Particle Acceleration and the Quiescent and Flare Emissions in Sgr A* (and other AGNs?)

In collaboration with

Siming Liu, Alex Lazarian, Fulvio Melia and graduate students

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Astro-ph 0403487, 0506151, 0603136 and 137
Outline

Accretion in Black Holes
Observations of Sgr A*
Emission Mechanisms
Stochastic Acceleration
Quiescent mm and X-ray Emission
NIR and X-ray Flares
Radio and TeV Emission
## Accretion in Black Holes

<table>
<thead>
<tr>
<th>Luminosity $\sim L_{\text{edd}}$</th>
<th>Luminosity $\ll L_{\text{edd}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Accretion Rate</strong></td>
<td><strong>Low Accretion Rate</strong></td>
</tr>
<tr>
<td>Optically Thick</td>
<td>Optically Thin</td>
</tr>
<tr>
<td>High Density</td>
<td>Low Density</td>
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<tr>
<td>Thermal Equilibrium</td>
<td>Collisionless Plasma?</td>
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<td>High Efficiency</td>
<td>Low Efficiency</td>
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<tr>
<td>Cold</td>
<td>Hot</td>
</tr>
<tr>
<td>Geometrically Thin</td>
<td>Geometrically Thick</td>
</tr>
</tbody>
</table>

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*Luminosity ~$L_{\text{edd}}$* refers to a luminosity close to the Eddington luminosity, indicating high accretion rates and certain physical conditions. *Luminosity $\ll L_{\text{edd}}$* indicates a much lower luminosity, suggesting low accretion rates and different physical states.
Accretion in Black Holes

Muller 2004
Some Basic Parameters for Black Hole in Sgr A*  

- **Distance**: \( D \approx 8 \text{ kpc} \)  
- **Black Hole Mass**: \( M_{BH} \approx 4 \times 10^6 M_{\text{sun}} \)  
- **Eddington Luminosity**: \( L_{EDD} \approx 10^{45} \text{ erg/s} \)  
- **Schwarzschild Radius**: \( r_s = 1.2 \times 10^{12} \text{ cm} \)  
- **Angular size**: \( \vartheta_s = r_s / D = 10^{-5} \text{ arcsec} \)  
- **Timescales**:  
  \[ \tau_s = 40(R / r_s) \text{ sec} \]  
  \[ \tau_{Kep} \approx 400(R / r_s)^{3/2} \text{ sec} \]
## Energy Flow

<table>
<thead>
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<th>Gravitational Energy Release of Protons and Ions</th>
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<td>Generation of Turbulence via Instabilities</td>
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<td>Electron Acceleration by the Turbulence</td>
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<td>Radiation Produced by Electrons and Protons</td>
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Accretion Flow in Kerr Black Holes

\[ \frac{P_{\text{mag}}}{P_{\text{gas}}} \]

Observation of Sagittarius A*
Radio Observations, VLA

(From Zhao et al. 2004)
In flare-state, Sgr A*'s X-ray luminosity can increase by more than one order of magnitude.

The X-ray flare lasted for a few hours. Significant variation in flux was seen over a 10 minute interval.
NIR Flares From Sgr A*
Quasi-periodic Modulation

Genzel et al. 2003
Sgr A* June 2003, NIR/X-ray Flare

Eckart et al. (2004)

$L_{X\text{-ray}} \approx 6 \times 10^{33}$ erg/s, $L_{NIR} \approx 5 \times 10^{34}$ erg/s

while $L_{EDD} \approx 10^{45}$ erg/s

Baganoff 2005
HESS

H.E.S.S. Preliminary

HESS Collaboration 2004
Emission Mechanisms in Sagittarius A*
\[ \nu L_{\nu} = 10^{36} \text{ ergs/s} \]

\[ \nu L_{\nu} = 10^{33} \text{ ergs/s} \]
Broadband Spectrum

\[ M = 4.0 \times 10^6 M_\odot \]
\[ D = 8.0 \text{ kpc} \]

Soft NIR Flares

Hard X-ray Flares
Emission Mechanisms in General

“Thermal” Synchrotron and SSC:

