Meteor Shower Fluxes with All Sky Cameras

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Meteoroids 2019

Overview

- Why Fluxes?
- Why All-Sky?
- The process described far too quickly
- Mass index measurements for five major showers

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Why Fluxes?

Fluxes are the physical quantity describing the number of meteoroids impacting a surface per unit area and time. This quantity links the parent body orbit and ejection physics to the meteor rates observed at Earth. More importantly for the MEO, this is the number that goes into spacecraft risk assessments.

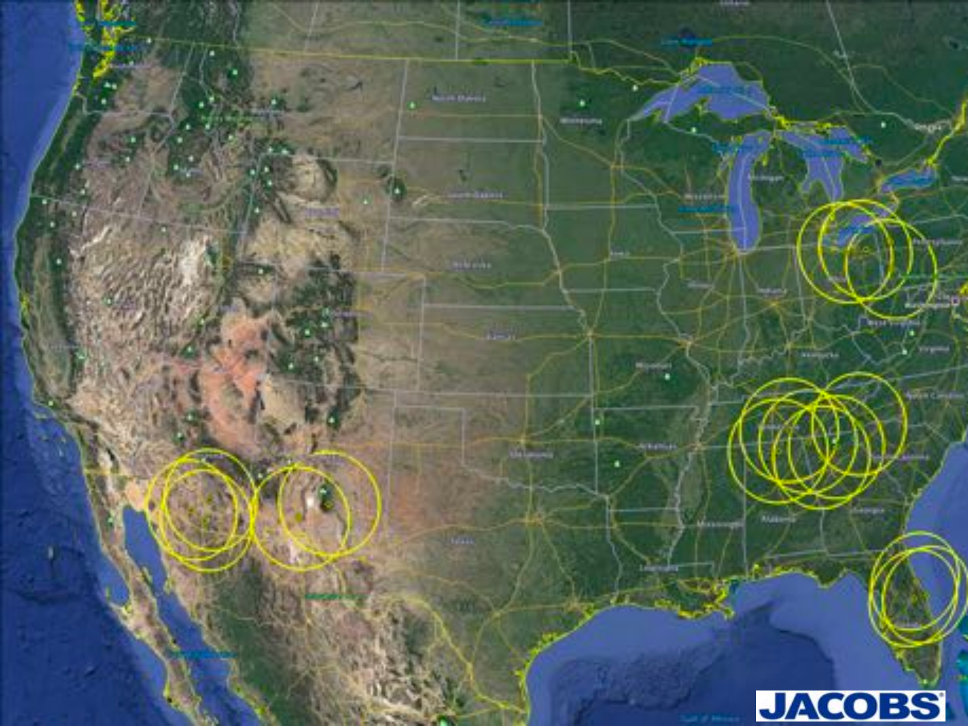
Flux $\times$ Mission Time $\times$ Surface Area $\rightarrow$ # of Impacts

Why All Sky?

NASA's All Sky Fireball Network has been operating since 2008, and in the past five years newly deployed cameras have greatly increased coverage.

- The masses of meteoroids typically detected in the All Sky cameras put them at the top of the spacecraft threat regime.
- Including flux measurements from Wide Field ($\sim 21^\circ \times 15^\circ$) cameras with Canadian Meteor Orbit Radar (CMOR) allows the mass index to be measured.

$$\frac{dN}{dm} = N_0 \left(\frac{m}{m_\star}\right)^{-s}$$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We Need Four Numbers

We need four numbers to measure a flux:

1. The number of meteors detected that satisfy certain quality cuts, N.
2. The collecting area of the sky within the camera fields of view that detected each event, A_i.
3. The total exposure time in which the cameras that detected the event could feasibly observe similar events, t_i.
4. The limiting mass/absolute magnitude of the flux measurement, which corresponds to the least massive/luminous meteoroid for which the flux is measured.

We need to make sure we are making sensible choices in calculating all four of these numbers. Focusing on limiting magnitude in this talk, speak to me offline to discuss the other three!

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A Survey Perspective

Each night of observation can be treated as an independent astronomical survey of meteors. The detector is a volume of the sky at the intersection of ≥ 2 All Sky cameras.

In an ideal situation we have a model describing the probability of detecting a particular meteor at a particular location in a particular camera (or combination of cameras) at a particular time. This is known as the selection function, and maps the observed SAMPLE of meteors to the UNDERLYING POPULATION of meteors.

Selection Functions are HARD

Selection Functions

Most flux algorithms are designed for pairs of cameras with $\sim 10^\circ - 50^\circ$ FOV's, and attempt to model this selection function from first principles. At a minimum we need to account for:

- Differential sensitivity due to camera effects (flat fielding, background).
- Differential sensitivity due to sky effects (range, angular rate).
- Differential sensitivity over the course of the night (radiant geometry, weather, Moon).

Usually requires serious laboratory and simulation effort to fully characterize.

We're not going to do that

An Empirical Method

For most surveys, there is a region of parameter space where we expect high ($\sim 100\%$) completeness.

- We can identify this region using the data themselves.
- These same data will help us calculate the other numbers we need for fluxes.
- Ideal for All Sky cameras with very complex selection functions.

There are a few trade-offs, however:

- Need large parent sample.
- Large sample decimated by completeness restriction.
- Need to average over entire night and camera network.

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Calculating the Limiting Magnitude

Fit distribution of absolute magnitudes for that night to a Gumbel model. Peak of histogram as determined by this fit is M_{lim}. We assume 100% completeness for meteors brighter than M_{lim} for the entire survey (i.e., at all times in every camera combination). No further corrections for differential sensitivity are needed.

