SIGNATURES OF AN ENCOUNTER BETWEEN THE G2 CLOUD AND A JET FROM Sgr A* 

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1. INTRODUCTION

The recent discovery of the G2 cloud of dense, ionized gas on a trajectory toward Sgr A*, the black hole at the dynamical center of the Galaxy, offers a unique opportunity to observe an accretion event onto a massive black hole as well as to probe its immediate environment. Simulations and models predict increased X-ray and radio variability resulting from increased accretion driven by drag on an atmosphere of hot, X-ray-emitting gas surrounding Sgr A*. Here, we present X-ray and radio light curves of the emission resulting from the potential encounter of the G2 cloud with a relativistic jet from Sgr A*. This interaction would violently shock a portion of the G2 cloud to temperatures $\sim10^6$ K, resulting in bright X-ray emission from the dense, shocked gas as it adiabatically expands. The 2–10 keV luminosity may reach $\sim$10 times the quiescent X-ray flux of Sgr A*. Approximately 3 $L_\odot$ is emitted above 10 keV at the peak of the light curve, with significant softening of the spectrum occurring as the gas subsequently cools. Observations with NuSTAR would therefore be able to confirm such an event as well as determine the cloud speed. At radio wavelengths, the associated synchrotron radio emission may reach levels of a few janskys.

Key words: accretion, accretion disks – black hole physics – galaxies: active – Galaxy: center

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1.1. A Jet from Sgr A*

The broadband spectrum of the quiescent emission from Sgr A* has been modeled in terms of emission from the base of a relativistic jet, and Very Long Baseline Array (VLBA) measurements suggest that the position angle (P.A.) of the outflowing material is $\sim$90° (Markoff et al. 2007). Short timescale variability of Sgr A* and the time delay between the peaks of radio emission at different frequencies has also been interpreted in the context of a jet or outflow from Sgr A* (Yusef-Zadeh et al. 2006; Maitra et al. 2009). These measurements suggest a mass outflow rate $\lesssim2 \times 10^{-8} M_\odot$ yr$^{-1}$.

On larger, but subparsec scales, a number of observations indicate a collimated outflow or a jet from Sgr A*. A chain of radio blobs links Sgr A* to the “minicavity” at 8.4 GHz (Yusef-Zadeh et al. 1990; Wardle & Yusef-Zadeh 1992). The minicavity, roughly at P.A. $\sim 60^\circ$ from Sgr A*, shows enhanced Fe II line emission, a high electron temperature, and is kinematically disturbed (Eckart et al. 1990; Lutz et al. 1993). Infrared observations have also discovered two dust features with cometary morphology along the line between Sgr A* and the minicavity (Muzi´c et al. 2010), and their orientation is suggestive of an
outflow from young massive stars or from Sgr A* (Lutz et al. 1993; Muzić et al. 2010).

Radio observations of Sgr A* have provided a tantalizing detection of a jet-like linear feature emanating symmetrically from Sgr A* on a scale of ~3 pc (Yusef-Zadeh et al. 2012). A number of radio continuum features with X-ray and Fe ii line counterparts and linearly polarized features are also detected along the axis of this 3 pc jet feature. The feature is projected at an angle that appears to be parallel to the angular momentum axis of the clockwise stellar disk and the orbital plane of G2. The axis of the jet from Sgr A* is estimated to be at P.A. ~ 60°. Model fitting of the polarization of the near-IR emission from Sgr A* infers the spin axis of Sgr A* to be similar to the P.A. of the jet (Zamaninasab et al. 2011). Based on the interaction of the jet and the minicavity, the mass outflow rate in the jet is estimated to be 10^{-6} M_⊙ yr^{-1}, with a Lorentz factor γ ~ 3. The symmetric jet appears to disturb the ionized gas surrounding Sgr A*, producing the high negative velocity (i.e., at the minicavity) along the approaching side of the jet, whereas shock-heated X-ray-emitting gas (along the northern arm) is detected on the receding side of the jet.

This motivates us to investigate potential signatures of the interaction of a jet emanating from Sgr A* and the G2 cloud. The collimated appearance of the jet on parsec scales suggests that the jet close to Sgr A* must be narrow with a diameter of d_j ~ 3000 R_⊙. Figure 1 shows a schematic diagram of the geometry of the jet and G2 as they interact with each other. In this scenario, the G2 cloud is assumed to be tidally stretched as it sweeps the jet and G2 as they interact with each other. In this scenario, the jet from Sgr A* is estimated to be at P.A. ~ 60°. Model fitting of the polarization of the near-IR emission from Sgr A* infers the spin axis of Sgr A* to be similar to the P.A. of the jet (Zamaninasab et al. 2011). Based on the interaction of the jet and the minicavity, the mass outflow rate in the jet is estimated to be 10^{-6} M_⊙ yr^{-1}, with a Lorentz factor γ ~ 3. The symmetric jet appears to disturb the ionized gas surrounding Sgr A*, producing the high negative velocity (i.e., at the minicavity) along the approaching side of the jet, whereas shock-heated X-ray-emitting gas (along the northern arm) is detected on the receding side of the jet.

