THE SGR B2 X-RAY ECHO OF THE GALACTIC CENTER SUPERNova EXPLOSION THAT PRODUCED SGR A EAST

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ABSTRACT

Using a combination of one-dimensional and three-dimensional hydrodynamic simulations, we have carried out the first in-depth analysis of the remnant’s evolution and its various interactions: with the stellar winds flowing out from the inner ∼2 pc; with the supermassive black hole, Sgr A*; and with the 50 km s−1 molecular cloud behind and to the east of the nucleus. We have found that, unlike previous estimates, a rather “standard” supernova explosion with energy ∼1.5 × 1051 ergs would have been sufficient to create the remnant we see today and that the latter is probably only ∼1700 yr old. We have found that the passage of the remnant across the black hole would have enhanced the accretion rate onto the central object by less than a factor of 2. Such a small increase cannot explain the current Fe fluorescence observed from the molecular cloud Sgr B2; this fluorescence would have required an increase in the luminosity of Sgr A* by 6 orders of magnitude several hundred years ago. Instead, we have uncovered what appears to be a more plausible scenario for this transient irradiation: the interaction between the expanding remnant and the 50 km s−1 molecular cloud. The first impact would have occurred about 1200 yr after the explosion, producing a 2–200 keV luminosity of ∼1039 ergs s−1. During the intervening 300–400 yr, the dissipation of kinetic energy subsided considerably, leading to the much lower luminosity (∼1036 ergs s−1 at 2–10 keV) we see today.

Subject headings: acceleration of particles — Galaxy: center — radiation mechanisms: nonthermal — stars: winds, outflows — supernova remnants — X-rays: diffuse background

Online material: color figures

1. INTRODUCTION

The conditions in the inner 3 pc of the Galaxy are set in large part by the complex interaction of over a dozen strong Wolf-Rayet star winds and the enveloping 50 km s−1 Giant Molecular Cloud (M 0.02–0.07), combined with the gravitational pull of the central supermassive black hole (Sgr A*; see Melia & Falcke [2001] for a recent review). The large number of massive stars in this compact region suggest an additional influence: supernova explosions. Sgr A East is the likely remnant of such an event. An earlier consideration of its interaction with the molecular cloud, based on the energetics and time required to carve out the central cavity now occupied by Sgr A East (Mezger et al. 1989), pointed to an unusually powerful explosion with an energy of ∼1052 ergs or greater and a remnant age exceeding ∼10,000 yr. Such extreme conditions led to speculation about the source of this explosion being something other than a normal supernova explosion, despite the fact that the nucleosynthetic yields all seem to agree well with normal thermoneutral or core-collapse supernovae (Maeda et al. 2002; Sakano et al. 2004; Park et al. 2005). All these estimates, however, ignored the importance of the stellar winds in clearing out the medium into which the supernova ejecta expanded following the incipient event. Simulations indicate that massive star winds will clear out much of the surrounding molecular cloud (Rockefeller et al. 2004), leading to densities as low as 1 cm−3 near the origin of the supernova. With the area cleared, the current morphology of Sgr A East is actually consistent with a normal supernova explosion energy (∼1051 ergs). In addition, the relatively low gas density in the wind-filled region and the consequent more rapid expansion of the remnant into the surrounding medium lead to an inferred age much younger than 10,000 yr, probably <2000 yr.6

Rockefeller et al. (2005) focused on the X-ray ridge to the northeast of Sgr A*, formed by the interaction of the stellar winds (which emanate from within the cavity enclosed by the circum-nuclear disk [CND]) and the slowing supernova ejecta expanding away from the site of the explosion that produced Sgr A East. In this paper, we discuss several additional features that have emerged from our simulations, along with other important implications of a young supernova remnant. These include the remnant’s evolution, its impact on the supermassive black hole’s accretion, and the spatial distribution of heavy elements formed in the supernova progenitor. In particular, we wish to examine the consequences of a young supernova remnant colliding with the 50 km s−1 cloud, focusing on the X-ray illumination this would have produced on extended objects, such as the molecular cloud Sgr B2, ∼300 lt-yr to the northeast of Sgr A*. Sgr B2’s current emission of a strongly fluoresced Fe line appears to be the X-ray “echo” of that interaction, providing the best (circum-stantial) evidence of the impact the supernova would have had on the Galactic center in the past several hundred years.

We begin by describing the current observational status of Sgr B2 (§ 2) and then take a step back to discuss the basic principles

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6 One way to test such a young age is through the structure, and ionization timescales, of the X-ray emission (Maeda et al. 2002; Sakano et al. 2004; Park et al. 2005). If Sgr A East were a simple remnant, it would be difficult to fit the spectrum of such a young remnant to the observed X-ray emission. However, the complex nature of the Galactic center makes it difficult, without much more detailed calculations, to place constraints on the remnant age. We defer such a calculation to a later paper.
of shock expansion in the Galactic center (§ 3). Using a combination of three-dimensional and one-dimensional simulations, we then show how the supernova shock would have affected the accretion rate onto Sgr A* (§ 4) and the concurrent evolution of the supernova remnant Sgr A East (§ 5), focusing on how these interactions might have accounted for the irradiation of Sgr B2.