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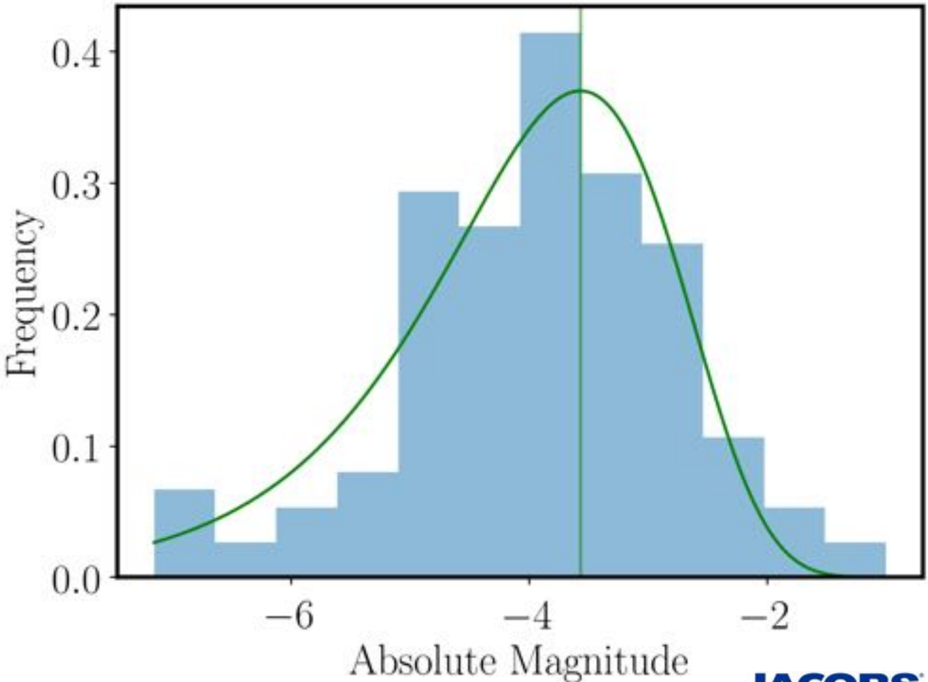

0.4
0.3
0.2
0.1
0.0
Frequency
−6
−4
−2
Absolute Magnitude

The Flux

With event specific collecting area and exposure time already calculated, we then determine the flux down to our limiting magnitude as:

$$\mathsf{F}(< \mathsf{M_{lim}}) = \sum_{\mathsf{i}} \frac{1}{\mathsf{A_i t_i}}$$

We turn this into a mass limited flux.

$$2.25 \, \mathsf{log}_{10} \left(\frac{\mathsf{m_{lim}}}{1 \, \mathsf{g}} \right) = -8.75 \, \mathsf{log}_{10} \left(\frac{\mathsf{v}}{1 \, \mathsf{km \, s}^{-1}} \right) - \mathsf{M_{lim}} + 11.59$$

We will determine equivalent ZHR values and compare to visual reports from that same night.

Five Showers

1. Geminids (GEM), 2015-Dec-15
2. Perseids (PER), 2016-Aug-12
3. Leonids (LEO), 2018-Nov-19
4. Quadrantids (QUA), 2016-Jan-04
5. Orionids (ORI), 2017-Oct-22

For GEM we have an independent mass index. For the others we will measure it using these data. For all five showers we will compare results to visual ZHR for that night. Note there are ZERO free parameters for the ZHR comparison, and we are extrapolating over four orders of magnitude...

Comparisons to IMO Values

Shower	IMO (r/s)	This Work (r/s)	Equivalent ZHR	IMO ZHR
GEM	$2.6/1.95$	$2.04/1.71$	56 ± 11	55
PER	$2.4/1.87$	$1.72/1.54$	120 ± 22	118
LEO	$2.5/1.92$	$1.97/1.68$	29 ± 6	$24^{\dagger}$
QUA	$2.1/1.74$	$2.43/1.89$	45 ± 10	33
ORI	$2.5/1.92$	$2.06/1.72$	33 ± 17	25

Conclusions

1. This algorithm calculates physically calibrated meteor shower fluxes for an All Sky camera network.
2. Empirical calculations avoid the need for a selection function, if one has a large parent sample willing/able to be pared down.
3. Combining these fluxes with radar and other optical cameras provides new mass index measurements.
4. All five showers give mass indices and equivalent ZHR's consistent with past measurements.

Backup Slides

Starting Calculations - The Sample

We first need to curate a sample of shower meteors for the given night:

1. Event is considered to be detected ONLY in the cameras that saw it at elevation angles above 20°. We require detection in at least two cameras.
2. Every event will have its own collecting area and exposure time, calculated using the combination of cameras that observed it above 20° elevation.

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Starting Calculations - II

We store a few more bits of information needed for fluxes.

1. Beginning height distribution will be used to determine a detector volume that depends on the shower in question and event's camera combination.
2. Peak magnitude distribution will be used to determine the limiting meteor magnitude for the night.

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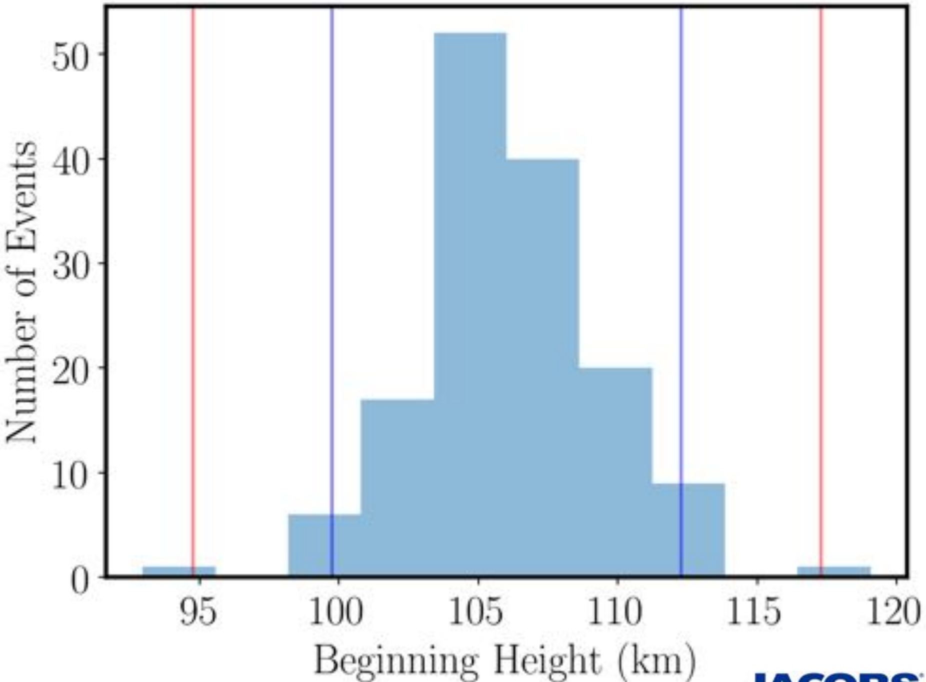
Detector Volume

Detector volume depends on the cameras that saw the event and the shower in question, but not time.

1. Height range in volume is calculated using central 95^{th} percentile range of beginning height distribution, padded by 5 km.
2. Construct lat/lon/height corners of all cameras that saw the event, transform into Earth-Centered Earth-Fixed (ECEF) coordinates. Corners define an initial volume.
3. Break this volume up into adjacent spheres of 4 km radius.
4. Identify all spheres that satisfy elevation angle and height restrictions.
5. This list of sphere positions gives us a collecting volume.

