THE X-RAY RIDGE SURROUNDING SAGITTARIUS A* AT THE GALACTIC CENTER

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ABSTRACT

We present the first detailed simulation of the interaction between the supernova explosion that produced Sgr A East and the wind-swept inner ∼2 pc region at the Galactic center. The passage of the supernova ejecta through this medium produces an X-ray ridge ∼9″–15″ to the northeast of the supermassive black hole Sagittarius A* (Sgr A*). We show that the morphology and X-ray intensity of this feature match very well with recently obtained Chandra images, and we infer a supernova remnant age of less than 2000 yr. This young age—a factor of 3–4 lower than previous estimates—arises from our inclusion of stellar wind effects in the initial (preexplosion) conditions in the medium. The supernova does not clear out the central ∼0.2 pc region around Sgr A* and does not significantly alter the gas profile around the central black hole upon passage through the Galactic center.

Subject headings: accretion, accretion disks — black hole physics — Galaxy: center — radiation mechanisms: thermal — stars: winds, outflows — X-rays: diffuse background

Online material: color figures

1. INTRODUCTION

While Sagittarius A* (Sgr A*) dominates the gravitational dynamics in the central parsecs of the Galaxy, many other components are required to explain the wealth of detailed observations of this busy region (for a recent review, see Melia & Falcke 2001; see also Maeda et al. 2002). For example, the medium within which Sgr A* is embedded—bounded by the circumnuclear disk (CND; with inner radius ∼2–3 pc)—has a temperature of ∼1.3 keV and emits a Chandra-detectable glow of diffuse X-rays (Baganoff et al. 2003). Rockefeller et al. (2004) have shown that this emission may be understood as the result of mutual interactions between the winds of Wolf-Rayet and O/B stars within ∼1 pc of the supermassive black hole.

The CND is perhaps the shredded remains of a giant molecular cloud that passed by Sgr A*. The cavity within the inner ∼2–3 pc of this structure may itself have been created by the ablative influence of the cumulative wind outflow, which has by now produced a bubble of hot, ionized plasma. To make matters even more complex, observations of the supernova (SN) remnant Sgr A East suggest that its broadband emission arises from shock heating in a recent (<10,000 yr old) supernova (or other explosive outburst; see Mezger et al. 1989) originating within ∼3 pc of the black hole.

Any comprehensive model of this region must therefore include the effects of all these components: the supermassive black hole, the Wolf-Rayet and O/B winds, the dense CND, and the expanding supernova remnant, which we now see predominantly as a radio-emitting shell. Although interacting winds can explain the bulk of the diffuse X-ray flux from the inner ∼2–3 pc, several other features seen in the Chandra X-ray image are not as easy to explain without the influence of some other interaction. In particular, a well-defined ridge of X-ray emission just outside the central region, to the northeast of Sgr A* (see Fig. 1), may be evidence of an ongoing collision between the SN ejecta and the cumulative Wolf-Rayet and O/B winds emanating from within the cavity (Maeda et al. 2002).

In this Letter, we model the expansion of the supernova, focusing on the effect this explosion has on the central few parsecs surrounding Sgr A*. We then directly compare the X-ray emission arising from the interaction zone with the actual Chandra image.

Interestingly, using the well-studied wind conditions at the Galactic center, we may also be able to place tighter constraints on the supernova explosion itself—both the released energy and the age of the remnant. With this knowledge, we can address several outstanding issues pertaining to the influence of this explosion on the morphology of the Galactic center. Did the supernova shock clear out the region surrounding the black hole, effectively shutting down what would otherwise have been a high accretion rate? Could the supernova have caused a brief increase in the accretion rate onto Sgr A*, producing a spike in X-ray emissivity that irradiated the X-ray-fluorescing Sgr B2 and other nearby molecular clouds some 300 yr ago (see, e.g., Sunyaev & Churazov 1998; Fromerth & Melia 2001)?

2. GENERAL PHYSICAL PRINCIPLES

Our simulation uses the SNSPH smoothed particle hydrodynamics code (Fryer et al. 2005b) to follow the supernova explosion as it crosses the Galactic center. We use the standard Monaghan spline kernel to calculate smoothed quantities (Monaghan & Lattanzio 1985), and following Rockefeller et al. (2004), we ignore self-gravity of the gas and assume a gamma-law equation of state (γ = 5/3) without radiative cooling. The domain of solution is a cube, 6 pc on a side, centered on the black hole. Particles that move beyond this domain, or within 0.06 pc of the origin, are removed to simulate outflow conditions. Our initial (preexplosion) conditions are taken from the structure of the wind-swept medium at the end of the simulation by Rockefeller et al. (2004). The initial particle distribution is constructed from an ∼1 million particle supernova explosion placed 2 pc due east, in right ascension, of the central supermassive black hole (and at the same z-position, along the
line of sight) within an \( \sim 6 \) million particle wind-filled Galactic center region. The choice of \( z \)-position for the origin of the explosion minimizes the distance between the explosion and Sgr A* and therefore maximizes the effect of the explosion on the central parsec of the Galaxy.

