# Recent corrections to meteoroid environment models

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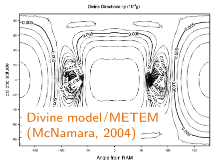
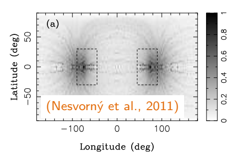
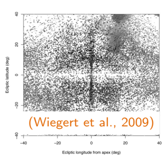
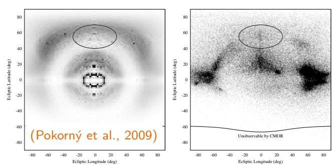
These slides have been prepared for presentation at the 2017 Fall AGU meeting in New Orleans. The left column of this document presents the slides themselves, while the right column provides explanatory notes.

## Meteoroid environment models



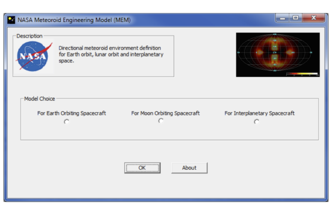






There are a host of meteoroid environment models out there, ranging from simple models that describe just a flux to detailed N-body models. They often focus on different components of the environment or use different data sources. I will *not* be attempting to review the entire body of work in this area. Instead, I'll be talking about my own recent efforts to improve our characterization of the meteoroid environment.

## Meteoroid Engineering Model Release 2.0 (MEMR2)

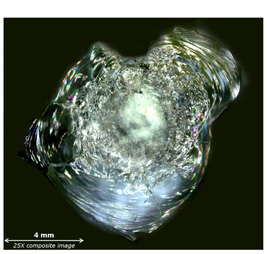



- Stand-alone software
- Computes meteoroid ($\mu$g or larger) environment relative to spacecraft
  - Does *not* compute cratering rate or risk of damage
  - *Does* provide all the information needed to do so
- Does not include temporal variations such as showers
- Most appropriate during design phase



My work is motivated by the model we produce, which is a piece of software called MEM. MEM focuses on characterizing the environment for risk-assessment purposes, and so we are specifically interested in meteoroids, not micrometeoroids or dust. MEM also does not concern itself with meteor showers, since those are a very minor component of the total meteoroid flux. Instead, this talk will deal with only the sporadic meteor complex.

## MEM components




*Meteoroid impact crater on shuttle window. Image provided by the NASA/JSC Hypervelocity Impact Technology (HVIT) Team.*

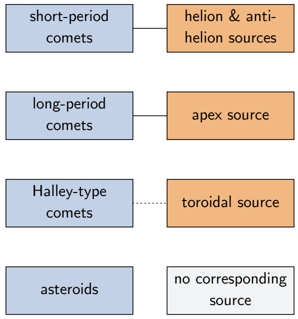
- Damage done by a meteoroid impact depends on:
  - mass (above $10^{-6}$ g)
  - velocity
  - density
  - impact angle
- We are revisiting each of these components for the next version of our Meteoroid Engineering Model (MEM).



It's not enough for MEM to describe the flux of microgram-or-larger meteoroids. We also need to describe the density, velocity, and directionality of these meteoroids, as all these properties influence the damage done to a spacecraft surface. We've been revisiting each of these properties in turn in preparation for our next update.

## Meteoroid Engineering Model

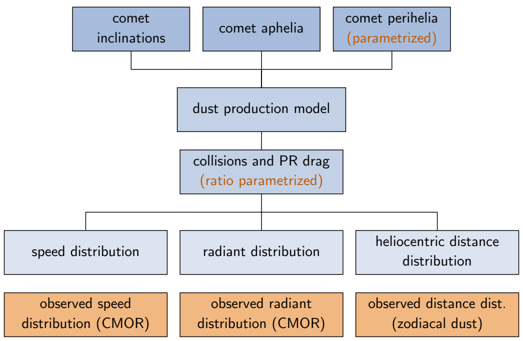
- MEM ...
  - is *not* purely empirical
  - is *not* an N-body simulation
  - *is* an analytic, physics-based model calibrated to match observations
- Jones (2004) linked parent populations to observed distributions, taking radiative forces and collisions into account
- Physical model basically the same since 2004






But before describing how we plan to change it, I'm going to take a couple of slides to describe to you how our model works. It's not purely empirical, but neither is it the output of a large-scale N-body simulation. Instead, MEM makes use of a physics based model that Jim Jones derived by combining parent body characteristics with physical processes such as collisions, and comparing the result with groupings of meteoroids.

