THE DISCOVERY OF RADIO STARS WITHIN 10″ OF Sgr A* AT 7 mm

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ABSTRACT

Very Large Array observations of the Galactic center at 7 mm have produced an image of the 30″ surrounding Sgr A* with a resolution of ~82 × 42 milliarcseconds (mas). A comparison with IR images taken simultaneously with the Very Large Telescope identifies 41 radio sources with L-band (3.8 μm) stellar counterparts. The well-known young, massive stars in the central Sgr A* cluster (e.g., IRS 16C, IRS 16NE, IRS 16SE2, IRS 16NW, IRS 16SW, AF, AFNW, IRS 34W, and IRS 33E) are detected with peak flux densities between ~0.2 and 1.3 mJy. The origin of the stellar radio emission in the central cluster is discussed in terms of ionized stellar winds with mass-loss rates in the range ~0.8–5 × 10^{-5} M_⊙ yr^{-1}. Radio emission from eight massive stars is used as a tool for registration between the radio and infrared frames with mas precision within a few arcseconds of Sgr A*. This is similar to the established technique of aligning SiO masers and evolved stars except that radio stars lie within a few arcseconds of Sgr A*. Our data show a scatter of ~6.5 mas in the positions of the eight radio sources that appear in both the L-band and 7 mm images. Last, we use the radio and IR data to argue that members of IRS 13N are young stellar objects rather than dust clumps, supporting the hypothesis that recent star formation has occurred near Sgr A*.

Key words: galaxies: active – Galaxy: center – ISM: jets and outflows – radio continuum: stars – stars: early-type

Online-only material: color figures

1. INTRODUCTION

Most of the far-IR luminosity of the inner few parsec of the Galactic center (GC) region can be accounted for by the central cluster of emission-line stars distributed throughout the region (e.g., Gezari et al. 2003; Genzel et al. 2010). The central stellar cluster lies mainly within 1-10″ of Sgr A* and consists of about 100 young massive OB and WR stars distributed amongst several small clusters, such as IRS 16 and IRS 13, within disks made up of stars (Paumard et al. 2006; Lu et al. 2009). Near-IR observations imply strong ionized winds with velocities on the order of 700 km s^{-1} and a total mass-loss rate of 4 × 10^{-3} M_⊙ yr^{-1} (Martins et al. 2007) arising from the collection of the so-called disk stars in the central cluster. Sgr A* is thought to be fueled by partial capture of the winds from massive stars in the central cluster. The accretion rate was originally estimated from Brγ line measurements, indicating mass loss from individual cluster stars (Narayan et al. 1995; Coker & Melia 1997; Goldston et al. 2005; Falcke & Markoff 2009). The variability of the accretion rate was predicted by numerical simulations and analytical calculations accounting for the motion of individual mass-losing stars orbiting Sgr A*, with the time averaged accretion rate being then estimated to be ~10^{-6} M_⊙ yr^{-1} (Quataert 2004; Cuadra et al. 2006, 2008). Radio emission from stars can potentially provide independent determination of mass-loss rates in the form of ionized stellar winds, with implications for the accretion rate onto Sgr A*. In addition, these measurements can potentially identify the sites of the interaction of ionized stellar winds with gas near Sgr A*, constraining physical parameters of the interstellar medium near the black hole. Radio observations, however, have so far been unable to identify isolated massive stars in the central cluster.

We present the highest resolution continuum image yet obtained of the inner 30″ of the GC at 7 mm. Previous high-resolution 1.3 and 3.5 cm observations of this region were used to investigate the proper motion of H ii regions (Yusef-Zadeh et al. 1998; Zhao & Goss 1998; Zhao et al. 2009). Individual stellar sources could not be separated, however, from the ionized flow associated with orbiting gas (Zhao et al. 2009). Radio emission from ionized winds from young stars has already been detected from the Arches and Quintuplet clusters projected within 12″ of Sgr A* (Lang et al. 2005). The high-resolution images presented here show for the first time radio emission from relatively isolated massive stars in the central stellar cluster centered on Sgr A*. We determine the mass-loss rate from ionized stellar winds to be quite similar to those in the Arches and Quintuplet clusters.

