Constraining Cosmic-Ray Acceleration in the Magnetospheric Gaps of Sgr A*

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Abstract

Sagittarius A* (Sgr A*) is a potential very high energy (VHE) γ-ray and cosmic-ray source. We examine limits to gap-type particle acceleration in the magnetosphere of Sgr A*, showing that in the current phase of activity proton acceleration to PeV energies is possible, with injection powers into the environment usually limited to several $10^{36}\text{ erg s}^{-1}$. Compton upscattering of ambient soft photons by gap-accelerated electrons could yield TeV emission compatible with the detected VHE point source. We explore the dependency of the results on changes in the accretion rate showing that higher stages in the past are unlikely to increase the power output unless the inner accretion flows itself changed its configuration.

Unified Astronomy Thesaurus concepts: High energy astrophysics (739); Black hole physics (159); Galactic cosmic rays (567); Galactic center (565)

1. Introduction

The center of the Milky Way harbors a supermassive black hole (BH) of mass $M_{\text{BH}} \approx 4.3 \pm 0.3 \times 10^6 M_\odot$ (e.g., Boehle et al. 2016; Gillessen et al. 2017). Its location is coincident with the compact radio source Sgr A* at a distance of $d \approx 8.2 \text{ kpc}$ (Gravity Collaboration et al. 2019) that is known to exhibit periods of steady and variable nonthermal emission across the electromagnetic spectrum (e.g., see Genzel et al. 2010 for review).

At very high energies (VHEs) H.E.S.S. observations of the Galactic Center (GC) region have revealed a bright, pointlike γ-ray source spatially coincident with Sgr A*, along with extended (>100 pc) diffuse VHE emission correlated with massive gas-rich complexes in the Central Molecular Zone (CMZ; Aharonian et al. 2006; H.E.S.S. Collaboration et al. 2016, 2018). The latter correlation points to a hadronic origin of the diffuse emission where the γ-rays are produced in interactions of PeV protons with ambient gas. The spatial map of the diffuse VHE emission can thus be used to estimate the radial distribution of cosmic-ray (CR) protons within the CMZ. The resultant CR distribution appears compatible with quasi-continuous injection of $>100$ TeV protons from the vicinity of Sgr A*, and diffusive propagation for $\sim 10^4$ yr (H.E.S.S. Collaboration et al. 2016, 2018). The γ-ray point source at the GC, on the other hand, shows a power-law-type VHE spectrum (photon index $\sim 2.1 \pm 0.1$) from $\sim (0.1-10)$ TeV along with evidence for a cutoff (see Aharonian et al. 2009; MAGIC Collaboration et al. 2020), probably related to absorption of VHE gamma-rays by the ambient radiation field, and exhibits a modest luminosity of $L_{\text{VHE}} \sim 10^{38} \text{ erg s}^{-1}$.

The current quiescent bolometric luminosity of Sgr A* is rather low, at a level of $L_B \sim 10^{36} \text{ erg s}^{-1} \sim 2 \times 10^{-9} L_{\text{Edd}}$, suggesting that Sgr A* is accreting in a radiatively inefficient mode (e.g., Yuan & Narayan 2014). There is X-ray morphological evidence, however, that Sgr A* could have been brighter (i.e., temporarily exceeding $10^{38-39} \text{ erg s}^{-1}$) in the more recent past (e.g., Ponti et al. 2013; Zhang et al. 2015; Terrier et al. 2018). We note that in the more distant past (i.e., a few Myr ago) much higher accretion rates, up to several percent of the Eddington value, must have occurred if the Fermi bubbles are indeed caused by some former AGN-type jet activity (e.g., Guo & Mathews 2012; Yang et al. 2012).

Particle acceleration in the vicinity of the GC BH has been proposed as possible source for the observed VHE radiation and presumed CR injection (e.g., Aharonian & Neronov 2005a, 2005b; Levinson & Rieger 2011; H.E.S.S. Collaboration et al. 2016). In this Letter we revisit the potential of magnetospheric, gap-type particle acceleration for facilitating VHE and CR production. This is done by drawing on an advanced steady gap model (Katsoulakos & Rieger 2020) that allows us to incorporate realistic ambient radiation fields.