The structure of the supernova ejecta is set using a spherically symmetric model from Hungerford et al. (2005). This 15 \( M_\odot \) star is exploded with an energy of \( 1.5 \times 10^{51} \) ergs; these properties are typical of a supernova explosion, both in composition and energy. We place the explosion into our domain of solution after the shock has moved out for 1 yr, at which time the explosion material is still within 0.02 pc of the supernova site.

We assume that the density structure within the domain of solution at the time of the supernova explosion is dominated by matter lost by the Wolf-Rayet and O/B stars, plus the dense CND surrounding the central black hole. The CND is mimicked by 200 spherical clumps (totaling \( 10^4 M_\odot \)) in a torus with a low filling factor. The winds from these stars (which we assume have not changed noticeably in the past 10,000 yr) have blown a bubble in the Galactic center that is probably at the edge of the 50 km \( s^{-1} \) molecular cloud (Mezger et al. 1989).

Note, however, that our initial conditions do not include the initial molecular cloud blown out by the stellar winds. There is evidence that the supernova shock has reached the boundary between the windblown bubble and this cloud (Yusef-Zadeh et al. 1999). We also do not include the effect of mass loss from the supernova progenitor itself. However, the density structure near the X-ray ridge and the central black hole is dominated by the \( \sim 25 \) stars we do include (Rockefeller et al. 2004), and not by any outer stars or the surrounding molecular cloud.

We also neglect the motion of the stars themselves. Cuadra et al. (2005) simulated the interaction of winds from stars moving in the Galactic center on realistic trajectories and found that the angular momentum imparted to the gas had a noticeable effect on the flow within \( \sim 0.05 \) pc of Sgr A*; as expected, gas with sufficiently high angular momentum did not flow through the inner boundary of their simulation, and instead established a Keplerian profile. This additional angular momentum in the gas near Sgr A* would act as an extra barrier against the propagation of the supernova shock past the black hole.

### 3. Calculations and Results

Large density variations within the wind-swept Galactic center region—from \( \sim 1 \) particle \( cm^{-3} \) in diffuse regions to \( >10^3 \) particles \( cm^{-3} \) and above near Sgr A*—lead to an aspherical progression of the supernova shock. The ejecta flow primarily through the most diffuse regions, taking the path of least resistance and producing shocks where they collide with and are decelerated by the dense material. Figure 2 shows the density profile and position of a set of tracer supernova particles 650 yr after the launch of the explosion. This is roughly the time of deepest penetration of the ejecta into the region surrounding the black hole. The actual supernova shock has now moved across the Galactic center and has already passed beyond the southern and eastern edges of our simulation grid. The ejecta do not sweep through the central region, nor do they significantly alter the density of the inner 0.2 pc surrounding the black hole. A more detailed discussion of the effects of the supernova shock on the central region, the implications for the black hole accretion rate, and the possible excitation of Sgr B2 will be presented in Fryer et al. (2005a).

Mezger et al. (1989) estimated the age and energy of the supernova remnant by assuming the supernova was plowing through a \( 10^4 \) particle \( cm^{-3} \) molecular cloud. They calculated...
FIG. 3.—The 2–10 keV X-ray luminosity per 1′′ × 1′′ pixel from our simulation, shown at four different snapshots in time (160, 650, 1740, and 2560 yr after the supernova explosion). Pixel brightness scales logarithmically with luminosity; pixels with luminosities below $10^{29}$ erg s$^{-1}$ are black, and those with luminosities above $10^{32}$ ergs s$^{-1}$ are white. The light and dark contours indicate per-pixel luminosities of $10^{30}$ and $10^{31}$ ergs s$^{-1}$, respectively. At 160 yr, the shock from the supernova ejecta hitting the dense wind-dominated region surrounding Sgr A* produces an X-ray hot spot. The hot spot moves around Sgr A* as the head of the supernova shock sweeps around the central region (650 yr). After 1740 yr, the stellar wind material begins to reassert itself. The shock between it and the slower-moving ejecta forms an X-ray ridge (highlighted by the arc) with a 2–10 keV luminosity of roughly $3 \times 10^{31}$ ergs s$^{-1}$. This is our best estimate for the current state of the Galactic center. By 2560 yr after the launch of the explosion (800 yr from now), the luminosity of the ridge will be a factor of $\sim 3$ dimmer, and the feature will lie nearly 30′′ away from Sgr A*. The dashed line indicates the orientation of the Galactic plane. [See the electronic edition of the Journal for a color version of this figure.]

a supernova remnant age of 7500 yr, and to fit the observed shock temperature, they required an explosion energy in excess of $10^{52}$ ergs. However, the lower mean density in our wind-swept initial conditions allows us to account for the observed remnant characteristics with a more typical supernova explosion ($\sim 10^{51}$ ergs). Our simulation also suggests that the supernova remnant is younger than the estimate of Mezger et al. (1989). From the position of the shock, we can set a crude lower limit to the remnant’s age at $\sim 1000$ yr, but a more precise answer can be determined by comparing our predicted X-ray ridge properties to the observations shown in Figure 1.