Four Parameters

\[ n, B, k_B T = \gamma_{cr} m_e c^2, R \]

\[
\mathcal{L}_{\text{syn}} = \frac{16 e^4}{3 m_e^2 c^3} N B^2 \gamma_{cr}^2
\]

\[
= 2.0 \times 10^{36} \left( \frac{N}{10^{43}} \right) \left( \frac{B}{40 \, \text{G}} \right)^2 \left( \frac{\gamma_{cr}}{100} \right)^2 \text{ergs s}^{-1}
\]

\[
\mathcal{L}_{\text{SSC}} = \frac{U_{\text{syn}}}{U_B} \mathcal{L}_{\text{syn}} \approx \frac{8 \pi \mathcal{L}_{\text{syn}}^2}{c A B^2}
\]

\[
= 5.2 \times 10^{35} \left( \frac{\mathcal{L}_{\text{syn}}}{10^{36} \text{ergs s}^{-1}} \right)^2 \left( \frac{B}{40 \, \text{G}} \right)^{-2} \left( \frac{A}{r_S^2} \right)^{-1} \text{ergs s}^{-1}
\]
“Thermal” Synchrotron Spectrum

\[ F_\nu = \frac{4\pi R^3}{3D^2} \mathcal{E}_\nu, \]

\[ \mathcal{E}_\nu = \frac{\sqrt{3}e^3}{8\pi m_e c^2} B n x_M I(x_M) \]

\[ I(x_M) = \frac{4.0505}{x_M^{1/6}} \left( 1 + \frac{0.40}{x_M^{1/4}} + \frac{0.5316}{x_M^{1/2}} \right) \exp(-1.8899x_M^{1/3}) \]

\[ x_M = \frac{\nu}{\nu_c} = \frac{4\pi m_e c \nu}{3eB \gamma_c^2} = 1412 \ C^2_1 \ \nu_{14} R^2_{12} \ n_7^2 \ B^{-1}_1, \]
Thermal Synchrotron and SSC Details

\[ \alpha \equiv \frac{d \ln (\nu F_\nu)}{d \ln \nu} = 1.833 - 0.6300 x_M^{1/3} - \frac{0.1000 x_M^{1/4} + 0.2658}{x_M^{1/2} + 0.4000 x_M^{1/4} + 0.5316}, \]

\[ F_\nu = \frac{e^3}{2 \sqrt{3} m_e c^2} \frac{B n R^3}{D^2} x_M I(x_M) = 639.7 R_{12}^3 n_7 B_1 D_8^{-2} x_M I(x_M) \text{ mJy}. \]

\[ F_X(\nu) = \frac{2\pi e^7 n^2 B R^4}{3 \sqrt{3} m_e^3 c^6 D^2} \frac{\nu}{4 \nu_c \gamma_c^2} \int_{\gamma_c^{-1}}^{\infty} dx \int_0^1 dy \exp(-x) I \left( \frac{\nu}{4 \nu_c \gamma_c^2 x^2 y} \right) \left( 2 \ln y + 1 - 2y + \frac{1}{y} \right) \]

\[ \simeq 2.121 n_7^2 B_1 R_{12}^4 D_8^{-2} G \left( \frac{\nu}{4 \nu_c \gamma_c^2} \right) \mu \text{Jy}, \]

\[ G(z) = z \int_0^\infty dx \int_0^1 dy \exp(-x) I \left( \frac{z}{x^2 y} \right) \left( 2 \ln y + 1 - 2y + \frac{1}{y} \right) \]
Emission Processes During Flares

Thermal Synchrotron and SSC:

