The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus
Proceedings IAU Symposium No. 303, 2013
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doi:10.1017/S1743921314000921

A new perspective on the radio active zone at the Galactic center – feedback from nuclear activities

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Abstract. Based on our deep image of Sgr A using broadband data observed with the VLA† at 6 cm, we present a new perspective of the radio bright zone at the Galactic center. We further show the radio detection of the X-ray Cannonball, a candidate neutron star associated with the Galactic center SNR Sgr A East. The radio image is compared with the *Chandra* X-ray image to show the detailed structure of the radio counterparts of the bipolar X-ray lobes. The bipolar lobes are likely produced by the winds from the activities within Sgr A West, which could be collimated by the inertia of gas in the CND, or by the momentum driving of Sgr A*; and the poloidal magnetic fields likely play an important role in the collimation. The less-collimated SE lobe, in comparison to the NW one, is perhaps due to the fact that the Sgr A East SN might have locally reconfigured the magnetic field toward negative galactic latitudes. In agreement with the X-ray observations, the time-scale of $\sim 1 \times 10^4$ yr estimated for the outermost radio ring appears to be comparable to the inferred age of the Sgr A East SNR.

Keywords. Galactic center — ISM — supernova remnants — neutron stars — winds — outflows

1. Introduction

In the inner 40 parsecs, from the 1 Msec integration *Chandra* X-ray image, Morris *et al.* (2003) showed remarkable X-ray bipolar lobe structures (∼10 parsecs) centered at Sgr A*, extending in the direction perpendicular to the Galactic plane. The authors pointed out that a number of emission clumps in the bipolar lobes suggests a series of ejections from the circumnuclear disk (CND) or Sgr A West occurred on time scales of hundreds to thousands of years. The X-ray bipolar lobes imply ongoing activity from the circumnuclear region surrounding Sgr A*. Within this region, a well known radio emission shell, Sgr A East, is interpreted simply as a SNR (Jones 1974, Green 1984, Goss *et al.* 1985); the age of Sgr A East inferred from the various models spans a large range, from 1700 yr to $5{\times}10^4$ yr. Using X-ray data observed with the *Chandra* Observatory, Park *et al.* (2005) found a hard compact X-ray source, CXOGC J174545.5−285829, having unusual X-ray characteristics compared to most other X-ray sources near the Galactic center. The authors suggested that the X-ray object could be identified as a high-velocity neutron star, produced from the core-collapse supernova (SN) explosion that created the Galactic center supernova remnant (SNR), Sgr A East.

† The Karl G. Jansky Very Large Array (VLA) is operated by the National Radio Astronomy Observatory (NRAO). The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

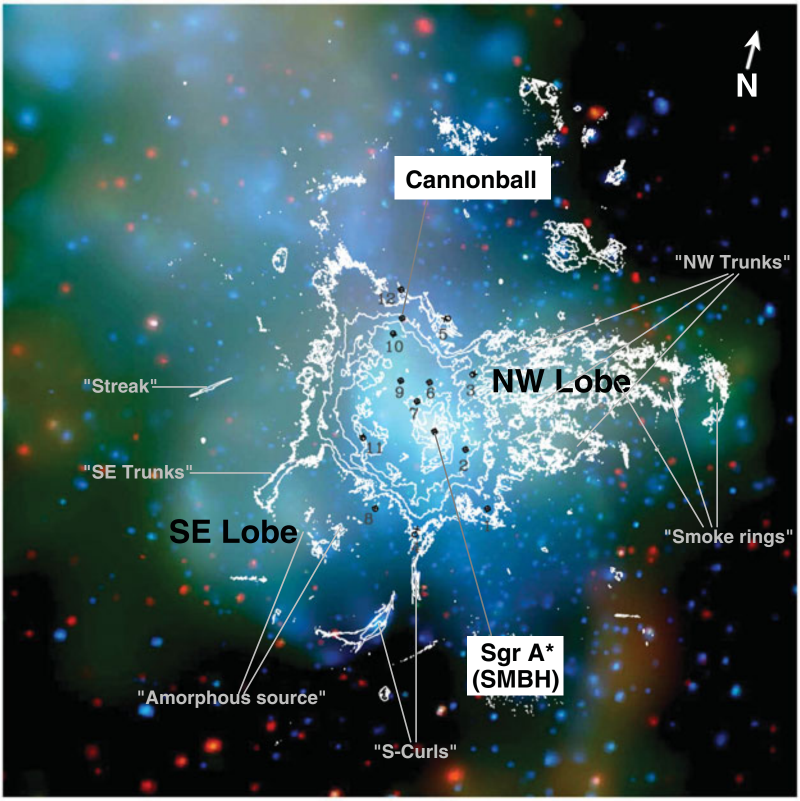

Figure 1. The VLA image at 5.5 GHz (contours, $\theta_{\mathrm{FWHM}} = 1.6'' \times 0.6''$) overlaid on the *Chandra* X-ray image (background presented online by Markoff 2010). The fourteen compact X-ray sources (open circles) and their radio identifications (crosses) are marked (see Zhao, *et al.* 2013). [A color version is available online.]