2. The Galactic Center BH and Vicinity

We assume that the BH in Sgr A* (horizon scale $r_h = G M_{\text{BH}}/c^2$) is rotating with angular momentum close to its maximum $\leq G M_{\text{BH}}^2/c$. The magnetosphere is threaded by a magnetic field whose strength is approximately comparable to the equipartition value $B_H \approx 10^8 \text{ m}\text{\textvisiblespace}^{1/2} \text{ G}$, where $m = M/M_{\text{Edd}}$ denotes the source accretion rate in terms of the Eddington one, $M_{\text{Edd}} \approx 0.1 M_\odot \text{ yr}^{-1}$. Radio (millimeter) polarization measurements indicate that the current accretion rate close to the BH is of order $M \sim 10^{-6} M_\odot \text{ yr}^{-1}$ (Bower et al. 2018), while radiative GRMHD models tend to favor even lower values, e.g., $M \sim 10^{-9} M_\odot \text{ yr}^{-1}$ (Drappeau et al. 2013). As noted above, a higher accretion activity might have been occurring in the past given the rich gas reservoir present in the GC vicinity (see Genzel et al. 2010). The above values suggest a typical field strength of $B_H \sim 100$ G for the present time, roughly compatible with other estimates (Dexter et al. 2010; Eatough et al. 2013).

In general, the soft photon field from the innermost parts of the accretion flow provide a major ingredient for the formation of pair cascades in the charge-starved regions (i.e., gaps) of BH magnetospheres (Levinson & Rieger 2011; Hirotani et al. 2017; Katsoulakos & Rieger 2020). In the following, we assume the inner accretion flow in Sgr A* to be hot and radiatively inefficient (ADAF), though possibly being supplemented by a cool gas phase on larger scales (e.g., Yuan & Narayan 2014; Murchikova et al. 2019). We use a simplified ADAF description (Mahadevan 1997) to characterize the ambient soft
3. Steady Gap Acceleration

The parallel electric field component $E_{||}$ facilitating particle acceleration obeys the generalized Gauss’s law (e.g., Katsoulakos & Rieger 2020)

$$\n \nabla \cdot \left( \frac{\mathcal{E}_{||}}{\alpha_t} \right) = 4\pi (\rho_e - \rho_{GJ}), \quad (1)$$

where $\rho_e$ is the actual charge density, $\rho_{GJ}$ is the GJ charge density, and $\alpha_t$ is the Laplace function (Thorne & MacDonald 1982). The electric field is caused by the difference of the actual charge density relative to the GJ value.

Seed electron–positron pairs injected into the gap region (of size $h$) will be accelerated along $E_{||}$, with their energies being limited by curvature and inverse Compton (IC) losses. The resultant $\gamma$-rays will undergo $\gamma\gamma$ annihilation with soft photons of the accretion disk, providing additional pairs to the gap. These secondary leptons will then also experience gap acceleration and $\gamma$-ray emission, triggering a third generation of leptons, and so on. The ensuing pair cascade develops until the charge density becomes sufficiently large to screen the parallel electric field.

The full gap structure, i.e., the distributions of the parallel electric field, the particle energy, the charge, and the $\gamma$-ray photon densities, can be derived by numerical integration of Gauss’s law along with the equations of motion and continuity for the pairs, and the Boltzmann equation for the $\gamma$-ray photons (e.g., Hirotani et al. 2017; Levinson & Segev 2017; Katsoulakos & Rieger 2020). In addition to the BH mass and accretion rate, the magnetospheric current is a central parameter for steady gap models. Defined as $J_0 = (\rho_e - \rho_{GJ})c \sqrt{1 - 1/\Gamma_e^2}$, where $\rho_e^G$ represents the positron/electron charge density and $\Gamma_e$ the lepton Lorentz factor, the current is a constant quantity along magnetic field lines. Since there is currently no strong evidence for jet activity in Sgr A* (though see also Issaoun et al. 2019), we explore gap solutions for low current values. We note that the steady-state solutions for $J_0 \geq 0.25 \rho_c$ in our model do not maintain physically consistent values in all quantities throughout the gap, and we thus disregard them. Here $\rho_c = \Omega B h / 2 \pi c$ is the effective GJ charge density. In the subsections below, we present gap solutions for different accretion regimes following the approach presented in Katsoulakos & Rieger (2020).

