Trajectory analysis of the potentially hazardous asteroid (101955) Bennu

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CL#13-3824
(101955) Bennu

- ~500 m
- B-type Carbonaceous Chondrite

Near-Earth asteroid Apollo
- Perihelion 0.9 au
- Aphelion 1.4 au

Target of OSIRIS-Rex asteroid sample return mission
Observations and Orbit

Discovered by LINEAR in September 1999

> 500 optical observations 1999 - 2013


Exceptionally constrained orbit:

Uncertainty semimajor axis 6 m!

Uncertainty orbital period 2 ms!
Astrometric treatment

Star catalog systematic errors

Different observatories, different performances

Chesley et al. 2010 debiasing and weighting scheme

Relaxed weights for overcrowded nights to mitigate correlations

Aggressive rejection scheme (biased observatories removed)
High precision dynamical model

Newtonian attraction

25 main belt perturbers

Einstein-Infeld-Hoffman formulation for relativity

Other:
- Earth’s $J_2$
- Solar radiation pressure
- Yarkovsky effect…
The Yarkovsky effect

Tiny perturbation, but secular effect in semimajor axis:

Accumulates quadratically with time along the orbit

Orbital deviations due to the Yarkovsky effect detectable from Bennu’s observation dataset

Yarkovsky acceleration $\sim 1 \text{ pm/s}^2$
(precision $\sim 1 \text{ fm/s}^2$)

CREDIT: Alexandra Bolling, NRAO/AUI/NSF
Physical model

- Size, shape, rotation period, spin orientation, albedo, thermal properties

- Density $0.96 \pm 0.13 \text{ g/cm}^3$

- Mass $(5.97 \pm 0.91) \times 10^{10} \text{ kg}$

Yarkovsky $\propto \rho^{-1}$

Bennu
Impacts on Earth are possible from 2100 to 2250.
Close approaches

<table>
<thead>
<tr>
<th>Year</th>
<th>CA distance</th>
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<tbody>
<tr>
<td>1654</td>
<td>516.79 $R_E$</td>
</tr>
<tr>
<td>1788</td>
<td>229.18 $R_E$</td>
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<tr>
<td>1848</td>
<td>185.65 $R_E$</td>
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<td>1911</td>
<td>332.55 $R_E$</td>
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<td>502.01 $R_E$</td>
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<td>344.46 $R_E$</td>
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<tr>
<td>2005</td>
<td>777.07 $R_E$</td>
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<td>921.77 $R_E$</td>
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<td>2060</td>
<td>117.46 $R_E$</td>
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<td>2080</td>
<td>364.96 $R_E$</td>
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<td>2135</td>
<td>47.12 $R_E$</td>
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</table>

- 2135 is the last deterministic close encounter
- Post-2135 predictions are statistical
If the asteroid passes through a keyhole, there is going to be an impact at a future encounter.
Risk assessment
# Impact probability $3.7 \times 10^{-4}$

<table>
<thead>
<tr>
<th>Year</th>
<th>$IP \times 10^6$</th>
<th>Keyhole width</th>
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<tbody>
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<td>2175</td>
<td>41.3</td>
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<tr>
<td>2176</td>
<td>3.1</td>
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<tr>
<td>2180</td>
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<tr>
<td>2180</td>
<td>19.5</td>
<td>3.5 km</td>
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<tr>
<td>2181</td>
<td>2.9</td>
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<tr>
<td>2181</td>
<td>1.3</td>
<td>0.6 km</td>
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<tr>
<td>2182</td>
<td>1.4</td>
<td>6.3 km</td>
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<tr>
<td>2182</td>
<td>3.6</td>
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<tr>
<td>2185</td>
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<tr>
<td>2185</td>
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<table>
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<th>Keyhole width</th>
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<tbody>
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<tr>
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<td>13.3 km</td>
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<tr>
<td>2198</td>
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<td>0.5 km</td>
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</tbody>
</table>
Sample return mission
Physical characterization of Bennu
Measure the Yarkovsky effect

Proposed kinetic impactor mission
Learn how to deflect an asteroid
Measure momentum imparted through the impact
Deflection experiment

\[ \Delta v_{SC} = \frac{m_{SC}}{m_A} v_\infty \]
\[ V_\infty \sim 15 \text{ km/s} \]
\[ \Delta v_{SC} \sim 0.1 \text{ mm/s} \]

Momentum enhanced by the ejecta

\[ \Delta v = \beta \frac{m_{SC}}{m_A} v_\infty \]
\[ \beta = \frac{\Delta v}{\Delta v_{SC}} \]

We expect \( 1 < \beta < 3 \), likely less than 2
β vs keyholes
Oblique impact

\[
\Delta \vec{v} = \frac{m_{sc}}{m_A} (\vec{v}_\infty - (\beta - 1)v_\infty \hat{n})
\]

How does the impact location affect Bennu’s trajectory?
Δv vs impact location

Δv, radial [mm/s]

Δv, out-of-plane [mm/s]

Δv, transverse [mm/s]
2135 b-plane vs impact location

$\beta = 1.5$

$\beta = 2$
Keyholes on Bennu’s surface

\[ \beta = 1.5 \]

\[ \beta = 2 \]
Equator only

\[ \beta = 1.5 \]

\[ \beta = 2 \]
$\beta$ vs keyholes
Can we avoid the keyholes?

Only one keyhole < 3 km
Low risk impact locations

Distribution on $\beta$  \quad \quad \quad \quad Impact probability distribution on Bennu’s surface

$log_{10}$ scale
Conclusions

• Bennu has the best constrained orbit in the catalog

• Reliable astrometric treatment and high precision dynamical model

• Yarkovsky effect & physical model $\rightarrow$ density 0.96 g/cm$^3$

• Risk assessment, probability of an Earth impact $3.7 \times 10^{-4}$

• Implications of a deflection experiment on Bennu’s trajectory and risk assessment
Acknowledgements

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Questions