A complete sample $\rightarrow$ any meteor brighter than M_{lim} would be detected anywhere within this volume.



Number of Events
0
10
20
30
40
50
95
100
105
110
115
120
Beginning Height (km)

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Detector Area

Now we project this into an area along the direction of the radiant. The radiant direction is determined at the time of the event for each sphere point.

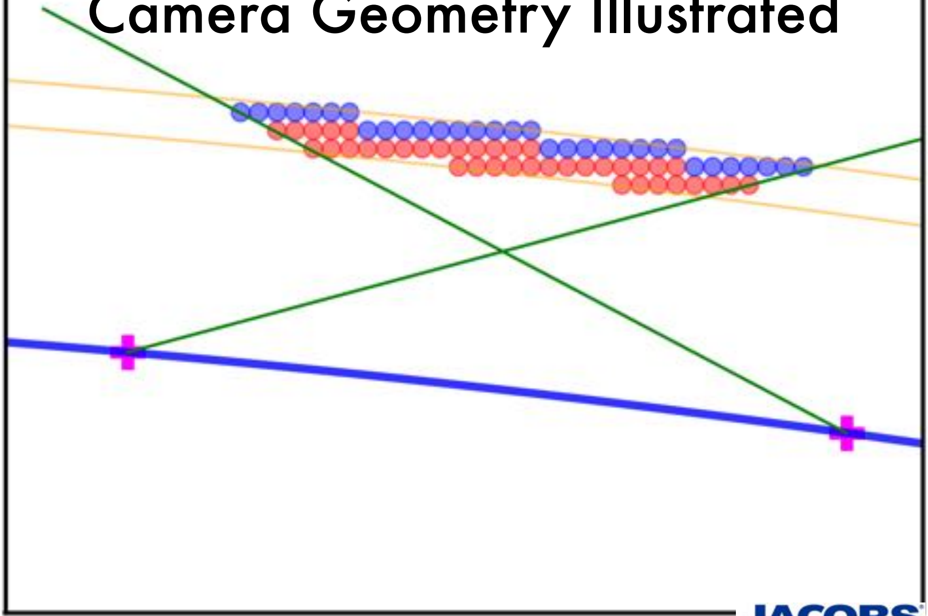
1. For each sphere center, move one diameter in the direction of the radiant.
2. If the minimum distance I am from a neighboring sphere in the detector volume is greater than 0.735r, I am outside the collecting volume and therefore exposed to the radiant.
3. Collecting area is simply $\frac{4}{\pi} \times N\pi r^2$, where N is the number of spheres exposed to the radiant in this calculation.
4. This generally corresponds to the "top layer" of the detector volume, but accounts for curvature of the Earth and possible edge effects.

Limiting Magnitude

Limiting Magnitude tells us WHICH flux we are measuring. We determine the limiting magnitude for the night across the entire network empirically using a Gumbel distribution fit.

Magnitudes in the subsequent plot are absolute (i.e., range corrected). We assume that our survey is complete to all sources brighter than M_{lim}.

Camera Geometry Illustrated



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Clear Time

Clear times are identified visually/manually. Total exposure time per event calculated as intersection of all times that combination of cameras could have seen meteors.

Flux Uncertainties

Uncertainties arise from two sources:

1. The Poisson fluctuations on the number of observed events $\left(\frac{F}{\sqrt{N}}\right)$.
2. The variance in area-time products between the observed events (estimated via bootstrap).

Total uncertainty is the sum of these two values in quadrature, and corresponds to $\sim 20 - 30\%$.

Equivalent ZHR

Both $F(< M_{lim})$ and s are directly measured from All Sky flux with other optical/radar measurements.

$$\frac{dN}{d\mathcal{L}} = N_0 \left(\frac{\mathcal{L}}{\mathcal{L}_\star}\right)^{-\alpha}$$

$$\alpha = 1 + 2.5 \log_{10} r \qquad s = 1 + 2.3 \log_{10} r$$

$$\left(\frac{\mathcal{L}_{lim}}{\mathcal{L}_{6.5}}\right) = 10^{(M_{lim} - 6.5)/-2.5}$$

$$\frac{F(< M_{lim})}{F(< 6.5)} = \left(\frac{\mathcal{L}_{lim}}{\mathcal{L}_{6.5}}\right)^{1-\alpha}$$

$$ZHR = \frac{F(< 6.5) * 37200\,km^2}{(13.1r - 16.5)\,(r - 1.3)^{0.748}}$$

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Mass Index and ZHR Uncertainties

Our mass index and equivalent ZHR measurements include other sources of uncertainty:

- Uncertainty in the limiting mass of the All Sky flux measurement.
- Uncertainty in the other optical/radar flux measurements.

We handle these with Monte Carlo simulations to get distributions of both the mass index and equivalent ZHR.

Geminids, 2015-12-15

- The same night utilized to estimate the mass of the entire Geminid stream at Meteoroids 2016 (Blaauw 2017).
- Three flux measurements previously published in that work: Wide Field, CMOR, and Lunar Impact cover mass range of 1.8×10^{-4} g $- 30$ g.
- Our calculation uses 93 Geminids, 49 of which are above the limiting magnitude of -2.98, which is a limiting mass of 3.1 g.
- Previous work measured s $= 1.70$ (r $= 2.0$).

