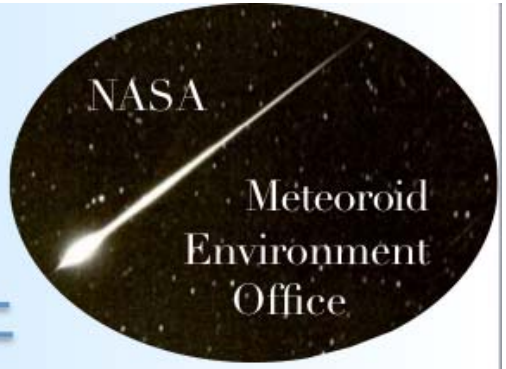
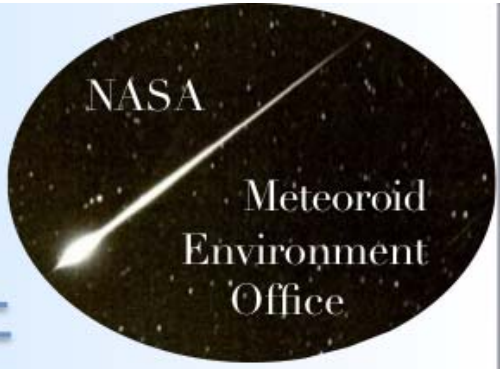
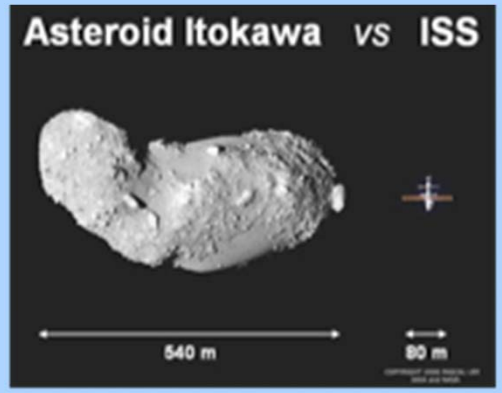


The Meteoroid Environment and Spacecraft

Bill Cooke
Lead, Meteoroid Environment Office
william.j.cooke@nasa.gov
(256) 544-9136

How NASA handles space debris





Near Earth Object Office (JPL)

Meteoroid Environment Office (MSFC)

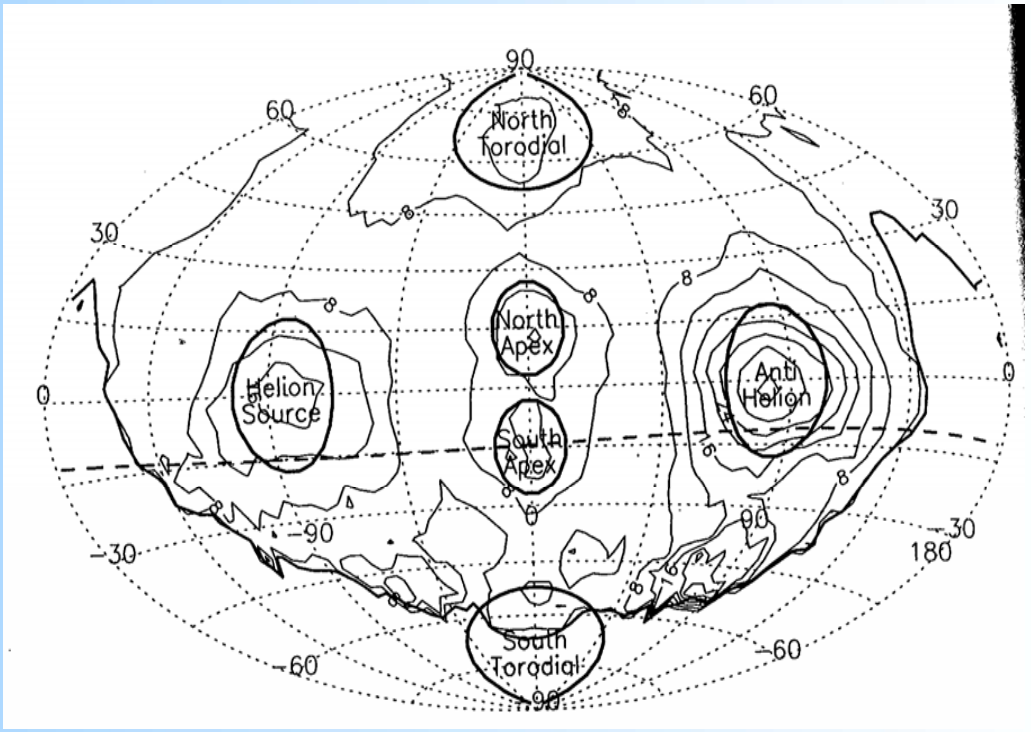
Orbital Debris Program Office (JSC)

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.

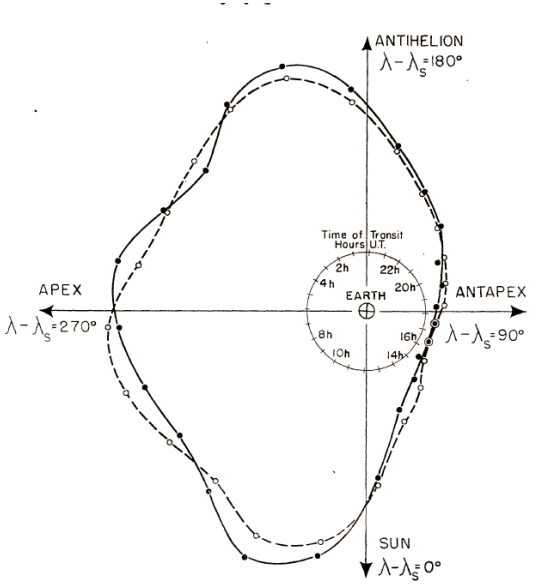
Sporadic Directionality

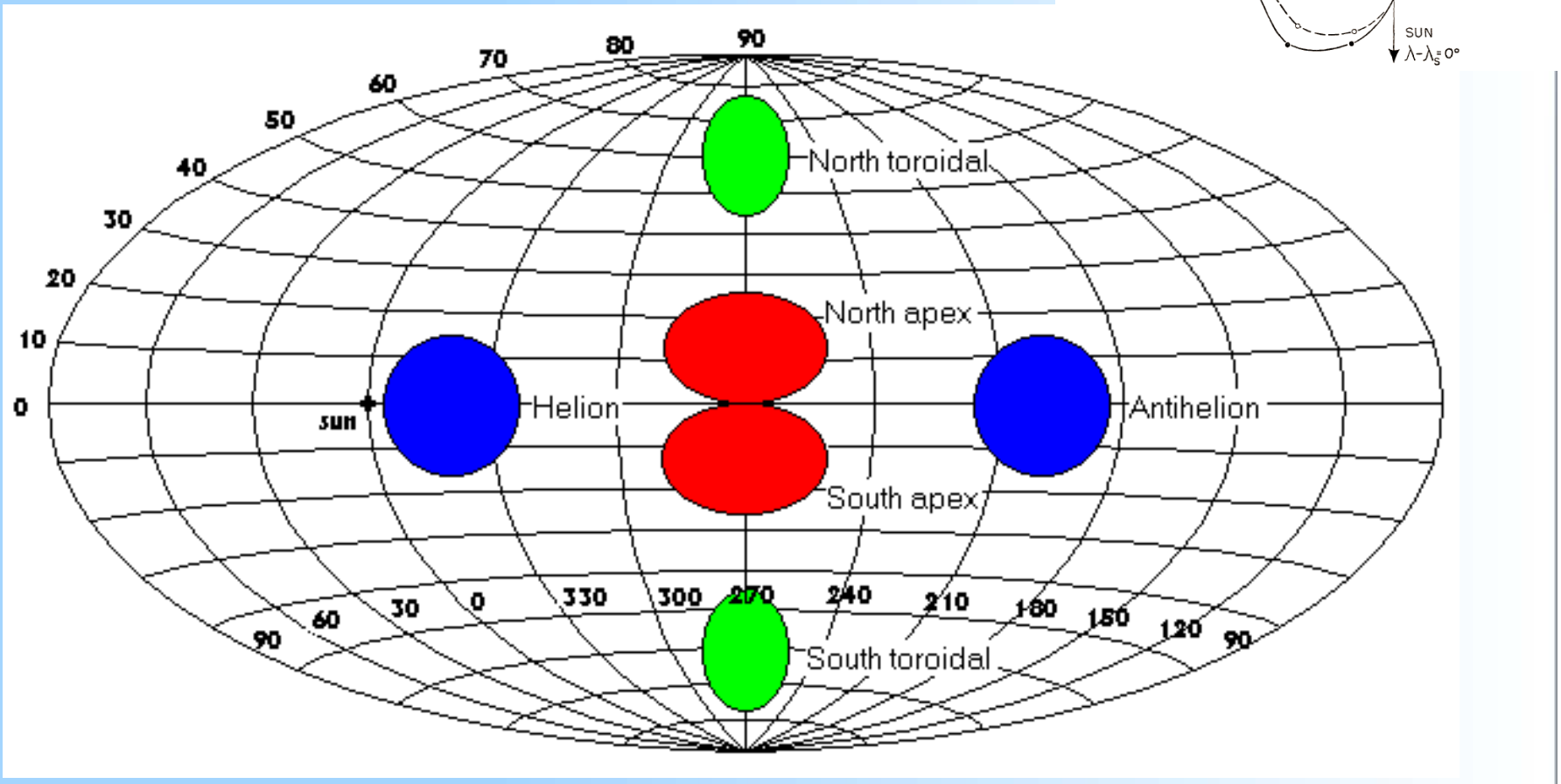
- The meteoroid background is **not** isotropic, as assumed by some models. 6 sources (radiants), as can be seen from diagram at right. Variants on this should hold true throughout inner Solar System.
- This has been known since 1957



