Impact Hazard Assessment for 2011 AG5
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### 2011 AG5 Earth Impact Risk Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torino Scale (maximum)</td>
<td>1</td>
</tr>
<tr>
<td>Palermo Scale (maximum)</td>
<td>-1.01</td>
</tr>
<tr>
<td>Palermo Scale (cumulative)</td>
<td>-1.00</td>
</tr>
<tr>
<td>Impact Probability (cumulative)</td>
<td>2.0e-03</td>
</tr>
<tr>
<td>Number of Potential Impacts</td>
<td>4</td>
</tr>
<tr>
<td>V_{impact}</td>
<td>14.67 km/s</td>
</tr>
<tr>
<td>V_{infinity}</td>
<td>9.55 km/s</td>
</tr>
<tr>
<td>H</td>
<td>21.8</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.140 km</td>
</tr>
<tr>
<td>Mass</td>
<td>4.1e+09 kg</td>
</tr>
<tr>
<td>Energy</td>
<td>1.1e+02 MT</td>
</tr>
</tbody>
</table>

Analysis based on 210 observations spanning 316.77 days (2010-Nov-08.629742 to 2011-Sep-21.398727)

Orbit diagram and elements available [here](http://neo.jpl.nasa.gov/risk/).

These results were computed on Mar 31, 2012

### 2011 AG5 Earth Impact Table

<table>
<thead>
<tr>
<th>Date</th>
<th>Distance (r_{Earth})</th>
<th>Width (r_{Earth})</th>
<th>Sigma Impact</th>
<th>Sigma LOV</th>
<th>Stretch LOV</th>
<th>Impact Probability</th>
<th>Impact Energy</th>
<th>Palermo Scale</th>
<th>Torino Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>YYYY-MM-DD</td>
<td>(r_{Earth})</td>
<td>(r_{Earth})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2040-02-05</td>
<td>0.31</td>
<td>1.04e-03</td>
<td>0.000</td>
<td>0.26494</td>
<td>3.70e+02</td>
<td>2.0e-03</td>
<td>1.05e+02</td>
<td>-1.01</td>
<td>1</td>
</tr>
<tr>
<td>2043-02-04</td>
<td>0.56</td>
<td>&lt; 1.e-04</td>
<td>0.000</td>
<td>0.24025</td>
<td>1.39e+06</td>
<td>4.6e-07</td>
<td>1.05e+02</td>
<td>-4.68</td>
<td>0</td>
</tr>
<tr>
<td>2045-02-04</td>
<td>0.52</td>
<td>1.01e-03</td>
<td>0.000</td>
<td>0.09607</td>
<td>5.53e+04</td>
<td>1.2e-05</td>
<td>1.05e+02</td>
<td>-3.29</td>
<td>0</td>
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<tr>
<td>2047-02-04</td>
<td>0.57</td>
<td>9.82e-04</td>
<td>0.000</td>
<td>0.37496</td>
<td>1.69e+05</td>
<td>3.6e-06</td>
<td>1.05e+02</td>
<td>-3.84</td>
<td>0</td>
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</tbody>
</table>
Background - 2011 AG5 in late 2011

- Discovered Jan. 2011 by Catalina Sky Survey
  - Pre-discovery obs. by Pan-STARRS dated Nov. 2010
  - Observations still covered only ~half of 625 day orbit
  - Asteroid was unobservable for a long period of time
- Earth impact probability: 1-in-500 for Feb. 5, 2040
  - Impact requires passage through 365 km keyhole on Feb. 3, 2023
  - Post-keyhole deflection is ~50x harder than before 2023
- In 2012, JPL did a full study to answer the key question:
  - If we wait until AG5 is observable again, and it turns out to be on a collision course, is there enough time to design, build, launch and execute a deflection mission before it passes through the keyhole in 2023, a time span of possibly 3
Heliocentric Orbit of 2011 AG5

Orbit of 2011 AG5 intersects Earth's orbit

Sun

Mars

Earth

2011 AG5
Impact Prob.: 1/500

Uncertainty in 2011 AG5’s position along its orbit on Feb. 5, 2040
Uncertainty Region at a Close Approach
2011 AG5 Uncertainty Region in 2023 b-plane

10,000 Monte Carlo points trace the uncertainty region

Keyhole size: ~365 km
2011 AG5 Keyhole in 2023 b-plane

10,000 Monte Carlo points trace the uncertainty region

Keyhole size: ~365 km
Position of 2011 AG5 in a Rotating Reference Frame
“Future” Observing Opportunities