The positions of compact radio stars can also be used to precisely register the radio and IR frames within a few arcseconds of Sgr A*. Aligning radio and IR frames is a technique that locates the position of the bright radio source Sgr A* in highly confused IR images (Menten et al. 1997; Reid et al. 2003, 2007). This well-established technique uses maser emission from IR identified evolved stars to carry out accurate astrometry. Here we use the same technique and show that radio emission from hot stars can also be used for astrometric measurements. Precision astrometry using either radio stars or SiO masers has the potential in the search for post-Newtonian deviations in the stellar orbit of the S2 star located within 0′′2 of Sgr A*. Last, a number of partially resolved radio sources have been detected toward IRS 13E and IRS 13N at 7 mm. The sources in IRS 13N are thought to be dust clumps with embedded stars or young stellar objects (YSOs). Here, we use 7 mm data to argue that they are not dust clumps and that they support the YSO hypothesis.

1″ corresponds to 0.039 pc at the GC distance of 8 kpc.
2. OBSERVATIONS AND DATA REDUCTION

The detection of radio stars in the GC is not a trivial task. This is due to the crowded environment, where Sgr A* and the extended ionized gas from the mini-spiral dominate the emission within the inner parsec of Sgr A*. Due to the bright diffuse emission from the mini-spiral, it is virtually impossible to unambiguously identify individual stellar sources in low-resolution radio continuum images. An additional difficulty with identifying radio sources is the quadratic increase of the scattering size of distant sources with wavelength \( \lambda^2 \) (e.g., Bower et al. 2006). To overcome these difficulties, we have conducted high-resolution observations of the GC at 7 mm with the Very Large Array (VLA).\(^7\) These observations also have the advantage that radio emission from the ionized winds of hot stars has inverted spectrum (e.g., Panagia & Felli 1975).

\(^7\) 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 VLA was used in its A configuration to carry out two pairs of observations at 7 mm, each separated by one day, on 2011 July 8–9 and August 31–2011 September 1. These high-resolution observations used two intermediate frequencies (IFs), 128 MHz wide, centered on 41.5 and 42.5 GHz. Each IF was composed of 64 channels, 2 MHz in width. J1331+3030 and J1744−3116 were used as the primary flux and complex gain calibrators, respectively. J1733−1304 was used to correct antenna pointing errors once every hour and was observed every 10 minutes to calibrate complex gains and bandpass. Individual data sets were self-calibrated in phase and amplitude to remove atmospheric phase errors. We fixed the average flux of Sgr A* to be 2.2 Jy in each observation before 54 channels were combined and self-calibrated in both phase and amplitude. Due to the intrinsic variability of Sgr A*, flux measurements taken from the combined radio image are uncertain by \( \sim 10\% - 15\% \). This is because the average flux of Sgr A* was not the same in each session. The final image (Figure 1) was constructed with a resolution of \( \sim 82 \times 42 \) mas with an rms noise of 61 \( \mu \)Jy per beam and a dynamic range of \( \sim 3.5 \times 10^4 \). The FWHM of the
Table 1