2. Radio bright zone

We have observed Sgr A with the VLA in the B & C arrays using the broadband (2 GHz) continuum mode at 5.5 GHz covering the central 13′ (30 pc) region of the radio bright zone at the Galactic center. With MS-MFS clean algorithm of CASA, we constructed a deep image, achieving an RMS noise level of 0.01 mJy beam^{-1}, or a dynamic range 80,000:1. The data reduction procedure is described by Zhao *et al.* (2013 in preparation). Our observations have revealed the detailed structures of both previously known and newly identified radio sources in this region. Numerous compact radio sources have been detected at a level of ∼0.1 mJy beam^{-1}. In general, the emission structure of the radio bright zone at 5 GHz is characterized by Sgr A West (the HII minispiral), Sgr A East (SNR) and radio filaments (Morris *et al.* 2013). The deep radio image has been compared with the *Chandra* X-ray (Figure 1) and *Hubble*/NICMOS Paschen-α images (Wang *et al.* 2010). In the radio, broad "Wings" (Figure 2a) extend 100″ (4 pc) from the tips of the minispiral (Sgr A West) to the NW and SE; the NW Wing appears to be along with several radio emission "Trunks" forming an elongated radio lobe with a size of 6′×3′ (14×7 pc) and oriented perpendicular to the Galactic plane, in projection. In the outer region of the NW lobe, a progression of three emission rings ("Smoke rings")

https://doi.org/10.1017/S1743921314000921 Published online by Cambridge University Press

