The Origin of Outflows in Evolved Stars
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How did the Stellar Winds of Massive Stars influence the Surrounding Environment in the Galactic Center?

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Abstract. In the Galactic center, there are many massive stars blowing strong stellar winds, which will strongly influence the surrounding environment and even the Galactic feedback. The Galactic center is quiescent at present, so the unique continuous energy input source is the massive star, consequently giving rise to many special features, such as the radio bubbles, the X-ray chimneys, the non-thermal filaments and high-metallicity abundance. However, it is difficult to quantify their contributions due to the complex environment in this region, and the past supernovae and Sgr A* activity are also important factors shaping these features. In this work, we discuss some structures possibly related to the stellar winds and perform preliminary simulations to study their evolution. We conclude the stellar winds can obviously influence a large scale $\sim$ 100 pc, and can possibly influence a larger scale environment indirectly.

Keywords. Galaxy: center, stars: winds, ISM: bubbles, supernova remnants

1. Introduction

The formation and evolution of galaxies are still mysterious. While the big picture is unambiguous, there are many unresolved confusing details, such as the galactic feedback and supermassive black hole (SMBH) formation. To understand these details, our Milky Way is the best laboratory, which can help us thoroughly check various features.

The most violent galactic feedback process usually happens in the Galactic center, such as the SMBH activity, supernovae and stellar winds, which can reshape the central structures and influence the evolution of the whole galaxy. Fermi bubbles and eROSITA bubbles are both possibly the kpc relics of such a process (Su et al. 2010; Predehl et al. 2020), and they will interact with the intergalactic medium, causing outflow and inflow. In addition, two newly-discovered structures, the radio bubbles and X-ray chimneys with a scale of hundreds parsecs (Heywood et al. 2019, Ponti et al. 2019), can also be taken as a part of the early-stage feedback process. These processes possibly originate from stellar activity or SMBH activity, but it is unclear which one is dominant. The identified supernova remnant (SNR) Sgr A East in the Galactic center implies many supernova explosions here over the past many years, and the X-ray reflection in the central molecular zone (CMZ) also implies the past SMBH X-ray flare (Ponti et al. (2013)). However, these past activities cannot be traced precisely.

The stellar winds of massive stars in this region are also efficient energy input sources, which can be detected directly. Therefore, we can study their influence on the environment in details. There are $\sim$ 200 massive stars (Dong et al. 2012) in the central tens of parsecs, some of which in the central several parsecs are the members of the nuclear star clusters (NSC). The stellar winds of NSC are so strong that they can even prevent the ejecta of SNRs into the central SMBH.

We in this work try to study the possible influence of stellar winds on those interesting structures, and perform a simulation to understand the stellar winds evolution of these massive stars. In Section 2, we describe these structures and their possible relation with the stellar winds. The simulation model and results are presented in Section 3. Section 4 is a summary.

2. Overview

2.1. *The galactic feedback*

The galactic feedback is usually dominated by two mechanisms, AGN or starburst, which push the gas to higher latitude and produce an outflow. In our Milky Way, the Fermi and eROSITA bubbles possibly originate from such an outflow, but it is uncertain whether they are produced by the AGN or starburst activity. Then some gas are accreted back to feed the host galaxy, while some gas just flow away or become diffuse gas surrounding the galaxy. We also detect gas falling into the Galactic disk at radio and X-ray wavelength (Kataoka et al. 2021).

In addition, we usually will neglect the contribution of stellar winds to the feedback, especially for extragalactic sources, because the stellar winds are much weaker than supernovae or SMBH activity. With the development of high-resolution observations, the stellar winds currently can be well studied in our Milky Way, but its relation with the Galactic feedback is still a puzzle. The assembly of many massive stars in the Galactic center implies they can possibly influence the feedback process. Meanwhile, Ressler et al. (2018) simulated the stellar winds of massive stars surrounding Sgr A*, and concluded the stellar winds can feed the SMBH. This can stimulate SMBH activity, then strengthen the outflow.

