Sgr A* and Sgr A East: Intimate Life in the Galactic Center

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Abstract. A hydrodynamic interaction between an old supernova remnant and a massive black hole is studied with the help of a high-resolution adaptive mesh refinement code. A series of multidimensional numerical models is obtained for a fixed distance between supernova explosion site and the black hole but different densities of the ambient medium. The interaction between the shell of the supernova remnant and the black hole results in a rapid increase of the emission from the vicinity of the black hole. Light curves of the gas heated by gravitational compression and hydrodynamical interactions are obtained assuming optically thin conditions. It is shown that the duration of the event and the peak luminosity critically depend on the density of the ambient medium. The model is applied to the data obtained by the Chandra satellite for the Galactic center.

1. Introduction

For several decades the structure and the contents of the Galactic center (GC) region remained a mystery kept away from the eyes of astronomers by dust extinction reaching $\approx 30$ magnitudes in optical part of the spectrum (Becklin et al. 1978). The earliest studies in the infrared (Stebbins & Whitford 1947) revealed an excess in the emission in the direction of the GC but provided no information about morphology. Several authors (Hagen & McClain 1954; McGee & Bolton 1954) speculated that a compact radio source located near the Galactic Center, Sgr A, may actually be associated with the nucleus of the Milky Way. Radio observations by McClain (1955) and Heeschen (1955) provided first indication of the complex nature of Sgr A.

The discovery of a sub-parsec scale radio source in the GC region (Balick & Brown 1974) provided initial support for idea that galaxies may harbor massive black holes in their nuclei (Lynden-Bell & Rees 1971; Rees 1974). High-resolution data obtained with the VLA (Brown, Jonston, & Lo 1981) and VLBI (Lo et al. 1981) allowed for identification of the compact non-thermal radio source, Sgr A*, as the primary candidate for the central massive object (Lo
The VLA also provided first detailed information about distribution of the gas in the central 10 pc revealing existence of a three-armed “mini-spiral” surrounding the central source (Ekers et al. 1983; Lo & Claussen 1983).

Observations obtained with the VLBA (Reid et al. 1999) and VLA (Backer & Sramek 1999) allowed to estimate the proper motion of the Sgr A*. This data alone rules out stellar origin of the central object and, if combined with the apparent size of Sgr A* (Lo et al. 1998; Krichbaum, Witzel & Zensus 1999; Doeleman et al. 2001), implies that its mass has to be $> 10^4 M_\odot$. More precise mass estimates based on near-infrared observations of stellar motions in the central region (Eckart & Genzel 1996; Genzel et al. 1997; Ghez et al. 1998; Eckart et al. 2002) yielded a value of $\approx 2.6 \times 10^6 M_\odot$.

The X-ray emission from the GC region has been originally detected by the Uhuru satellite (Kellog et al. 1971). A decade later Watson et al. (1981) found an extended emission from the central region and obtained the upper limit for the soft X-ray luminosity of the compact object. The extended emission was further studied with Ginga (Yamauchi et al. 1990), ASCA (Koyama et al. 1996), and Chandra (Bamba et al. 2002). GC imaging with BeppoSAX (Sidoli et al. 1999), ASCA (Sakano et al. 2002) and Chandra (Baganoff et al. 2002) allowed for resolving a part of the extended emission in a number of discrete sources.

Finally, the GC region is known to be a source of hard X-ray (Skinner et al. 1987; Churazov et al. 1994) and $\gamma$-ray emission (von Ballmoos, Diehl, & Schönfelder 1987; Mayer-Hasselwander et al. 1998), but no evidence for the emission from Sgr A* itself has been found so far. For more information about GC observations see reviews by Genzel and Townes (1987), Yusef-Zadeh, Melia, & Wardle (2000), and Falcke and Melia (2001).

The most puzzling property of the GC black hole candidate, Sgr A*, is its relative quiescence across the electromagnetic spectrum. However, it might have looked different in the past. A discovery of fluorescent X-ray emission from cold molecular clouds in the central region of the Galaxy together with the apparent lack of irradiating source suggests that not long ago Sgr A* might have been a bright source of high-energy photons (Sunyaev, Markevitch, & Pavlinsky 1993; Koyama et al. 1996). More recently, Murakami, Koyama, & Maeda (2001) found strong support for this idea and concluded that the Sgr B2 molecular cloud could have been irradiated by a transient source located at the very center of the Galaxy.

Maeda et al. (2002) argue that a likely cause of the last high-luminosity event was an interaction between Sgr A* and the supernova remnant Sgr A East. In the present communication we report preliminary results of hydrodynamical simulations related to this possibility.

2. Results and discussion

Numerical models were obtained with the help of the AMRA code (Plewa & Müller 2001) which utilizes an adaptive mesh refinement method and a high-order scheme to solve hydrodynamic equations.