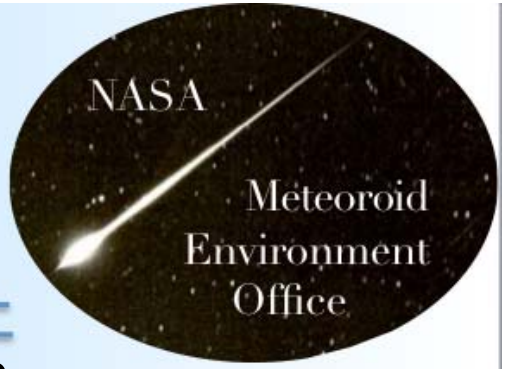
Jones & Brown (1999)

Sporadic Background : Radiant Distribution



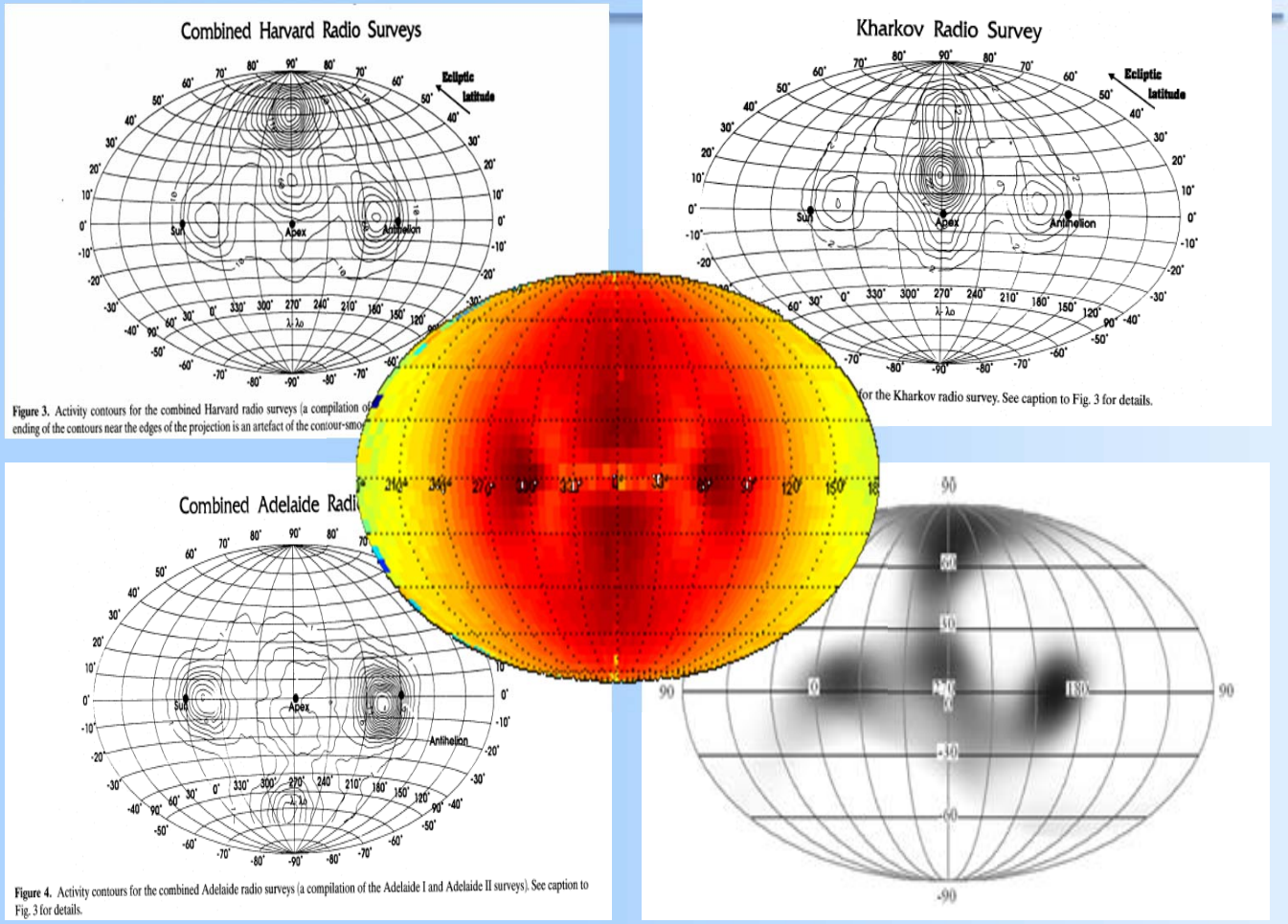


Source Origins



- 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



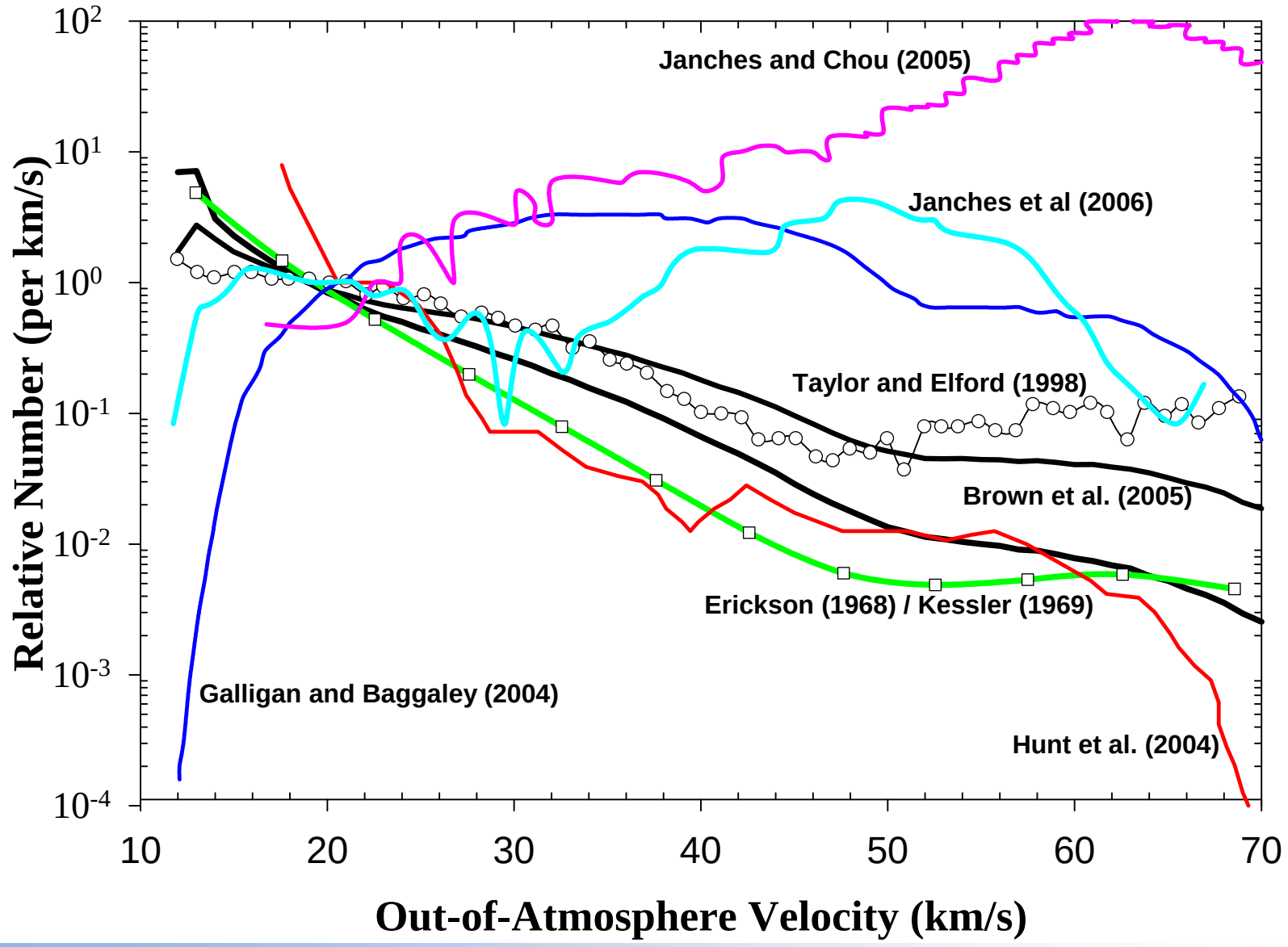
Jones and Brown, 1993
Campbell-Brown, 2007

