The Meteoroid Environment and Spacecraft

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How NASA handles space debris

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Difference between a meteoroid and asteroid?

• It’s all a matter of size, but there is no formal limit on the size of the biggest meteoroid or smallest asteroid
• Generally anything bigger than 10 meters in diameter is considered an asteroid
• However, the currently accepted process is that if it is detected in space and given a designation by the Minor Planet Center, it is an asteroid, no matter how big – example: 2008 TC3 is listed as an asteroid, despite being only 2 meters in diameter.
Sporadic Directionality

- The meteoroid background is **not** isotropic, as assumed by some models. 6 sources (radiants), as can be seen from diagram at right. Variants on this should hold true throughout inner Solar System.
- This has been known since 1957

*Jones & Brown (1999)*
Sporadic Background: Radiant Distribution
Source Origins

• Dynamical studies (e.g. Wiegert & Vaubaillon, 2008) indicate that
  – Helion sources originate mainly from Jupiter family comets (JFCs)
  – Apex sources from retrograde Halley family comets (HFCs) and long period comets.
  – Toroidal sources from prograde HFCs?
• >90% of meteoroids in inner Solar System come from comets
Sporadic Meteor Directionality

Center Plot – MEM run at 1AU heliocentric orbit, all plots ionization weighting

Jones and Brown, 1993
Campbell-Brown, 2007
Meteoroid Velocity Distribution

• Three main sources
  – Photographic (Super-Schmidt)
  – Specular Radar
    • (Harvard Radio Meteor Project (HRMP)
    • CMOR
    • AMOR
  – HPLA
    • ALTAIR
    • Jicamarca
    • Arecibo

• Photographic have lower number statistics and unique biases
  – Nighttime only
  – $\sim V^{3.5}$ dependence on light production
  – Detection sensitivity is function of angular velocity

• Radar has different biases
  – Ionization production also steep function of velocity $(V^{3.5-4})$
  – Initial trail radius, finite velocity and diffusion attenuation

• HPLA biases
  – Still controversy over how much and what sort of biases may or may not be present
A Question of Size

- Gravitational forces (perturbations, resonances) dominate for bigger particles
- Radiative forces increasingly dominant for particles < 100 microns:
  - Radiation pressure – Sun looks less massive.
  - PR Drag – tangential component of radiative force.
  - PR Drag tends to circularize orbits – expect most small particles from the asteroid belt to be moving roughly same speed as Earth at 1 AU (results in low encounter speed).
The velocity distribution of the sporadics varies with size, mostly at highest velocities.
Density

- ALTAIR radar determined ballistic coefficients (densities) from > 1000 meteor decelerations in atmosphere.
  - Would like equivalent in threat size regime (> 100μm).
  - Need better models of meteoroid structure.
Shape

- Meteoroid shapes are very irregular and can be roughly approximated by an ellipsoid.
- For penetration/damage assessments, it can be shown mathematically that they can be assumed spherical, unless some alignment mechanism exists outside the atmosphere.
- For icy particles, it’s hard to postulate such a mechanism.
Meteor Showers

• Meteor showers occur when the Earth (or a spacecraft) encounters a stream of material left behind by an asteroid or comet

• Sporadic background accounts for >90% of the integrated flux (risk)

• Levels of meteor shower activity:
  – Shower – normal; visual rates of 10-150 per hr
  – Outburst – enhanced activity; visual rates of 150-1000 per hour
  – Storm – intense activity; visual rates >1000 per hour
Meteor Shower Forecasting

- Stream modeling technique now used
- Particles ejected from comet and dynamically evolved. Ensemble of particles near target at chosen time determines shower characteristics.
  - Numerically intensive – many thousands (millions) of particles.
  - Multiple peaks; times and intensities of shower maxima can be obtained.
  - Shower durations difficult to derive.
2004 Perseids

Particles ejected hourly proportional to $r^3$ while Swift-Tuttle is inside 2.5 AU

60° cap angle

X (AU)

Earth's Path
- 9 rev (826 AD)
- 7 rev (1079 AD)
- 6 rev (1212 AD)
- 5 rev (1348 AD)
- 4 rev (1479 AD)
- 3 rev (1610 AD)
- 2 rev (1737 AD)
- 1 rev (1862 AD)
• Output for past years compared to IMO ZHR profiles or other historical observations. “Calibrates” the model and enables ZHR predictions for future.

• Only showers with potential to outburst/storm are evaluated using stream model technique. In other cases, an average observed ZHR profile is used.

• ZHRs converted to fluxes using visually-determined population/mass indices.
Annual Forecast

• Issued to NASA spacecraft programs (ISS, Shuttle, Chandra) and others as requested.
• Re-evaluations of outburst and storm predictions performed as new information becomes available.
• Maximum ZHRs, peak times, and durations are added to existing database of “normal” showers.
• Penetrating fluxes are generated at 1 hour intervals for entire year.
Why these sizes?
Verification

• Visual observations (ZHRs) are not only used in forecast generation, but also are used in validation of a shower forecast after the event.

