Satellite Origin and Evolution via Three-body Encounters

Craig Agnor
(Queen Mary University of London)
Irregular Satellites

- In the last decade over 100 irregulars have been discovered.
- Distant eccentric & Inclined orbits about planet
- R~10^2 km and smaller
- Commonly considered captured objects

Burns et al. (2001)
Satellite Capture – the Basics

- Orbital Energy

\[ E = \frac{1}{2} v^2 - \frac{GM_p}{r} \]

- Hyperbolic Encounter Orbit

\[ E = \frac{1}{2} v_{\infty}^2 \]

- Bound Satellite Orbit

\[ E = -\frac{GM_p}{2a} \]

- Capture Mechanisms
  - Pull down (Heppenheimer & Porco)
  - Collisions (Columbo)
  - Gas drag (e.g. Pollack et al. 1978)
Enabling Discoveries

• The Kuiper Belt (esp, large KBOs)

• Irregular satellites at each giant planet (e.g. Gladman, Holman, Sheppard)

• Improved understanding of giant planet formation and migration (e.g., core-accretion, Nice Model)

• Binary asteroids and KBOs

*Three-body encounters are common*
Close Encounters of the 3-body Kind

Basic types of encounters:
- Binary-Planet
- Planet-Planet with interlopers

Main Outcomes:
- Disruption of bound pairs
- Exchange of partners
- Creation of bound pairs
# Neptune’s Satellite System

<table>
<thead>
<tr>
<th>Satellite</th>
<th>$a_s/R_N$</th>
<th>$e$</th>
<th>$I(\degree)$</th>
<th>$R_s$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naiad</td>
<td>1.9119</td>
<td>0.000</td>
<td>4.74</td>
<td>29</td>
</tr>
<tr>
<td>Thalassa</td>
<td>1.9851</td>
<td>0.000</td>
<td>0.21</td>
<td>40</td>
</tr>
<tr>
<td>Despina</td>
<td>2.0823</td>
<td>0.000</td>
<td>0.07</td>
<td>74</td>
</tr>
<tr>
<td>Galatea</td>
<td>2.4560</td>
<td>0.000</td>
<td>0.05</td>
<td>79</td>
</tr>
<tr>
<td>Larissa</td>
<td>2.9157</td>
<td>0.000</td>
<td>0.20</td>
<td>94</td>
</tr>
<tr>
<td>Proteus</td>
<td>4.6639</td>
<td>0.000</td>
<td>0.55</td>
<td>209</td>
</tr>
<tr>
<td>Triton</td>
<td>14.064</td>
<td>0.0004</td>
<td>156.834</td>
<td>1353</td>
</tr>
<tr>
<td>Nereid</td>
<td>218.56</td>
<td>0.7512</td>
<td>7.23</td>
<td>170</td>
</tr>
<tr>
<td>S/2002 N1</td>
<td>638.</td>
<td>0.43</td>
<td>114.9</td>
<td>27</td>
</tr>
<tr>
<td>S/2002 N2</td>
<td>884.</td>
<td>0.27</td>
<td>50.4</td>
<td>16</td>
</tr>
<tr>
<td>S/2002 N3</td>
<td>931.</td>
<td>0.36</td>
<td>35.9</td>
<td>18</td>
</tr>
<tr>
<td>c02 N4</td>
<td>995.</td>
<td></td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>S/2003 N1</td>
<td>1890</td>
<td>0.49</td>
<td>125.1</td>
<td>18</td>
</tr>
<tr>
<td>S/2002 N4</td>
<td>1930</td>
<td>0.39</td>
<td>137.4</td>
<td>22</td>
</tr>
</tbody>
</table>
Post-Capture Tidal Evolution of Triton

- Tidal dissipation in Triton causes orbital decay
  \[ a_T < 2000R_N \rightarrow 14R_N \]
  \[ e_T: 1 \rightarrow 0 \]
  \[ q_T: 7R_N \rightarrow 14R_N \]

- Post capture orbit was eccentric
- Large Inclination is preserved through tidal evolution
Binary Exchange Capture

Requirements

1. 3-body Binary-Planet Encounter

2. Disruption of the binary

3. An encounter velocity ($v_\infty$) low enough for capture of one binary component.

Binary Exchange Capture
Tidal Disruption Radius of Binaries

Roche radius of a single body ($M_1$)

$$R_{Roche} = R_P \left( \frac{3 \rho_P}{\rho_1} \right)^{1/3}$$

Tidal disruption radius of a binary

$$r_{td} = R_P \left( \frac{a_B}{R_1} \right) \left[ \left( \frac{3 \rho_P}{\rho_1} \right)^{1/3} \left( \frac{1}{1 + M_2 / M_1} \right) \right]^{1/3}$$
Impulse Approximation
Impulse Capture Model

Speed decrease required for capture

\[ \Delta v_c = \sqrt{v_\infty^2 + \frac{2GM_p}{r}} - \sqrt{GM_p \left( \frac{2}{r} - \frac{1}{a_c} \right)} \]