2.2. *The radio bubbles and the X-ray chimneys*

The relation between stellar winds and large scale feedback is difficult to confirm, but the relation with some smaller structures, such as radio bubbles and the X-ray chimneys, can be discussed quantitatively. We simulated multi-supernovae explosions with strong magnetic field in the central 50 pc of our Galaxy, to simultaneously reproduce the radio bubbles and the X-ray chimneys (Zhang et al. 2021). The explosion frequency is 0.001 yr^{-1}, and the magnetic strength is $\sim 80\ \mu$G. The high explosion frequency make it a limb-brightening bubble, while the strong magnetic field can confine the supernovae ejecta, leading to an elongated shape. After 330 kyr, the simulated results can well match the morphology of the radio bubbles, the X-ray chimneys (see Figure 1). Moreover, even the thermal energy and X-ray luminosity are also roughly consistent with the observation, but a litter lower. Therefore, there are possibly other energy input sources, such as the stellar winds and pulsar wind nebulae.

In addition, in the simulation, we can also reproduce the non-thermal filaments (NTFs), a kind of mysterious structures discovered about 40 years ago, while there are many competitive models. The lifetime of these NTFs is obviously larger than a supernova remnant, so our multi-supernovae model cannot explain NTFs independently. A continuous energy input is necessary to sustain the filamentary shape and accelerate relativistic electrons.

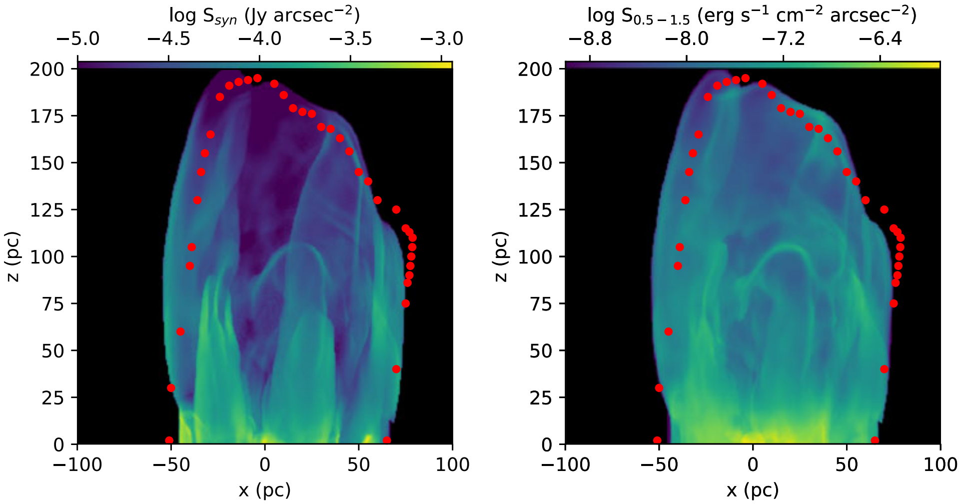

Figure 1. The red dotted line outlines the rim of the northern radio bubble. *Left:* Synchrotron emission, values lower than 10^{-5} Jy arcsec^{-2} are suppressed to enhance visualization of the faint features; *Right:* Synthetic $0.5 - 1.5$ keV X-ray intensity distribution in simulation, values lower than 10^{-9} erg s^{-1} cm^{-2} arcsec^{-2} are suppressed to enhance visualization of the faint features.

If the stellar winds are important, it can simultaneously solve the absence of the thermal energy and X-ray luminosity and the NTFs formation in our simulation. Therefore, a study of stellar winds' influence on central hundreds of parsecs is urgent.