We also present abundance distributions produced by the explosion (§ 6), which, if measured, could provide us with much tighter constraints on the supernova explosion energy. Finally, we return to Sgr B2 and conclude with a possible explanation for the origin of the illumination that produced the current fluorescent Fe emission.

2. THE PUZZLE OF SGR B2

The region within ~100 pc of Sgr A* contains giant molecular clouds with a mean number density \( \sim 10^4 \) cm\(^{-3} \) and a gas temperature on the order of 60 K (Lis & Carlstrom 1994). Over the past decade, several instruments, including the Advanced Satellite for Cosmology and Astrophysics (ASCA; Koyama et al. 1996; Murakami et al. 2000) and BeppoSAX (Sidoli 1999), have revealed a source of bright fluorescent Fe K\( \alpha \) line radiation within the cloud Sgr B2; several other smaller clouds also exhibit strong 6.4 keV line emission, but with low absolute fluxes compared to Sgr B2. The latter has a radius \( \sim 10–20 \) pc and a total enclosed mass \( \sim (2–6) \times 10^6 \) M\(_\odot \) (Lis & Carlstrom 1994). All of these fluorescing clouds produce a 6.4 keV line with an unusually large equivalent width (EW \( > 1–2 \) keV), although Sgr B2 stands out with the largest width, at \( \approx 2–3 \) keV. The surrounding continuum is quite flat and shows strong absorption below 4.5 keV and a sharp Fe K\( \alpha \) absorption feature at 7.1 keV.

The large EW is a strong indicator of how this fluorescent emission is produced (Sunyaev et al. 1993; Sunyaev & Churazov 1998; Fromerth et al. 2001). A cloud radiates via X-ray fluorescence when it is illuminated, either internally or externally, by an X-ray source. However, a steady source embedded within the cloud produces an upper limit to the EW of only \( \sim 1 \) keV (see, e.g., Fabian 1977; Vainshtein & Sunyaev 1980; Fromerth et al. 2001), regardless of how one chooses the parameters. The smaller molecular clouds might therefore be marginally consistent with an internal illuminator (see, e.g., Fromerth et al. 2001). However, Sgr B2 must necessarily be illuminated either by a time-dependent internal source whose flux has diminished or by an external source. In the former case, the continuum will have faded away relative to the line intensity; in the latter, we are not directly observing the full ionizing flux. In both cases, the equivalent width would be larger than in a situation where the continuum spectrum of the irradiating source is still visible.

Recently, Revnivtsev et al. (2004) reported an association of the hard X-ray source IGR J17475–2822 with Sgr B2, showing that the ASCA (3–10 keV) and International Gamma-Ray Astrophysics Laboratory (INTEGRAL) IBIS (20–400 keV) spectral components match very well. They showed that the combined spectrum at 3–200 keV can be well fit by a model in which X-rays from an external source, possibly at the location of Sgr A*, are scattered and reprocessed by a homogeneous spherical cloud of cold molecular hydrogen and helium gas, with iron abundance \( \sim 1.9 \) times solar.

The possible identification of Sgr A* as the external illuminator of Sgr B2 would provide some measure of its recent variability at X-ray energies. This association is motivated in part by the fact that the iron emission in Sgr B2 is strongest on the side of the cloud facing Sgr A* (Koyama et al. 1996). We may be witnessing an X-ray echo, delayed by 300–400 yr relative to the direct signal from the black hole, due to the light-travel time from the Galactic center out to Sgr B2’s position. In this scenario, the fluorescent Fe emission would then be direct evidence of the black hole’s enhanced X-ray emissivity some 300 yr ago.

Alternative scenarios seem to be falling out of favor (see, e.g., Revnivtsev et al. 2004). For example, although the time-dependent internal illuminator model can match the Fe line shape, as well as the external illuminator (Fromerth et al. 2001), the lack of any significant variation in the line flux with the passage of time argues against this geometry. The large EW of the 6.4 keV line implies that the primary source should have faded away before the ASCA observation of 1993. But the light crossing time of the Sgr B2 cloud is \( \sim 30–60 \) yr, so one might have expected to see a detectable decline of the 6.4 keV line flux in the 7 years between the ASCA and BeppoSAX observations, unless the irradiation of Sgr B2 is still ongoing because not all the X-ray waves have yet reached the cloud.

Although it is very tempting to invoke Sgr A* as the external illuminator, there are several reasons for taking a cautious view of this picture—chief among them is the fact that this scenario would require a change in the black hole’s 2–10 keV X-ray luminosity by a factor of \( \sim 10^6 \) in only 300 yr, from \( L_X \approx 5 \times 10^{38} \) ergs s\(^{-1} \) (Revnivtsev et al. 2004) to the currently observed value of \( L_X \approx 10^{33} \) ergs s\(^{-1} \) (Baganoff et al. 2003). This requires a dramatic change in the accretion rate and/or the accreted angular momentum onto the black hole—often ascribed to the effects of a nearby supernova explosion. One of the principal goals of this paper is to examine the role played by the recent Galactic center supernova in illuminating Sgr B2, which may alleviate the difficulties described above.