| IR Name      | R.A. (2000) (J2000) | Decl. (2000) (−29°00′) | Positional Accuracy (mas) | Astronomic Error (mas) | $\theta_a \times \theta_b$ (P.A.) | Peak Intensity (mJy beam$^{-1}$) | Integrated Flux (mJy) | ID |
|--------------|---------------------|------------------------|--------------------------|------------------------|---------------------------------|-------------------------------|---------------------|----|
| Sgr A*       | 40.0383 28.069       | ...                    | ...                      | ...                    | 2197.7                          | 2198.8                        | 0                   |
| IRS 34W5     | 39.7277 26.535       | 3.3                    | 11.2                     | ...                    | 0.77                            | 0.62                          | 6                   |
| IRS 34W6     | 39.7756 31.897       | ...                    | ...                      | 117 × 43 (7)           | 1.24                            | 3.18                          | 36                  |
| IRS 13E5-f   | 39.7786 29.568       | ...                    | ...                      | ...                    | 1.60                            | 2.06                          | 35                  |
| IRS 13E3-d   | 39.7941 29.617       | ...                    | ...                      | 84 × 40 (75)           | 5.23                            | 13.10                         | 33                  |
| IRS 13E2-c   | 39.7943 29.784       | ...                    | ...                      | 132 × 66 (5)           | 1.56                            | 1.67                          | 34                  |
| IRS 13Nγ-j   | 39.7987 29.010       | ...                    | ...                      | ...                    | 0.57                            | 0.41                          | 28                  |
| IRS 13N-f    | 39.8062 29.274       | ...                    | ...                      | ...                    | 0.85                            | 0.66                          | 24                  |
| IRS 13N-k    | 39.8075 28.985       | ...                    | ...                      | 47 × 16 (58)           | 0.57                            | 0.84                          | 29                  |
| IRS 15N-g    | 39.8083 29.161       | ...                    | ...                      | ...                    | 0.52                            | 0.61                          | 25                  |
| IRS 15N-h    | 39.8094 29.070       | ...                    | ...                      | ...                    | 0.50                            | 0.46                          | 26                  |
| IRS 13E1-a   | 39.8108 29.811       | ...                    | ...                      | ...                    | 0.61                            | 0.61                          | 30                  |
| IRS 13N-d    | 39.8162 29.451       | ...                    | ...                      | ...                    | 0.65                            | 0.98                          | 22                  |
| IRS 13E-b    | 39.8171 29.831       | ...                    | ...                      | ...                    | 0.69                            | 0.53                          | 31                  |
| IRS 13N-i    | 39.8173 29.030       | ...                    | ...                      | ...                    | 0.97                            | 0.90                          | 27                  |
| IRS 13Nβ-e   | 39.8181 29.285       | ...                    | ...                      | 77 × 38 (175)          | 0.89                            | 0.77                          | 23                  |
| IRS 13N-c    | 39.8198 29.505       | ...                    | ...                      | 76 × 41 (103)          | 1.04                            | 2.38                          | 21                  |
| IRS 13E-c    | 39.8250 28.783       | ...                    | ...                      | 59 × 32 (62)           | 1.64                            | 3.01                          | 32                  |
| X3           | 39.8478 30.445       | ...                    | ...                      | ...                    | 0.34                            | 0.65                          | 16                  |
| IRS 13Ne-a   | 39.8319 29.530       | ...                    | ...                      | ...                    | 0.74                            | 1.11                          | 19                  |
| IRS 13N-b    | 39.8382 28.946       | ...                    | ...                      | ...                    | 1.05                            | 2.58                          | 20                  |
| IRS 33E      | 39.8927 30.045       | ...                    | ...                      | ...                    | 0.55                            | 0.67                          | 17                  |
| IRS 16NW5    | 40.0451 26.847       | 10.8                   | 28.8                     | ...                    | 0.39                            | 0.27                          | 39                  |
| IRS 33E      | 40.0941 31.213       | 5.5                    | 8.6                      | ...                    | 0.44                            | 0.32                          | 5                   |
| IRS 16C      | 40.1177 27.513       | 4.2                    | 8.0                      | ...                    | 0.71                            | 0.68                          | 1                   |
| IRS 16SW     | 40.1245 29.018       | 8.6                    | ...                      | ...                    | 0.42                            | 0.47                          | 3                   |
| IRS 21-a     | 40.2095 30.696       | ...                    | ...                      | ...                    | 1.12                            | 2.35                          | 11                  |
| IRS 21-b     | 40.2183 30.845       | ...                    | ...                      | ...                    | 0.45                            | 0.56                          | 12                  |
| IRS 21-c     | 40.2194 30.742       | ...                    | ...                      | ...                    | 0.75                            | 0.37                          | 13                  |
| IRS 21-d     | 40.2254 30.718       | ...                    | ...                      | 117 × 57 (16)          | 1.06                            | 3.28                          | 15                  |
| IRS 16NE5    | 40.2594 27.126       | 2.2                    | 9.7                      | ...                    | 1.32                            | 1.22                          | 2                   |
| IRS 16SE2c   | 40.2637 29.200       | 4.3                    | 12.9                     | ...                    | 0.59                            | 0.39                          | 4                   |
| IRS 1W-a     | 40.4370 27.463       | ...                    | ...                      | 73 × 45 (12)           | 0.38                            | 0.76                          | 40                  |
| IRS 1W-b     | 40.4398 27.597       | ...                    | ...                      | 19 × 16 (3)            | 0.56                            | 5.64                          | 41                  |
| IRS 5-a      | 40.6938 18.268       | ...                    | ...                      | ...                    | 0.47                            | 0.41                          | 9                   |
| IRS 5-b      | 40.6956 18.179       | ...                    | ...                      | 15 × 11 (8)            | 0.49                            | 2.85                          | 10                  |

Notes.

