Black Hole Binary Formation through Stellar Dynamics in Galactic Nuclei

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Extreme G environment
~Every galaxy has a Supermassive Black Hole $10^6-9M_\odot$
The majority of stars in the field and clusters are born in binaries or higher multiples, e.g., Sana et al. 2012.
Extreme G environment in our backyard

Study and infer on the general population

Finding new puzzles

The central 10 arcsec ~ 0.4pc

Ghez et al 2005
Binaries in Galactic Nuclei

Galactic Center - Observational evidence

- **3 Known Binaries**: IRS 16SW, ~19.5d, 50M⊙ @ 0.05pc (Ott et al. 1999; Martins et al. 2006); IRS 16NE @~0.1pc, 224d, e~0.3 (Pfuhl et al. 2014); E60 @~0.1pc, 2.3d, 30M⊙ (Pfuhl et al. 2014)

- Binary fraction of massive stars **may be** comparable to young clusters (e.g., Ott et al. 1999; Rafelski et al. 2007; Pfuhl et al. 2014) or **larger** (Alexander et al. 2008)
Each observation has been processed using the techniques described in Muno et al. (2003). In brief, for each observation we corrected the pulse heights of the events for position-dependent charge-transfer inefficiency (Townsley et al. 2002a), excluded events that did not pass the standard ASCA grade filters and Chandra X-ray Center (CXC) good-time filters, and removed intervals during which the background rate flared to above the mean level. Finally, we applied a correction to the absolute astrometry of each pointing using three Tycho sources detected strongly in each Chandra observation (Baganoff et al. 2003). We estimated combined accuracy of our astrometric frame and of the positions of the individual X-ray sources by comparing the offsets between 36 foreground X-ray sources that were located within 50 of Sgr A* (Muno et al. 2003) and their counterparts from the

| TABLE 1 Observations of the Inner 20 pc of the Galaxy |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Aim Point (deg) | Start Time (UT) | Sequence | Exposure (s) | R.A. (J2000.0) | Decl. (J2000.0) | Roll (deg) |
| 549 | 1999 Sep 21 02:43:00 | ................. | 0242 | 40,872 | 266.41382 | 29.0130 | 268 |
| 549 | 2000 Oct 26 18:15:11 | .................. | 1561 | 35,705 | 266.41344 | 29.0128 | 265 |
| 549 | 2001 Jul 14 01:51:10 | ................... | 1561 | 13,504 | 266.41344 | 29.0128 | 265 |
| 549 | 2002 Feb 19 14:27:32 | ................. | 2951 | 12,370 | 266.41867 | 29.0033 | 91 |
| 549 | 2002 Mar 23 12:25:04 | ................. | 2952 | 11,859 | 266.41897 | 29.0034 | 88 |
| 549 | 2002 Apr 19 10:39:01 | ................. | 2953 | 11,632 | 266.41923 | 29.0034 | 85 |
| 549 | 2002 May 7 09:25:07 | .................. | 2954 | 12,455 | 266.41938 | 29.0037 | 82 |
| 549 | 2002 May 22 22:59:15 | ................ | 2943 | 34,651 | 266.41991 | 29.0041 | 76 |
| 549 | 2002 May 24 11:50:13 | ................ | 3663 | 37,959 | 266.41993 | 29.0041 | 76 |
| 549 | 2002 May 25 15:16:03 | ................ | 3392 | 166,690 | 266.41992 | 29.0041 | 76 |
| 549 | 2002 May 28 05:34:44 | ................ | 3393 | 158,026 | 266.41992 | 29.0041 | 76 |
| 549 | 2002 Jun 3 01:24:37 | ................ | 3665 | 89,928 | 266.41992 | 29.0041 | 76 |
| 549 | 2004 Jul 5 22:33:11 | ................ | 4683 | 49,524 | 266.41605 | 29.0124 | 286 |
| 549 | 2005 Feb 27 06:26:04 | ................. | 6113 | 4,855 | 266.41870 | 29.0035 | 91 |