3.1. Results for the Current Accretion Stage

Figure 2(a) summarizes the electric field solutions for the present accretion rate ($\dot{m} = 10^{-8}$) adopting six different values for the magnetospheric current, ranging from $J^s = -0.01$ to $J^s = -0.244$, where $J^s = J_c/(c n_e)$. A field line inclination $\theta = 30^\circ$, a soft photon source size $r_d = 5 r_g$, and a BH mass $M_{BH} = 4.3 \times 10^{6}M_\odot$ have been adopted throughout.

As can be seen, the gap extension increases as the global current increases. Roughly speaking, we obtain gap sizes of the order of $r_g$ for the chosen parameters; see Table 1. Small current values (e.g., $J^s = -0.01$) lead to highly underdense gaps, needing additional charge injection at the boundaries, while for higher current values (e.g., $J^s = -0.244$) the GJ charge density at the outer boundary is approached (see Figure 2(b)), so that force-free jet formation might occur, potentially contributing to the observed emission (e.g., Davelaar et al. 2018).

We determine the available voltage drop, $\Delta V_{gap}$, by integrating $E_{||}$ along the width of the gap, while the gap power $L_{gap} \times J_0 \Delta V_{gap}$ is determined by the rate of the lepton energy gain multiplied by the number of the particles within the gap. For the parameters used here, the gap luminosity typically
limits on possible CR power outputs. While CR injection has often been treated phenomenologically (e.g., Levinson 
Boldt 2002; Neronov et al. 2009), a detailed scenario for CR injection into the gap would in principle be needed to quantify the amount of gap power carried by CRs.

Our gap solutions yield radiation-limited lepton Lorentz factors $\Gamma_e \lesssim 2 \times 10^5$. The associated curvature emission peaks at energies $\epsilon_{cur} = (3/4\pi)(\hbar c/r_g)\Gamma_e^2 \lesssim 0.4$ GeV, while IC emission reaches up to $\epsilon_{ic} \sim \Gamma_e m_e c^2 \sim 10^2$ TeV. Absorption of multi-TeV $\gamma$-rays in the ADAF photon fields decisively contributes to the cascade development in the gap. The observed $\gamma$-ray spectrum of Sgr A* in fact shows a cutoff above $\epsilon_\gamma \sim 10$ TeV. Since photons with $\epsilon_\gamma$ preferentially interact with soft photons of $\epsilon_s \sim 0.1$ eV, having a spectral luminosity $L_\gamma \sim 10^{34}$ erg s$^{-1}$ (Figure 1), the characteristic optical depth $\tau_{\gamma\gamma} = \sigma_{\gamma\gamma} n_e r_g$ is of order $\tau_{\gamma\gamma} \sim 0.03$, using $\sigma_{\gamma\gamma} \sim 0.2$ cm$^2$ g$^{-1}$ and $n_e = L_\gamma/(4\pi r_g^2 c^2 \epsilon_\gamma)$. This suggests that VHE photons of energy $\epsilon \leq \epsilon_\gamma$ are able to escape from the BH vicinity, consistent with observations. Hence, it is possible that at the current epoch magnetospheric processes in Sgr A* may drive both TeV $\gamma$-ray as well as PeV CR production.

3.2. Results for Past Accretion Stages

Changes in the accretion environment will impact the gap characteristics. To investigate structural variations of the gap due to possible changes in the accretion rate in the past, we also explore higher values, up to $\dot{m} = 10^{-6.5}$, while keeping the constant current $J_0^* = -0.1$). The results are shown in Figure 2(c) and Table 2.