3. SUPERNOVA SHOCKS AT THE GALACTIC CENTER

Molecular cloud remnants, inflowing plumes, and hot ionized bubbles all combine to form a complex density structure across the Galactic center, rendering it inappropriate for the “spherically symmetric cow” approach preferred by most theorists. These deviations from isotropy are well reflected in the anisotropic propagation of the supernova shock. Figure 1 shows the initial three-dimensional density structure used in our simulations. We have here made the same model assumptions as Rockefeller et al. (2005), who determined the density profile solely by the mass-losing stars interacting with the dense CND within the gravitational potential of the central supermassive black hole. We have also assumed that the stellar wind ejecta have not changed significantly in the past \( \sim 5000–10,000 \) years. Figure 2 shows a 0.2 pc slice of this density structure centered on Sgr A* at the time of the explosion.

Before we discuss the propagation of the shock through this complex density distribution, we review the spherically symmetric picture and consider the three basic evolutionary phases of supernova remnants and their shocks (Cox 1972; Chevalier 1974).

Phase I (free-streaming)—The supernova explosion initially propagates essentially unimpeded by the surrounding medium. This phase ends roughly when the supernova has swept up a mass equal to the preexplosion mass of the progenitor.

Phase II (adiabatic)—The remnant evolves into a second phase in which cooling is still not important. The shock can be described using adiabatic, self-similar blast wave solutions (Sedov 1959; Taylor 1950a, 1950b).

Phase III (snow plow)—The final phase occurs when radiative cooling becomes important. In this phase, the thermal energy of the shock is rapidly radiated and the shock moves forward by momentum conservation alone. This phase ends when the velocity...
of the shock decreases below the sound speed of the surrounding medium.

For a 15 $M_\odot$ star, the end of the free-streaming phase ($t_{\text{free-streaming}}$) and the remnant’s radial extent ($R_{\text{free-streaming}}$) at that time are given, respectively, by the expressions

$$t_{\text{free-streaming}} \approx 2000E_{51}^{-1/2}n^{-1/3} \text{ yr}$$

$$R_{\text{free-streaming}} \approx 5.3n^{-1/3} \text{ pc},$$

as functions of supernova explosion energy $E_{51}$ (in units of $10^{51}$ ergs) and density of the surrounding medium $n$ (in units of $\text{cm}^{-3}$). Here we have assumed that the velocity is $(E_{SN}/M_{SN})^{1/2}$ (where $E_{SN}$ and $M_{SN}$ are the supernova energy and mass, respectively), which, however, underestimates the lead shock speed. We can use these spherical estimates, combined with the density structure at the Galactic center (Fig. 2), to follow the free-streaming phase along specific paths. That portion of the supernova shock that moves away from Sgr $A^*$ (where the number density is low: $\sim 1 \text{ cm}^{-3}$) does not decelerate significantly until it hits the 50 km s$^{-1}$ molecular cloud that surrounds the Galactic center (roughly 4 pc from the launch site of the supernova). But the ejecta moving toward Sgr $A^*$ propagate through an increasingly dense medium. The remnant on this side of the explosion leaves the free-streaming phase more than 0.5 pc away from Sgr $A^*$.

Beyond the free-streaming phase, but before radiative cooling becomes important, the shock propagates adiabatically. This phase lasts for a period set by the cooling time of the shock. Wheeler et al. (1980) estimated the radial and temporal extent of the shock for different cooling functions. When lines dominate, they find

$$t_{\text{cooling}} \approx 110E_{51}^{0.22}n_4^{-0.56} \text{ yr}$$

$$R_{\text{cooling}} \approx 0.29E_{51}^{0.29}n_4^{-0.43} \text{ pc},$$

where $n_4$ is the number density in units of $10^4 \text{ cm}^{-3}$. For the segment of the shock directed toward the Galactic center, where densities are in the range of $10^3$–$10^4 \text{ cm}^{-3}$, the shock travels less than 0.5 pc before cooling takes over. From these rough calculations, we might therefore expect the shock to just reach Sgr $A^*$. However, as we see in §4, the fact that the shock can flow around this dense region, made impenetrable by the persistent outward ram pressure of the stellar winds, means that the shock actually never reaches the Galactic center. Correspondingly, the ejecta moving away from the Galactic center have a much more extended adiabatic phase; it lasts until they hit the molecular cloud, at which point the phase ends almost immediately.

Timing is also important. The total travel time for the ejecta to reach the nucleus is just 600 yr. If the molecular cloud is 4 pc away from the explosion site, our rough velocity estimate leads to the shock leaving the adiabatic phase at roughly 1600 yr. Let us now compare these results to the actual numerical calculations.

### 4. TIME-DEPENDENT ACCRETION ONTO SGR A$^*$

We use both one-dimensional and fully three-dimensional simulations to trace the evolution of the supernova remnant and to provide us with a basic understanding of its effect on the
Galactic center. Of course, in the one-dimensional case, we model the properties of the medium into which the shock front expands in an angle-averaged sense. Under the assumption of spherical symmetry, we have found that the shock passes through both its free-streaming and adiabatic phases prior to reaching Sgr A\(^*\), but that it is less clear whether or not the shock actually reaches Sgr A\(^*\) before cooling and assimilating into its surroundings.