Fig. 1.—Images of the 100 arcsec around the super-massive black hole Sgr A* (c3) which illustrate the appearance of CXOGC J174540.0 290031. Left: Image created from the average of 13 observations (650 ks exposure) taken between 1999 September and 2003 June, demonstrating the quiescent state of the region. Right: Image created from 2 observations (99 ks) taken on 2004 July 5–7, in which a new transient X-ray source is evident 2 B5 south of Sgr A* (circle). The location of twin lobes of the radio transient identified with the VLA are indicated by diamonds. Finally, a portion of the diffuse emission brightened coincident with the transient outburst (ellipse). Both images are displayed at the 0 B5 resolution of the detector. They were generated from the raw counts and then scaled to correct for the relative exposures and the spatially varying effective area of the detector.

- X-ray Binaries; Many in the inner 1pc (e.g., Muno et al 2005a,b, Hailey et al 2018)
- Hypervelocity stars
- *Stellar disk properties = Large binary fraction (Naoz et al 2018)
Binaries
Here and There
Binaries Are Everywhere

Would you like them here or there?
Binaries in Galactic Nuclei

Hierarchical triple system

Not to scale!

Orbit normal

inclination

“inner”

“outer”

Sgr A*
Binaries in Galactic Nuclei

Hierarchical triple system

$L_z \sim \sqrt{1 - e^2 \cos \iota} = \text{const}$

$L_{z1}$ conserved only to lowest order (quadrupole= axis-symmetric potential) and for a test particle (massless particle)!

Kozai 1962, Lidov 1962

Not to scale!

For initially inclined system $\geq 40^\circ$

Sgr A*

“inner”

“outer”

The Eccentric Kozai-Lidov Mechanism

EKL:

- Allow for the z-component of the angular momenta of the inner and outer orbit to change - already at the quadrupole level

- Expanding the approximation to the octupole level (e.g., Ford et al 2000, Blaes et al 2002 - already done before us!!!)

- Both the magnitude and orientation of the angular momentum can change larger parts of the parameter space

See for review: Naoz (2016), ARA&A


Extreme eccentricities!
Binaries in Galactic Nuclei

GR effects: e.g., Ford et al 2000, Naoz, Kocsis, Loeb, Yunes 2013

\[ m_1 = 10 M_\odot \]
\[ m_2 = 1 M_\odot \]
\[ M_{SMBH} = 4 \times 10^6 M_\odot \]
\[ a_1 = 10 AU \]
\[ a_2 = 0.003 pc \]
\[ e_2 = 0.8 \]

Binaries in Galactic Nuclei

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\end{align*}

Compare to: “Standard” (quadrupole) Kozai

Binaries in Galactic Nuclei

EKL

Sgr A*
Binaries in Galactic Nuclei and their neighbors

- no EKL

- unbinding the binary!

- e.g., Binney & Tremaine
- Also: Perets et al. 2007, Hopman 2009, Antonini et al. 2010

Not to scale!
Binaries in Galactic Nuclei and their neighbors

Soft Binaries

- GR precession (inner orbit)
- oct timescale
- quad timescale
- unbinding timescale
- nominal system: $a_1 = 3\text{au}$, $e_2 = 0.5$

~0.1pc

inside ~0.1pc

Binaries in Galactic Nuclei

Looking at soft binaries
+ EKL
+ 1PN
+ GW
+ Unbinding
+ Disruption
+ Newtonian precession

For hard binaries see: Antonini et al. 2010; Antonini & Perets 2012

Binaries in Galactic Nuclei

![Graph showing the evolution of eccentricity and inclination over time for different background stars.](image)

- **Left panel:** Graph of inclination ($i$) versus time ($t$) for different background stars with and without octupole level run.
- **Middle panel:** Graph of eccentricity ($1-e$) versus time ($t$) for different background stars with and without octupole level run.
- **Bottom panel:** Graph of semi-major axis ($a$) versus time ($t$) for different background stars with and without octupole level run.

