3

Figure 3. Top two panels: inner 10″ × 7″ of Sgr A* with different contrasts in order to bring out the extended radio dark clouds and star associated with IRS 3. The bottom two panels are the same size as the top two panels, except they show the extinction and 3.8 μm images (Schödel et al. 2009).

Figure 4. Top: grayscale image of the region surrounding IRS 3 and IRS 7, showing dark patches coincident with the envelopes of these two stars at 44 GHz with a resolution of 0″0.84 × 0″042 (PA = −5°65). The white dashed lines trace the dark radio features. Bottom: similar to the top panel, except at 3.8 μm.

http://home.strw.leidenuniv.nl/~moldata/radex.html
envelope is clumpy, giving $M_{\text{env}} = 0.3 \, M_\odot$, with most mass residing in clumps with 5% filling factor (implying $n_\text{H} \approx 3 \times 10^4$ cm$^{-3}$). This would produce the observed CS ($5-4$) line emission. Although this envelope contains 1/5 the original number of CS molecules, each lies in a clump with five times the original density: the rate of collisional excitation of each CS molecule, and hence the rate of $J = 5-4$ photon emission per CS molecule, is increased fivefold. Individual clumps have $0.8$ mag of extinction at $2 \mu$m. This can be reconciled with the observed average extinction (see Figure 2(b)) if the beam filling fraction is $0.3$.

The volume and area filling fractions imply that the envelope consists of $\sim 16$ clumps with size $\sim 0.014$ pc, or 0''7. Adopting a dust temperature of 100 K in the envelope implies an average thermal continuum of $\sim 90 \, \mu$Jy per 0''39 x 0''38 beam at 226 GHz, similar to the millimeter enhancement coincident with the CS emission and IR extinction, which are broadly consistent with the structure seen in the mid-infrared emission.

Infrared $^{13}$CO ($v = 1 - 0$) and H$_2^+$ absorption lines have also been detected toward IRS 3 (Goto et al. 2014). One broad velocity component is at 60 km s$^{-1}$, ranging between 51 and 85 km s$^{-1}$. This velocity feature has not been detected toward IRS 1W a few arcseconds away from Sgr A*. The physical characteristics of H$_2^+$ suggest density and temperature that are consistent with the above estimates from CS measurements. Goto et al. (2014) interpret the 60 km s$^{-1}$ feature as arising from the inner parsec but associated with the circumnuclear molecular ring. Given that the infrared absorption lines have similar characteristics to the CS line emission discussed above, it is possible that absorption features come from the envelope of IRS 3. Based on photospheric modeling, Pott et al. (2008) estimate $M \sim 6 \times 10^{-5} \, M_\odot$ yr$^{-1}$. The timescale to eject $0.3 \, M_\odot$ is then $\sim 5000$ yr, implying a terminal wind speed $v \sim 20$ km s$^{-1}$ to yield an envelope radius $r \sim 0.1$ pc, consistent with the extent of the CS emission. The envelope may, of course, extend to greater radii but not be visible in CS if molecules are dissociated by the strong external far-UV field at the Galactic center. Alternatively, the envelope may be truncated if significant mass loss from IRS 3 has only been taking place over the past 5000 yr, or it could be tidally stripped.

Tidal effects may be responsible for the distortion of the envelope as IRS 3 orbits Sgr A*. Alternatively, the asymmetry may be due to an asymmetric outflow from IRS 3, as numerous post-AGB stars reveal this structure (Richards et al. 2011; Lykou et al. 2015, p. 203). We cannot rule out this possibility, but given the elongation of IRS 3 along its proper motion and the presence of extended molecular and dust emission distributed to the south of IRS 3, we consider that the elongation of IRS 3 at 3.8 $\mu$m is due to tidal distortion, as described below.