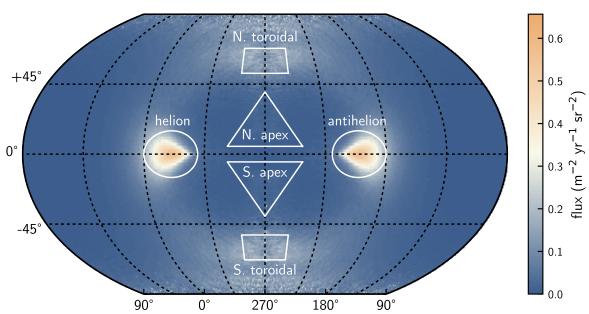
## Meteoroid Engineering Model (MEM)






For each group, he took what he did know about the parent body population and physical processes and parametrized the rest. These parameters were then fit to match the observed characteristics of the corresponding meteoroid population.

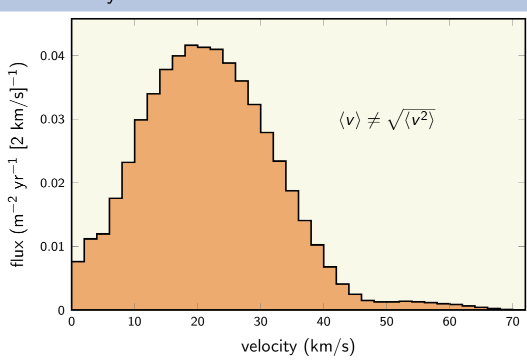
## Meteoroid directionality is not isotropic






The result is a model that is both physics-based and that matches key observations. For instance, the directionality of the model contains the same meteoroid "sources" that we observe, such as these concentrations of meteoroids coming from the sunward and anti-sunward directions.

## Meteoroid velocity is not uniform





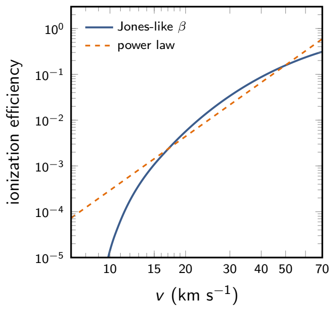

The velocity distribution is also tuned to match the speed distribution measured by the Canadian Meteor Orbit Radar, one of our primary data sources.

## Velocity distribution de-biasing

Ionization efficiency

- Meteor ionization increases with speed, and does not occur below $v_0 \sim 9$ km s$^{-1}$.
- Detections are complete to smaller masses at higher $v$.
- We use the Jones ionization efficiency[a] to de-bias the radar meteor speed distribution efficiency[b]

[a]Jones, 1997; Thomas et al., 2016
[b]Moorhead et al., 2017






Now that you hopefully have a feel for what our meteoroid model does and needs to do, I'll shift to talking about our efforts to improve it. For instance, we have re-derived our velocity distribution using the same data source – CMOR – but with a more modern treatment of ionization efficiency. Radars detect the ionization produced by meteors, and meteors ionize much more readily at high speeds. You therefore have to take this into account to get an idea of what the mass-limited speed distribution looks like.

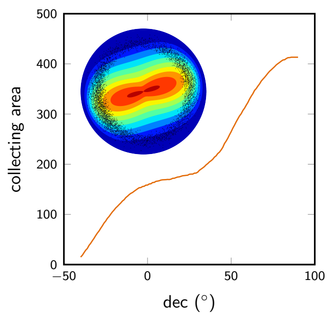
Recent work done by Zoltan Sternovsky's group – which I think we'll hear more about in the next talk – tends to support the Jones (1997) equations for ionization efficiency. The big difference between this and the power law we used in the past is that it drops to zero for non-zero velocity. That makes a big difference at the low end of your speed distribution.