- a Unless noted, positions are accurate to 25 mas.
- b Fifteen percent uncertainty in flux due to scaling to Sgr A*, which is a variable source.
- c Radio stars used for astrometry.

The primary beam is 1′ at 7 mm. The pair of observations is separated by 53 days from each other, so the effective epoch of the combined image is 2011 August 4. We employed background-subtracted two-dimensional Gaussian fits using JMFIT in AIPS for measuring the properties of individual sources in the final radio image.

Eight sources were used to register the radio and IR images: IRS 16C, IRS 16NE, IRS 16NW, IRS 16SE2, IRS 33E, IRS 34W, AF, and AFNW (see Table 1). An L-band (3.8 μm) image (Figure 2) of the GC region was taken with the European Southern Observatory Very Large Telescope (VLT) on 2011 July 7. A color composite image using radio and IR data is shown in Figure 1(b). The IR image, shown in green in Figure 1(b), is produced with the NaCo adaptive optics imager and covers a field of view of ~43′. The eight radio sources are relatively isolated and are easily distinguished from extended ionized gas, as can be seen in Figure 1(a). The registration of the radio and IR images was accomplished as follows. The right ascension (R.A.) and declination (decl.) positions of the eight sources were measured in the radio map produced from the 2011 July 8 data by fitting elliptical Gaussians to the sources. The formal errors in the centroids of these measurements are on the order of 6 mas. The predicted x/y coordinates of the eight sources in the IR image were then computed by transforming the radio R.A./decl. values into the IR image plane using the original World Coordinate System (WCS) definition of the IR image. We then measured the actual x/y positions of the eight sources in the IR image by fitting elliptical Gaussians with the IRAF/STSDAS.
Figure 2. 3.8 μm image shows a larger view than presented in Figure 1. All radio stars are labeled except sources 9 and 10, which lie outside the displayed region (see Table 1).

(task “n2gaussfit.”) The IR image is oversampled, with FWHM for point sources of ~4.4 pixels, and a pixel scale of 0.0272. The formal uncertainties of the centroids of the individual sources in the IR image are less than 1/100 of a pixel, or < 1 mas. The predicted and measured x/y coordinates of the sources in the IR image were then used to compute a geometric transform between the radio and IR image spaces, using the IRAF task “geotran.”

The resulting transform was then applied to the IR image to assign a new WCS and ultimately to remap the IR image into the same WCS space as the radio image. The transform solution showed rms residuals to the fit of the eight source positions of ~6.5 mas. The error in the absolute position of Sgr A* is estimated to be ~2.8 mas. The total error in position for radio stars when cross correlated with IR images is then estimated to be ~7.1 mas. The residuals in the positions of the eight sources in the IR image space are listed in Table 1. The residuals are consistent with the uncertainty of the R.A./decl. measurements in the radio image (~6 mas) and also must include an unknown component of uncertainty due to residual distortions in the construction of the mosaic. The nine radio stars coincide with some of the most luminous sources in the GC and the Galaxy as a whole (Paumard et al. 2006). Most of them show P-Cygni profiles, thus presenting strong evidence for stellar winds (Najarro et al. 1997; Martins et al. 2007). Although spectral index values of the radio stars are not available, the emission is most likely thermal, resulting from expanding ionized winds in the envelope of hot stars (Panagia & Felli 1975). We expect an insignificant contribution from nonthermal emission at 7 mm (Contreras et al. 1996).
Table 2

| IR Name | $M$ (Radio) | $M$ (IR) | Integrated Flux Terminal Velocity |
|---------|-------------|----------|----------------------------------|
|         | ($10^{-5} M_\odot$yr$^{-1}$) | ($10^{-5} M_\odot$yr$^{-1}$) | (mJy) | (km s$^{-1}$) |
| 34W     | 1.81        | 1.30     | 0.61                            | 650 |
| IRS 16NW | 0.90        | 1.1      | 0.27                            | 600 |
| IRS 16C | 1.75        | 1.1      | 0.68                            | 650 |
| 33E     | 0.76        | 2.20     | 0.32                            | 450 |
| AF      | 2.63        | 1.80     | 0.91                            | 700 |
| AFNW    | 2.10        | 3.2      | 0.56                            | 800 |
| IRS 16E2 | 4.95        | 7.0      | 0.39                            | 2500 |
| IRS 16NE | 3.28        | ...      | 1.22                            | 700 |
| IRS 16SW | 1.58        | ...      | 0.47                            | 700 |