Speed change from binary disruption

\[ \Delta v_i \approx \frac{M_j}{M_i + M_j} \left( \frac{G(M_1 + M_2)}{a_B} \right)^{1/2} \]
Example Triton Capture: $M_T - \frac{M_T}{10}$

\[
M_1 = M_T \quad M_2 = \frac{M_T}{10} \quad a_B = 20R_1 \quad e_B = 0 \quad l_B = 0 \quad q_{\text{enc}} = 8R_N
\]

Agnor & Hamilton (2006)
Estimating Binary Characteristics for Capture

- Simulations show that the pericenter of capture orbit is comparable to that of the encounter
  - $q_c \sim q_e$

- Disruption along capture orbit $r_{td} > q_c$ constrains binary semi-major axis.
  \[
  \left( \frac{a_B}{R_1} \right) > \left( \frac{q_c}{R_p} \right)
  \]

- Describe the capture orbit with pericenter & eccentricity ($q_c$ & $e_c$)

- We set $\Delta v_i = \Delta v_c$ and determine the mass of the escaping companion required.

- Disruption and capture at pericenter ($q_c$) allows
  - smallest $\Delta v$ needed for capture
  - smallest $a_B$
  - smallest escaping companion mass ($m_c$)
Jovian Irregulars

- For disruption

\[
\left( \frac{a_B}{R_1} \right) > \left( \frac{q_c}{R_p} \right)
\]

- Contour values indicate the logarithm of companion mass in grams

- Points show orbits of known irregulars
Jovian Irregulars

- For disruption
  \[ \left( \frac{a_B}{R_1} \right) > \left( \frac{q_c}{R_p} \right) \]

- \( e \sim v_\infty / v_K = 0.10 \)
Capture via Binary-Planet Encounter

- smallest $\Delta v$ is needed for capture to orbits with
  - small pericenters
  - Big orbits (large $a$ & $e$)

Best Candidates are at Neptune!

- **Triton** $a_B/R_1 > 5$ $m_c > 10^{24} \text{ g} \ (\sim 0.02 M_T)$ Includes binaries similar to Pluto/Charon (Agnor & Hamilton 2006)

- **Nereid** $a_B/R_1 > 45$ $m_c > 10^{25} \text{ g} \ (\sim M_{Pluto})$ Includes binaries similar to Pluto/Nix Pluto/Hydra.

- Nereid’s eccentric orbit ($e=0.75$) may be an artifact of capture rather than from perturbations from Triton.
Capture of Irregulars

- Capture of distant irregulars directly to observed orbits requires:
  - \( \frac{a_B}{R_1} > 100-300 \) (for binary disruption)

  - Jupiter \( m_c > 10^{27} - 10^{28} \) g
  - Saturn \( m_c > 10^{26} - 10^{27} \) g
  - Uranus \( m_c > 10^{25} - 10^{26} \) g
  - Neptune \( m_c > 10^{25} - 10^{26} \) g

- Capture directly to observed orbits involves exchanges of distant satellites between large planetary embryos and planets (i.e. swapping irregulars) ….
Capture First, Orbit Evolution Second

- Alternatively small mass binaries can facilitate capture to:
  - Small pericenter
  - Large orbits / eccentricity. (Philpott et al. 2010, Gaspar et al. 2011)

- Post-capture eccentricity evolution is then required to deliver objects to observed orbits, by e.g.
  - gas drag
  - collisions
  - planet migration (Cuk & Gladman 2006)
3-body Capture & Planet Evolution

Giant Planet Formation:
- Low encounter velocity
  \[ V_\infty \approx 0 \text{ km/s} \]

Migration (e.g. Nice Model):
- Planet-Planet scattering
  (Nesvorny et al. 2007)
- Planetesimal-driven migration
  (Vokrouhlicky et al. 2008)
  
  - Binary-planet encounters

- Higher encounter velocity
  \[ V_\infty \approx 5 \text{ km/s} \]
Capture During Planetesimal-Driven Migration

Vokrouhlicky et al. 2008

- Binary-planet exchange capture
- Assumed binary distribution
- Nice model encounters

Results:
- Capture efficiency is low
- Capture orbits are too eccentric

captured bodies observed irregulars
Capture During Planet-Planet Scattering

Nesvorny et al. 2007

- Planet scattering in a sea of planetesimals
- Use Nice model scattering dynamics

Results:

- Capture efficiency reasonable
- Capture orbits agree with observed irregs

All planets must be involved in scattering.

captured bodies observed irregulars
Summary

- In principal 3-body encounters can account for the capture of any satellite.

- Impulse model allows simple estimates of required encounter parameters needed for capture.

- Capture and survival of irregular satellites are very sensitive to late planetary evolution
  - the context for capture is the key

- Three-body encounters offer a viable mechanism to explain the origin of irregular satellites, & Triton.
3-body Capture of Phobos & Deimos

- Three-body capture works in principal for the terrestrial planets.

- Capture orbit would be eccentric and inclined.

- The general challenges for a capture origin (high e, I) remain.

- It is difficult to conceive of Martian satellites as pristine captured asteroids.