## Radar bias corrections

Limiting mass also depends on:

- Beam pattern/radiant visibility
- Range
- Initial trail radius effect[a]
- Pulse repetition effect
- Finite velocity effect

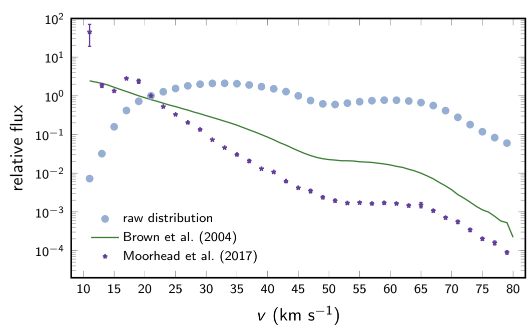
[a]Jones & Campbell-Brown (2005)






Ionization efficiency isn't the whole story, though – detectability also depends on things like your beam pattern, the declination of the meteor radiant, and distance to the meteor. And there are a suite of radar observing biases, such as the initial trail radius effect, which occurs when the radius of the meteor trail is comparable to the radar wavelength and you get destructive interference.

## Velocity distribution de-biasing



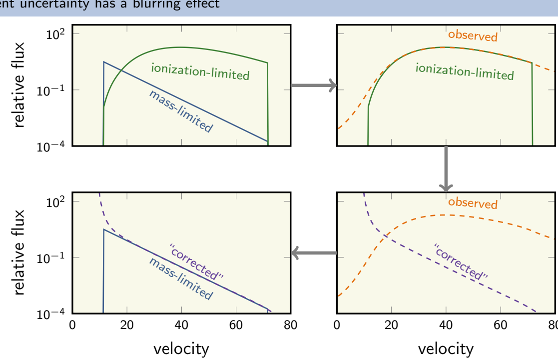



After taking all that into account, you end up with a substantially different speed distribution than what you observed. Here, you see the raw meteor speed distribution observed by the Canadian Meteor Orbit Radar as blue circles. The green line represents an older debiasing of the distribution that matches what we have in our model now. You'll notice that it is significantly steeper than the raw distribution – that's due to the ionization efficiency correction. Finally, our new debiasing yields the distribution that appears as purple dots, which is even steeper.

You may also notice that there is a sharp spike in the slowest speed bins that looks a bit odd. When I played around with quality cuts on the data, it changed that spike by quite a lot.

## Velocity distribution sharpening

Measurement uncertainty has a blurring effect



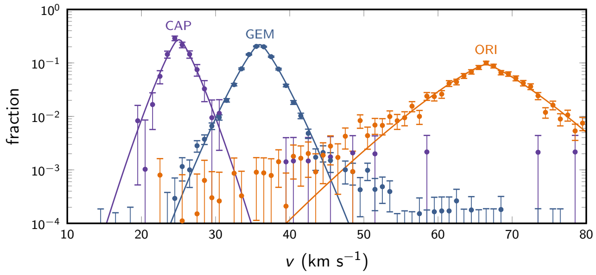



This cartoon demonstrates what's going on with that spike. If your true, mass-limited speed distribution looks something like this straight line, then your true, ionization-limited speed distribution looks like the green curve. But in reality you have measurement uncertainty, and that will tend to blur the distribution so that you measure something more like this orange curve. If you then try to correct that orange curve for ionization efficiency, the number of low speed meteors blows up, and you end up predicting way more low speed meteors than are actually there.

You can try to avoid this by placing severe quality cuts on your data, but that has the potential of introducing additional biases. So we need a different way to handle this problem.

## Velocity distribution sharpening
Constructing a filter

- We use meteor showers to characterize our observation "filter" ...



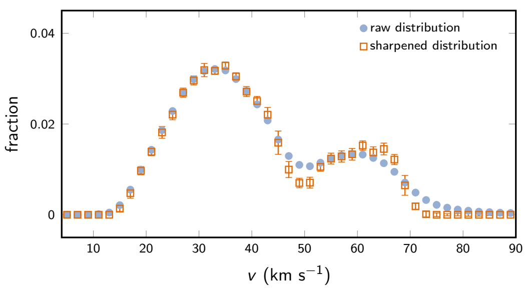



What I decided to do was handle the blurring effects of measurement uncertainty in a way that's analogous to handling blurred images. If you know exactly how the data is blurred – the filter or point-spread function – you can try and invert that process to obtain a sharpened image or distribution.