• A few weeks are allowed for the numbers to be revised. We do not use the “real-time” ZHRs unless there is an anomaly investigation with tight deadlines.
• Despite numerous study recommendations, effects/risk assessors still do not use directional meteoroid models
  – Directional models increase model execution times (computers are cheap)
  – Can’t be put in a spreadsheet (spacecraft CAD models used in risk assessments have thousands of elements, yet environments are to be reduced to “back of the envelope” level?)
  – ISS uses a simple model (SSP-30425)
    • SSP-30425 underestimates risk by at least a factor of 2 and is mathematically inconsistent. It does not even match the data upon which it is based.
• Too much emphasis on risk posed by meteor showers
  – One model has only showers, neglects sporadic background!
  – Concern seems to be justified during Perseid outbursts (OLYMPUS in 1993, Landsat 5 in 2009)

• Better environment education needed
  – Handbook in work
  – Training class
Mariner IV

What: NASA planetary exploration spacecraft.


Consequences:

◆ Cosmic dust detector registered 17 hits within 15 minutes; 2-3 orders of magnitude more hits estimated over entire craft.

◆ Bombardment caused temporary change in attitude but no loss of power; torqued about the roll-axis.

◆ One-degree temperature drop indicative of thermal shield damage.

Outcome: Resumed normal operation within ~1 week.
Olympus

What: ESA communication satellite.

Event: Struck by a Perseid near the time of the shower peak in August 1993.

Consequences: Impact-generated plasma cloud produced current that disabled the attitude control system; spacecraft sent tumbling.

Outcome: By the time attitude was restored the onboard fuel had been exhausted, ending the mission.
Chandra X-Ray Observatory

What: NASA observatory.

Event: Struck by a sporadic near the time of Leonid shower peak in November 2003.

Consequences:

– Pointing stability discrepancy indicated strike, as no evidence of spurious thruster firings or an indication of an internal cause.

– Change in momentum – caused a “wobble”.

Outcome: All systems continued to operate normally following the event.
XMM-Newton

What: ESA science satellite.

Event: CCD struck by a south toroidal sporadic on September 17, 2001.

Consequences: Loss of 35 pixels

Outcome: Normal operations continued; anomaly investigation
LandSAT 5

**What:** Remote sensing satellite

**Event:** Struck by a Perseid near the time of the shower peak on August 13, 2009.

**Consequences:** Gyro temporarily failed; spacecraft began tumbling.

**Outcome:** Normal operations restored by August 17.
Backup
Meteoroid Engineering Model

- Models the sources of the sporadic meteoroid environment from cometary and asteroidal populations
- Evolved particles from comet families to inner solar system using processes such as catastrophic collisions and poynting-robertson drag
- Resulting theoretical distributions of sporadic orbital elements are the basis for all versions of MEM
- Individual source distributions (Short Period – Helion/Anti-Helion, Long Period – Apex etc) validated against only published set of meteor radar data (HRMP) at time of release, (Jones, 2001)
  - with HRMP corrections applied
- Strengths of individual source distributions derived from CMOR measurements, 2001
• Flux as a function of mass follows Grun formalism, for mass range $10^{-6}\, \text{g} \leq m \leq 10^2\, \text{g}$

• MEM flux and speed derived together, not separately as in previous models (SSP30425, TM4527)

• Evolving particles from comet and asteroid populations produces same directionality as observed by HRMP, CMOR, AMOR, Adelaide, Jicamarca radio meteor surveys,
Original MEM Validation Efforts

- HRMP was only published set of radar meteor data to compare
- HRMP dataset had a typo which resulted in an underestimation of high speed meteors (Taylor & McBride, 1995)
- HRMP data was corrected before comparing to MEM
- Biases between sources are more prevalent than biases within sources (P. Brown communications)
- CMOR data was used to determine relative strength between sources back in 2001

Speed Distribution of radar meteors from the Apex source as determined by HRMP, MEM
• Short Period Comet Sources of Helion/Antihelion match well between HRMP and MEM

• Long Period Comet Sources Apex sources match well

• Toroidal did not match as well, still debate on what contributes to Toroidals

![Speed Distribution of radar meteors from the Helion/Antihelion sources as determined by HRMP, MEM](image1)

![Speed distribution of radar meteors from the Toroidal Sources as determined by HRMP, MEM](image2)
Comparison to CMOR Measurements

![Graph showing comparison between UWO - Uniform Mass and MEM - TOA measurements. The graph plots speed (km/s) on the x-axis and number on the y-axis, with data points and lines indicating the distribution.]
MEM Deficiencies

• Original dynamics did not include resonances - Weigert and Vaubaillon (2008) showed that this neglect will result in underestimate of high-speed peak. Work underway to fix this (new distributions delivered).

• Speed/directionality not size-dependent (also in work).

• Need to incorporate ALTAIR/optical density distributions (Analysis of 30+ hours of data recently completed).