2.3. *SNR Sgr A East*

In addition to the importance of stellar winds on the hundreds of parsecs, they are also essential for studying SNR Sgr A East, the unique confirmed SNR in the Galactic center. We simulate the interaction between the shock wave of Sgr A East and the stellar winds of NSC, which can well reproduce the radio morphology of the SNR and an X-ray ridge structure between Sgr A* and the explosion of Sgr A East after $\sim$ 800 years (see Figure 2). However, the X-ray emission inside the SNR is faint, inconsistent with the observation. Because the adiabatic expansion will lead to sharp cooling inside, the bremsstrahlung emission is weak.

The simulation assumes the surrounding environment of the supernova is dominated by the stellar winds of NSC, but there are many molecular clouds or clumps in reality, which can block the shock wave and stimulate the formation of reverse shock. The reverse shock come back to the explosion center and heat the central ejecta, then produce X-ray emission, which is a reasonable explanation for the weak X-ray emission inside. However, the observed clouds are not enough to produce such strong shock wave. We also suggest a stellar wind envelop of the progenitor can be heated directly by the forward shock to produce the X-ray emission, but this is related to non-equilibrium ionization model in the hydrodynamical simulation, which need to be further developed.

The simulation also shows the ejecta cannot propagate into the central 0.4 pc radius due to the strong stellar winds of NSC, which implies the supernova cannot affect the Sgr A* directly.

2.4. *IRS 13E*

In the aforementioned cases, the stellar winds are possibly important, but not dominant. However, next to the Sgr A*, in a complex IRS 13E, the stellar wind is the main

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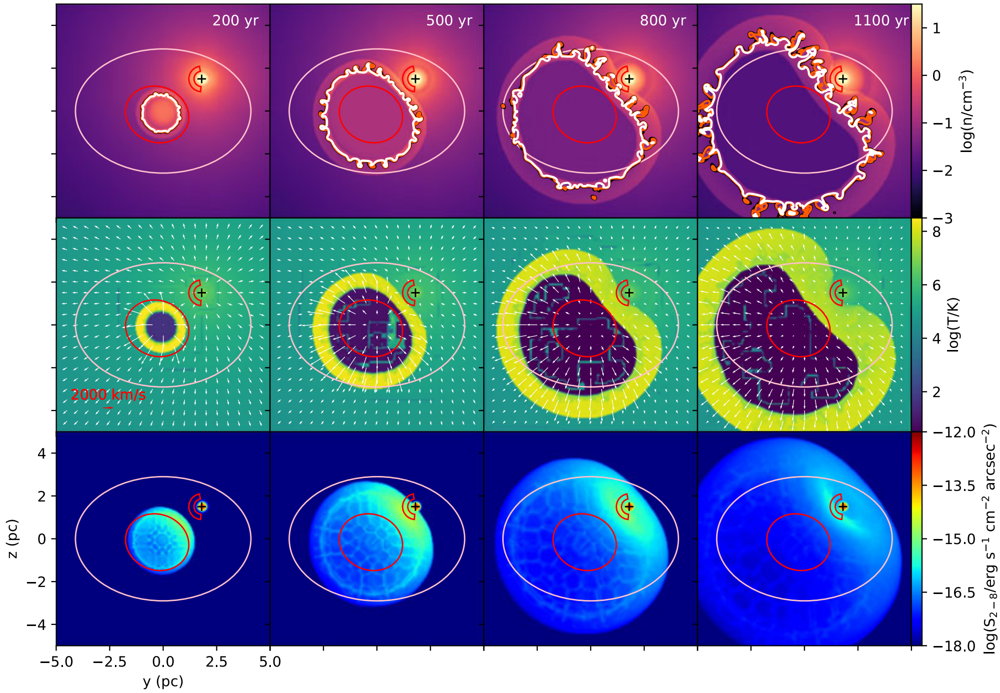

Figure 2. Density (top rows), temperature (middle rows) and X-ray intensity (bottom rows) after 200, 500, 800 and 1100 yr with an explosion energy of 5 $\times$ 10^{50} erg s^{-1} and free hydrogen abundance. The pink and red circle outline the radio and X-ray morphology, while the black plus and red arc indicate the Sgr A* and X-ray ridge, respectively. The ejecta is outlined by the contour, in which the white, red and black indicate 0.9, 0.5, 0.1, respectively. The white arrows indicate the velocity. The density and temperature maps both show slices through the x = 1 pc.(From Zhang et al. 2022, to be submitted.)

character. We simulate the collision of stellar winds from massive stars (Zhu et al. 2020), which can match the X-ray luminosity and even the spectrum (see Figure 3).