A simple criterion for tidal extension is that the expansion timescale is of order of the orbital timescale around Sgr A*:

$$r/v \approx (GM/R^3)^{0.5},$$

where $R \sim 0.8$ pc is the distance from Sgr A* and $r$ is the shell radius. To explore the envelope’s distortion, we model it as a set of fluid elements that are launched radially outward from

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**Figure 5.** Tidal distortion of the envelope of IRS 3 for different assumed positions along the line of sight, either in the foreground (left column) or in the background (right column) relative to Sgr A*. In each panel, black, red, and blue points indicate the position in the sky of fluid elements ejected radially from IRS 3 2500, 5000, and 7500 yr ago, respectively, at the assumed wind velocity of 20 km s$^{-1}$ (see text). The black plus sign in each panel indicates the location of Sgr A*.
IRS 3 as it orbits Sgr A* and subsequently follow their ballistic trajectories in the gravitational field of Sgr A*. In other words, each fluid element follows an independent Keplerian orbit consistent with its launch position and velocity. This ballistic approximation is reasonable, as the outflow is supersonic, and so the dynamical effect of pressure is negligible until the fluid elements start to intersect $\sim 1/2$ an orbital period after launch.

The orbit of IRS 3 is not completely determined a priori because its line-of-sight velocity and location within the inner parsec along the line of sight are unknown, nor has acceleration in its proper motion across the sky been observed. However, the projected location of IRS 3 relative to Sgr A* and its proper motion are both well determined (Schödel et al. 2009). We adopt $+50 \text{ km s}^{-1}$ as the line-of-sight velocity, representative of the mean velocity of the CS emission that we assume arises from its envelope. Then we vary the line-of-sight distance $z$ relative to the distance to Sgr A*. A particular choice of $z$ means that the instantaneous velocity and displacement of IRS 3 relative to Sgr A* are specified, sufficient to specify its orbit. We adopt $4 \times 10^6 \text{ M}_\odot$ and 8 kpc as the mass and distance of Sgr A*, and R.A. and decl. offsets of IRS 3 from Sgr A* as $\Delta \text{R.A.} = -2^\circ 341 \pm 0^\circ 009$, $\Delta \text{decl.} = 3^\circ 848 +0^\circ 016$ with velocities $v_{\text{R.A.}} = 179.1 \pm 5.6 \text{ km s}^{-1}$, $v_{\text{decl.}} = 31.2 \pm 4.0 \text{ km s}^{-1}$ (Schödel et al. 2009). We adopt a $z$-axis directed away from the observer, with $v_z = 50 \text{ km s}^{-1}$, and $z = 0$ at the distance of Sgr A*, so, e.g., $z = +0.1 \text{ pc}$ lies 0.1 pc beyond Sgr A*.

We compute the ballistic evolution of fluid elements ejected from IRS 3, 2500, 5000, and 7500 yr ago, and plot their position on the the sky relative to Sgr A* as black, blue, and red points, respectively, in Figure 5, for different choices of $z$. The blue shell should correspond to the extent of the CS envelope, which has an estimated flow time of $\sim 5000 \text{ yr}$. If $z \lesssim -0.8 \text{ pc}$, or $z \gtrsim 0.6 \text{ pc}$, the tidal distortion of the shell is too small, whereas if $-0.6 \text{ pc} \lesssim z \lesssim 0.4 \text{ pc}$, the tidal distortion is too severe. We therefore conclude that if the CS emission arises from the envelope of IRS 3, then IRS 3 currently lies either $\sim 0.7 \text{ pc}$ in front of Sgr A*, or $\sim 0.5 \text{ pc}$ behind it.

According to Viehmann et al. (2005), the 3.8 $\mu$m isophotes of IRS 3 have major axis orthogonal to the direction toward Sgr A* and have a bow shock morphology perhaps caused by winds from the cluster of massive stars orbiting Sgr A* or an outflow from Sgr A*. However, this morphology is very dissimilar to the head-tail ionized structure associated with the bow shock source IRS 7 (Rieke & Rieke 1989; Yusef-Zadeh et al. 1989; Yusef-Zadeh & Melia 1992). There is no evidence of an envelope of ionized gas surrounding the innermost millimeter shell of IRS 3. There is weak radio continuum emission from the outer distorted shell (see Figure 2(b)). Thus, it seems unlikely that the NE–SW structure of IRS 3 at 3.8 $\mu$m is produced by external winds. Instead, we suggest that the outer shell asymmetry is produced by tidal effects tending to stretch the envelope along the orbit of IRS 3. It is also possible that the dust shells to the south of IRS 7 could be generated by the tidal tails from an earlier episode of mass loss from IRS 3 (see the $z = +0.4$ panel in Figure 5).