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

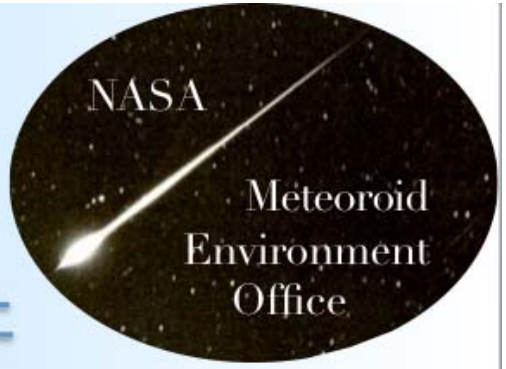
Meteoroid Velocity Distribution

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

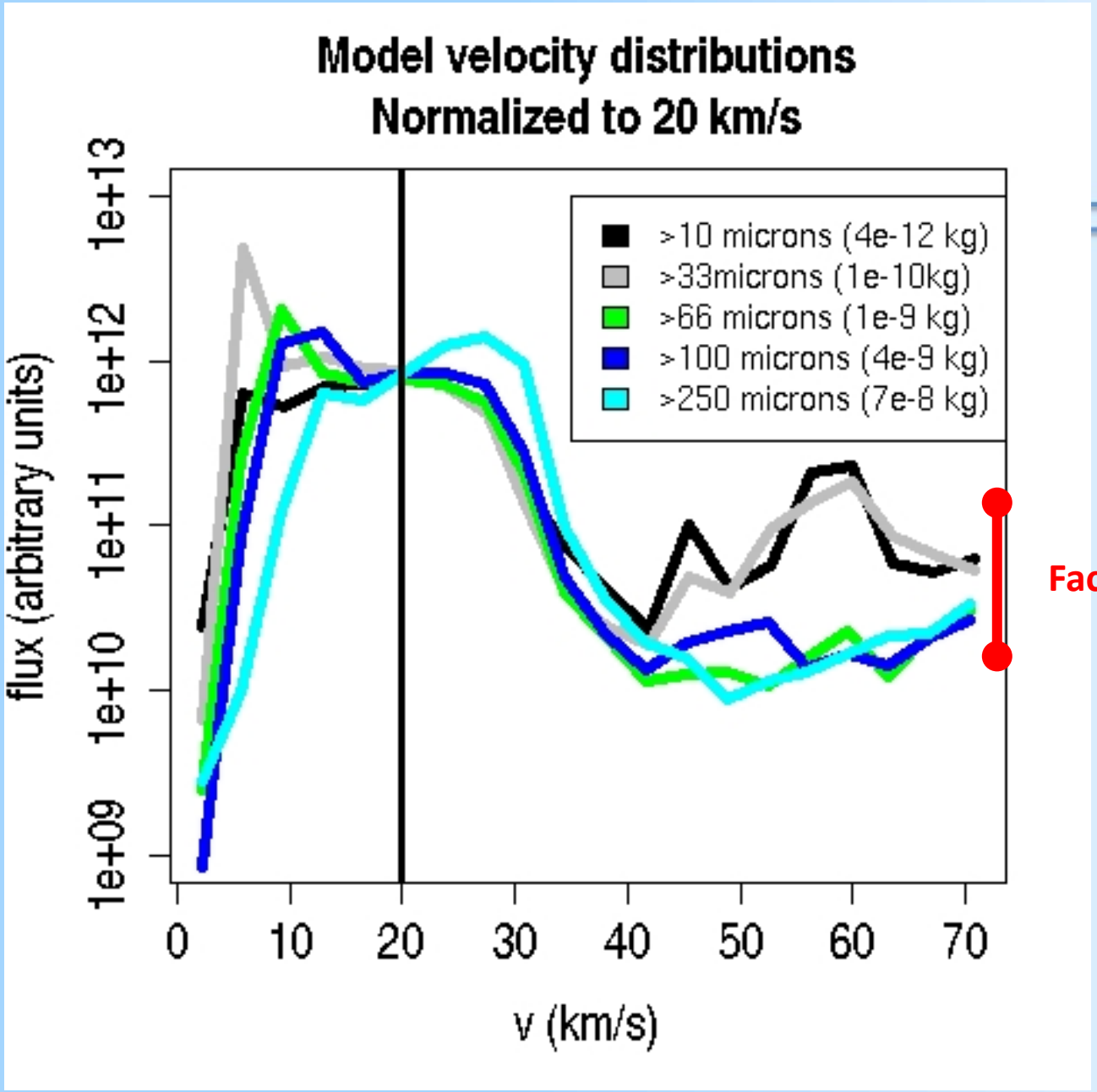
- Photographic have lower number statistics and unique biases
  - Nighttime only
  - ~$V^{3.5}$ dependence on light production
  - Detection sensitivity is function of angular velocity
- Radar has different biases
  - Ionization production also steep function of velocity ($V^{3.5\text{-}4}$)
  - Initial 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

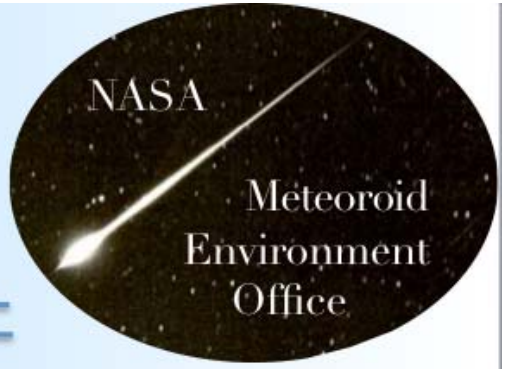

Relative Number (per km/s)
Out-of-Atmosphere Velocity (km/s)
Janches and Chou (2005)
Janches et al (2006)
Taylor and Elford (1998)
Brown et al. (2005)
Erickson (1968) / Kessler (1969)
Galligan and Baggaley (2004)
Hunt et al. (2004)

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).





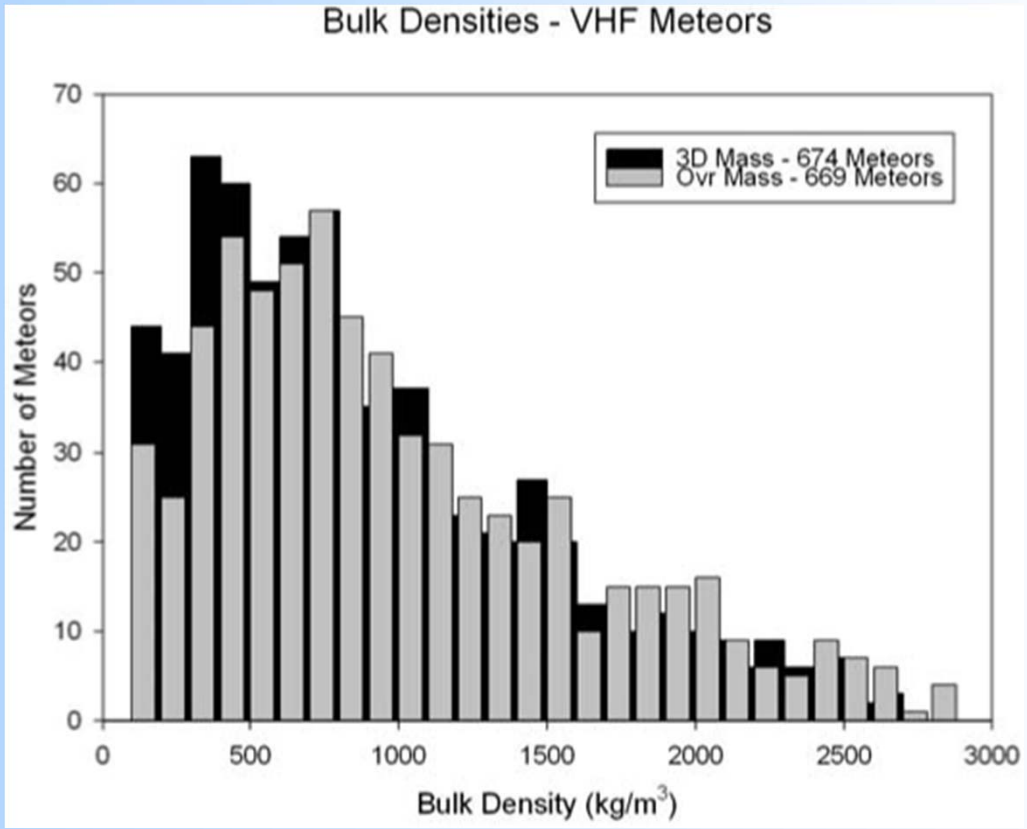
Factor of 10

The velocity distribution of the sporadics varies with size, mostly at highest velocities.

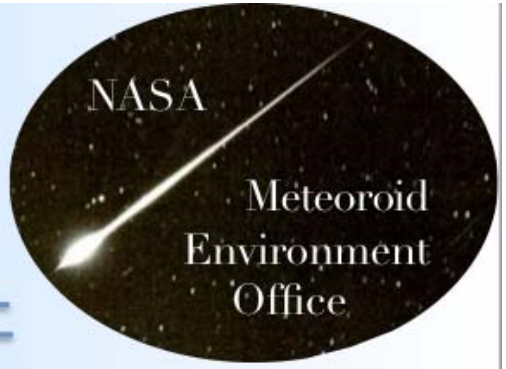
Density

- ALTAIR radar determined ballistic coefficients (densities) from > 1000 meteor decelerations in atmosphere.

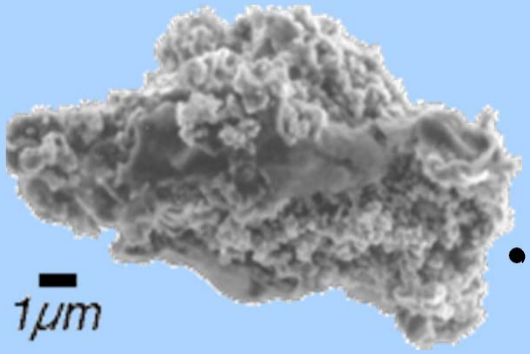
- Would like equivalent in threat size regime (> 100μm).
- Need better models of meteoroid structure.