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2. ESTIMATES AND LIGHT CURVES

Before computing model light curves for this interaction, we first adopt nominal values of the critical physical parameters and estimate the strength of the emission expected in X-rays and radio. Before being tidally sheared, G2 had a diameter ~300 R_⊙ and a number density of hydrogen nuclei 3 x 10^5 cm^{-3}, corresponding to a mass of 10^{-5} M_⊙ (Gillessen et al. 2012, 2013). G2 will be tidally sheared along its orbit and compressed perpendicular to it (e.g., Saioth et al. 2012). Here we assume that at the point of interaction with the jet, the cloud is stretched to a length L_{sh} = 10^4 R_⊙, while its transverse dimension is L_j = 10^3 R_⊙. This combination of dimensions implies that the cloud density is very close to its initial density, so we simply adopt n_e = 3 x 10^6 cm^{-3} as the hydrogen density. The temperature in the cloud is maintained close to 10^4 K by efficient cooling (Saitoh et al. 2012). The sound speed is therefore ~10 km s^{-1}. At pericenter, the orbital velocity is very close to the escape velocity, i.e., 6400 km s^{-1}. We choose a lower nominal shock speed, v_s = 3000 km s^{-1}, partly because interaction may occur prior to or subsequent to periastron, and because the cloud velocity may not be perpendicular to the jet. The final quantity that we require is the diameter of the jet, which we set at d_j = 300 R_⊙. This implies an opening angle of about 8°, consistent with estimates based on tentative detection at radio wavelengths (Yusef-Zadeh et al. 2012).

2.1. X-ray Flux

Now we consider the emission from the immediate post-shock gas, which has a temperature T = 3μv_g^2/16k = 1.25 x 10^8 K, where k is Boltzmann’s constant and μ is the mean particle mass, number density n_H = 4n_e = 1.2 x 10^6 cm^{-3}, and emits X-rays with a radiative power per unit volume Λ = n_e^2σ_f(T), where we approximate the results of Böhringer & Hensler (1989) for gas of twice solar metallicity by f(T) ~ 1.5 x 10^{-23}((T/4 x 10^6)^{-2}+(T/4 x 10^6)^{-3/2}) erg s^{-1} cm^2 when 2 x 10^6 < T < 10^7 K and f(T) ~ 1.2 x 10^{-23}((T/1.5 x 10^7)^{-1}+(T/4 x 10^6)^{-3/2}) erg s^{-1} cm^2 when T > 10^7 K. The shock interaction creates thermal energy at a rate

\[ L_{\text{shock}} = \frac{1}{2} \rho v_g^2 L_j d_j \approx 1200 \ L_\odot \]

over a period

\[ t_{\text{int}} = \frac{L_j}{v_g} = 1.3 \ yr. \]

The radiative timescale for the shocked gas,

\[ t_{\text{rad}} = \frac{5}{2} \frac{kT}{\Lambda f(T)} \approx 72 \ yr, \]

is long compared to its timescale for expansion,

\[ t_{\text{exp}} = \frac{L_j}{c_g} = 0.24 \ yr, \]

so the gas cools by adiabatic expansion. Thus the peak luminosity is approximately the power radiated by the hot gas generated by the shock over an expansion timescale. The thermal energy in this gas is approximately L_{\text{shock-exp}}, yielding an estimate

\[ L_X \approx \frac{L_{\text{shock}} t_{\text{exp}}}{t_{\text{rad}}} \approx 4.7 \ L_\odot. \]
2.2. Radio Flux

We adopt an analogous approach to estimating the radio flux arising from synchrotron emission from relativistic electrons accelerated by the shock. We assume that the power that the shock wave deposits into relativistic electrons is \( \epsilon L_{\text{shock}} \), with a nominal efficiency \( \epsilon = 0.01,^3 \) and that the electrons are produced with an \( E^{-2} \) spectrum. Here the relevant radiative cooling time is the synchrotron loss timescale for the electrons that dominate the emission at, say, \( v = 1.4 \) GHz, so we also need to estimate the post-shock field strength, which we parameterize as \( B^2 = 8\pi \epsilon_B \rho_v v^2 \). In supernova remnants (SNR) shocks, the magnetic field is amplified by cosmic-ray acceleration to levels \( \epsilon_B \sim 10^{-2} - 10^{-3} \) (Vink 2012; Helder et al. 2012; Ellison et al. 2010), so we adopt \( \epsilon_B = 0.01 \), yielding \( B \approx 0.12 \) G. These electrons have energy \( E_e \approx 26 \) MeV, with loss time

\[
T_{\text{synch}} \approx 20 \text{ yr.} \tag{6}
\]