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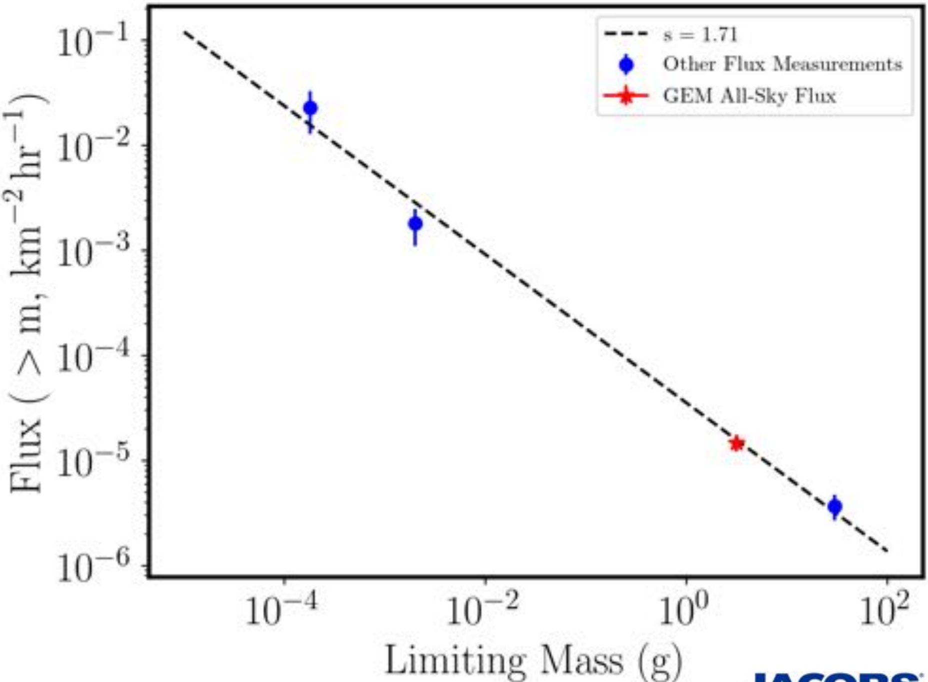
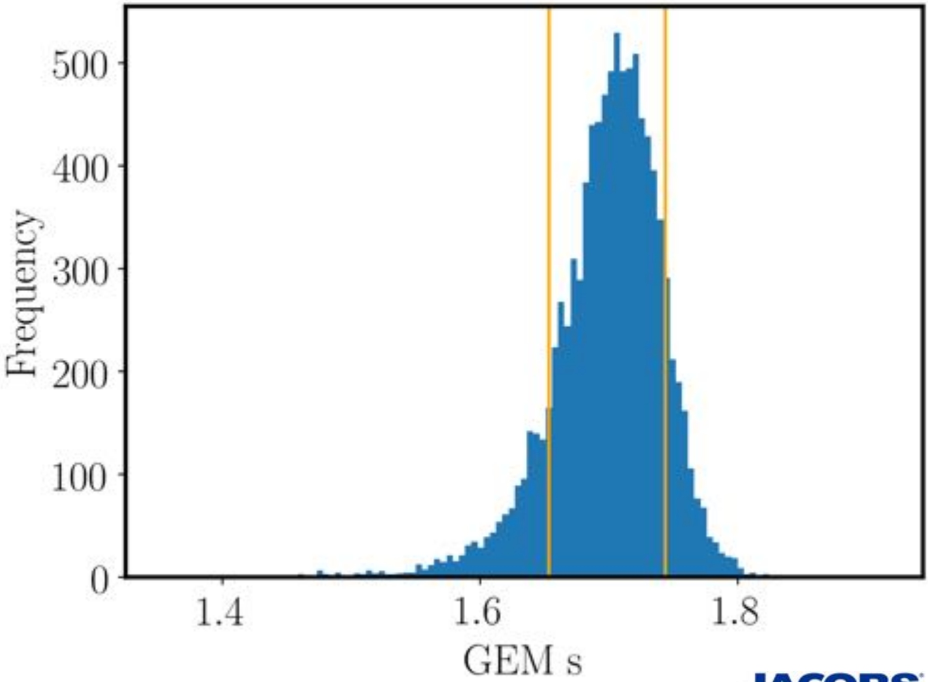
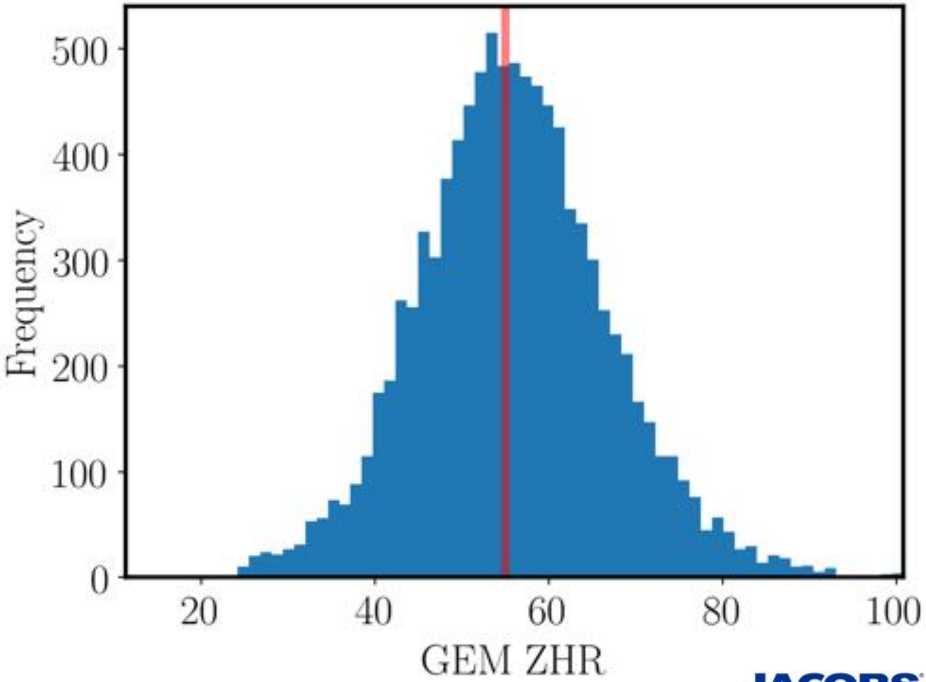


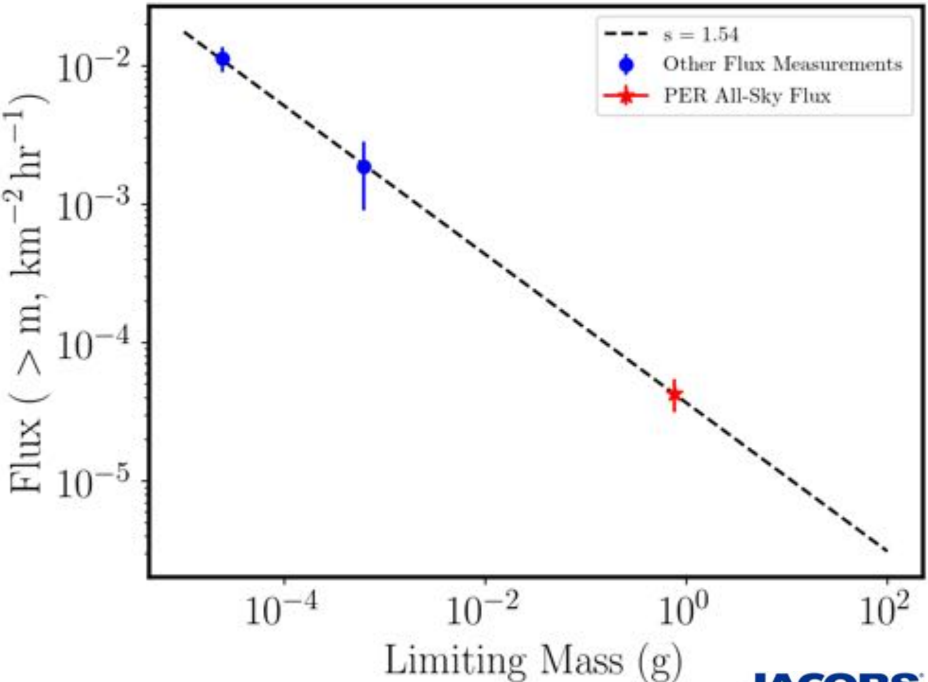
s = 1.71
Other Flux Measurements
GEM All-Sky Flux
Flux (> m, km^{-2}hr^{-1})
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
Limiting Mass (g)


