LIGO sources in AGN disks: Building black hole is like building planets



Wladimir Lyra

California State University

Jet Propulsion Laboratory



Collaborators

Jillian Bellovary (AMNH), Saavik Ford (AMNH), Brandon Horn (AMNH), Bence Kocsis (ELTE), Nathan Leigh (AMNH), Zoltán Haiman (Columbia), Mordecai Mac Low (AMNH), Barry McKernan (AMNH), Brian Metzger (Columbia), Hagai Perets (Technion), Zsolt Sándor (ELTE), Lisa Winter (Boulder)











Motivation

LIGO BH Masses:



GW150914: 36 and 29 M_{\odot} LVT151012: 23 and 13 M_{\odot} GW151226: 14 and 7 M_{\odot} GW170104: 31 and 19 M_{\odot}

Large masses + misaligned spins challenge stellar evolution-based BH-BH merger theories

We need a new theory!

Diversion: Let's talk about planets

Planets impact the gas dynamics in their parental disk





Diversion: Let's talk about planets

Planet-disk interaction leads to angular momentum exchange (migration)



Migration – Thermodynamics matter



Kley & Crida (2008)

Disk Evolution



Lyra, Paardekooper, & Mac Low (2010)

Migration Traps

Planet-disk interaction leads to angular momentum exchange





Lyra, Paardekooper, & Mac Low (2010)

Migration in Evolutionary Models

Σ (g/cm²)

Disks evolve in time, due to photoevaporative winds and viscous evolution 3.0 1000 4.0 100 4.4 4.6 4.7 4.8 100 L 0.1 1.0 10.0 0.1 1.0 10.0 r (AU) 10 r_p (AU) Single planets in a planetary trap evolve in lockstep with the gas at the accretion timescale. At some point, the **disk becomes too thin** to drive accretion. The planet decouples and is 2 0 released in a safe orbit.

Rule of thumb: Migration is

outwards in steep temperature gradients,

> inwards in isothermal regions.



Lyra, Paardekooper, & Mac Low (2010)

Resonance Trapping



Migration in resonance !

Sandor, Lyra & Dullemond (2011)

Growing larger stuff in migration traps

Resonance trapping

FORMATION OF PLANETARY CORES AT TYPE I MIGRATION TRAPS

ZSOLT SÁNDOR¹, WLADIMIR LYRA², AND CORNELIS P. DULLEMOND^{1,3} Draft version January 6, 2011

ABSTRACT

One of the longstanding unsolved problems of planet formation is how solid bodies of a few decimeters in size can "stick" to form large planetesimals. This is known as the "meter size barrier". In recent years it has become increasingly clear that some form of "particle trapping" must have played a role in overcoming the meter size barrier. Particles can be trapped in long-lived local pressure maxima, such as those in anticyclonic vortices, zonal flows or those believed to occur near ice lines or at dead zone boundaries. Such pressure traps are the ideal sites for the formation of planetesimals and small planetary embryos. Moreover, they likely produce large quantities of such bodies in a small region, making it likely that subsequent N-body evolution may lead to even larger planetary embryos. The goal of this Letter is to show that this indeed happens, and to study how efficient it is. In particular, we wish to find out if rocky/icy bodies as large as 10 M_{\oplus} can form within 1 Myr, since such bodies are the precursors of gas giant planets in the core accretion scenario.



Mars-mass protoplanets added at migration trap

Resonance broken by N-body interaction, that disturbs the resonance

Orbital migration of interacting planets in a radiative evolutionary model

Combines **migration + N-body + photoevaporation + turbulence** modelled as stochastic forcing (Laughlin et al. 2004, Ogihara et al. 2007)



Horn, Lyra, Mac Low & Sándor (2012)

Orbital migration of interacting planets in a radiative evolutionary model



Horn, Lyra, Mac Low & Sándor (2012)

Back to black holes, and migration traps



- Protoplanets → stellar mass black holes
- Protoplanetary disk →
 SMBH accretion disk
- Black holes can migrate too!
- \rightarrow MIGRATION TRAPS

Result \rightarrow lots of black hole mergers, making bigger and bigger black holes?!

Torque calculation:

- Surface density gradient $\alpha = -\frac{\partial \ln \Sigma}{\partial \ln r}$
- Temperature gradient $\beta = -\frac{\partial \ln T}{\partial \ln r}$
- Entropy gradient $\xi = \beta (\gamma 1)\alpha$
- Scale height h/r
- Optical depth au

Torque calculation:

- Surface density gradient $\alpha = -\frac{\partial \ln \Sigma}{\partial \ln r}$
- Temperature gradient $\beta = -\frac{\partial \ln T}{\partial \ln r}$
- Entropy gradient $\xi = \beta (\gamma 1)\alpha$
- Scale height h/r
- Optical depth

Total torque:

$$\Gamma = \frac{\Gamma_{ad}\Theta^2 + \Gamma_{iso}}{(\Theta + 1)^2}$$

$$\frac{\gamma \Gamma_{ad}}{\Gamma_0} = -0.85 - \alpha - 1.7\beta + 7.9\xi/\gamma$$

τ

Torques:

$$\frac{\Gamma_{\rm iso}}{\Gamma_0} = -0.85 - \alpha - 0.9\beta$$

$$\Theta = t_{rad}/t_{dyn}$$

Paardekooper+ 10 Lyra+ 10

AGN disk models



Sirko & Goodman 2003

Thompson, Quataert & Murray 2005

Migration Traps: a simple example



Migration traps in S&G model



Bellovary et al 2016



Sirko & Goodman 2003 disk model: TWO TRAPS

Migration traps in S&G model



Sirko & Goodman 2003 disk model: TWO TRAPS

Migration traps in TQM model



Thompson Quataert & Murray 2005 disk model: ONE TRAP

Traps (maybe) exist. What next?

- 3-D N-body modeling of migrating BHs
- 1-D static disk based on Sirko & Goodman 2003
- Examine migration of single and multiple objects

Migration of a single object



Migration and merger of two objects

• 50 M_{\odot} BH and 30 M_{\odot} BH

 Form a binary upon reaching trap



Bellovary et al. in prep

Binary Details: formation





Bellovary et al. in prep

Binary Details: center of mass frame

1.5 Orbital eccentricity **BH** 1 1.0 **BH 2 Orbital energy lost** 0.5 to gas (which we 0.0 \mathbf{r} do not track) Center of -0.5 **Eventually** Mass plunging orbits -1.0 cause merger -1.5 -0.5 0.0 1.0 0.5 -1.0 Х

Bellovary et al. in prep

Worst Case scenario!

- Physics not included*:
 - Gas drag
 - GW energy losses

Both will speed up the merger!



*among many many other effects

GW Implications

• LIGO: Provides explanation for large masses

LISA: runaway growth in disk creates an IMBH (10²-10³ M_☉), if merge with SMBH we get an EMRI

 EM Counterparts... the AGN wins (but! target next searches on AGN instead of galaxies for improved efficiency!)

In Summary

- Migration traps may exist in AGN disks
- Compact objects can grow and merge quickly in the traps (LIGO sources)
- Growth can result in IMBH!

The Future

- N > 2 bodies
- Actual hydro simulations
- Modify torque prescription to include retrograde orbiters, multiple orbiters, feedback from BH accretion, ++