Again, the radiative loss time is long, so that we can use a similar expression as for the X-rays to estimate the synchrotron luminosity, and then use \( L_{\text{synch}} \approx 4\pi d^2 \nu S_{\nu} \) to find the flux, yielding

\[
S_{\nu} \approx \frac{1}{4\pi d^2 v} \frac{\epsilon L_{\text{shock, exp}}}{T_{\text{synch}}} \approx 5.1 \text{ Jy,} \tag{7}
\]

which significantly exceeds the \( \sim 1 \) Jy quiescent flux from Sgr A* at 1.4 GHz.

2.3. Light Curves

To compute approximate X-ray light curves, we characterize the shocked gas by its cross-sectional area \( A \), density, temperature, and velocity \( v \) perpendicular to \( A \). These quantities all evolve as the gas moves downstream. The cross section expands at a rate \( dA/dt = L_j c_s \), where \( c_s \) is the adiabatic sound speed, and the associated drop in density and increase in temperature are found by conservation of mass and momentum and noting that the expansion is adiabatic, so that \( \rho v^3 + P \) and \( \rho v / \rho_0^{5/3} \) are constant. The resulting profile allows us to compute the X-ray emissivity by integrating the volume emissivity of the 2–10 keV X-ray emission, i.e.,

\[
\Lambda[\exp(-2kT/V) - \exp(-10kT/V)],
\]

as the gas moves downstream. We have not accounted for extinction but this is not expected to be severe as the spectrum is hard (\( kT \approx 10 \) keV).

The synchrotron light curves are computed based on the assumption that the field and electrons are advected along with the post-shock gas. The magnetic field must be tangled if it is significantly larger than the preshock field, so its strength scales as \( \rho^{1/3} \). Meanwhile, the electrons’ individual energies scale as \( \rho^{1/3} \) while preserving their spectral index: as a result, the electron and magnetic energy densities both scale as \( \rho^{4/3} \) and the synchrotron emissivity scales as \( \rho^{7/3} \).

The resulting X-ray and 1.4 GHz light curves for our fiducial parameters are shown in Figure 2, respectively. For our nominal parameters (solid curves), the X-ray light curve (upper panel) begins sharply once shocked gas begins to be created by the interaction of G2 with the jet. The luminosity rises rapidly as the mass of shocked gas increases, but the rate of increase in \( L_X \) declines once adiabatic expansion starts to cool the oldest gas. During this phase, the net change in the shocked gas is the addition of successively older and cooler layers of gas at the extreme downstream end of the shocked gas, and the change in luminosity corresponds to the emission from this oldest layer. The rise in luminosity terminates once the interaction ends and the cooling gas is no longer being supplemented by newly shocked material. As the luminosity is dominated by this material, the initial decline is sharp, but then tails off as the shocked gas slowly cools off. The peak luminosity is consistent with the rough estimate given by Equation (5); the extreme sharpness of the initial decline from the peak reflects the artificially sharp truncation of shock heating in our treatment. The 1.4 GHz light curve behaves similarly, as shown in the lower panel of Figure 2. Note that the peak flux density at 1.4 GHz is a few times lower than the estimate in Equation (7) because significant emission occurs at higher frequencies. Also plotted are the light curves for different choices of shock speed. At lower speeds, the X-ray luminosity and synchrotron emission drop sharply because the shock luminosity depends quadratically on the cloud speed \( v_c \). At higher speeds, the radio flux increases similarly, but the X-ray flux does not because the gas temperature is so high that much of the X-ray emission emerges at energies exceeding 10 keV.

We illustrate this in the top panel of Figure 3 by comparing the luminosities in different X-ray bands between 5 and 80 keV for our nominal shock speed of 3000 km s\(^{-1}\). The peak luminosities between 5–10 and 20–40 keV are similar because the shocked

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3. This is distinct from the fraction \( n = 0.05 \) of shocked electrons that are assumed to be accelerated by Narayan et al. (2012) and Sadowski et al. (2013), equivalent to \( \epsilon \approx 2 \) and 0.4, respectively.
gas initially has $kT \approx 10$ keV. Once the interaction between G2 and the jet ceases, the spectrum becomes softer as the shocked gas cools by adiabatic expansion. The lower panel shows the effect of increasing $v_g$ to 5000 km s$^{-1}$. Now the gas is shocked to $kT \approx 25$ keV, with a corresponding dramatic increase in the power radiated between 20–40 and 40–80 keV relative to the lower energy bands. We conclude that observations with NuSTAR would be ideally suited to determine the gas temperature and the shock speed.