Frequency
0
100
200
300
400
500
1.4
1.6
1.8
GEM s


Frequency
500
400
300
200
100
0
20
40
60
80
100
GEM ZHR

Perseids, 2016-08-12

- Peak activity night during Perseid outburst.
- Our flux measurement uses 146 Perseids, 77 of which are brighter than -3.57.



s = 1.54
Other Flux Measurements
PER All-Sky Flux
Flux (> m, km^{-2}hr^{-1})
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-4}
10^{-2}
10^{0}
10^{2}
Limiting Mass (g)

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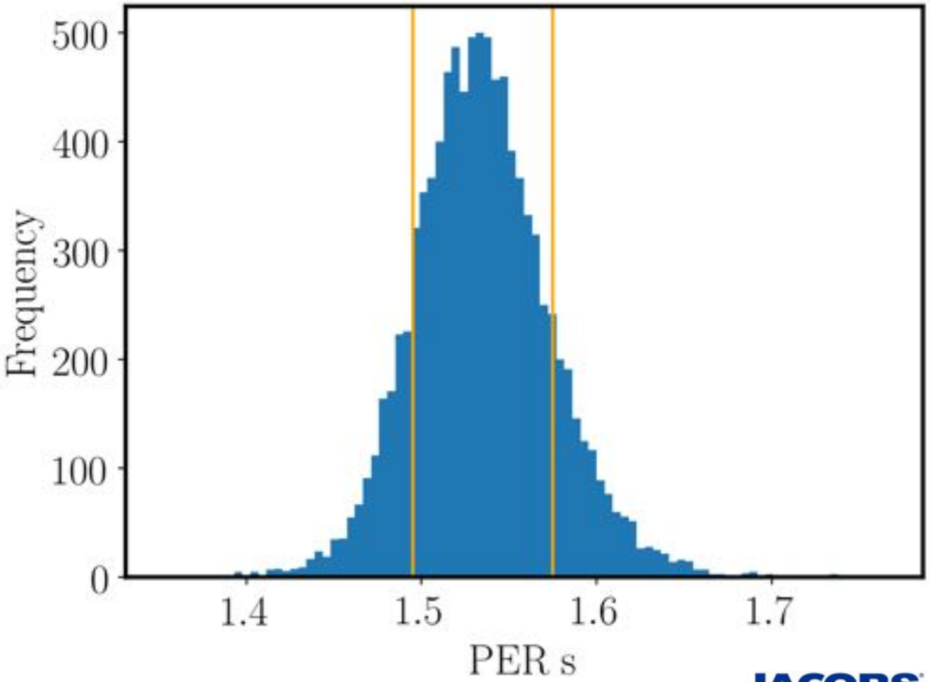
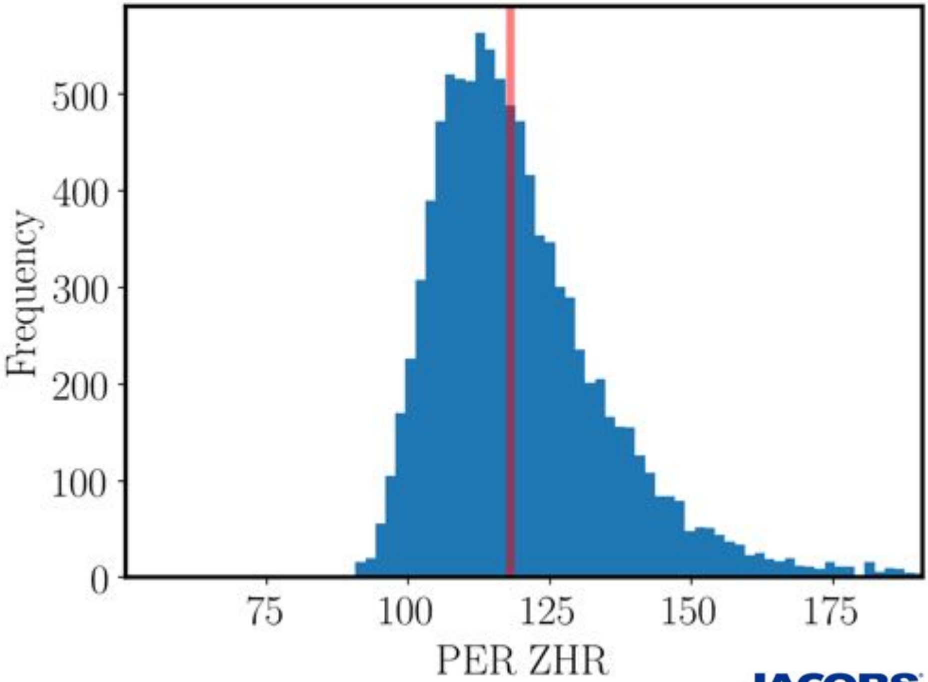