Fortunately, CMOR sees plenty of meteor showers, which hit the atmosphere with close to a single speed. So if we look at the spread of velocities that we get for members of a meteor shower, we can use that to characterize our filter.

## Velocity distribution sharpening
(Moorhead, submitted to MAPS)

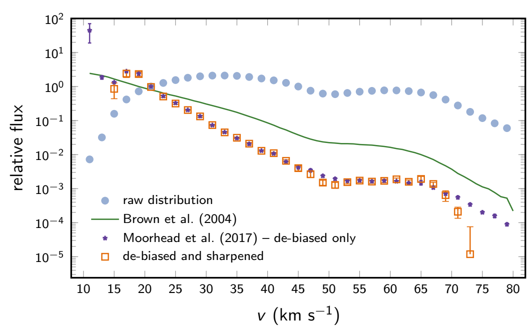
- When we "sharpen" the raw distribution, hyperbolic meteors disappear naturally.






This plot shows you the raw speed distribution before and after I "sharpen" it using my shower-determined filter. You can see that the peaks and troughs are a little more pronounced. Seemingly hyperbolic meteors disappear from the data entirely. And, while it's hard to see on a linear scale, the sharpened distribution is consistent with having no meteors at all slower than 14 km s$^{-1}$.

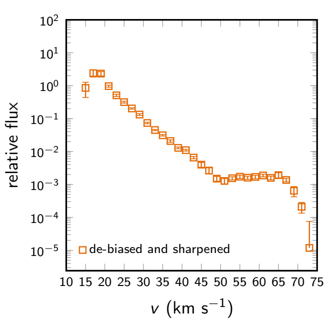
## Velocity distribution sharpening

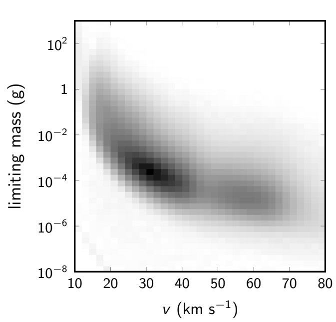





Here the velocity distribution has been both sharpened and de-biased (orange squares), and you can see that the spike disappears completely.

## Velocity distribution sharpening






I'd like to make one caveat about this "mass-limited" speed distribution, however. This process relies on the assumption that the speed distribution does not change with mass. However, models predict that it does change with mass at smaller mass scales, and it's also possible that the speed distribution of 1 g meteoroids differs from that of $10^{-5}$ g meteoroids. So we are continuing to investigate the speed distribution with other instruments to see how this varies with particle size.

## Meteoroid densities

- Density measurements are few and far between.
- We need a density proxy. Two possibilities:
  - $K_B$ – a combination of observable quantities (height, velocity, etc.) that supposedly reflects a meteoroid's "strength."
  - $T_J$ – a combination of orbital quantities (semimajor axis, eccentricity, and inclination) that is used to divide objects into "dynamical types"
- We used a recent survey of meteoroid densities to check which quantity was better correlated with density. The result was surprising …

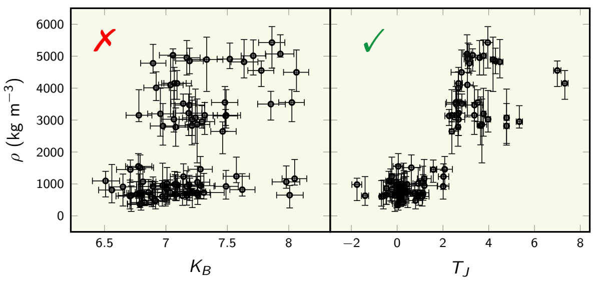


I'm now going to switch to discussing meteoroid density. While we can measure millions of meteoroid velocities with an instrument like CMOR, we can do no such thing with density. What few densities we have are mostly the results of painstaking recreations of meteor light curves and trajectories. In order to extrapolate these to the entire meteoroid environment, we need a density proxy.

Meteor astronomers have frequently made use of a quantity called $K_B$, or Ceplecha type, as a crude measure of meteoroid physical properties. The idea is that the height and speed at which a meteoroid begins to ablate probes its material strength and density. Alternatively, Kikwaya calculated about 100 meteoroid densities and found that they were correlated with Tisserand parameter, or dynamical type. We suspected that Ceplecha type might be a better proxy, and so we plotted density against $K_B$ to compare it with the density-$T_J$ correlation.

