Stellar Relaxation Processes Near the Galactic Massive Black Hole

Tal Alexander

Weizmann Institute of Science
Introduction

WHY RELAXATION?

1 Getting stars to the MBH (the “loss-cone problem”)
   Tidal flares, Tidal captures, Extreme Mass Ratio Inspiral GW events,
   Hyper Velocity Stars, The “last pc problem” binary MBH merger, ULXs?

2 Exotic stellar populations around MBHs
   Origin and properties of the S-stars and disk stars in the Galactic Center, M31
Introduction

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OUTLINE

1 Relaxation by Massive Perturbers
2 Mass segregation around MBHs
3 Resonant Relaxation
[1] Accelerated relaxation by massive perturbers

Large-angle deflection:

\[ r_c \sim \frac{2GM}{v^2} \]

Deflection rate:

\[ \Gamma \sim nvr_c^2 \propto nM^2/v^3 \]

Obs. MPs in central 100 pc

\[ \sim 10^8 \text{ stars of } 1M_\odot \]

\[ \sim 10^2 \text{ MPs of } 10^{4-7} M_\odot \]

Example:

\[ \left( \frac{nM^2}{GMC} \right) / \left( nM^2 \right)_* \sim 10^{2-8} \]
[1] Accelerated relaxation by massive perturbers

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Obs. MPs in central 100 pc
\[
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\sim 10^2 \text{ MPs of } 10^4-7 \, M_\odot
\]

Example:
\[
\left( \frac{nM^2}{GMC} \right) / \left( \frac{nM^2}{\star} \right) \sim 10^{2-8}
\]

Implications

- **Accelerated relaxation** in gas-rich galaxies.  
  (Spitzer & Schwarzschild 1951)

- **Higher rate of close star–MBH interactions**  
  (Zhao, Haehnelt & Rees 2002)

  (Fast “loss-cone refilling”).

- **Especially efficient when loss-cone is too large for refilling by stellar relaxation:**
  Stellar binary disruption, binary MBH merger.

  (Perets, Hopman & Alexander 2007)
Massive perturbers in the Galactic center

Molecular clouds ($r < 100$ pc) (Oka et al 2001)
and clumps ($r < 5$ pc) (Christopher et al 2005)

Stellar clusters at $r < 100$ pc
(Figer et al 1999, 2002; Borissova et al 2005)

Perets, Hopman & Alexander 2006
Binary disruptions: captured and hyper-velocity stars

**White dwarf binary period**

\[ \langle a \rangle \sim \left( \frac{M_\star}{M_2} \right)^{2/3} a_2 \]

**Captured white dwarf orbit**

\[ v_\infty^2 \sim \sqrt{2GM_2^{2/3} M_\star^{1/3} / a_2} \]

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Willems & Kolb 2004

Hills 1991

Perets, Hopman & Alexander 2006
Massive Perturbers: Galactic implications

- **Obs**: 10 – 30 S-stars (< 0.04 pc) (Eisenhauer et al 2005)  
  - **Prediction**: 5 – 40

- **Obs**: 43 ± 31 HVSs (Brown et al 2005)  
  - **Prediction**: 10 – 50

- **Prediction**: Increased WD EMRI rates; low-e EMRIs? (Miller et al 2005)
Massive perturbers: Rapid Binary MBH mergers

Mass segregation in the Galactic Center
Red Clump Giants as low-mass test particles

Girardi et al. 2000
Alexander & Sternberg 1999
Mass segregation in the Galactic Center?

![Graph showing number density vs. projected radius](image)

Schödel et al. 2007

Not the Bahcall-Wolf solution: \( n_H \propto r^{-7/4} \), \( n_L \propto r^{-3/2} \) (Levi 2006, MSc thesis)
A new regime of mass segregation?

Infall and inspiral in the diffusion limit

\begin{align*}
J &= J_c(E) \\
\log E_	ext{isco} &< \log E < \log E_	ext{crit} \\
\log J &> \log J_c(E) \\
1D J\text{-scattering} &< \text{"Spherical background"} \\
\end{align*}

Lightman & Shapiro 1977; Cohn & Kulsrud 1978

Direct infall (plunge)

\begin{align*}
t_J &\sim \left[ J/J_c(E) \right]^2 t_E
\end{align*}

Hopman & Alexander 2005

GW inspiral
Mass segregation and EMRI GW event rates

Mass segregation can increase EMRI GW event rate by $\times \mathcal{O}(100)$
[3] Resonant relaxation

Perturbing stars

Stationary ellipses in point mass potential

Planar rosettes in spherical potential

Effect on perturbed star

Scalar resonant relaxation

Vector resonant relaxation

Rauch & Tremaine 1996; Rauch & Ingalls 1998
Resonant relaxation

RR: Near-Keplerian N-body simulations

\[ \Delta E/E \propto \tau^{1/2} \]
\[ \Delta J_s/J_c(E) = (1-e^2)^{1/2} = f(\Delta E, \Delta J) \rightarrow \propto \tau \]
\[ \Delta J_s/J_c(E) = 3^{1/2} \Delta J_s/J_c(E) \]

Calibrating resonant relaxation

![Graph showing resonant relaxation efficiency for inspiral and plunge processes.]

- Stellar Relaxation Processes Near the Galactic Massive Black Hole
- Resonant relaxation

Rauch & Tremaine 1996

Hopman & Alexander 2006
Evidence for RR in the Galactic Center

Hopman & Alexander 2006
Summary

► Relaxation: new twists in an old problem
  ▶ Massive perturbers and loss-cone refilling
  ▶ New regime of mass segregation
  ▶ Resonant relaxation and inspiral

► Implications
  ▶ GW event rates and wave form properties
  ▶ Binary MBH merger times
  ▶ Hyper Velocity Stars
  ▶ ”Exotic” stellar populations

► The Galactic Center: A dynamical laboratory