As the ambient soft photon field becomes stronger and cascade formation more efficient with higher accretion rates, the gap width essentially decreases with increasing accretion rate, i.e., down to $h \sim 0.1 r_g$ for $\dot{m} = 10^{-6.5}$. As a consequence, the available voltage difference and gap power decrease (see Katsoulakos & Rieger 2018). Thus, despite the fact that the magnetic field strength threading the horizon increases, the voltage difference...
falls, $\Delta V_{\text{gap}} \lesssim 10^{15}$ V for $m \approx 10^{-7.5}$, diminishing the potential for PeV CR production. Similarly, achievable electron Lorentz factors are reduced to $\Gamma_e \sim 6 \times 10^6$ for $m = 10^{-6.5}$. Table 2 suggests an approximate dependence $\Delta V_{\text{gap}} \propto m^{-1}$ and $L_{\text{gap}} \propto m^{-0.6}$ over the range considered.

4. Conclusions

The above results suggest that at the present accretion stage, the BH in Sgr A* is in theory a rather effective electron and CR accelerator. As such, IC upscattering in Sgr A* could in principle contribute to the GC point source seen by current VHE instruments (e.g., Aharonian et al. 2009; Archer et al. 2016; MAGIC Collaboration et al. 2020). While full radiative modeling is required, a spectral cutoff above $\sim$10 TeV, related absorption of VHE gamma-rays by the ambient disk photon field is likely to remain a persistent feature of gap-related VHE emission. With its superior resolution, the upcoming Cherenkov Telescope Array will soon make it possible to probe deeper into the true nature of the GC VHE source (Cherenkov Telescope Array Consortium et al. 2019). Complementary Event Horizon Telescope observations are likely to shed further light on the innermost accretion flow in Sgr A* (Event Horizon Telescope Collaboration et al. 2019).

The accessible voltage differences in the BH magnetosphere of Sgr A* can exceed $\sim 10^{15}$ V, allowing for PeV CR production. Our results suggest the power for quasi-continuous CR injection into the GC region to be limited to several $10^{46}$ erg s$^{-1}$. If the diffuse VHE emission in the CMZ were to be related to the GC BH (HESS Collaboration et al. 2016), this would thus constrain the (average) spatial diffusion coefficient within the CMZ to $D \lesssim 10^{29}$ cm$^2$ s$^{-1}$ for $>10$ TeV protons. While restrictive, this would still be compatible with empirical diffusion models suggesting $D \approx 5 \times 10^{28}$ (E/10 TeV)$^{1/3}$ cm$^2$ s$^{-1}$ (e.g., Strong et al. 2007; Fujita et al. 2017). Progress in characterizing the turbulence field structures that ultimately determine the CR transport properties within the CMZ will help to better assess this.

Though the GC BH could be a CR PeVatron, no significant contribution to the observed Galactic CR spectrum is expected under normal conditions. In fact, provided the disk remains ADAF type, the gap power and potential do not increase considering higher accretion stages in the past, as the gap extension becomes smaller with higher accretion rates. An exception to this could be possible, however, for extreme states in the past in which the inner accretion flow changed its configuration. This might have occurred during the GC phase associated with the generation of the Fermi bubbles $\sim$1–10 Myr ago (e.g., Guo & Mathews 2012; Fujita et al. 2017; Jaupart et al. 2018), and deserves further investigation.

While the results shown here are based on a simplified disk and magnetic field model, we expect them to be quite generic for quasi-steady gap models. Exploring varying disk emission and the characteristics of non-steady gaps where the lepton multiplicity could potentially exceed one (e.g., Levinson & Cerutti 2018) is a goal of future work.