What these spherically symmetric simulations do not include are multidimensional geometric effects. Just as an ocean wave flows around a rocky promontory, the supernova shock will flow around the dense, stellar wind–filled region surrounding Sgr A\(^*\). Using the SNSPH code described in C. L. Fryer et al. (2006, in preparation), we have modeled the propagation of the supernova through the inner 3 pc region surrounding the Galactic nucleus (for details, see Rockefeller et al. 2005). The density profile was taken from Rockefeller et al. (2004), and the supernova was assumed to occur with an energy of \(1.5 \times 10^{51}\) ergs in a progenitor with a mass of 15 \(M_\odot\) (Hungerford et al. 2005a). We placed it at longitude \(0.89\) pc and latitude \(1.47\) pc relative to Sgr A\(^*\) in Galactic coordinates, or 2 pc due east of Sgr A\(^*\) in right ascension (but at the same radial distance from us). We have also modeled a more energetic explosion (\(\sim 1.2 \times 10^{52}\) ergs) by artificially

| Simulation  | Energy \((10^{51}\) ergs) | \(D_{\text{Sgr A*}}\) (pc) | \(T_{\text{GMC}}\) (yr) | Remnant Age (yr) |
|------------|----------------------------|-----------------|----------------|-----------------|
| Standard   | 1.5                        | 0.4             | 1200           | 1700            |
| Energetic  | 12                         | 0.2             | 400            | 700             |

\(^a\) The distance of closest approach of the shock to Sgr A\(^*\).
\(^b\) The time it would have taken for the shock to reach the 50 km s\(^{-1}\) Giant Molecular Cloud.

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increasing the velocity of the ejecta by a factor of 3; Table 1 summarizes the properties of both simulations. In determining how close the supernova shock penetrates into the wind-dominated region surrounding Sgr A*, these two simulations span the range of possible progenitors. However, this study does not investigate the range of yields we could get from different progenitors.

Figure 3 shows a series of snapshots recording the temporal evolution of the supernova explosion and the resulting remnant from our three-dimensional ($\sim 10^{51}$ ergs) simulation. The contours indicate regions with different densities, while the vectors highlight the supernova shock; the black vectors correspond to the supernova ejecta themselves, and the gray vectors indicate shocked wind material. The shock collides with and flows around the inner 0.4 pc region primarily along paths of lowest density. It ultimately clears out much of the inner 3 pc region, except for those portions shadowed by the CND or by the outflowing winds from the central 0.4 pc. The depth to which our simulated shock penetrates in the direction of Sgr A* may be checked by simply comparing the ram pressure of the supernova shock with that of the winds. At 430 yr, the shock is within $0.4–0.5$ pc of the black hole. The density and velocity of the shock are roughly $3 \text{ cm}^{-3}$ and $4000 \text{ km s}^{-1}$, respectively. The corresponding values for the wind outflow are $100 \text{ cm}^{-3}$ and $700 \text{ km s}^{-1}$. The energy density (or equivalently, the ram pressure $pv^2$) of one flow is equal to that of the opposing flow, and neither makes headway. This roughly marks the time of maximum penetration of the supernova shock, which eventually flows around the central region. By 1400 yr after the explosion, the ram pressure of the supernova shock decreases below that of the wind, and the latter begins to reassert itself.

In the $\sim 10^{52}$ erg simulation (shown in Fig. 4 in a similar series of snapshots), the shock moves much faster and penetrates deeper into the stellar wind region surrounding Sgr A*. By 170 yr, the shock is within 0.2 pc of the black hole, but as in the standard-energy

**Fig. 4.** Same as Fig. 3, but now for the $1.2 \times 10^{52}$ erg explosion. The shock penetrates to within $0.1–0.2$ pc of Sgr A*, reaching maximum penetration at only 200–270 yr. It clears out the Galactic center more comprehensively than the $\sim 10^{51}$ erg explosion, but some material is still shadowed by the dense stellar wind region surrounding Sgr A*. By 1200 yr, the stellar winds have begun to reassert themselves. [See the electronic edition of the Journal for a color version of this figure.]
of 2 for a short period of time. Similarly, the accreted specific angular momentum beyond 0.4 pc, and the stellar winds, which have begun to reassert themselves central region, clearing out most of the material except for the CND.

For a factor of a million, allowing it to be the transient irradiator of Sgr B2 several hundred years ago. If Sgr B2 was indeed illu-

The supernova shock—never gets closer than 0.1 pc from the Galaxy, Herrnstein & Ho (2005) examined the interaction between the Sgr A East shell and the 50 km s$^{-1}$ cloud and concluded that the expansion of the former apparently did not move a significant amount of the latter’s mass. This is consistent with the results of our simulation, in which the supernova ejecta at first moved rather quickly through the medium surrounding Sgr A*, which had been mostly cleared out by the powerful winds of stars situated within ~2–3 pc of the black hole. But Sgr A East is clearly interacting with the 50 km s$^{-1}$ cloud now, as evidenced by the presence of seven 1720 MHz OH maser emission regions within several arcminutes of the Galactic center (Yusef-Zadeh et al. 1996, 1999). This transition of the OH molecule is a powerful shock diagnostic and is collisionally pumped by H$_2$ molecules at the site where C-type supernova shocks drive into adjacent molecular clouds. Most of these maser spots are located to the southeast of Sgr A*, at the boundary of Sgr A East and M 0.02–0.07. In addition, Zeeman splitting measurements suggest that the magnetic field at these locations is of order 2–4 mG. Both the relatively high intensity of this field and the intense OH maser emission indicate that the shock at the interface between Sgr A East and M 0.02–0.07 must be very strong, since the impact is compressing the gas and the field lines.