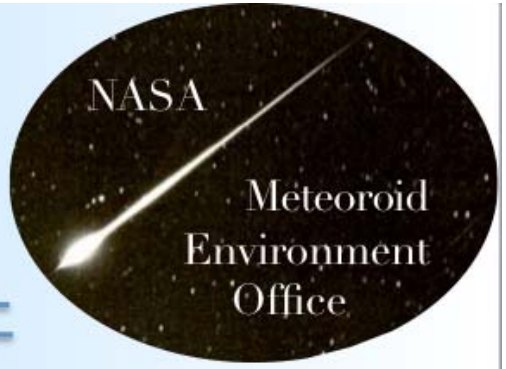
Shape



- 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.

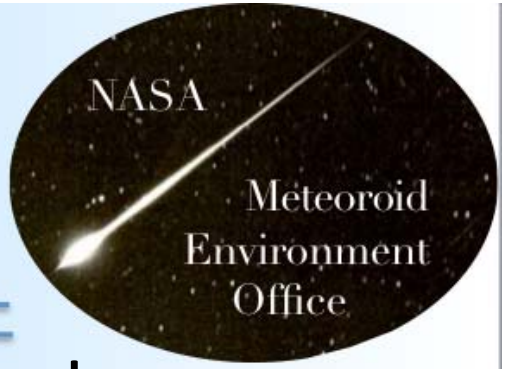


Meteor Showers

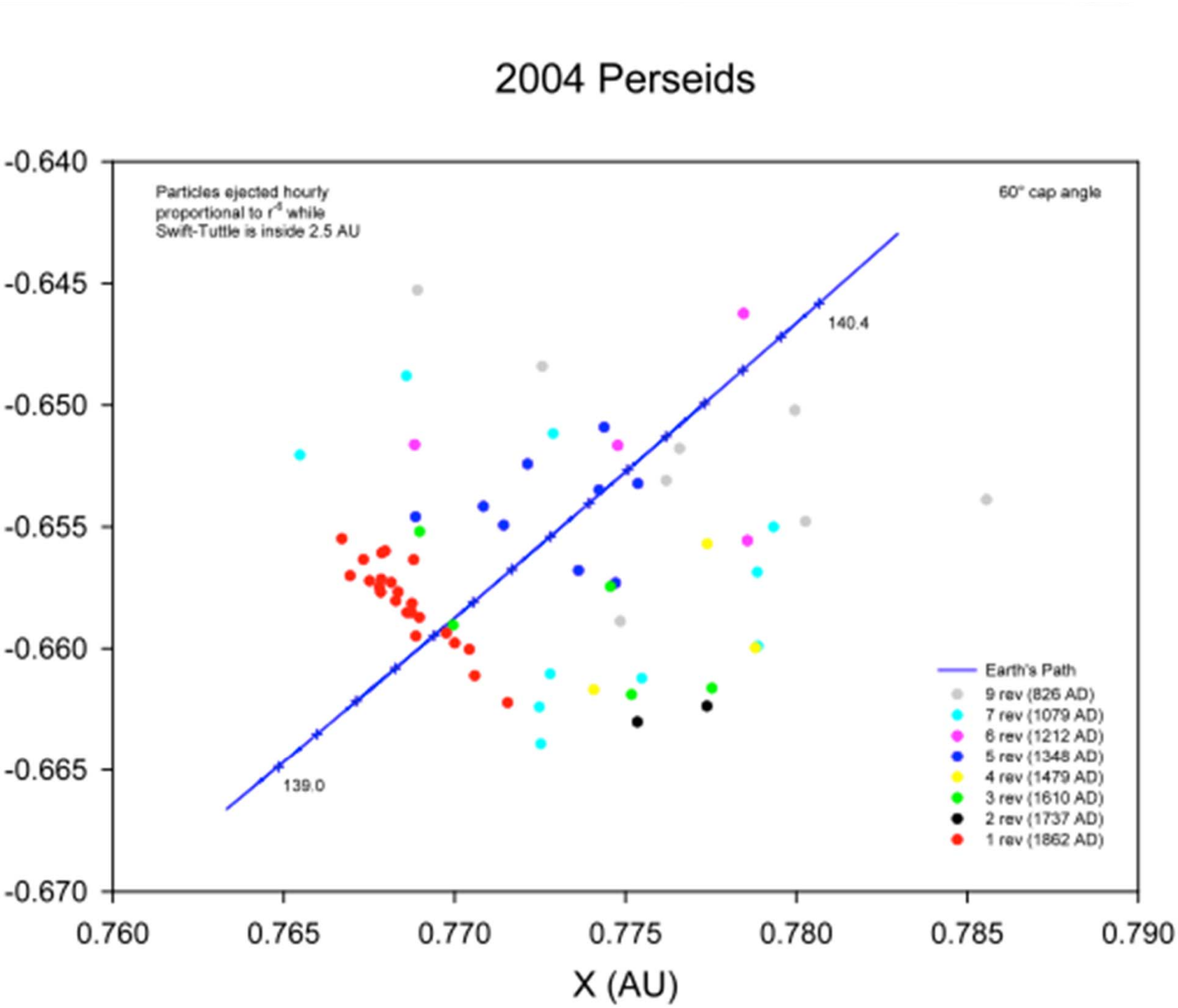


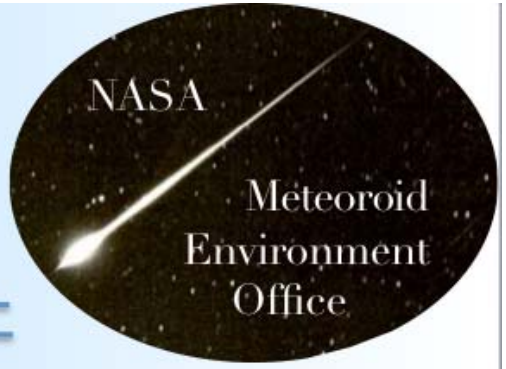
- Meteor showers occur when the Earth (or a spacecraft) encounters a stream of material left behind by an asteroid or comet
- Sporadic background accounts for >90% of the integrated flux (risk)
- Levels of meteor shower activity:
  - Shower – normal; visual rates of 10-150 per hr
  - Outburst – enhanced activity; visual rates of 150-1000 per hour
  - Storm – intense activity; visual rates >1000 per hour

Meteor Shower Forecasting



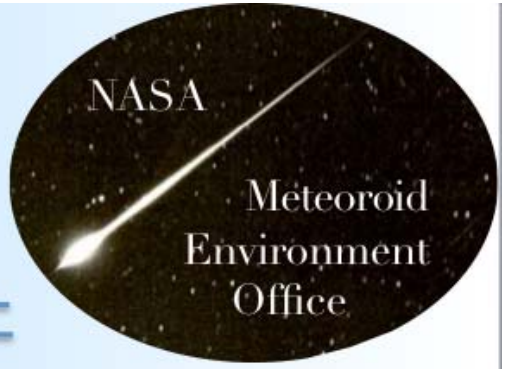
- Stream modeling technique now used
- Particles ejected from comet and dynamically evolved. Ensemble of particles near target at chosen time determines shower characteristics.
  - Numerically intensive – many thousands (millions) of particles.
  - Multiple peaks; times and intensities of shower maxima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


2004 Perseids
Particles ejected hourly
proportional to r^-4 while
Swift-Tuttle is inside 2.5 AU
60° cap angle
140.4
139.0
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)
-0.640
-0.645
-0.650
-0.655
-0.660
-0.665
-0.670
0.760
0.765
0.770
0.775
0.780
0.785
0.790
X (AU)



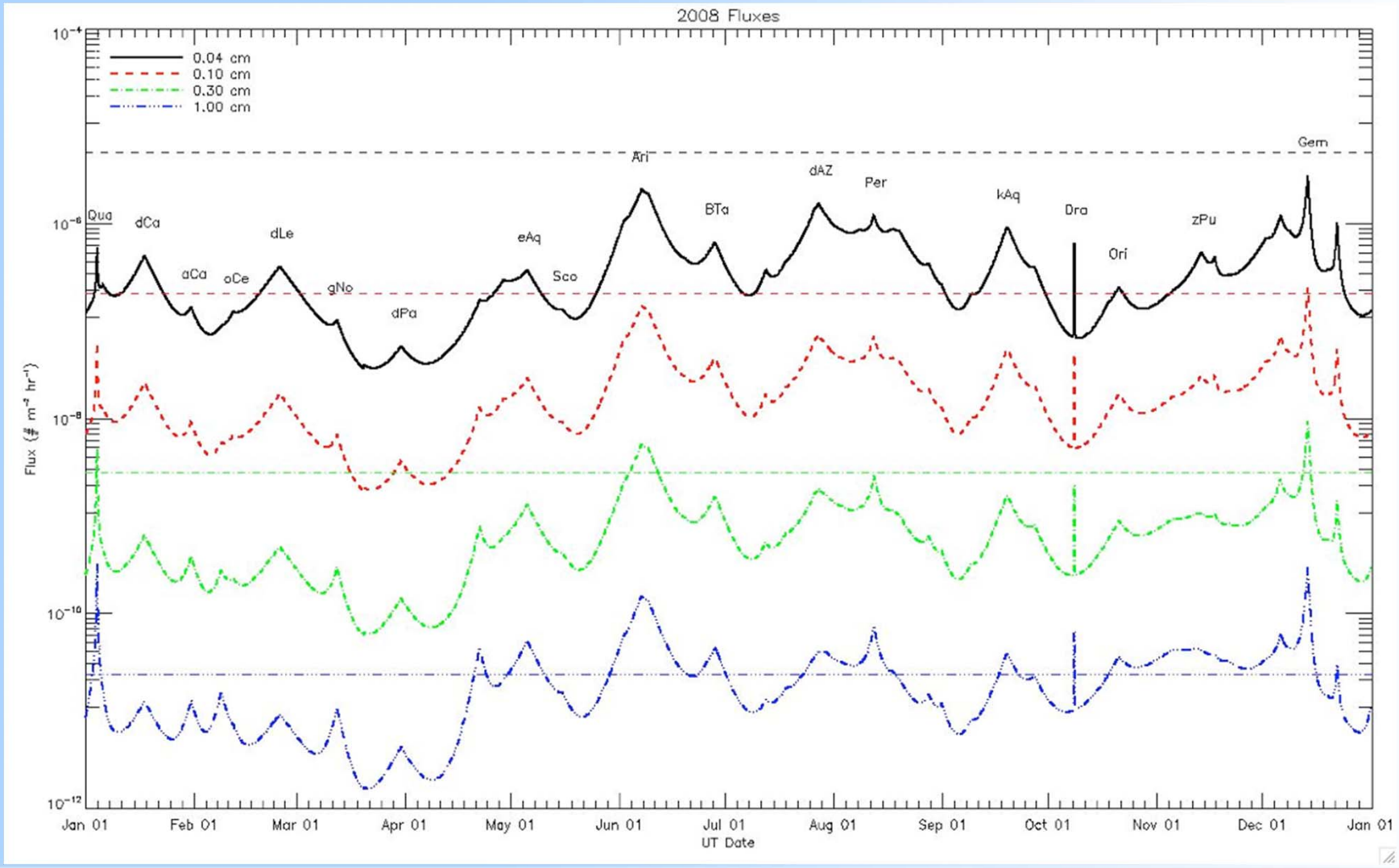
- Output for past years compared to IMO ZHR profiles or other historical observations. "Calibrates" the model and enables ZHR predictions for future.
- Only showers with potential to outburst/storm are evaluated using stream model technique. In other cases, an average observed ZHR profile is used.
- ZHRs converted to fluxes using visually-determined population/mass indices.