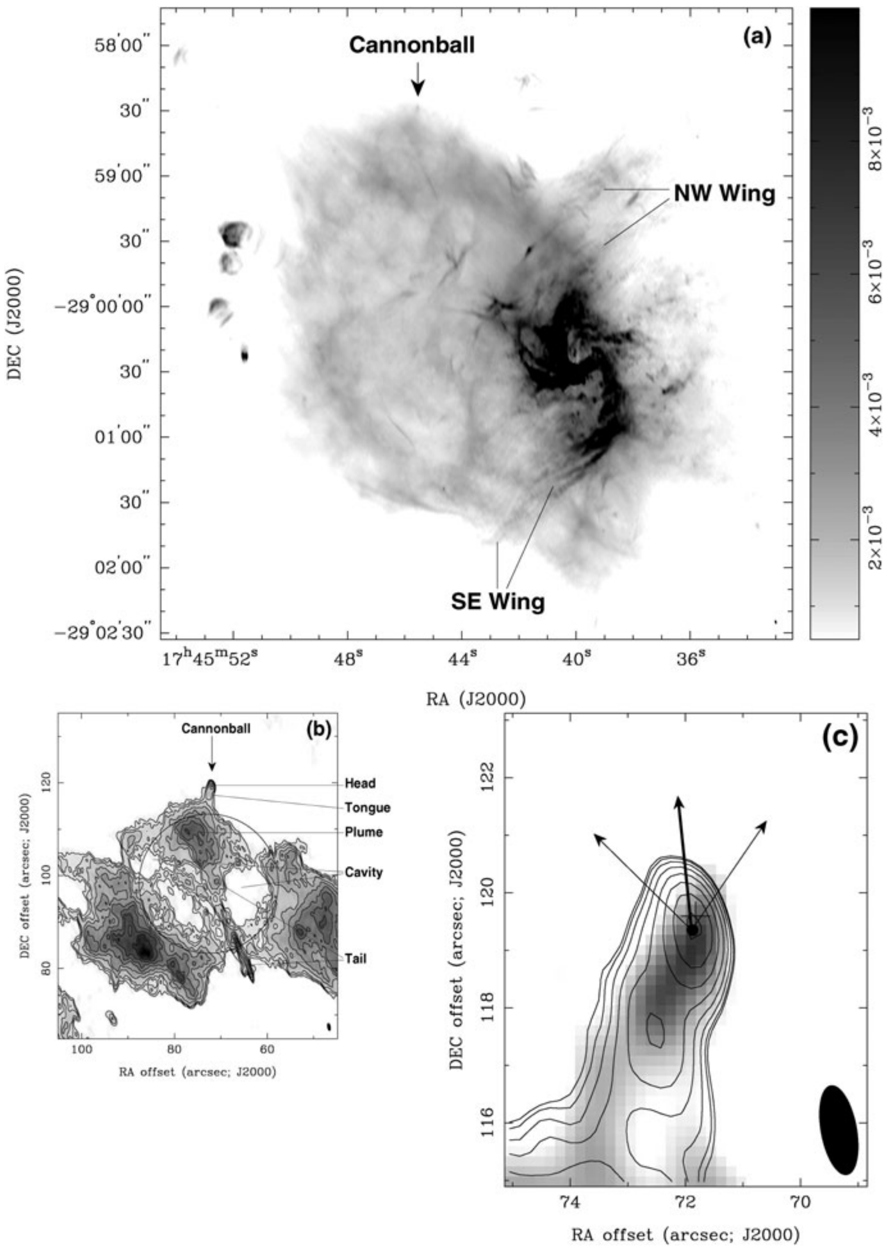

Figure 2. (a) A new 5.5-GHz VLA image of Sgr A East and West along with the radio counterpart of the Cannonball. **(b)** The radio structure of the PWN; the radio components possibly associated with the PWN are labeled. **(c)** Proper motion vector (bold arrow) of the Cannonball with 3σ uncertainty in direction (light arrows) anchored at the peak of the radio source observed in 2012 (contours) that is overlaid on the VLA image observed in 1987 (gray scale). The FWHM beam sizes of above images are $\theta_{\rm FWHM} = 1.6'' \times 0.6''$.

is present, indicating a thermal free-free origin based on an almost identical structure in the Paschen-α image. The NW radio lobe matches well with its X-ray counterpart (Figure 1). An amorphous radio emission structure at the tip of the SE Wing and an emission trunk ($120'' \times 20''$, or 4.6×0.8 pc) are located in the SE X-ray lobe that appears

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to be confined by the "Streak" and the southern "Curl" filaments (Morris *et al.* 2013). Since the implied accretion rate onto the central SMBH is far below the Eddington limit, the direct activity from accretion appears to contribute little to the feedback to the ISM in this region at the present time. The bipolar X-ray lobes are likely produced by the winds from the activities within Sgr A West, which could be collimated by the inertia of the gas in the CND or by the momentum driving of Sgr A*; and the poloidal magnetic fields likely play an important role in the collimation. The less-collimated SE lobe, in comparison to the NW one, is perhaps due to the fact that the Sgr A East SNR might have locally reconfigured the magnetic field toward negative Galactic latitudes. The massive stars near the "Smoke rings" (personal communication from Hui Dong & Jon Mauerhan, 2013) are likely the main sources for the ionization of the local gas. If the filamentary structure perpendicular to the major-axis of the NW lobe is a wave pattern in a magnetized-rotating plasma, propagating from Sgr A West with an Alfvén velocity $v_A \approx 218\ \mathrm{km\,s^{-1}}\ \left[\frac{B}{1\ \mathrm{mG}}\right]\left[\frac{n_i}{10^2\ \mathrm{cm^{-3}}}\right]^{-1/2}$, a time scale of $\sim 1\times10^4$ yr is estimated for the wave traveling to the outermost ring, given a B-field strength of a few mG and an ion number density of $\sim 10^2\ \mathrm{cm^{-3}}$ in the nuclear environment. In good agreement with the estimate for the X-ray lobes, this time scale, by coincidence, appears to be comparable to the age of the Sgr A East SNR inferred from the Cannonball (Zhao *et al.* 2013).

3. Radio counterpart of the Cannonball

The radio object was detected both in the VLA image from 2012 observations at 5.5 GHz and in archival VLA images from observations in 1987 at 4.75 GHz and in the period from 1990 to 2002 at 8.31 GHz. The radio morphology of this object is characterized as a compact, partially resolved point source located at the northern tip of a radio "tongue" (Figure 2b) similar to the X-ray structure observed by *Chandra* (Park *et al.* 2005). Behind the Cannonball, a radio counterpart to the X-ray plume is observed. This object consists of a broad radio plume with a size of $30''\times15''$, followed by a linear tail having a length of $30''$. The compact head and broad plume sources appear to have relatively flat spectra ($\propto \nu^\alpha$) with mean values of $\alpha = -0.44\pm0.08$ and -0.10 ± 0.02, respectively, and the linear tail shows a steep spectrum with the mean value for α of -1.94 ± 0.05. The total radio luminosity integrated from these components is $\sim 8\times10^{33}$ erg s^{-1}, while the emission from the head and tongue amounts to only $\sim 1.5\times10^{31}$ erg s^{-1}. Based on the images obtained from the two epochs' observations at 5 GHz, we infer a proper motion of the object: $\mu_\alpha = 0.001\pm0.003''\ \mathrm{yr^{-1}}$ and $\mu_\delta = 0.013\pm0.003''\ \mathrm{yr^{-1}}$ (see Figure 2c). With an implied velocity of 500 $\mathrm{km\,s^{-1}}$, a plausible model can be constructed in which a runaway neutron star surrounded by a pulsar wind nebula (PWN) was created in the event that produced Sgr A East. The inferred age of this object, assuming that its origin coincides with the center of Sgr A East, is approximately 9000 yr.

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