500
400
300
200
100
0
Frequency
1.4
1.5
1.6
1.7
PER s



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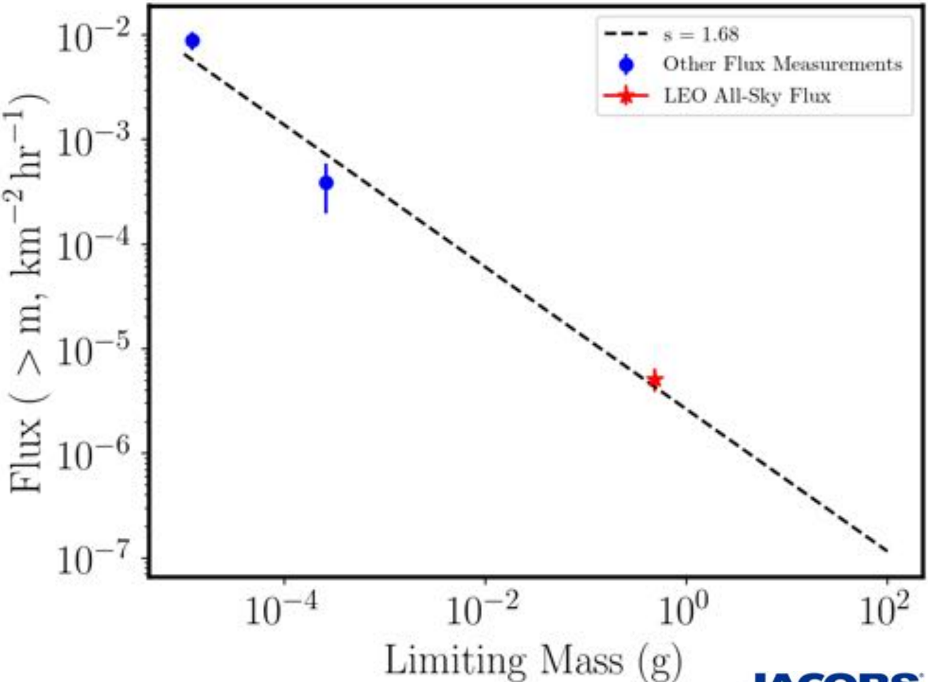
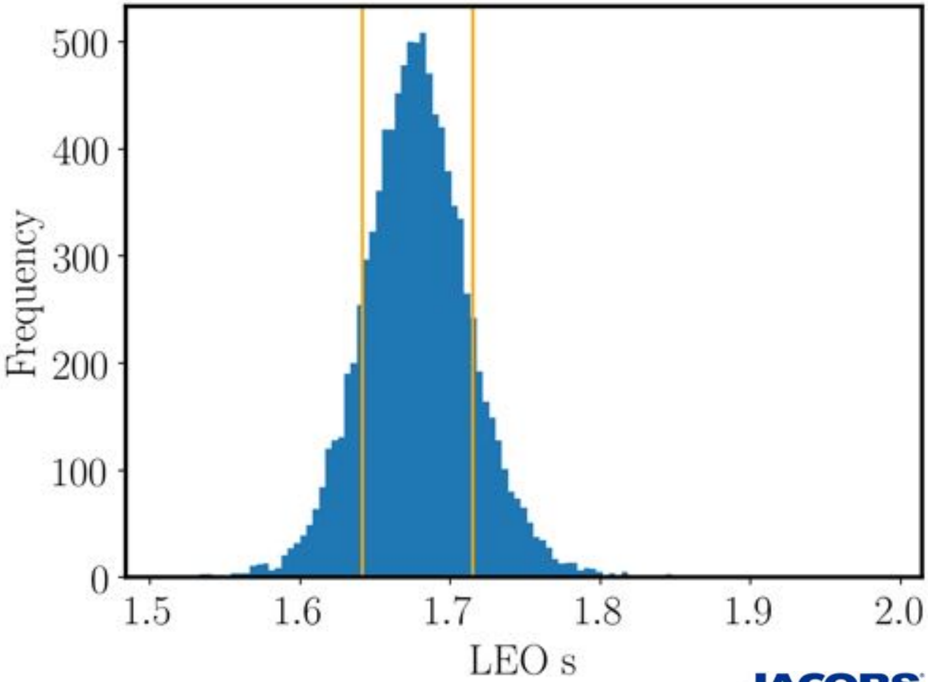
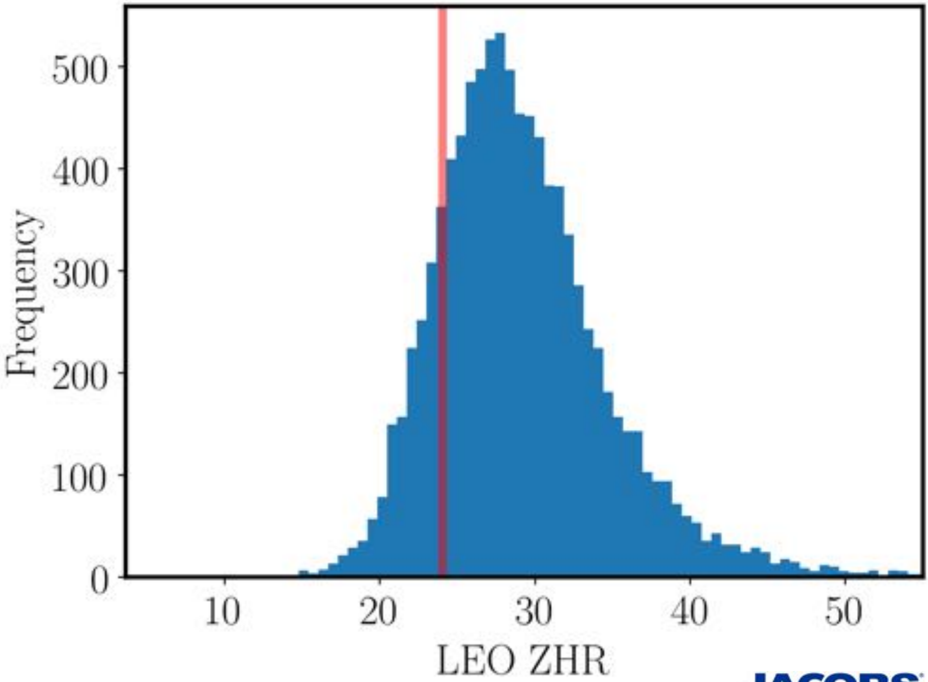
Leonids, 2018-11-19

- No visual ZHR data for this night in IMO database.
- Night before had ZHR $= 16$, night after had ZHR $= 24$.
- The latter night (ZHR $= 24$) is plotted on the histogram.
- We have 38 Leonids, 22 of which are brighter than -3.72.


s = 1.68
Other Flux Measurements
LEO All-Sky Flux
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Flux (> m, km^{-2}hr^{-1})
10^{-4}
10^{-2}
10^{0}
10^{2}
Limiting Mass (g)
JACOBS