Annual Forecast

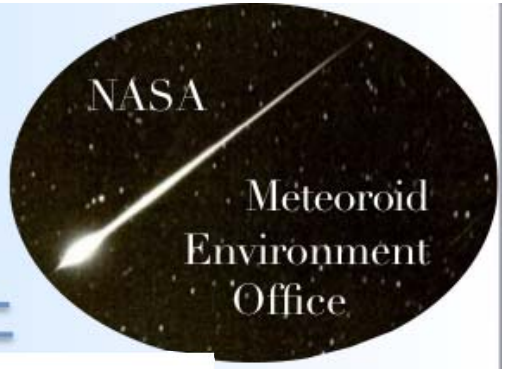


- Issued to NASA spacecraft programs (ISS, Shuttle, Chandra) and others as requested.
- Re-evaluations of outburst and storm predictions performed as new information becomes available.
- Maximum ZHRs, peak times, and durations are added to existing database of “normal” showers.
- Penetrating fluxes are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

NASA Meteoroid Environment Office



Why these sizes?



Potential Shuttle Damage

Window Replacement

EVA Suit Penetration

Radiator Penetration

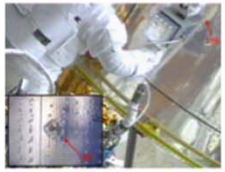
RCC Penetration

TPS Tile Penetration

Cabin Penetration

Cargo Bay Damage

Lunar Impact Monitoring



Spacecraft Surface Inspections

Atmospheric Optical (Visual, Video, Intensified Video)

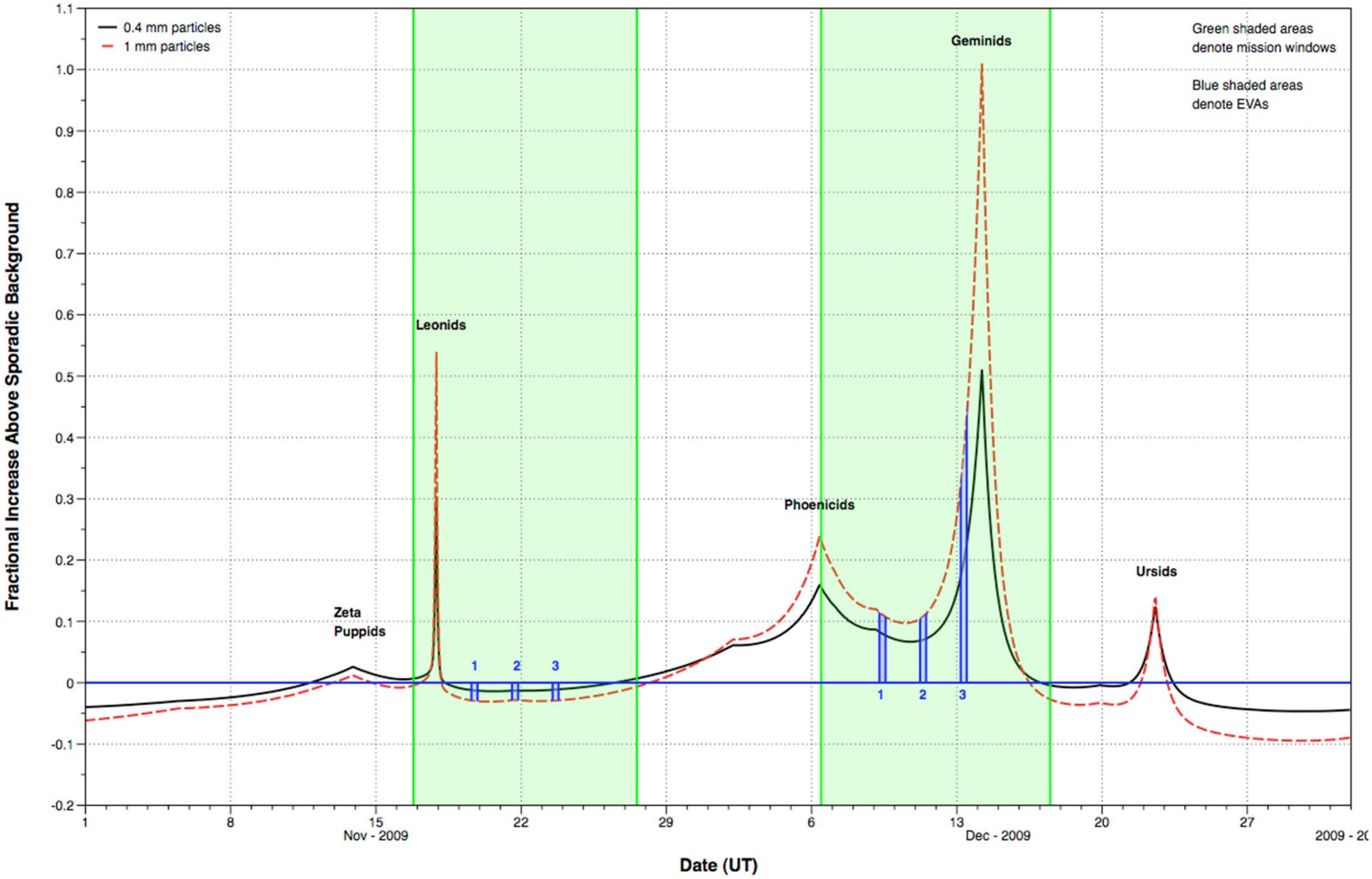
Patrol Radars (CMOR)