We determined the mass-loss rate of individual radio stars assuming the standard model for a spherically symmetric, homogeneous wind of fully ionized gas with $T = 1 \times 10^4$ K and expanding with a constant terminal velocity (Panagia & Felli 1975). We assumed twice solar metallicity, a mean molecular weight $\mu = 2$ and adopted terminal velocities of IR stars, as given by Martins et al. (2007). Table 2 compares the mass-loss rates of several radio and IR stars, with rates determined from the radio measurements and from detailed model atmosphere calculations (Martins et al. 2007). Integrated fluxes and terminal velocities are also listed. IRS 16NE and IRS 16SW are binaries (Pfuhl et al. 2014), thus their model atmosphere calculations are not available. The mass-loss rates obtained using the radio and IR techniques agrees with each other to within a factor of two with the exception of IRS 33E. The mass-loss rate of this star derived from radio measurements is a third of that from model atmosphere calculations given by Martins et al. (2007). This disagreement may reflect on the assumption that stellar winds are not clumpy and there is no nonthermal emission from radio stars. We note that mass-loss rate estimates are similar to those of radio stars in the Arches and Quintuplet clusters (Lang et al. 2005).

3.2. Radio and IR Astrometry

We selected eight of the nine hot stars for astrometric measurements. To determine if the detected radio sources have IR stellar counterparts, we used an $L$-band (3.8 $\mu$m) image which was taken on 2011 July 7. In order to register the $L$-band image with the VLA radio image, we matched eight stellar IR sources within about 10$''$ from Sgr A* that are detected in the 7 mm radio map. Note that there should not be any offset in the position of stars due to proper motion because the radio and IR images were taken within one day of each other. The radio counterpart to IRS 16SW is in a confused region, so was not used in astrometric analysis. Figure 2 shows a larger view of the region shown in Figure 1 at 3.8 $\mu$m but with R.A., decl. coordinates labeled. All 41 sources listed in Table 1 have IR counterparts. We have also detected radio star candidates with no IR counterparts.

Previous studies used the stellar SiO masers located beyond $\sim7''$ of Sgr A* to register the radio and IR frames (Menten et al. 1997; Reid et al. 2003, 2007). This technique achieves positional accuracy of individual masers to $\sim1$ mas (Reid et al. 2007). Individual sources such as IRS 16NE show positional errors of 2.2 mas in the 7 mm radio image. Our approach of using radio stars to register the IR frames yields a statistical accuracy of the registration $\sim6.5$ mas. The eight radio stars used in our registration are distributed within $\sim10''$ of Sgr A*.

This registration has allowed us to cross-identify stellar sources in radio and infrared images.

3.3. Young Stellar Objects Versus Dust Clumps

In addition to the hot mass-losing stars listed in Table 2, we detected multiple radio sources coincident with IR-identified stars and stellar clusters: 2 in IRS 1W, 4 in IRS 21, 6 in the IRS 13E cluster, 2 in IRS 5, and 11 in the IRS 13N cluster (Paumard et al. 2006; Lu et al. 2009; Maillard et al. 2004; Schödel et al. 2005; Muzic et al. 2008; Perger et al. 2008; Fritz et al. 2010; Eckart et al. 2004, 2013; Sanchez-Bermudez et al. 2014). Figure 3 shows 7 mm and $L$-band images of the IRS 13E and IRS 13N clusters located 3.5 SW of Sgr A*. IRS 13E consists of several early-type stars (e.g., Fritz et al. 2010; Eckart et al. 2013). Stellar sources IRS 16NE and IRS 16SW are binary systems and display evidence of X-ray emission resulting from colliding winds (Coker et al. 2002).