The present interaction region between Sgr A East and M 0.02–0.07 appears to be $\sim 1'–1.5'$ in projection from Sgr A* (Yusef-Zadeh et al. 1996; Herrnstein & Ho 2005). At the distance to the Galactic center, this corresponds to $\sim 2.4–3.6$ pc; taking projection into account, we infer $\sim 4$ pc as a reasonable estimate of the distance between the interaction site and Sgr A*. Thus, with our chosen supernova site 2 pc due east (in right ascension) of Sgr A*, it would have taken $\sim 1200$ yr for the shock front to reach the molecular cloud traveling at a speed of $v \sim (2E_{\text{SN}}/M_{\text{SN}})^{1/2} \sim 2500$ km s$^{-1}$.

Figure 6 shows several snapshots in time of the velocity of propagation for three one-dimensional explosion calculations. The basic setup of these models is a diffuse ($n < 10$ cm$^{-3}$) wind-swept region with an outer dense ($n > 10^4$ cm$^{-3}$) molecular cloud, roughly starting at 4 pc. As we would expect from the Sedov blast wave similarity solution (Sedov 1959; Taylor 1950a, 1950b), the shock decelerates as it propagates through the diffuse wind-swept

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**Fig. 5.**—Mass accretion rate (top) and accreted specific angular momentum (bottom) as functions of time for the standard (solid line) and energetic (dotted line) simulations. The standard simulation undergoes a small (~20%) change in accretion rate around the time of closest approach of the supernova shock to Sgr A* (~650 yr), while the energetic simulation shows an increase in $M$ of nearly a factor of 2 for a short period of time. Similarly, the accreted specific angular momentum ($\lambda$, in units of $r_\odot$ $\equiv GM/c^2$) changes by $\sim 20\%$ in the standard simulation, but undergoes a brief increase of more than a factor of 2 in the energetic simulation.

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\[ \text{Note that this boundary is at a radius of } 0.06 \text{ pc. The mass flux in Fig. 5 is not the accretion onto the black hole itself. Magnetic fields and radiation pressure can prevent much of this matter from ever reaching the innermost stable orbit surrounding the black hole.} \]
medium. If the diffuse density were higher, the shock would decelerate faster and reach the molecular cloud at a later time. If the explosion energy were higher, the shock would move faster and hence reach the molecular cloud earlier. In all cases, the shock essentially hits a wall at the molecular cloud and bounces back, sending a reverse shock through the diffuse, lower density region.

The energy dissipated when the shock interacts with the molecular cloud can be a significant, albeit transitory, source of high-energy radiation. Supernova remnants interacting with molecular clouds are efficient electron accelerators and sources of hard X-ray and γ-ray emission (Bykov et al. 2000). The energy spectrum of the nonthermal electrons is shaped by various processes, including first- and second-order Fermi acceleration in a turbulent plasma, and energy losses due to Coulomb, bremsstrahlung, synchrotron, and inverse Compton interactions. The spectrum produced by these particles between \(~1\) keV and \(~1\) MeV is essentially a power law, \(\nu F_\nu \propto \nu^{-\alpha}\), with \(\alpha \approx 0.25\). The efficiency of energy transfer from the shock flow to the nonthermal electrons is roughly 5%, although the actual value depends on the velocity of the shock, the density in the cloud, and the radiative efficiency; the efficiency may be lower, but under some conditions, it could be as much as a factor of 2 greater. Since the detailed calculation of the particle acceleration and radiation is beyond the scope of the present paper, here we simply adopt 5% efficiency as the fiducial value and calculate the overall X-ray/γ-ray luminosity from the Sgr A East/M 0.02–0.07 interaction site by estimating the shock energy dissipation rate from our one-dimensional simulation and assuming that all of the nonthermal particle energy is eventually radiated. We note that with our simplified one-dimensional simulations, the reverse shock ultimately produces many regions of compression, bouncing backward and forward. However, these subsequent shocks are unlikely to be as strong as the first in the aspherical geometry of the Galactic center. Here we focus only on the energetics of the first (or leading) impact.

The \(~2–200\) keV luminosity resulting from the interaction we are simulating here is shown as a function of time in Figure 7. This light curve is calculated with the conservative assumption, described above, that only 5% of the dissipated energy in the leading shock is converted into photons above 2 keV. Since the 50 km s\(^{-1}\) molecular cloud does not completely envelop the Galactic center, we also assume that the interaction site occupies only \(4\pi/3\) of solid angle; this estimate is, of course, only a rough approximation, but it does not significantly impact our conclusion.