<table>
<thead>
<tr>
<th>Date</th>
<th>Brightness (mag)</th>
<th>Solar Elong. (deg)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 2012</td>
<td>24.5</td>
<td>42</td>
<td>Requires Keck. ‘MKO12’</td>
</tr>
<tr>
<td>Apr. 2013</td>
<td>25.5</td>
<td>50</td>
<td>Requires HST. ‘HST13’</td>
</tr>
<tr>
<td>Sep. 2013</td>
<td>23.6</td>
<td>175</td>
<td>Requires 2-4m aperture</td>
</tr>
<tr>
<td>Nov. 2015</td>
<td>22.9</td>
<td>170</td>
<td>Requires 2-4m aperture</td>
</tr>
<tr>
<td>June 2016</td>
<td>22.9</td>
<td>85</td>
<td>Requires 2-4m aperture</td>
</tr>
<tr>
<td>Sep. 2018</td>
<td>23.1</td>
<td>175</td>
<td>Requires 2-4m aperture</td>
</tr>
<tr>
<td>Oct. 2020</td>
<td>23.5</td>
<td>172</td>
<td>Requires 2-4m aperture</td>
</tr>
<tr>
<td>Feb. 2023</td>
<td>14.3</td>
<td>135</td>
<td>Radar Opportunity</td>
</tr>
</tbody>
</table>

- Oct. 2012 obs. require large aperture & favorable conditions
  - (In fact obtained by Tholen et al. using Gemini 8m and UH 2.2m)

- April 2013 HST observations
  - Would require advance characterization of star field

- “Normal” observations begin in Sept 2013
  - First observations likely in early August
Maximum Impact Probability vs. Time

Assumes 2011 AG5 is actually on an impact course.
• Secondary keyholes exist but are < 100 m down to a few meters wide.
• Safe harbor zones: -8,000 km to -1,500 km on left & +2,00 km to +12,00 km on right.
• Left safe harbor is preferred because it corresponds to front side impact by S/C.
Deflection Campaign  (see poster by Damon Landau)

- Kinetic impactor deflection with observer spacecraft
  - Examine both chemical & solar electric propulsion (SEP) missions
  - Require precursor rendezvous spacecraft arriving >2 months before impactor to aid targeting and confirm successful deflection

- Tune spacecraft mass to obtain the desired deflection
  \[ \Delta V = \frac{\beta}{M} \cdot \frac{V_\infty}{m} \]
  - \( \beta \) is the momentum enhancement due to impact ejecta (likely range: 1 to 4)
  - \( M \) is the mass of the asteroid
  - Take safety factor of 10 on \( \beta/M \), and so strive for >10 \( R_E \) deflection
  - But if \( \beta/M \) is much higher than expected could lead to a deflection approaching 100 \( R_E \)

- Without early reconnaissance it may be impossible to ensure that deflection moves asteroid to a “safe harbor” (8-44 \( R_E \))
Mission Timelines

Phase A/B

Phase C/D

Chem Rend.

Chem. Imp.

SEP Missions

Maximum Impact Probability

Baseline

With MKO12

With HST13

With 2021 RZ S/C

Year

Post Keyhole Mission Designs

Post keyhole missions are ~50 more challenging but there are viable rendezvous/deflection options after 2023 that could be carried out with existing launch vehicles.

Backup in case pre-keyhole missions unsuccessful

Both chemical and SEP propulsion options are available
Post-Keyhole Deflection Options (Delta IV Heavy)

Impact $\Delta b$, Earth radii

Launch Year

Arrival Year

2024 2026 2028 2030 2032 2034 2036 2038 2040

2024 2026 2028 2030 2032 2034 2036 2038 2040
Key Conclusions from the 2012 Report:

- If 2011 AG5 really is on an collision trajectory, the next observations will cause the impact probability to jump to ~10% or more.
- In the unlikely case where the 2012/2013 observations do not eliminate the potential hazard, there is time to plan and carry out a pre-keyhole rendezvous and deflection mission from that point.
- There exist numerous viable rendezvous/deflection mission options both before and after keyhole in 2023.
- The full report is available online: http://neo.jpl.nasa.gov
Postscript: Uncertainty Region Before 2012 Obs.
Postscript: Uncertainty Region After 2012 Obs.

2011 AG5: Position Uncertainty for 2040 Earth Encounter

- Region of Uncertainty
- Earth
- Moon’s orbit
- Direction of Motion Relative to Earth
- Earth’s orbit

10M km