Unlike compact, hot stars, a number of radio sources are partially resolved, as shown in Column 6 of Table 1. A significant deconvolved size of hot stars could not be measured, thus they are likely to be unresolved. By contrast, sources in the IRS 13N cluster, such as IRS 13Nβ (source 23 in Table 1) have typical deconvolved beam sizes of 77 $\times$ 38 mas. There is a debate as to whether some members of IRS 13E and IRS 13N clusters are dust clumps with embedded stars or YSOs (Muzic et al. 2008; Fritz et al. 2010; Eckart et al. 2013). There are two arguments against members of IRS 13N being dust clumps. First, IRS 13N has a flux density 1.34 Jy at 3.8 $\mu$m (Viehmann et al. 2006), which yields a luminosity estimate $4\pi d^2 v S_{\nu} = 6 \times 10^4 L_\odot$ after correcting for 2 mag of extinction. If IRS 13N is a dust clump with no embedded source, we estimate a heating rate $\sim(400\text{AU})^2 \times L_\nu/(4\pi(0.5\text{pc})^2) \sim 1200L_\odot$, assuming a typical distance of 0.5 pc from the GC, a source size of 800 AU ($0.1$) and UV radiation field of corresponding to a luminosity $L_\nu \approx 2 \times 10^5 L_\odot$ from the GC (Serabyn & Lacy 1985). The IR luminosity of IRS 13N exceeds the heating rate of IRS 13N by an order of magnitude. External heating by the intense stellar UV radiation field in the inner parsec of the galaxy, is insufficient, so an internal source of heating is needed. This favors the suggestion that these sources are dusty stars. Eckart et al. (2013) have made a number of arguments based on the motion of the IRS 16 cluster and the interstellar material surrounding the cluster that favor the young age of the IRS 13N cluster. We have also studied spectral energy distribution fitting of IRS 13N which is consistent with a grid of model calculations of YSO candidates (F. Yusef-Zadeh et al. 2014, in preparation).

The second line of argument is that the radio emission is consistent with thermal bremsstrahlung from ionized gas that is being photoevaporated from a disk by the UV radiation field from hot stars in the inner parsec of the Galaxy. The measured radio flux, $\sim2$ mJy at 43 GHz, implies a volume emission measure $\int n_e^2 dV = 6 \times 10^{8} \text{cm}^{-3}$. Assuming a homogeneous source of FWHM $\approx 0.1$ and $T_e = 8000$ K yields a source radius $\sim400$ AU and $n_e \approx 2.5 \times 10^5 \text{cm}^{-3}$, with an optical depth $\sim0.02$. The mass of ionized gas is then $M_i \approx 3 \times 10^{-4} M_\odot$. Hot stars in the inner parsec of the Galaxy do not create sufficient numbers of ionizing photons to explain this mass of ionized gas. The total production rate is estimated to be $Q_{\text{LyC}} \approx 2.5 \times 10^{50} \text{s}^{-1}$ (Genzel et al. 1994), implying an incident ionizing photon flux $Q/(4\pi(1 \text{pc})^2) \approx 2 \times 10^{12} \text{sec}^{-1} \text{cm}^{-2}$. This is in rough agreement with the hydrogen recombination rate per unit area in the ionized gas, $\alpha(2p)^2 n_e^2 r \approx 1 \times 10^{12} \text{sec}^{-1} \text{cm}^{-2}$. Assuming that the ionized gas expands at the sound speed $c_s \approx 15 \text{km s}^{-1}$.
for $T = 8000 \text{K}$, the mass-loss rate due to photoevaporation is $M_i/(r/c_s) \approx 2.2 \times 10^{-6} M_\odot \text{yr}^{-1}$. This must be replenished on the expansion time scale $r/c_s \approx 140 \text{yr}$, implying the existence of a reservoir of neutral material, presumably a disk associated with the YSO.

4. SUMMARY

We have detected a number of stellar sources within the inner $10''$ of Sgr A* in $7 \text{mm}$ radio continuum images with astrometric precision of $\sim 6.5$ mas. The radio emission from GC stars is at a level consistent with ionized winds from hot massive stars with mass-loss rates determined from detailed modeling of the atmospheres (Najarro et al. 1997; Martins et al. 2007). We also detected several radio sources in IRS 13N and IRS 13E suggesting that thermal radio emission from ionized gas is being photoevaporated from disks of YSOs by UV radiation from hot stellar sources in the GC. This possibility is consistent with the idea that ongoing star formation is taking place within $0.5 \text{pc}$ of Sgr A* (Eckart et al. 2013; Yusef-Zadeh et al. 2013; Sanchez-Bermudez et al. 2014).

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