The results shown in Figure 7 clearly establish the possibility that the interaction between the supernova that created Sgr A East and the Giant Molecular Cloud produced the transient X-ray flux whose echo we see today in the Fe fluorescence of Sgr B2. This conclusion comes with several caveats, however, mostly having to do with uncertainties in the overall irradiating luminosity. First, recall that the shock will bounce off of the molecular cloud and send a reverse shock back through the outflowing ejecta, causing the total \(\geq 2\) keV emissivity to be higher than the value we have calculated here; this is potentially good for the model. Second, when we allow for additional dimensions in the calculation, the shock may flow around the molecular cloud, so the shock in Sgr A East may not be as strong as we find in our one-dimensional simulation; of course, this will lower the yield of nonthermal particles and hence the \(2–200\) keV luminosity. Which of these factors wins out may ultimately determine whether or not this model is correct. The geometrical effects can also alter the time evolution of this emission; the best-studied example of shock interaction is the emission from the rings of 1987A. As the shock moves around the ring material, it will brighten but then
decay. How fast this decay occurs depends sensitively on the model. In the case of SN 1987A, Borkowski et al. (1997) found that the decay of the X-rays occurred much faster than simple one-dimensional estimates predict. Much more work must be done modeling the initial conditions and the shock evolution in order to obtain a similar understanding of the evolution of Sgr A East. Given the level of sophistication of our current calculations, we can only say that both the luminosity and the timing associated with the peak of the dissipation seem to be those required to account for the properties of Sgr B2. Our calculation shows that within the last \( \sim 400–500 \) yr, over \( 10^{39} \text{ergs s}^{-1} \) were released in photons with energy above 2 keV.

It is beyond the scope of this paper to calculate in detail the spectrum of the irradiating flux, but we note from the work of Bykov et al. (2000) that the radiation produced by the nonthermal particles is essentially a power law with flux \( F(\nu) \propto \nu^{-0.75} \). Thus, the integrated luminosity in the 2–10 keV range should be \( \sim 20\% \) of the total. With reference to Chandra’s spectral band, our predicted X-ray flux is therefore roughly one-fifth the value shown in Figure 7. Assuming that the peak irradiance occurred 400 yr ago, the 2–10 keV flux level now appears to be in plausible agreement with the recently measured X-ray luminosity of the entire supernova remnant (SNR) Sgr A East: \( \mathcal{L}_X \approx 10^{35}–10^{36} \text{ergs s}^{-1} \) (Sakano et al. 2004; F. K. Baganoff 2005, private communication). Under this scenario, an older remnant would be a better fit to the current emission from Sgr A East at the expense of getting recent enough emission to explain Sgr B2. Since our calculated light curve is also a good match to the required illumination of Sgr B2 by a \( \sim 2–200 \) keV spectrum with a peak luminosity of \( \sim 10^{39} \text{ergs s}^{-1} \) some 300–400 yr ago (Revnivtsev et al. 2004), we see that both the temporal variation of the high-energy flux and its associated spectrum are consistent with all the currently available data.

6. OTHER CONSTRAINTS ON THE RECENT GALACTIC CENTER SUPERNOVA

Two uncertainties dominate our solution of the Sgr B2 illumination problem: the supernova explosion itself and the environment through which the explosion traveled. Understanding the environment requires first trying to get a full three-dimensional structure from observations and then extrapolating that structure backward in time (a process that also requires knowledge of the supernova explosion and its progenitor star). Here we focus instead on possible observations that can help constrain the supernova explosion only. In particular, we study the issue of the SNR’s age and related issues concerning the origin of the explosion and its energy.

Rockefeller et al. (2005) found that the structure of the X-ray ridge and its X-ray flux constrained the remnant’s age. They assumed a roughly standard (\( 1.5 \times 10^{51} \) ergs) explosion, a radial position of the origin of the supernova set to the radial position of Sgr A*, and a central region whose structure is dominated by the interaction of the stellar winds with the CND and a central supermassive black hole. In this paper, we have expanded this study to include a much more energetic, \( \sim 1.2 \times 10^{52} \) ergs, explosion. By carrying out a similar study of the X-ray luminosity and shape of the X-ray ridge, we estimate the age of the remnant produced by the strong explosion to be 700 yr. It may be difficult to explain the current luminosity of Sgr A East with such a young, strong supernova explosion.

Clearly, the remnant’s age corresponding to either explosion energy is much less than previously thought. But can we place an upper limit on this age? Figure 8 shows the 2–10 keV luminosity of the X-ray ridge. Observations of this ridge can be fit with a two-component model to its luminosity: a 1 keV component with a flux of \( 5.8 \times 10^{-13} \text{ergs cm}^{-2} \text{s}^{-1} \), and a 5.6 keV component with a flux of \( 3.92 \times 10^{-13} \text{ergs cm}^{-2} \text{s}^{-1} \); these fluxes translate to luminosities of \( 4.4 \times 10^{33} \) and \( 3.0 \times 10^{33} \text{ergs s}^{-1} \), respectively, assuming a distance of 8.0 kpc to the Galactic center. If we assume that only the 5.6 keV component is actually associated with the interaction that produces the ridge, we find that the standard simulation matches this luminosity at \( \sim 1700 \) yr; the energetic simulation matches it at \( \sim 700 \) yr. A factor of 2 uncertainty in the flux would place an upper age limit at \( \sim 2100 \) yr for the standard explosion and at \( \sim 900 \) yr for the energetic event.