3. DISCUSSION AND CONCLUSION

We have shown that if the G2 cloud encounters a jet from Sgr A* during its passage around pericenter, then it is likely to produce detectable X-ray emission. The X-ray luminosity is far larger than expected from the drag interaction of G2 with a hot medium centered on Sgr A* because of the violence with which the cloud encounters the jet, which shocks a fraction of the cloud to high temperatures and high density. The greatest uncertainties in estimating the luminosity are the density and geometry of the incoming cloud, which may be significantly compressed by the tidal effects of Sgr A* (Saitoh et al. 2012). Close to pericenter, G2 will be strongly compressed in the direction perpendicular to the orbital plane (Saitoh et al. 2012), and the density will increase by orders of magnitude. This increases the emission from the shocked gas, which is proportional to $n^2 L$, but decreases the probability of interaction with the jet. The decays in the curve due to adiabatic expansion are also unique to this model, reflecting the fact that the shocked cloud material is overpressured. Observations using NuSTAR would provide a strong test of this scenario, as the high temperature and subsequent expansion of the shocked gas produces detectable spectral evolution in the X-ray light curves between 5 and 80 keV. We also predict a detectable radio flux based on the assumption that 1% of the kinetic luminosity is deposited into relativistic electrons and that the magnetic field is amplified to a level similar to that inferred for SNRs.

The greatest uncertainty is whether a jet from Sgr A* is sufficiently aligned with the orbital plane of G2 for an interaction to even occur. Figure 4 (top panel) shows the range of jet inclinations that lie within 5° of the orbital plane as a function of jet P.A. We have plotted the inclination’s cosine so that solid angle is directly proportional to area, allowing assessment of probabilities. A randomly oriented jet has probability $\approx 0.087$ of lying within 5° of the plane, precisely the fraction of the plot area lying within the target shaded region. The blue rectangles indicate the ranges of jet orientation previously inferred either from Sgr A* emission models or from parsec-scale jet-like features identified in radio and X-rays: (1) combined disk/jet models of the emission at 7 mm detected using VLBA (Markoff...
et al. 2007, M07), (2) the normal to the accretion disk orientation inferred from modeling the submillimeter very long baseline interferometry observations of Sgr A* (Broderick et al. 2011, B11), (3) polarization of NIR flaring (Zamaninasab et al. 2011, Z11), (4) a 0.5 pc jet-like feature identified in X-rays (Muno et al. 2008, M08), and (5) a parsec-scale radio jet (Yusef-Zadeh et al. 2012, YZ12). In the latter two cases, the inclination ranges are very uncertain. We adopt ±45° from the plane of the sky for the X-ray jet. For the radio jet, the P.A. ≈ 238° side of the jet is directed between 30° and 60° in front of the plane of the sky so that it can collide with material to form the minicavity (Yusef-Zadeh et al. 2012). The uncertainty in both jet orientation and the orbital plane makes a reliable estimate impossible, but given the tendency of the inferred jets to follow the orbit of G2, odds of one in three or four are not implausible. What is clear is that the orbital plane will eventually be accurately determined, and the presence or absence of a jet interaction signature would place useful constraints on the orientation of a jet from Sgr A*.

The center and lower panels of Figure 4 show the shock speed and epoch of a potential interaction as a function of jet P.A. The shock speed is equated to the azimuthal component of G2’s orbital velocity as this will be normal to the jet. As we expect significant emission only for shock speeds exceeding 2000 km/s (unless the density of G2 is significantly enhanced by tidal effects), the relevant range of PA and epoch is +100 to −100 deg for early 2013–mid-2014 for the Gillessen et al. (2013) orbit, and −140 deg to +70 deg for mid-2013–end 2014 for the Phifer et al. (2013) orbit. In either case, we expect appreciable emission if the cloud collides with the B11, Z11, and Y12 jets at PA ~ 60 deg and the M07 and M08 jets at PA ~ 85 deg.

In summary, we have described a model in which the G2 cloud runs into a relativistic jet from Sgr A* and have predicted X-ray and radio light curves that are distinct from those produced by the collision of G2 with the hot atmosphere of Sgr A*. Monitoring the emission from Sgr A* at hard X-rays using NuSTAR may be particularly useful in testing the proposed model.

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