ALTAIR/Arecibo Radars

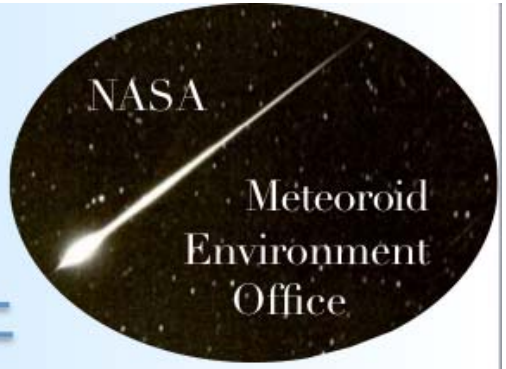
0.001 0.01 0.1 1 10 100 1000

Meteoroid Diameter in Centimeters

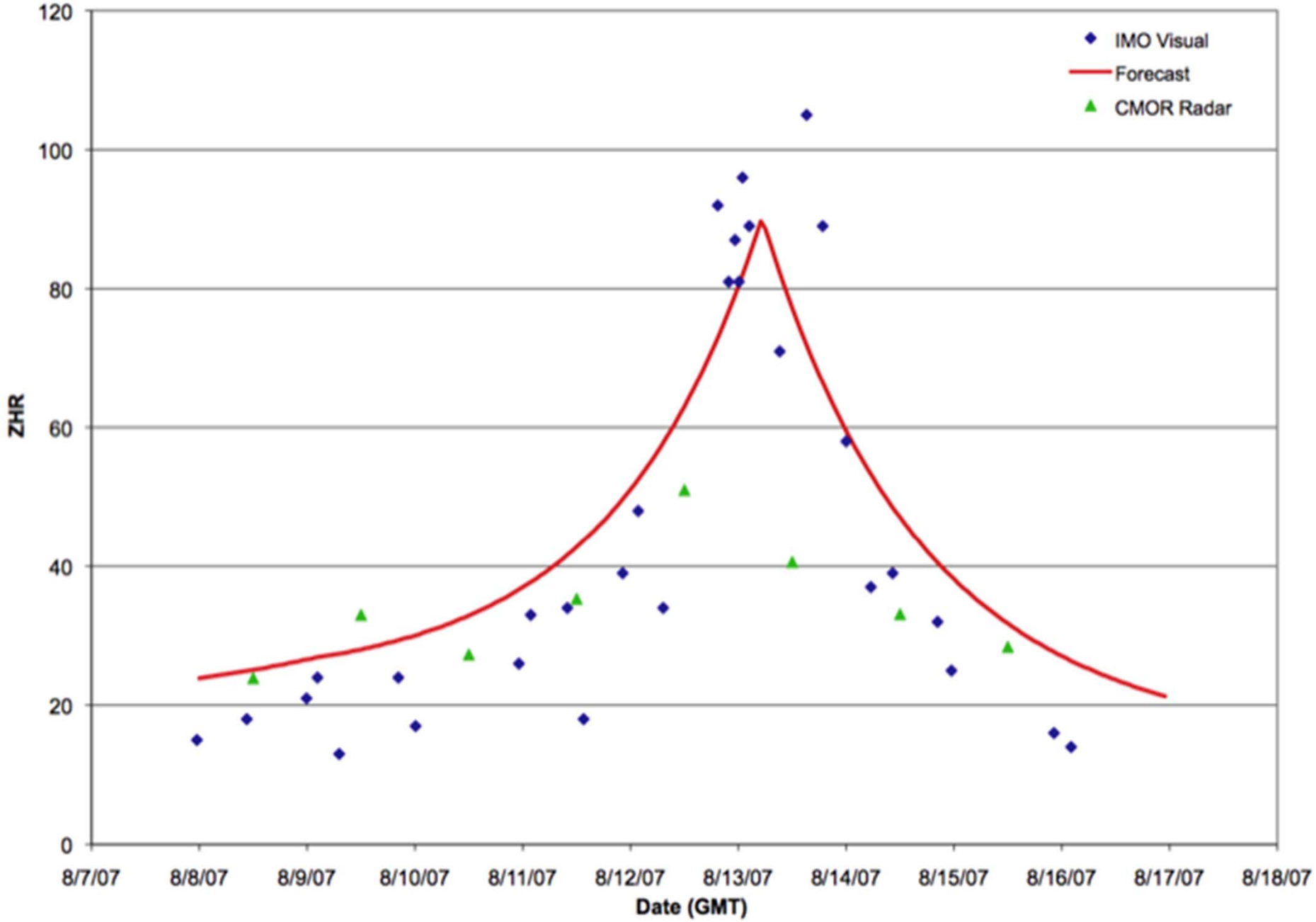
Bill Cooke/Nick Johnson

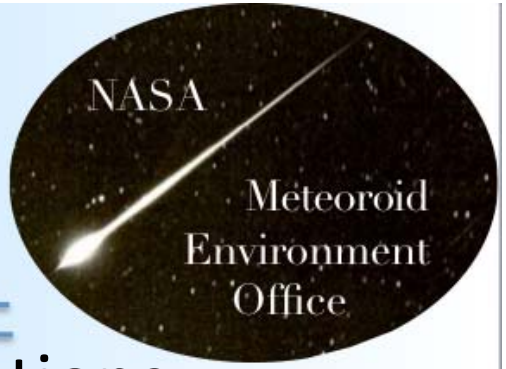

0.4 mm particles
1 mm particles
Green shaded areas
denote mission windows
Blue shaded areas
denote EVAs
Geminids
Leonids
Phoenicids
Ursids
Zeta
Puppids
1
2
3
1
2
3
Fractional Increase Above Sporadic Background
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
1
8
15
22
29
6
13
20
27
Nov - 2009
Dec - 2009
2009 - 20
Date (UT)

Verification

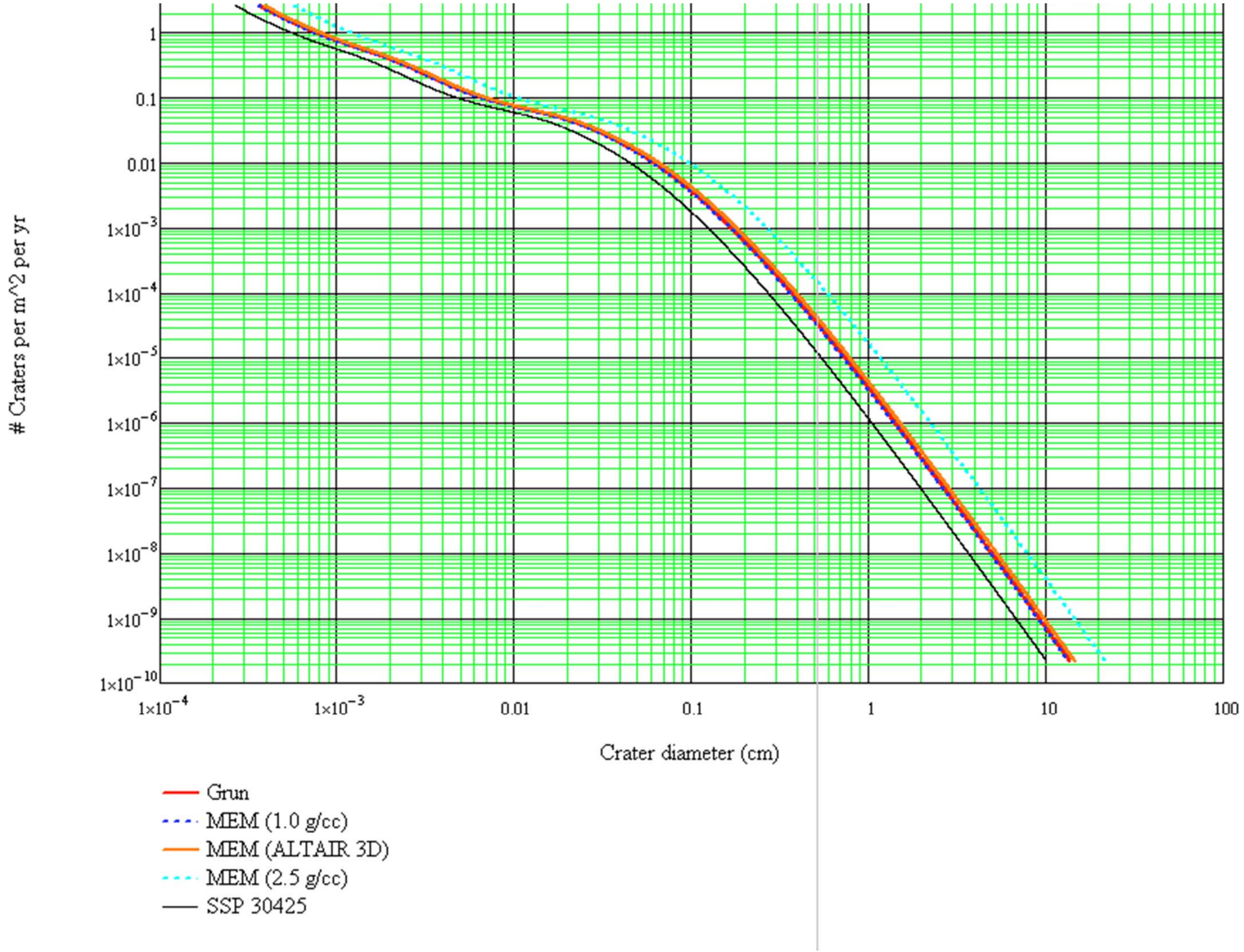


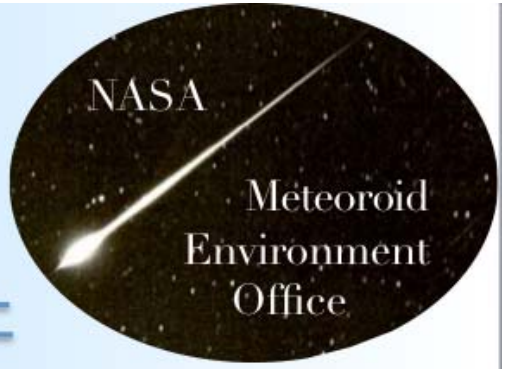
- Visual observations (ZHRs) are not only used in forecast generation, but also are used in validation of a shower forecast after the event.
- A few weeks are allowed for the numbers to be revised. We do not use the “real-time” ZHRs unless there is an anomaly investigation with tight deadlines.


120
100
80
60
40
20
0
ZHR
IMO Visual
Forecast
CMOR Radar
8/7/07
8/8/07
8/9/07
8/10/07
8/11/07
8/12/07
8/13/07
8/14/07
8/15/07
8/16/07
8/17/07
8/18/07
Date (GMT)



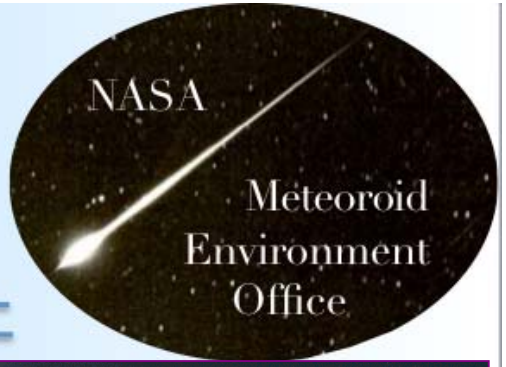
- Despite numerous study recommendations, effects/risk assessors still do not use directional meteoroid models
  - Directional models increase model execution times (computers are cheap)
  - Can't be put in a spreadsheet (spacecraft CAD models used in risk assessments have thousands of elements, yet 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.