The column-integrated X-ray emission from our models is shown in Figure 3 in a series of temporal snapshots. For very energetic shocks, the high compression ratio at the point of impact can lead to significant particle acceleration and consequent nonthermal emission, but by this time in the interaction, the dominant 2–10 keV emission mechanism is expected to be optically thin bremsstrahlung (see Rockefeller et al. 2004; Fryer
et al. 2005a for details). The supernova shock reaches the dense inner 0.2–0.3 pc of the Galactic center in 160 yr and sweeps around this area after 650 yr.

By 1740 yr after the explosion, the supernova shock has swept beyond our simulation grid. However, over 95% of the mass in the supernova ejecta is moving at less than half the speed of the shock front. This slow-moving material continues to impinge on the inner 0.2–0.3 pc of the Galaxy. It is the interaction between the stellar winds pushing against the slow-moving supernova ejecta that produces the X-ray ridge observed today (Fig. 1). (Note that we placed the origin of the supernova explosion directly east of Sgr A*, while the observed origin is farther north; in both the Chandra image and our simulation, the X-ray ridge appears on the side of Sgr A* closest to the explosion’s origin.)

For direct comparison between our simulation and the properties evident in Figure 1, we restrict our attention to the region bounded by the 9° and 15° arcs in this image; this appears to be the scene of dominant interaction at the present time. The observed flux is accurately modeled with two components at different temperatures: a 5.6 keV component with a 2–10 keV flux of $3.92 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$, and a 1 keV component with a 2–10 keV flux of $5.8 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$; these correspond to 2–10 keV luminosities of $3.0 \times 10^{35}$ ergs s$^{-1}$ and $4.4 \times 10^{33}$ ergs s$^{-1}$, respectively, at a distance of 8 kpc from the Galactic center.

In our simulation, both the location of and the X-ray intensity from this region vary with time, so we have essentially two important constraints on the comparison between theory and observation. We suspect that the 1 keV component arises from either foreground or background emission; this is supported by the fact that the luminosity-weighted temperature in this region of our simulation is 4.9 keV after 1740 yr. From our simulation, we find that the column-integrated 2–10 keV luminosity from the interaction within the swath highlighted in Figure 3 is $3.6 \times 10^{33}$ ergs s$^{-1}$ after 1619 yr, and $2.7 \times 10^{33}$ ergs s$^{-1}$ after 1740 yr. These values are within 20% of the observed luminosity of the 5.6 keV component, and the good match between theory and observation for both the morphology and the X-ray radiance of the ridge therefore provides us with compelling evidence that ~1700 yr must be a reasonable estimate for the remnant’s age.

As the velocity of the impinging supernova ejecta decreases, the X-ray ridge moves out and dims. By 2560 yr, the ridge will have moved out 30°, and its flux should then be 3 times lower than its (current) 1740 yr value.

4. CONCLUSION

Our simulation of the passage of Sgr A East across the Galactic center has produced several new insights into the structure of the environment within ~3 pc of Sgr A*. The front of the supernova remnant flowed around the Galactic center ~1100 yr ago (650 yr after the supernova explosion). The shock front pushed back the combined winds from the Wolf-Rayet and O/B stars, but did not penetrate within ~0.2 pc of the accreting supermassive black hole. The collision between the supernova ejecta and the central winds produces a ridge of X-ray–emitting gas ~9°–15° to the northeast of the black hole. Comparing our simulation with the observations allows us to estimate the age of the supernova remnant to be ~1700 yr. We predict that this X-ray ridge will move out and dim with time. In ~800 yr, it should be roughly twice its current distance from Sgr A*, and a factor of ~3 dimmer.

The supernova did not significantly alter the inflow rate of gas through our inner boundary. We discuss this and the implications for the accretion rate onto the black hole in greater detail in an upcoming paper (Fryer et al. 2005a). For now, we note that the choice of z-position for the origin of the supernova explosion, and the absence of angular momentum in the gas due to motions of the wind-producing stars, each actually exaggerates the influence of the simulated explosion on the environment near Sgr A*. Increasing the distance between the Sgr A* and the origin of the explosion, or including additional angular momentum support for the gas within ~0.1 pc of the black hole, would weaken the already small effect of the explosion on the gas profile near Sgr A*.

Our simulations demonstrate how rich in information the X-ray observations of the Galactic center are. Although this region contains several complex flows that are difficult to simulate completely, the extensive body of data contains many features that we can employ to tightly constrain the calculations. In Fryer et al. (2005a), we will discuss in more detail the hydrodynamic evolution of the shock and calculate the emission as the shock hits the large molecular cloud to form Sgr A East. We will also report in detail the metallicity gradients expected within Sgr A East as a function of time and distance from Sgr A*, providing yet another observational signature that may be used to better constrain this remnant’s age.

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