**Figure 2.**

**Results:** EKL-induced mergers and GW-only mergers.

- EKL-induced merger occurs at 1623 years whereas the quadrupole-level run results in a non-merger.

**Figure 3.**

- **Left panel:** Graph showing the distribution of EKL-induced and GW-only mergers for mutual inclination versus merger time.
- **Middle panel:** Graph showing the distribution of EKL-induced and GW-only mergers for mutual inclination versus merger time.
- **Bottom panel:** Graph showing the distribution of EKL-induced and GW-only mergers for mutual inclination versus merger time.

**Equations:***

- $m_1 = 12.8 M_\odot$, $m_2 = 63.3 M_\odot$
- $m_{MBH} = 1 \times 10^6 M_\odot$
- $a_1 = 5.1$ AU, $a_2 = 936$ AU
- $e_1 = 0.014$, $e_2 = 0.4$, $i = 92.8$

**References:**

- Naoz, Fabrycky (2016)
- Thompson (2013)
- Aharon & Perets (2015)
- Kocsis & Tremaine (2011)
- Stephan et al. (2012)
- Aharon & Perets (2013)
- Naoz et al. (2015)

**See Randall & Xianyu (2018) for quad level.**
Binaries in Galactic Nuclei

Monte-Carlo simulations

Binaries in Galactic Nuclei

Monte-Carlo simulations


Monte Carlo simulations

\[ n(r) \sim r^{-2} \quad \text{Bahcall \& Wolf (1976)} \]

\[ n(r) \sim r^{-3} \quad \text{de-projection of a disk} \]

After 3-body stability

inside \sim 0.1\,\text{pc}
Binaries in Galactic Nuclei

BH merger rate

\[ \Gamma_{\text{tot}} = n_g f_{\text{SMBH}} \Gamma \]

\[ \Gamma = N_{\text{bin}} f_{\text{merge}} \gamma_{\text{EKL}} \]

Galaxies # density:

\[ n_g = 0.02 \text{ Mpc}^{-3} \text{ e.g., Conselice et al. (2005)} \]

And: \[ f_{\text{SMBH}} \sim 0.5 \]

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**Binaries in Galactic Nuclei**

BH merger rate

\[ \Gamma_{\text{tot}} \sim 1 - 14 \text{ Gpc}^{-3}\text{yr}^{-1} \]

or know \( N_{\text{bin}} \)

e.g., continues SF, (e.g., Löckmann et al. 2010) +

Population Synthesis of surviving binaries
(e.g., Petrovich & Antonini 2017)

BH merger rate - Dynamical Channels

\[ \Gamma \sim 1 - 14 \text{ Gpc}^{-3} \text{ yr}^{-1} \quad \text{Hoang, Naoz et al (2018)} \]

\[ \Gamma \sim 1.5 \text{ Gpc}^{-3} \text{ yr}^{-1} \quad \text{O’Leary et al (2009)} \]
\[ \Gamma \sim 0.5 - 15 \text{ Gpc}^{-3} \text{ yr}^{-1} \quad \text{Petrovich & Antonini (2017)} \]
\[ \Gamma \sim 5 - 50 \text{ Gpc}^{-3} \text{ yr}^{-1} \quad \text{Rodriguez et al (2016,2018)} \]
\[ \Gamma \sim 8 - 80.5 \text{ Gpc}^{-3} \text{ yr}^{-1} \]

\[ \Gamma \sim 1 - 14 \text{ Gpc}^{-3} \text{ yr}^{-1} \quad \text{not to scale!} \]

inside \( \sim 0.1 \text{ pc} \)

inside few pc

\[ \Gamma \sim 1 - 14 \text{ Gpc}^{-3} \text{ yr}^{-1} \]

+ see Bartos et al (2018) for binaries near AGN accretion disk
Can we disentangle between them?

Binaries in Galactic Nuclei

Punchline

• SMBH at the galactic nuclei can lead to BH merger
• Insensitive to \( n \sim r^{-\alpha} \) or other outer orbit precession
• Rates comparable to other dynamical channels
• Possible distinguishable