Such a short remnant age has serious implications for the chemical enrichment from this supernova. The \(^{56}\text{Ni}\) (which decays into the main iron products of the supernova) is produced only in the inner layers of the star. The explosion quickly develops into a homologous expansion (meaning that the ejecta velocity is proportional to the radius); the iron, produced in the inner layers of the ejecta, moves slowly outward. In our standard explosion, it is never moving faster than about 2000 km s\(^{-1}\) (in contrast, the highest velocity in the energetic explosion is roughly 6000 km s\(^{-1}\)). If the iron moved at this high velocity without decelerating, our standard-energy supernova would not enrich regions in the Galactic center beyond 3.6 pc, but because the iron does decelerate (along with the rest of the shock), this number is closer to 2 pc (Fig. 9). In the energetic explosion, the iron travels faster and penetrates farther into the Galactic center medium. Indeed, the intermediate-weight elements (e.g., silicon and magnesium) have traveled beyond our computational grid boundaries. From Figure 9, we see that elements made near the iron layer are, like the iron, limited to a reduced region around the origin of the supernova; elements made farther out in the star extend much farther into the surrounding region. In addition, there is a zone shadowed by the stellar winds around Sgr A* that is not enriched at all by the supernova.

There are two major caveats to these abundance plots. First, we have assumed a spherically symmetric explosion and subsequent

![Figure 8](image-url)
expansion. But we now know that core-collapse supernovae are far from symmetric (see Hungerford et al. [2003] and [2005a] for reviews). Asymmetries in the explosion will allow some iron to mix much farther out in the star and, due to the homologous outflow, achieve higher velocities. However, the bulk of the iron will not reach velocities significantly different from what we have obtained in our spherical models. We also did not incorporate into our energetic event the greater yield of heavy elements in a stronger explosion (Hungerford et al. 2005b). The more energetic event could produce a factor of 2 more iron, and 10 times more $^{44}$Ti, but the basic distribution would remain the same.

The X-ray-ridge observations push for a young SNR. Using the inferred ages from the X-ray ridge, we expect the iron to still be close to the origin of the supernova explosion (farther out for the strong explosion than for the weak explosion). Following our simulations to 5000 yr after the supernova explosion, we find that the stellar winds push back the remnant. If the SNR were 5000–10,000 yr old, the iron that had not left the inner 2–3 pc region around Sgr A* due to its own expansion velocity would have been swept out by the stellar winds as these winds re-establish their dominance on this central region. High-resolution abundance maps could either confirm or cast into doubt the young age predicted by the X-ray ridge. In addition, such maps could help locate the origin of the explosion. Indeed, since the submission of this paper, Park et al. (2005) have found that the bulk of the iron enhancement is located very close to the origin of the

Fig. 9.—Abundance plots for both the standard (left column) and energetic (right column) explosions. The top panels show the nickel (iron) abundance surrounded by the silicon abundance. Note that at this time, because the silicon was produced farther out, it had a higher expansion velocity and has therefore mixed farther out. The silicon-to-iron ratio should be much higher than typical solar abundances at these larger distances. The bottom panels show the inner titanium (made in the outer part of the region where the iron is made) surrounded by the magnesium abundance, for comparison. [See the electronic edition of the Journal for a color version of this figure.]
supernova. The winds from the Wolf-Rayet stars clustered near Sgr A* would have swept this material away for an old remnant. Combined with better models of Sgr A East, such information will also constrain the supernova energy. One way to get this information is to look for evidence of compositional variation in the dust grains and molecular gas in the denser regions: e.g., in the CND, the northern ridge, or the western streamer (Herrnstein & Ho 2005). Depending on the supernova energy, age, and location, one or more of these dense regions may be enriched by metals from the supernova itself. From the standard supernova explosion simulation, we expect only the CND to be enriched by iron or even silicon. Since elements such as silicon and magnesium are primarily tied up in dust grains, depending sensitively on the physical conditions, accurate abundance measurements may be difficult to obtain.

Emission from radioactive elements is less sensitive to the physical conditions and could also provide some clues. The major intermediate-age elements are 44 Ti and 59Ni. Unfortunately, for the standard supernova explosion energy, the age of the remnant is so much larger than the ~60 yr half-life of 44 Ti that the resultant high-energy flux from its decay is 10 million times fainter than that of 1987A (for the energetic explosion with its likely higher 44 Ti yield and younger age, this value is still a million times fainter than 1987A). This is well beyond any detection limit. However, the 59 Ni flux (with its 75,000 yr lifetime) could be as high as $2.5 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$ (possibly even higher for the energetic explosion). Although beyond detectable limits of current instruments (Leising 2002), this flux may be observed with an improved generation of high-energy telescopes.

None of these observational constraints are easy to obtain. We provide this information to encourage and justify experimental and observational programs that might be able to shed more light on this complex problem.