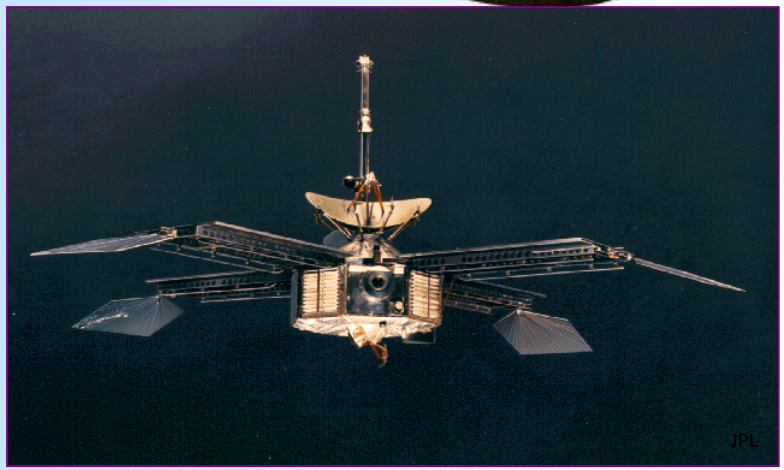

Craters per m^2 per yr
1
0.1
0.01
1×10^-3
1×10^-4
1×10^-5
1×10^-6
1×10^-7
1×10^-8
1×10^-9
1×10^-10
1×10^-4
1×10^-3
0.01
0.1
1
10
100
Crater diameter (cm)
Grun
MEM (1.0 g/cc)
MEM (ALTAIR 3D)
MEM (2.5 g/cc)
SSP 30425



- 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.

Event: Encountered meteoroid stream between the orbits of Earth and Mars in September 1967.

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.

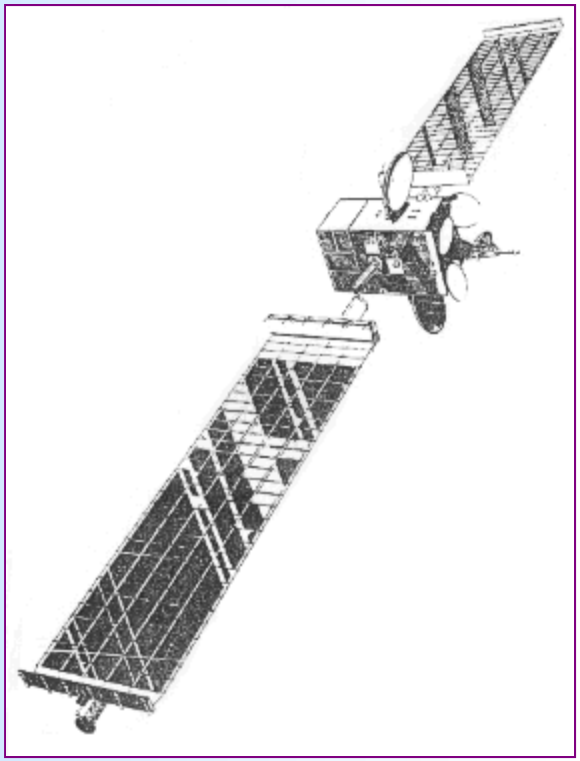
Olympus

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.


Chandra

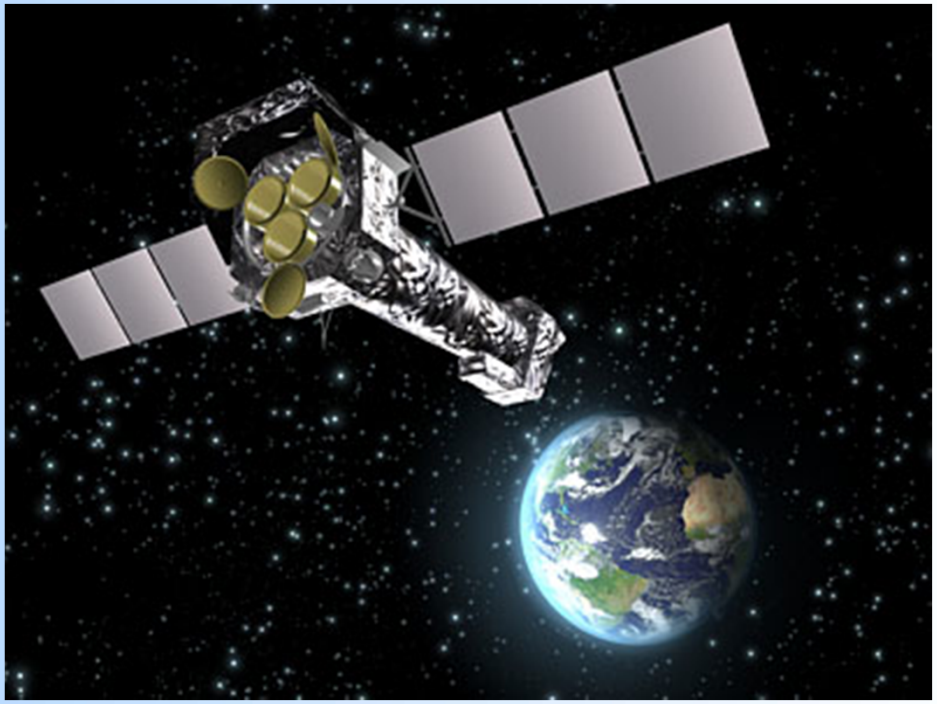
XMM-Newton

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



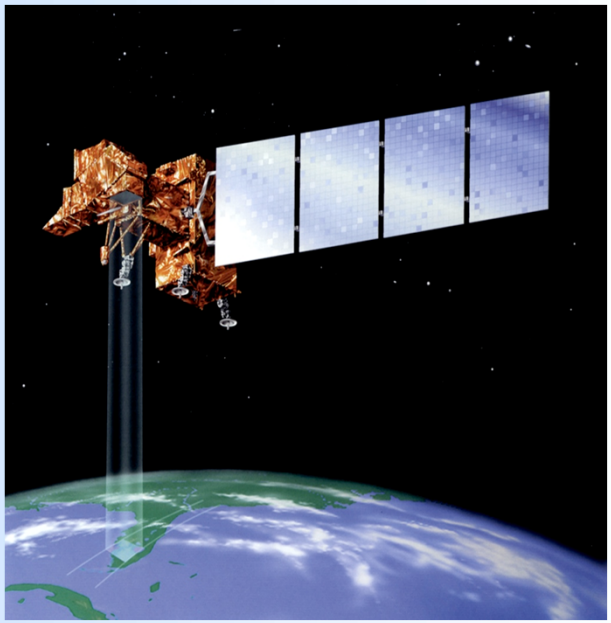
LandSAT 5

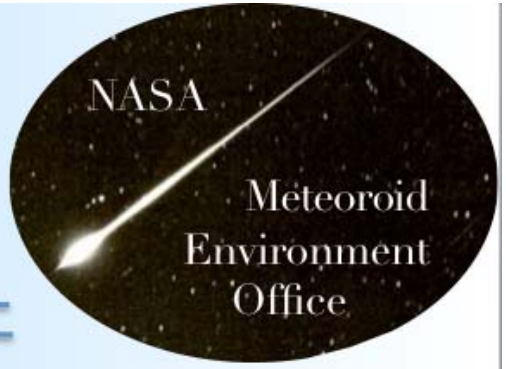
What: Remote sensing satellite

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

Consequences: Gyro temporarily failed; spacecraft began tumbling.

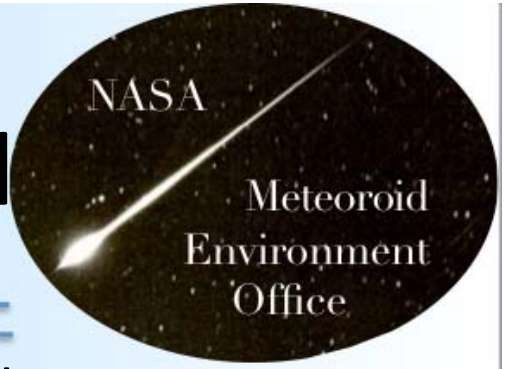
Outcome: Normal operations restored by August 17.