This work shows the stellar winds can be sufficiently strong to produce high X-ray emission flux. In the Galactic center, the interstellar environment can be largely affected by the stellar winds from massive stars. However, some works related to larger scale structures did not take it serious, which deserve more careful studies.

3. Simulation Model and Results

To quantify the influence of stellar winds, we perform a preliminary simulation for the $\sim$ 200 massive stars in the Galactic center. In the simulation, we assume the mean mass loss rate and wind velocity of these massive stars as 10^{-5} M$_\odot$ yr^{-1} and 2000 km s^{-1}. In the NSC, the mean distance between two stars is so small that we cannot well distinguish them in the simulation, so we take them as one source with a mass loss rate and velocity of 10^{-3} M$_\odot$ yr^{-1} and 100 km s^{-1}. The initial interstellar medium (ISM) density is 0.1 H cm^{-3}. In addition, we take into account the gravitational potential of Sgr A*, NSC and the nuclear disk.

The simulation results after 160 kyr are shown in Figure 4. The stellar winds have blown out the central 100 pc, and are still pushing the outer ISM, which can obviously influence the formation and evolution of the radio bubbles and the X-ray chimneys. Their total energy input during 160 kyr is 2 $\times$ 10^{52} erg, a large value comparable to ten

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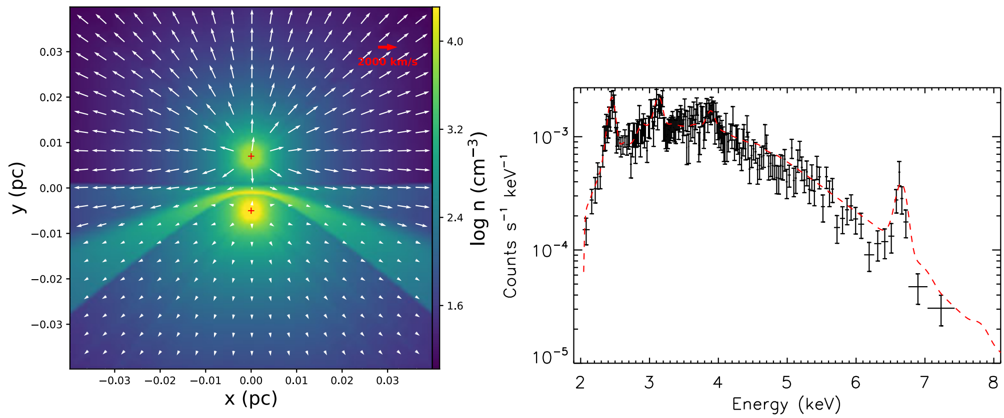

Figure 3. Illustration of the fiducial colliding wind simulation. *Left*: Density distribution in the $z = 0$ plane, overlaid by vectors representing the local velocity. The positions of the two WR stars are marked by '+' signs. *Right*:A comparison between the observed ACIS-S spectrum (black data points) and the simulation-predicted spectrum (red dashed curve). The latter has been multiplied by the energy-dependent foreground absorption and convolved with the instrumental response.