The central source (CS), representing Sgr A* black hole, is a point mass $m_{CS} = 2.6 \times 10^6 M_\odot$, surrounded by an accreting region of radius $r_{CS}$. In most
cases we employ \( r_{CS} = 4 \times \Delta z \), where \( \Delta z \) is the resolution of the finest grid \( (\Delta z \approx 2.8 \times 10^{14} \text{ cm}) \).

The supernova explosion energy, \( E = 1 \times 10^{51} \text{ erg} \), is constant for all models. Since the parameters of the interstellar medium at the GC are not well-known, runs with ambient density \( n_H \) of \( 10^2, 3.16 \times 10^2 \) and \( 10^3 \text{ cm}^{-3} \) are performed. The ambient pressure is the same in all models, and its value corresponds to a temperature \( T_{amb} = 10^4 \text{ K} \) in the \( n_H = 10^3 \) model. Optically thin radiative cooling with metallicity 4 times larger than the solar one is employed.

For each density of the ambient medium we calculate a 1-D model of the SNR with the resolution \( \Delta r \approx 4.5 \times 10^{15} \text{ cm} \). Its evolution is followed for \( 10^4 \) years, and then the model is mapped onto a 2-dimensional cylindrical grid. At the same time, the CS is positioned at the symmetry axis, in front of the remnant shell, and approximately 0.5 pc away from it.

Table 1 gives radii of our 1-D remnants at \( t = 1 \times 10^4 \text{ yr} \) \( (r_{SNR}) \), and distances between explosion site and CS \( (r_{CS}) \). As it can be seen from Fig. 1, models obtained with different ambient densities differ mainly in their final radii, and width of the shell (the shell is thicker, and its velocity is lower, in denser ambient media). We will see that the latter property has a direct implication for accretion onto the CS.

Fig. 2 shows the density distribution in the 2-D model for \( \log n_{amb} = 2.5 \) (a detailed discussion of all cases will be presented in the forthcoming publication). An early stage of the evolution \( (t = 12643 \text{ yr}) \), shortly before the material from the shell starts falling into the CS, is displayed in the left panel in Fig. 2. As one can clearly see, it takes about 2000 years years for CS gravity to completely deform the SNR shell. The accretion begins from a tip of the cusp extending towards the CS, but part of the shell material flows past the accretor to form an "external bubble" behind it (middle panel, \( t = 12712 \text{ yr} \)). We find that this bubble forms unless the width of the shell is much smaller than the radius of the CS.

During later stages of the interaction the external bubble does not seem to have a significant influence on the evolution \( (t = 13400 \text{ yr}, \text{ right panel in Fig. 2}) \). Instead, we observe a formation of a fast \( (v \approx 5000 \text{ km/s}) \) wind blowing from the CS region into the interior of the remnant. In the the right panel of Fig. 2, this wind is shocked at a distance of \( \approx 1 \text{ pc} \) from the CS to temperatures \( > 10^8 \text{ K} \) with pre-shock densities \( n \approx 0.02 n_H \). We note that the mechanism of wind formation in our model resembles that of a jet-like flow found by Fryxell, Taam, & McMillan (1987) in their study of the axisymmetric flow past a gravitating sphere.
Figure 1. Structure of the 1-D supernova remnants at $t = 1 \times 10^4$ yr. Gas densities and velocities are shown for $\log n_H = 2$ (thin solid), 2.5 (dotted), and 3 (thick solid).
Figure 2. Structure of the 2-D model in the vicinity of the Central Source for $\log n_H = 2.5$. The image is 0.2 pc on a side and the CS is located at the left axis in the middle. The density field in log scale is shown at $t = 12643$ (left panel), $12712$ (middle panel), and $13400$ yr (right panel), with $\log \rho_{\text{min}} = -25$ (black) and $\log \rho_{\text{max}} = -19$ (white).

In Fig. 3 we show accretion rates and luminosities during the first few hundreds years of the accretion episode. In all cases the increase in both accretion rate and luminosity is very rapid. Otherwise, the degree of correlation between accretion rate and luminosity is rather poor, presumably due to inadequate resolution in the immediate vicinity of the CS. As we do not resolve the Schwarzschild radius, our model provides only lower limits for the luminosity. However, we note that the model predicts a copious production of energetic emission with the peak luminosity approaching $10^{39}$ erg/s for the low-density model. For intermediate and high density the luminosity exceeds the lower limit ($L_X \gtrsim 10^{39}$ erg/s, Murakami et al. 2001) required to explain the existence of the X-ray reflection nebula in the Galactic center.

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Figure 3. Model accretion rates (top panel) and grid luminosities for $T > 5 \times 10^6$ K (bottom panel) during early stages of the accretion phase. The data is plotted with thin solid, dotted, and thick solid lines for $\log n_H = 2$, 2.5, and 3, respectively.
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