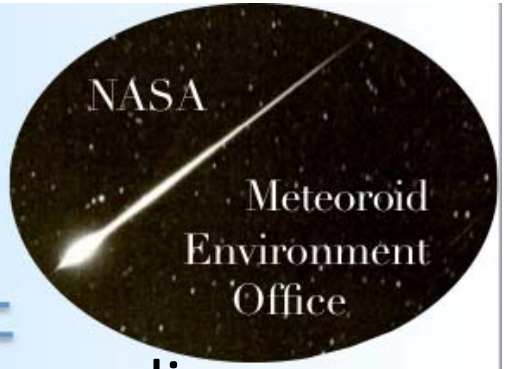


Backup

Meteoroid Engineering Model



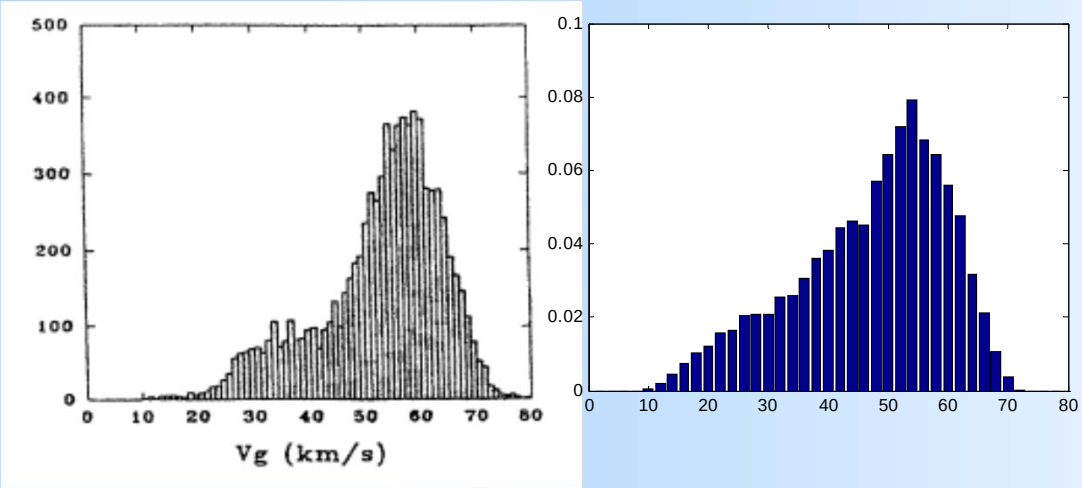
- Models the sources of the sporadic meteoroid environment from cometary and asteroidal populations
- Evolved particles from comet families to inner solar system using processes such as catastrophic collisions and poynting-robertson drag
- Resulting theoretical distributions of sporadic orbital elements 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} g <= m <= 10^{2}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,

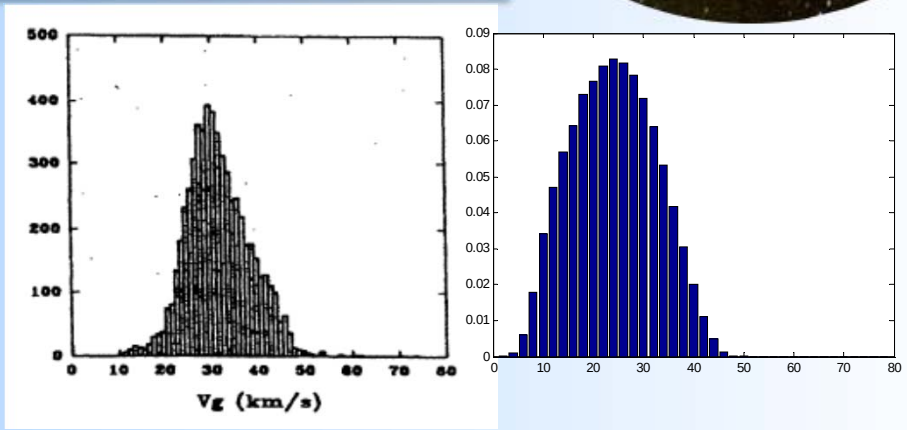
Original MEM Validation Efforts

- 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

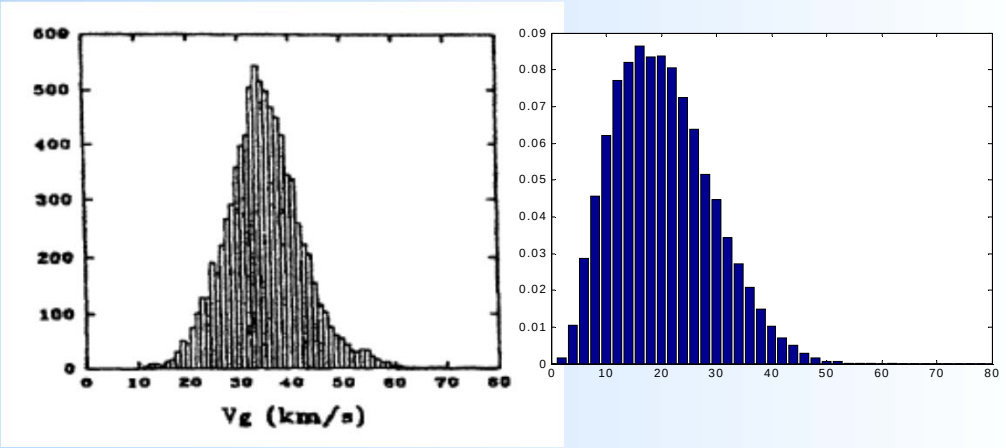


Speed Distribution of radar meteors from the Apex source as determined by HRMP, MEM

- 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

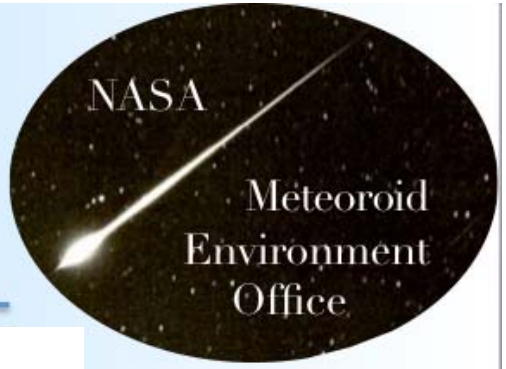


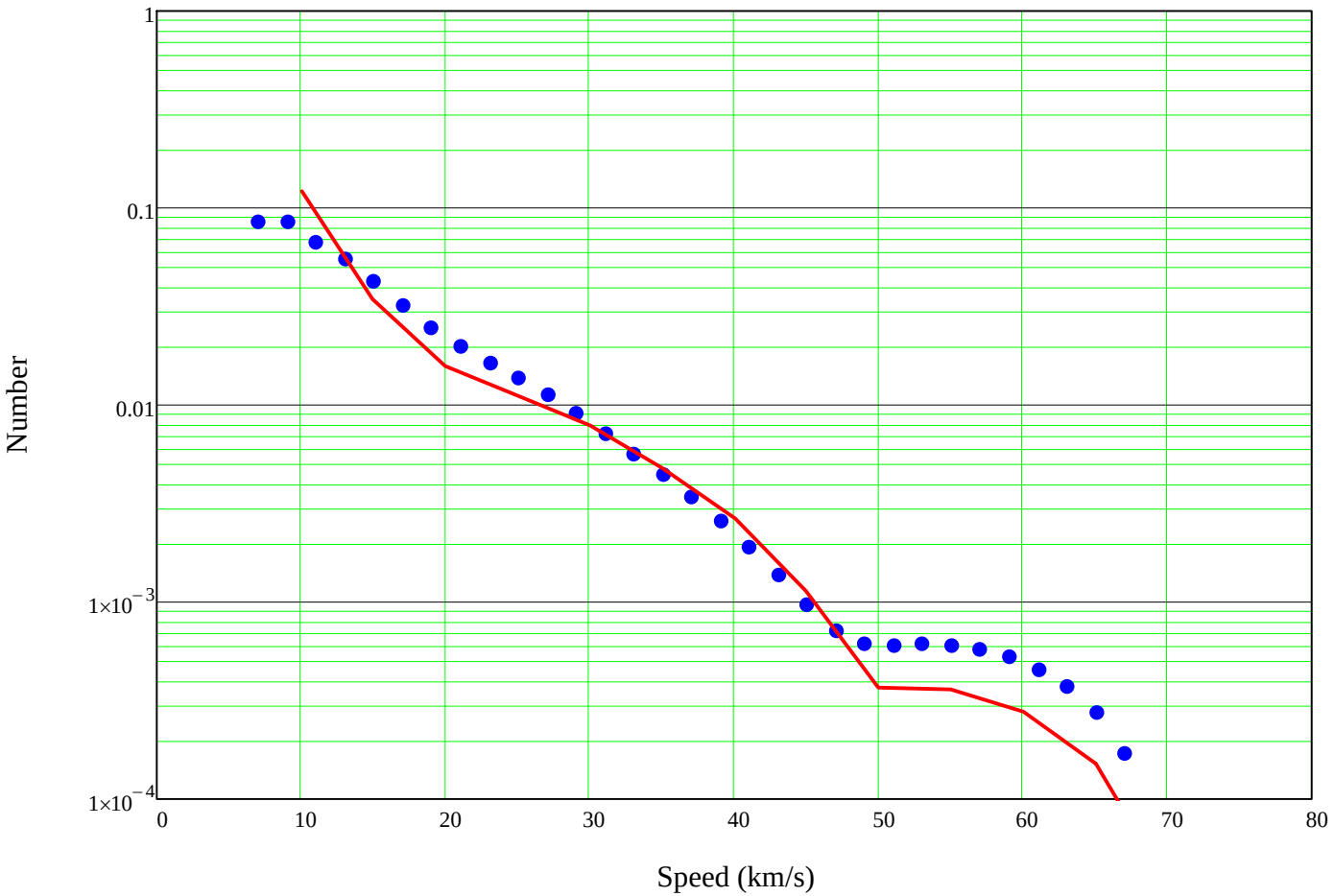
Speed Distribution of radar meteors from the Helion/Antihelion sources as determined by HRMP, MEM



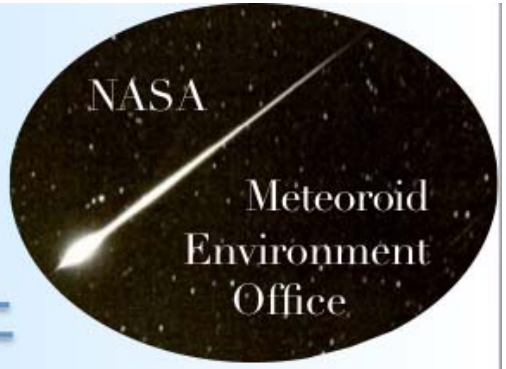
Speed distribution of radar meteors from the Toroidal Sources as determined by HRMP, MEM

Comparison to CMOR Measurements





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).