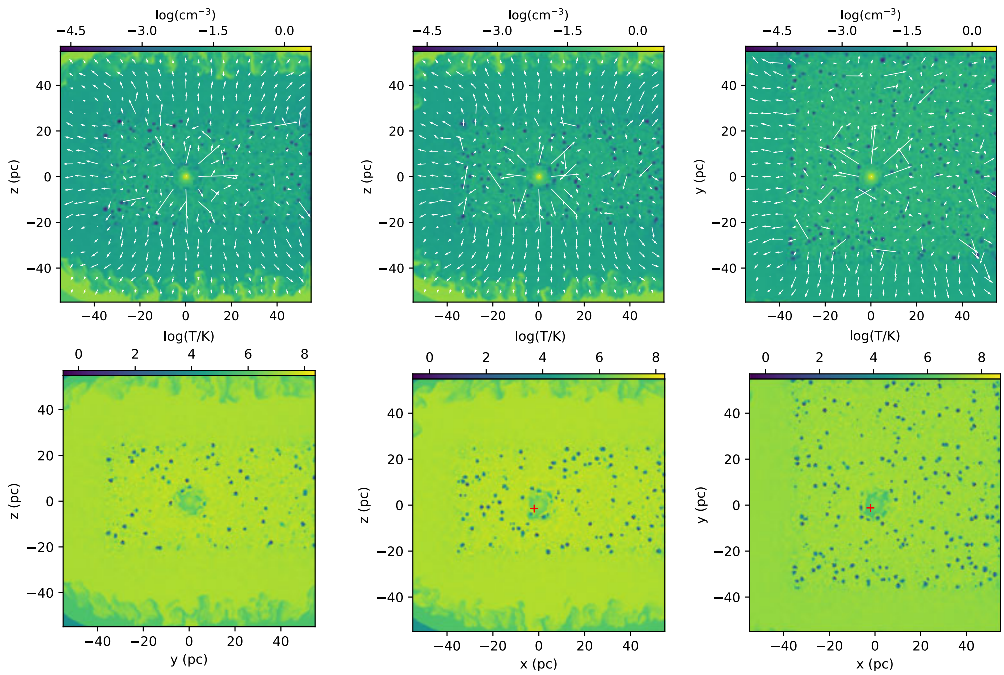

Figure 4. Density (top rows) and temperature (bottom rows) maps after 160 kyr. The white arrows show the velocity. The z-axis runs along the line of sight.

supernovae. However, its relation with the Fermi bubbles and eROSITA bubbles need further investigation.

4. Summary

From large scale to small scale, the influence of the stellar winds on the environment of the Galactic center becomes more important. The X-ray luminosity and thermal energy

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of X-ray chimney may be contributed by the stellar winds which can also sustain the existence of NTFs. Our simulation also shows the interior X-ray emission of SNR Sgr A East is faint without stellar winds or more molecular components.

References

Dong, H. and Wang, Q. D. and Morris, M. R. 2012, *MNRAS*, 425, 884
Heywood, I., Camilo, F., Cotton, W. D., Yusef-Zadeh, F., et al., 2019, *Nature*, 573, 7773
Kataoka, Jun and Yamamoto, Marino and Nakamura, Yuki et al. 2021, *ApJ*, 908, 14
Predehl, P. and Sunyaev, R. A. and Becker, W. et al. 2020, *Nature*, 588, 227
Ponti, G. and Hofmann, F. and Churazov, E. et al. 2019, *Nature*, 567, 347
Ponti, Gabriele and Morris, Mark R. and Terrier, Regis et al. 2013, *Cosmic Rays in Star-Forming Environments*, 34, 331
Ressler, S. M. and Quataert, E. and Stone, J. M. 2018, *MNRAS*, 478, 3544
Su, Meng and Slatyer, Tracy R. and Finkbeiner, Douglas P. 2010, *ApJ*, 724, 1044
Zhang, Mengfei and Li, Zhiyuan and Morris, Mark R. 2021, *ApJ*, 913, 68
Zhou, Ping and Leung, Shing-Chi and Li, Zhiyuan et al. 2021, *ApJ*, 908, 31
Zhu, Zhenlin and Li, Zhiyuan and Ciurlo, Anna et al. 2020, *ApJ*, 897, 135