500
400
300
200
100
0
Frequency
1.5
1.6
1.7
1.8
1.9
2.0
LEO s



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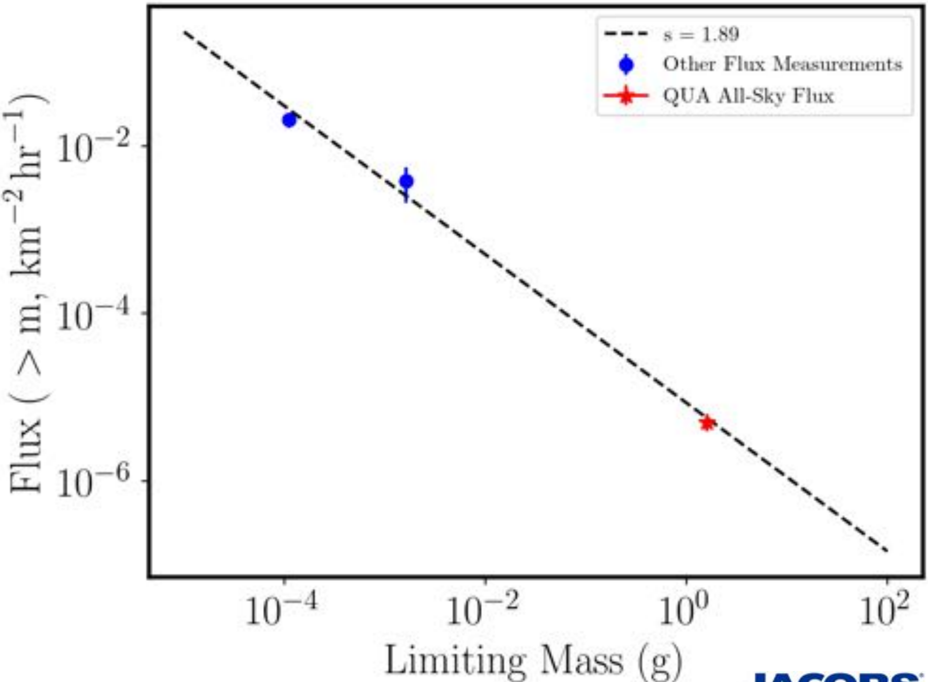
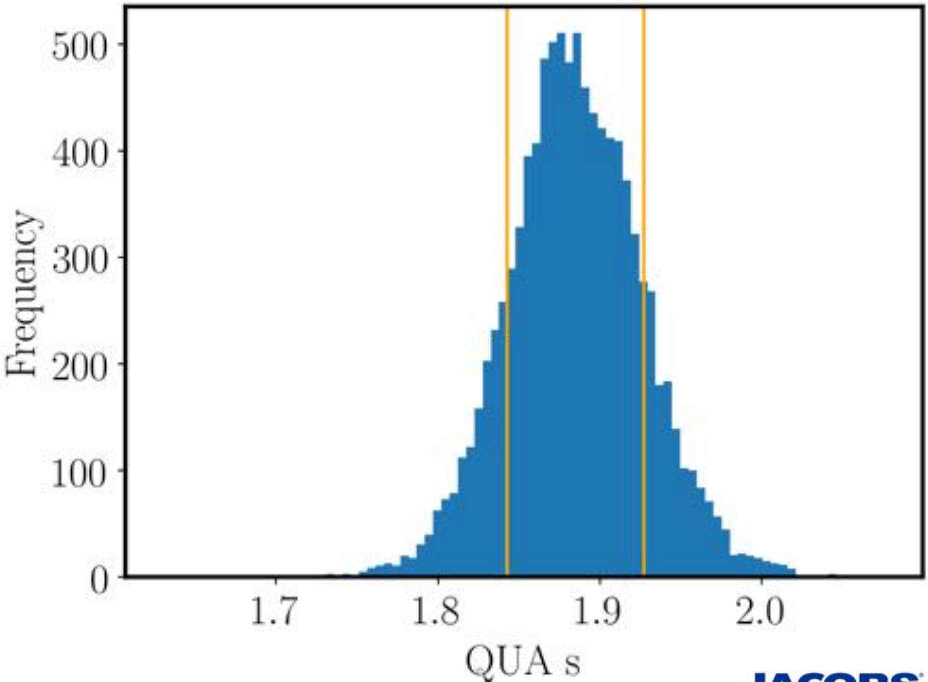
Quadrantids, 2016-01-04

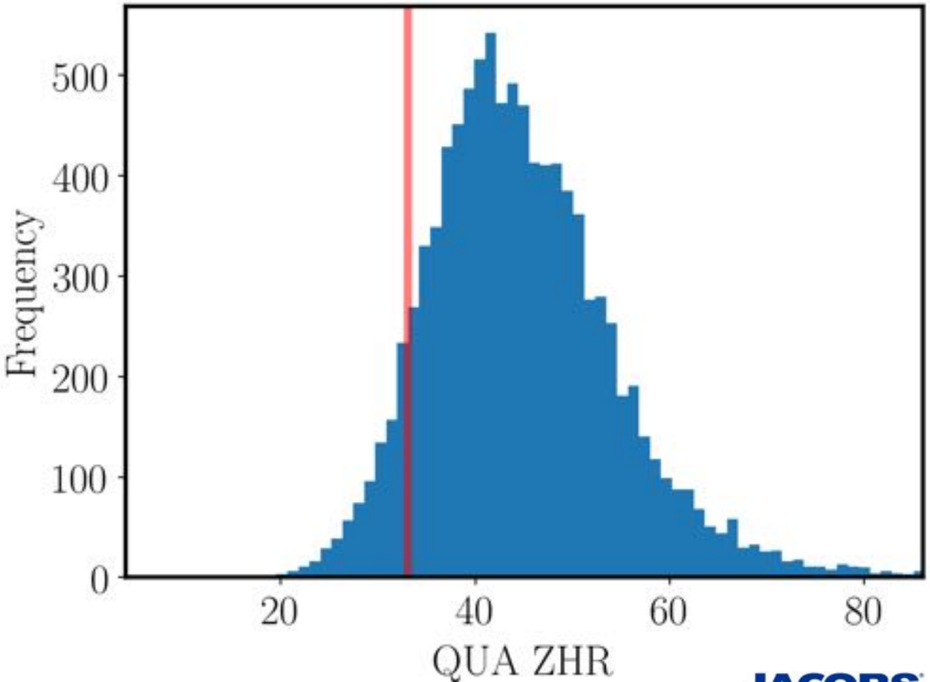
- Integrated over the entire night. Note the peak was 2016-01-03...
- 40 Quadrantids, 21 brighter than -2.83.



s = 1.89
Other Flux Measurements
QUA All-Sky Flux
Flux (> m, km^{-2}hr^{-1})
10^{-2}
10^{-4}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
Limiting Mass (g)