$N = 3.8 \times 10^{42}$

$k_B T = 75 m_e c^2$

Liu et al. 2006
Emission Mechanism for the $TeV$ Source

Synchrotron Self-Compton

$B=90\mu G$

Emission Mechanism for the $TeV$ Source

Photo-Meson Interactions

$E > 10^{18} eV$

Emission Mechanism for the $\text{TeV}$ Source

Proton-Proton Interactions

PARTICLE ACCELERATION

in

Galactic Center Quiescent and Flare Sources
ACCELERATION MECHANISMS

General

A: Electric Fields: **Parallel to B Field**
   
   *Unstable leads to TURBULENCE*

B: Fermi Acceleration
   
   1. **Shock or Flow Divergence:** *First Order*
   
   *Shocks and Scaterers; i.e. TURBULENCE*

   2. **Stochastic Acceleration:** *Second Order*
   
   *Scattering and Acceleration by TURBULENCE*

**TURBULENCE**
PLASMA TURBULENCE AND STOCHASTIC ACCELERATION

1. Generation

Magneto-Rotational Instability  (MRI)

\[ R_e = \frac{L V}{\nu} \gg 1, \quad R_m = \frac{L V}{\eta} \gg 1 \]
1. Generation

\[ \frac{R_e}{\nu} \gg 1, \quad \frac{R_m}{\eta} \gg 1 \]

2. Cascade: *Nonlinear wave-wave int.*

\[ \omega(k_1) + \omega(k_2) = \omega(k_3); \quad k_1 + k_2 = k_3 \]
PLASMA TURBULENCE AND STOCHASTIC ACCELERATION

1. Generation

\[ R_e = \frac{LV}{\nu} \ggg 1, \quad R_m = \frac{LV}{\eta} \ggg 1 \]

2. Cascade: Nonlinear wave-wave int.

\[ \omega(k_1) + \omega(k_2) = \omega(k_3); \quad k_1 + k_2 = k_3 \]

3. Interactions with Particles: Resonant int.

\[ \omega = k_\| v \mu + n\Omega_i / \gamma \]
Wave-Particle Interactions

- Dominated by Resonant Interactions

\[ D_{ij} = \pi e^2 \sum_{n = -\infty}^{+\infty} \int d^3k \langle d_{ij} \rangle \delta \left( k \cdot \mathbf{v} - \omega + \frac{n\eta_0}{\gamma} \Omega_0 \right), \]

- Lower energy particles interacting with higher wavevectors or frequencies
2. PLASMA TURBULENCE AND STOCHASTIC ACCELERATION

1. Generation (MRI) \( R_e = \frac{LV}{\nu} \gg 1, \quad R_m = \frac{LV}{\eta} \gg 1 \)

2. Cascade: *Nonlinear wave-wave int.*

\[ \omega(k_1) + \omega(k_2) = \omega(k_3); \quad k_1 + k_2 = k_3 \]

3. Interactions with Particles: *Resonant int.*

\[ \omega = k\| v \mu + n\Omega_i / \gamma \]

A. Damping of Waves
B. Acceleration of Particles
Turbulence Spectrum

General Features:
- Injection scale: $k_{\text{min}}$
- Cascade and index $q$
- Damping scale or $k_{\text{max}}$

Kinetic Equation:
\[
\frac{\partial W(k,t)}{\partial t} = \dot{Q}_p(k,t) - \gamma(k)W(k,t) + \nabla_i [D_{ij} \nabla_j W(k,t)] - \frac{W(k,t)}{T_{\text{esc}} W(k)}
\]

- $\dot{Q}_p(k)$: Rate of wave generation.
- $T_{\text{esc}}$: Wave leakage timescale.
- $\gamma(k) = \gamma_c + \gamma_p$: The damping coefficients.
- $D_{ij}$: Wave diffusion tensor.
COUPLED EQUATIONS

1. Kinetic Equations

\[
\frac{\partial N}{\partial t} = \frac{\partial}{\partial E} \left[ D_{EE} \frac{\partial N}{\partial E} - (A - \dot{E}_L)N \right] - \frac{N}{T_{esc}} + \dot{Q}^p
\]

\[
\frac{\partial W}{\partial t} = \frac{\partial}{\partial k_i} \left[ D_{ij} \frac{\partial}{\partial k_j} W \right] - \Gamma(k)W - \frac{W}{T_{esc}(k)} + \dot{Q}^W
\]