## Meteoroid densities

- Kikwaya et al. (2011) constrained densities for $\sim 100$ small meteoroids using ablation modeling.
- Co-authors provided the data to calculate $K_B$ and $T_J$



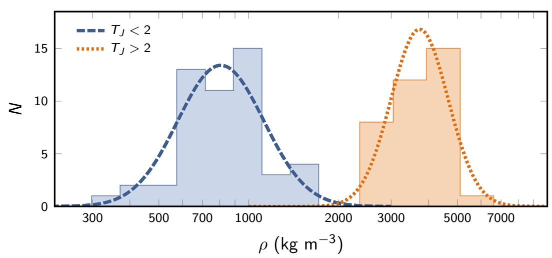



The results really surprised us – we found that $K_B$ was hardly correlated with meteoroid density at all. The relationship between density and $T_J$ that Kikwaya found was much better, at least within his data set.

## Density distribution

Moorhead et al. (2017)

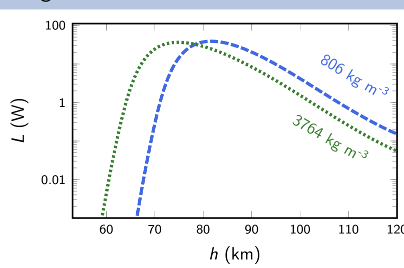
- We divide meteoroids into two groups and assign a density distribution to each:
  - $T_J < 2$ – HTCs, NICs – apex and toroidal
  - $T_J > 2$ – JFCs, asteroids – helion/antihelion






We therefore decided to use $T_J$ as the basis for building our sporadic meteoroid density model. We fit two gaussians to the Kikwaya data, and assign high densities to the helion and antihelion source, and low densities to the apex and toroidal sources.

## Density de-biasing




- Density does not affect peak brightness ($L$); denser meteors simply peak at lower heights (see plot).
- Thus, no significant density bias in observations.



I was concerned that this difference in density might lead to observational biases that we'd also have to account for. However, it appears that changing only density does not change the peak brightness of a meteor significantly.

## Density de-biasing

- Impact crater depth *does* depend on $\rho$:

$$\text{depth} \propto \rho^{4/27}$$

- Ratio of radiation pressure to gravity also depends on $\rho$:

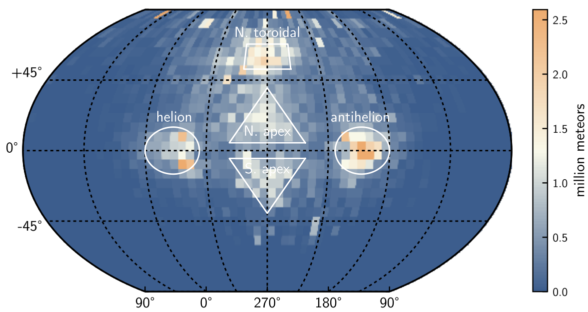
$$F_r/F_g \propto \rho^{-2/3}$$

- Density affects the conversion of $\beta$-limited to mass-limited distributions, or mass-limited to crater-limited distributions.



It *does*, however, affect the damage it does to spacecraft – a denser meteoroid will penetrate deeper into a spacecraft surface for the same mass. For those of you that care more about science than spacecraft, it also affects how you convert the results of N-body simulations to a mass- or luminosity-limited distribution.

## Meteoroid directionality






If we convert our new velocity and density distributions into a crater-limited directionality map, we get a radiant distribution in which the helion and antihelion sources dominate much more than they do in the observations.

## Summary

- We have revisited the meteoroid velocity, density, and directionality distributions.
- Our velocity distribution is:
  - derived from radar (CMOR) observations,
  - de-biased using modern ionization efficiency, and
  - sharpened to remove uncertainty smoothing.
- Our density distribution is based on Kikwaya et al. (2011).
  $K_B$ was not well-correlated with $\rho$ in any data set we examined.
- ~40% of radar meteors are associated with the helion/ antihelion sources.
  After de-biasing, we find that ~80% of craters are associated with these sources.