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References

Aharonian, F., Akhperjanian, A. G., Anton, G., et al. 2009, A&A, 503, 817
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006, Natur, 439, 695
Aharonian, F., & Neronov, A. 2005a, ApJ, 619, 306
Aharonian, F., & Neronov, A. 2005b, Ap&SS, 300, 255
Archer, A., Benbow, W., Bird, R., et al. 2016, ApJ, 821, 129
Baganoff, F. K., Bautz, M. W., Brandt, W. N., et al. 2001, Natur, 413, 45
Boehle, A., Ghez, A. M., Schödel, R., et al. 2016, ApJ, 830, 17
Bower, G. C., Broderick, A., Dexter, J., et al. 2018, ApJ, 868, 101
Brinkerink, C. D., Falcke, H., Law, C. J., et al. 2015, A&A, 576, A11
Cherenkov Telescope Array Consortium, Acharya, B. S., Agudo, I., et al. 2019, Science with the Cherenkov Telescope Array (Singapore: World Scientific)
Dachary, J., Moschiodotzis, M., Bronzwaer, T., & Falcke, H. 2018, A&A, 612, A34
Dexter, J., Agol, E., Fragile, P. C., & McKinney, J. C. 2010, ApJ, 717, 1092
Drappeau, S., Dibi, S., Dexter, J., Markoff, S., & Fragile, P. C. 2013, MNRAS, 431, 2872
Eattough, R. P., Falcke, H., Karuppusamy, R., et al. 2013, Natur, 501, 391
Event Horizon Telescope Collaboration, Akyma, K., Alberdi, A., et al. 2019, ApJL, 875, L2
Falcke, H., Goss, W. M., Matsuo, H., et al. 1998, ApJ, 499, 731
Fujita, Y., Murase, K., & Kimura, S. S. 2017, JCAP, 04, 037
Genzel, R., Eisenhauer, F., & Gillessen, S. 2010, RevMP, 82, 3121
Ghez, A. M., Wright, S. A., Matthews, K., et al. 2004, ApJ, 601, L159
Gillessen, S., Plewa, P. M., Eisenhauer, F., et al. 2017, ApJ, 837, 30
Gravity Collaboration, Abuter, R., Amorim, A., et al. 2019, A&A, 625, L10
Guo, F., & Mathews, W. G. 2012, ApJ, 756, 181
H.E.S.S. Collaboration, Abdalla, H., Abramowski, A., et al. 2018, A&A, 612, A9
H.E.S.S. Collaboration, Abramowski, A., Aharonian, F., et al. 2016, Natur, 531, 476
Hirotani, K., Pu, H.-Y., Lin, L. C.-C., et al. 2017, ApJ, 845, 77
Horstmeier, S. D., Ghez, A. M., Tanner, A., et al. 2002, ApJL, 577, L9
Issaoun, S., Johnson, M. D., Blackburn, L., et al. 2019, ApJ, 871, 30
Jaupart, E., Parizot, E., & Allard, D. 2018, A&A, 619, A12
Katsoulakos, G., & Rieger, F. M. 2018, ApJ, 852, 112
Katsoulakos, G., & Rieger, F. M. 2020, ApJ, 895, 99
Levinson, A., & Boldt, E. 2002, ApJ, 576, 265
Levinson, A., & Cerutti, B. 2018, A&A, 616, A184
Levinson, A., & Rieger, F. 2011, ApJ, 730, 123
Levinson, A., & Segev, N. 2017, PhRvD, 96, 123006
MAGIC Collaboration, Acciari, V. A., Ansoldi, S., et al. 2020, arXiv:2006.00023
Mahadevan, R. 1997, ApJ, 477, 585
Murchikova, E. M., Pinney, E. S., Pancoast, A., & Blandford, R. D. 2019, Natur, 570, 83
Neronov, A. Y., Semikoz, D. V., & Tkachev, I. I. 2009, NJPh, 11, 065015
Ponti, G., Morris, M. R., Terrier, R., & Goldwurm, A. 2013, in Cosmic Rays in Star-Forming Environments, ed. D. F. Torres & O. Reimer (Berlin: Springer), 331
Schödel, R., Morris, M. R., Muzic, K., et al. 2011, A&A, 532, A83
Serabyn, E., Carlstrom, J., Lay, O., et al. 1997, ApJL, 490, L77
Strong, A. W., Moskalenko, I. V., & Ptuskin, V. S. 2007, A&ARv, 15, 285
Terrier, R., Clavel, M., Soldi, S., et al. 2018, A&A, 612, A102
Thorne, K. S., & MacDonald, D. 1982, MNRAS, 198, 339
Yang, H. Y. K., Ruszkowski, M., Ricker, P. M., Zweibel, E., & Lee, B. 2012, ApJ, 761, 185
Yuan, F., & Narayan, R. 2014, ARA&A, 52, 529
Zhang, S., Quataert, E., & Narayan, R. 2003, ApJ, 598, 301
Zhao, J.-H., Young, K. H., Herrnstein, R. M., et al. 2003, ApJL, 586, L29

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