2. Energy Balance

\[
\dot{W}_{nonth} \equiv \int \Gamma_{nonth}(k)W(k)d^3k = \dot{\varepsilon} \equiv \int A(E)N(E)dE
\]

3. Rate Coefficients

\[
A(E) = \frac{d[v^2D(p)]}{4p^2dp} = \int_{k_{min}}^{\infty} d^3k W(k)\Sigma(k,E)
\]

\[
\Gamma_{nonth}(k) = \int_{E_0}^{\infty} dE N(E)\Sigma(k,E)
\]
Model Parameters

In principle: Density \( n \)
Temperature \( T \)
Magnetic Field \( B \)
Scale (geometry) \( R \)
Level of Turbulence

\[ (\frac{\delta B}{B})^2 \quad or \quad (\frac{\delta v}{v_{Alfven}})^2 \]
**Kinetic Equation Coefficients**

- Acceleration rate or time: $\tau_{ac}$
- Loss rate or time: $\tau_{loss}$
- Escape rate or time: $T_{esc}$

**Characteristic Times:**

$$\tau_p^{-1} \propto \Omega_e (\delta B / B)^2 \text{ and } T_{cross} \approx R / \sqrt{2} v$$
EXAMPLES OF Timescales And Spectra For 3 Models

Alfven Velocity

\[ \frac{v_A}{c} = 0.1 \]
Electron Acceleration During NIR and X-ray Flares
Submm, NIR and X-rays from the Disk

\[ \frac{P_{\text{mag}}}{P_{\text{gas}}} \]

Stochastic Electron Acceleration

\[
\frac{\partial N}{\partial t} = \frac{\partial}{\partial \gamma} \left[ \frac{\partial \gamma^2 N}{\partial \gamma} - \left( 4\gamma - \frac{4\gamma^2 \tau_{ac}}{\tau_0} \right) N \right] - \frac{N}{T_{esc}} + \dot{Q}
\]

\[
\tau_{ac} = \frac{C_1}{f_{turb}} \frac{cR}{v_A^2}
\]

\[
\tau_{syn}(\gamma) = \frac{9m_e^3 c^5}{4e^4 B^2 \gamma} = \frac{\tau_0}{\gamma}
\]

\[
\gamma_{cr} = \frac{\tau_0}{4\tau_{ac}} = \frac{9m_e^3 c^4 v_A^2 f_{turb}}{16e^4 RB^2 C_1} = 30 \left( \frac{R}{r_S} \right)^{-1} \left( \frac{n}{10^7 \text{cm}^{-1}} \right)^{-1} \left( \frac{f_{turb}}{C_1} \right)
\]
Stochastic Electron Acceleration

Continuous injection, heating, & cooling.

\[ \delta = \left( \frac{9}{4} + \frac{2\tau_{ac}}{T_{esc}} \right)^{1/2} - 1.5 \]

Without injection: Continuous heating and cooling

Maxwellian
Acceleration Scenario for Flares

Simplify the model: Simpler Kinetic Equation

Parametric approach: \( \tau_{ac} = \text{const.}, \ L_{turb} \approx L_{\text{Synch}} \)

One less parameter: \( f_{turb} = (\delta B / B)^2 \approx 1 \)
Stochastic Electron Acceleration

\[ \mathcal{L}_{\text{Turb}} = C_2 v_A B^2 R^2 = 6.901 \times 10^{34} C_2 R_{12}^2 n_7^{-1/2} B_1^3 \text{ ergs s}^{-1} \]

\[ \mathcal{L}_{\text{syn}} = \frac{64\pi e^4}{9m_e^2 c^3} n R^3 B^2 \gamma_c^2 = 8.949 \times 10^{34} C_1^{-2} R_{12} n_7^{-1} B_1^2 \text{ ergs s}^{-1} \]

\[ R_{12} n_7^{1/2} B_1 = 1.297 C_1^{-2} C_2^{-1}, \]

\[ \gamma_c = \tau_0 / \tau_{ac} = 41.08 C_1^{-1} R_{12}^{-1} n_7^{-1} \]
Emission by Accelerated Electrons