7. CONCLUSIONS

The fact that Sgr A East had little impact on Sgr A*’s accretion rate as the remnant passed across the Galactic center is of some consequence to the question of how Sgr B2 and other nearby molecular clouds produce their strong fluorescent Fe line emission at 6.4 keV. This puzzle has been viewed as an important indicator of past high-energy activity at the Galactic center, but with very little guidance from gas dynamic studies, until now.

This is where our results from the three-dimensional and one-dimensional simulations enter the discussion. One might have thought that the passage of the SNR’s front across Sgr A* could have triggered a significant increase in the rate of gas infall, possibly even producing an enhanced accretion rate onto the black hole to fuel its $\sim 10^6$ factor increase in X-ray luminosity. The implication of this model would be that the supernova shock passed through the Galactic center some 300–400 yr ago. As we have seen, however, the gas dynamics within the inner 3–4 pc of the Galaxy negates this possibility, because the strong, cumulative outflux of matter from the interior of the CND prevents Sgr A East from penetrating closer than $\sim 0.2$ pc from Sgr A*. At best, the black hole’s accretion rate could have increased by possibly 20%–30%, far short of the value required to account for the irradiation of Sgr B2.

Instead, our modeling of Sgr A East’s interaction with the Galactic center has produced what we believe is a far more plausible scenario for the variable illumination of Sgr B2 several hundred years ago. As we saw earlier, the remnant’s shock front apparently reached the Galactic center some 160 yr after the supernova explosion and swept around the inner 0.2–0.3 pc region in ~650 yr. Our modeling of the X-ray ridge northeast of Sgr A* suggests that we are viewing the interaction between the remnant and the winds flowing out from the ionized cavity ~1700 yr after the supernova event. There is strong observational evidence that Sgr A East is now also interacting with the so-called 50 km s$^{-1}$ molecular cloud behind Sgr A* (Yusef-Zadeh et al. 1999). But this interaction should have produced an intense X-ray/γ-ray glow when the impact first occurred, due to the initial rapid dissipation of kinetic energy flux into heat, nonthermal particle acceleration, and radiation. Given the proximity of the supernova event site to the Galactic center (only several parsecs away from Sgr A*), the ensuing irradiation of Sgr B2 would still show the telltale characteristics of a Galactic center source, albeit now a diffuse X-ray/γ-ray emitter, rather than a point source associated directly with Sgr A*. The key constraint is that Sgr A East’s X-ray/γ-ray glow should have ended less than ~400 yr ago (approximately 1350 yr after the supernova explosion), the light-travel time between the interaction site and Sgr B2.

There may even be related evidence that the X-ray/γ-ray glow may have persisted closer to the present time, perhaps to within the past 100 or 200 yr. In their analysis of Sgr A East and its X-ray properties, Maeda et al. (2002) showed that the ionized gas halo into which Sgr A East is currently expanding (i.e., in regions other than where it is colliding with the 50 km s$^{-1}$ cloud) may have been ionized by the same irradiator that produced the current fluorescence in Sgr B2. For an ambient gas density $\sim 10^3$ cm$^{-3}$, the required luminosity would have been $\sim 10^{40}$ ergs s$^{-1}$, but since the recombination time in such a gas is shorter than ~300 yr, the (still) high ionization fraction in the interstellar medium (ISM) argues for a period of irradiation extending to well within 300 yr of the present. However, the current X-ray luminosity from the Sgr A East shell, including the region of interaction with the 50 km s$^{-1}$ cloud, places a rather severe constraint on how rapidly the X-ray/γ-ray glow must have subsided to its present value. This 2–10 keV limit is $\approx 10^{48}$ ergs s$^{-1}$ if we take the whole shell into account. A reduction in the solid angle subtended by the interaction zone at the site of the explosion would lower this level even farther.

This new picture of Sgr A East and the Sgr B2 X-ray echo arises from the inclusion of stellar winds in the Galactic center. Despite the current effects from the recent supernova, the cluster of mass-losing stars surrounding Sgr A* has mostly dominated the dynamics of the Galactic center for over 100,000 yr. Stellar winds almost certainly have cleared out a bubble surrounding Sgr A*, and it is because of the lower resulting density in the region surrounding Sgr A* that we require a younger SNR and a more standard $10^{51}$ erg explosion energy. Computational limits, compounded by the extremely complex nature of the inner 5 pc surrounding Sgr A*, make it very hard to determine the density and temperature structure definitively, especially at the edges of the wind-swept bubble. Without knowing the exact structure of the cleared-out region, especially near the position of Sgr A East, it is impossible to accurately calculate the age of the remnant from the conditions of Sgr A East. This is why Rockefeller et al. (2005) preferred the remnant age estimates from the X-ray ridge.

On the theoretical plane, several additional steps remain to be taken. These include a more thorough examination of the nonthermal particle injection and radiation at the remnant-cloud
interface, and a subsequent analysis of the time-dependent spectrum illuminating Sgr B2 and other nearby clouds. We have started work on this, and the results should be out soon. Eventually, when the necessary computational resources become available, it would be very helpful to redo these calculations in three dimensions. Observationally, this work would benefit from a high-resolution mapping of the metal abundances surrounding the explosion site. The morphology of this distribution should be directly coupled with the energetics of the explosion and the age of the remnant.

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