In summary, millimeter and radio images of the inner $10''$ of Sgr A* reveal stellar and circumstellar emission from IRS 3. The envelope of this AGB star is argued to be distorted and disrupted by the tidal force of Sgr A*. We also showed that the dusty envelopes of stars could have their imprints on radio continuum images. These dark radio stars are produced in the same way that radio dark clouds are originated by being embedded within an ionized medium.

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References

Cotton, W. D. 2008, PASP, 120, 439
Gillessen, S., Genzel, R., Fritz, T. K., Eisenhauer, F., et al. 2013, ApJ, 763, 78
Gillessen, S., Genzel, R., Fritz, T. K., et al. 2012, Natur, 481, 51
Goto, M., Geballe, T. R., Indriolo, N., et al. 2014, ApJ, 786, 96
Karlsson, R., Sandqvist, A., Fathi, K., & Martin, S. 2015, A&A, 582, A118
Lykou, F., Hron, J., Paladin, C., et al. 2015, Why Galaxies Care about AGB Stars III: A Closer Look in Space and Time, Vol. 497
Martin, S., Martin-Pintado, J., Montero-Castaño, M., Ho, P. T. P., & Blundell, R. 2012, A&A, 539, A29
Matthews, L. D., Reid, M. J., & Menten, K. M. 2015, ApJ, 808, 36
Montero-Castaño, M., Herrnstein, R. M., & Ho, P. T. P. 2009, ApJ, 695, 1477
Moser, L., Sánchez-Monge, Á., Eckart, A., et al. 2016, arXiv:1603.00801
Muzic, K., Schödel, R., Eckart, A., Meyer, L., & Zensus, A. 2008, A&A, 482, 173
Panagia, N., & Felli, M. 1975, A&A, 39, 1
Pott, J.-U., Eckart, A., Gendemann, A., et al. 2008, A&A, 478, 413
Richards, A. M. S., Assaf, K. A., Bains, I., et al. 2011, in Asymmetric Planetary Nebulae 5 Conf., Poster Session, ed. A. A. Zijlstra et al
Rieke, G. H., & Rieke, M. J. 1989, ApJL, 344, L5
Roche, P. F., & Aitken, D. K. 1985, MNRAS, 215, 425
Schödel, R., Merritt, D., & Eckart, A. 2009, A&A, 502, 91
Schödel, R., Najarro, F., Muzic, K., & Eckart, A. 2010, A&A, 511, A18
Tanner, A., Ghez, A. M., Morris, M. R., & Christou, J. C. 2005, ApJ, 642, 742
Van der Tak, F. F. S., Black, J. H., Schöier, F. L., Jansen, D. J., & van Dishoeck, E. F. 2007, A&A, 468, 627
Viehmann, T., Eckart, A., Schödel, R., et al. 2005, A&A, 433, 117
Woods, P. M., Schöier, F. L., Nyman, L.-Å., & Olofsson, H. 2003, A&A, 402, 617
Yusef-Zadeh, F. 2012, ApJL, 759, L11
Yusef-Zadeh, F., Bushouse, H., Schödel, R., et al. 2015, ApJ, 809, 10
Yusef-Zadeh, F., & Melia, F. 1992, ApJL, 385, L41
Yusef-Zadeh, F., Morris, M., & Ekers, R. 1989, in Proc. IAU 136, The Center of the Galaxy, ed. M. Morris (Dordrecht: Kluwer), 443
Yusef-Zadeh, F., Rosster, M., Wardle, M., et al. 2013, ApJL, 767, L32
Yusef-Zadeh, F., Wardle, M., Schödel, R., et al. 2016, ApJ, 819, 60