$M = 4.0 \times 10^6 M_\odot$

$D = 8.0 \text{ kpc}$
Summary-I

• Flares from Sgr A* are produced near the event horizon of the black hole
• NIR and X-ray emissions are produced via thermal synchrotron and SSC by energetic electrons accelerated by plasma waves.
• The observed NIR or X-ray fluxes and spectral indexes can be used to measure B, R, n, and T, which will result in a better understanding of the flare energizing mechanism and may lead to a measurement of the black hole spin.
LARGE SCALE EMISSIONS

Long Wavelength Radio

Escaping Electrons

TeV gamma-rays

Escaping protons

Acceleration and Emission in the Jet
Acceleration within $20r_s$
Long Wave Radio and $TeV$ Emission from the escaping particles in the JET

Stochastic Acceleration of Electrons and Protons

\[ M = 4.0 \times 10^6 \text{M}_\odot \]
\[ D = 8.0 \text{ kpc} \]
Proton Acceleration

Source is too bright in the radio band.

Source is optically thin at 7mm

Cooling is too efficient to produce 7 mm emission

\[ \beta_A \equiv \frac{v_A}{c} = 7.3 \left( \frac{B}{1 \text{G}} \right) \left( \frac{n}{1 \text{cm}^{-3}} \right)^{-1/2}. \]
The *TeV source* is likely produced via pp scatterings by protons accelerated near the black hole and diffusing toward large radii.

Should the *7mm emission* be produced by electrons in the acceleration region, the acceleration region must be strongly magnetized and *far from equipartition*.
Structure of the Accretion Flow


cm and mm via Synchrotron and proton acceleration

Sub-mm, NIR, and X-ray via Synchrotron and SSC

Conclusions

In combination with the theory of Stochastic Acceleration by plasma waves and MHD simulations, observations over a broad energy range can be used to detect the properties of the black hole and its accretion flows.
Example

\[ \alpha = 0.5, \quad \nu_{14} = 1.429, \quad F_\nu = 7 \text{ mJy} \]

\[
R_{12} = 0.08471 \ C_1^2 C_2^{6/7} D_8^{10/7}
\]

\[
n_7 = 2.266 \ C_1^{-4} C_2^{-10/7} D_8^{-12/7}
\]

\[
B_1 = 10.17 \ C_1^{-2} C_2^{-8/7} D_8^{-4/7} \left( \frac{xM_o}{7.311} \right)^{-1/7}
\]

\[
\gamma_c = 214.0 \ C_1 C_2^{4/7} D_8^{2/7}
\]
Example

\[ \tau_{ac} = 5.845 C_1^3 C_2^{12/7} D_8^{6/7} \text{ mins} \]
\[ \tau_\nu = 1.784 \times 10^{-7} C_1^{-5} C_2^{-16/7} D_8^{-8/7} \]
\[ U \simeq \frac{L_{\text{syn}}}{4 \pi c R^2} = 127.9 C_1^{-4} C_2^{-12/7} D_8^{-6/7} \]

\[ \alpha_X(z) = 1.1 , \]
\[ F_X(z) = 0.0033 \mu\text{Jy} \]
Implications

Thermal Synchrotron Sources

\[ R_{12} n_7^{1/2} B_1 = 1.297 \, C_1^{-2} C_2^{-1}, \]

\[ \gamma_c = \frac{\tau_0}{\tau_{ac}} = 41.08 \, C_1^{-1} R_{12}^{-1} n_7^{-1} \]

Can be generalized to Comptonization dominant sources e.g., X-ray binaries, to address the coupling of electrons and protons via turbulence

\[ \frac{\partial N}{\partial t} = \frac{\partial}{\partial \gamma} \left[ \frac{\gamma^4}{\tau_{ac}} \frac{\partial \gamma^{-2} N}{\partial \gamma} + \frac{\gamma^2}{\tau_0} N \right] \]
Constraining $C_1$ and $C_2$

$F_v = 12 \text{ mJy}$
$F_x = 0.22 \mu\text{Jy}$