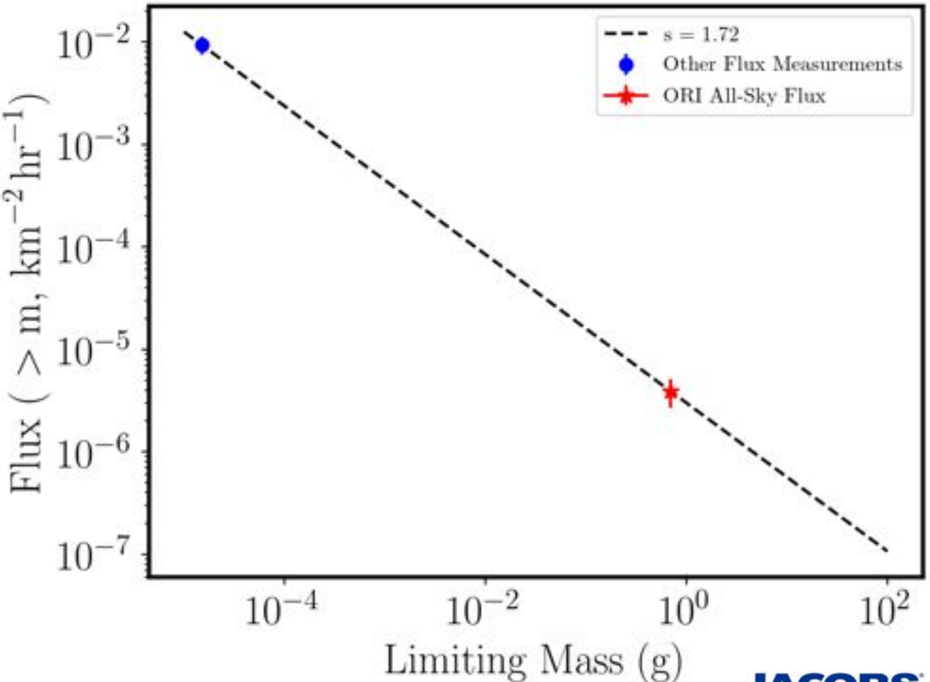
500
400
300
200
100
0
Frequency
1.7
1.8
1.9
2.0
QUA s



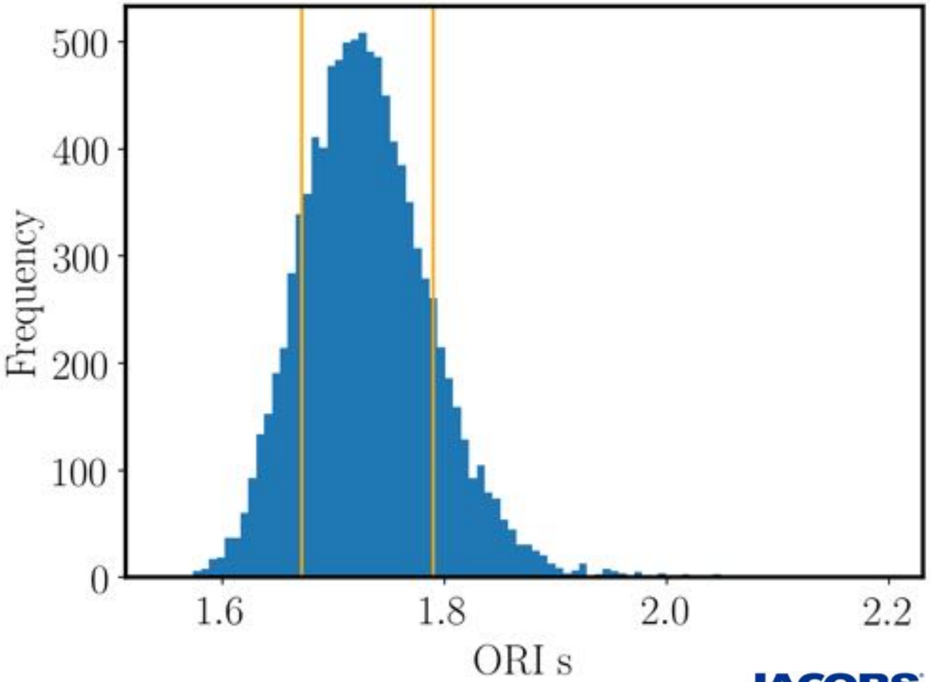
Frequency
500
400
300
200
100
0
20
40
60
80
QUA ZHR

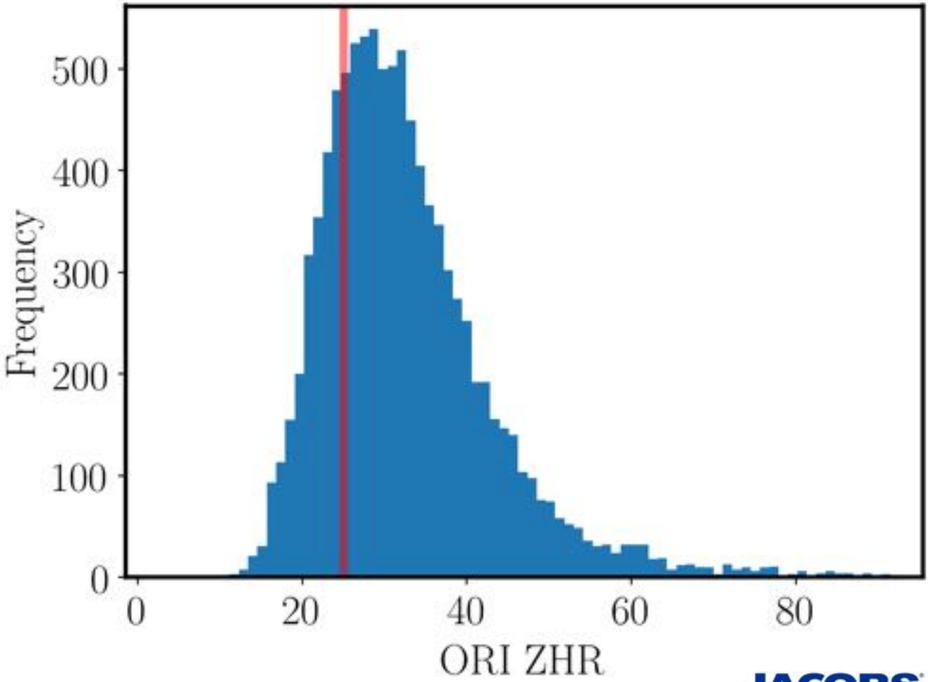
Orionids, 2017-10-22

- We have 28 Orionids, 15 brighter than -3.84.
- This sample pushes the algorithm as far as it can go, but the results are still in line with expectations.



s = 1.72
Other Flux Measurements
ORI All-Sky Flux
Flux (> m, km^{-2}hr^{-1})
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-4}
10^{-2}
10^{0}
10^{2}
Limiting Mass (g)


500
400
300
200
100
0
Frequency
1.6
1.8
2.0
2.2
ORI s



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