Numerical Simulation of Meteors as a Means of Debiasing AMOS Data

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Overview

Contents

objective	What are we doing?
implementation	How do we do it?
results	What have we done?

Objective

To **determine** the total meteoroid flux utilizing data from **AMOS**

- an **extrapolation** from collected data
- we need to
  - analyze the detection ability of AMOS
  - calibrate the system
  - **de-bias** the observations
- estimate the flux

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Two possible approaches

- correct sources of bias one by one
- **simulate** the population and try to match it to observational data

Algorithm

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4. filter visible events and apply observational bias
   - distance
   - atmospheric attenuation
   - limiting magnitude
   - altitude
   - ...

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5. calculate the statistic and compare to AMOS data
6. adjust the particle distribution and observational bias parameters
7. repeat

Simulation

Model

Designed by **Whipple** (1938), improved by **Öpik** (1955) and **Ceplecha** (2001)

We will assume

- spherical particles
- moving in a straight line

And we will need

- equations of motion
- equations of luminance
- to construct a virtual CCD image
- to compute the statistic

Equations of motion

- braking equation

$$\mathrm{d}v = -\frac{\Gamma A}{m^{1/3}\rho^{2/3}}\rho_{\mathrm{air}}v^2\,\mathrm{d}t$$

- equation of ablation

$$\mathrm{d}m = -\frac{\Lambda A}{2Q}\frac{m^{2/3}}{\rho^{2/3}}\rho_{\mathrm{air}}v^3\,\mathrm{d}t$$

- equation of luminance

$$L = \tau(v)\frac{\Lambda A}{4Q}\frac{m^{2/3}}{\rho^{2/3}}\rho_{\mathrm{air}}v^5$$

  - $\tau(v)$ determined by **Jones & Halliday (2001)**

Simulation of flight

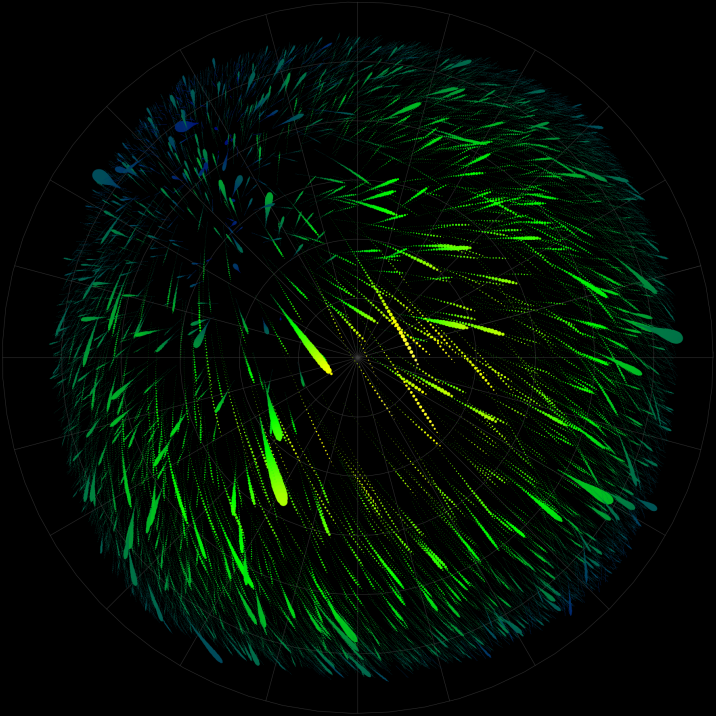
Equations are solved by the Runge–Kutta integrator (RK4)

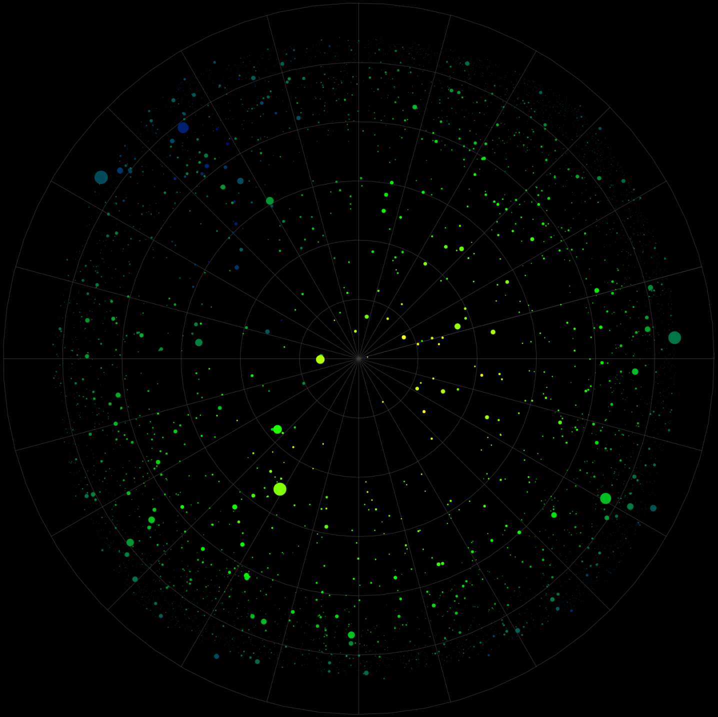
- until complete ablation of the particle
- properties recorded in every `Frame` (1/15 second)
- multiple integration steps between frames

Virtual observations

Next, we create observations

- multiple observers on the ground
- each represents an AMOS camera
- only the brightest frame is analyzed





Selection bias

Detection efficiency is not constant!

- probability of detection is higher for meteors that are
  - bright
  - fast
  - close to zenith
  - ...

Selection bias – quantitative

Bias summarized in **detection probability functions**

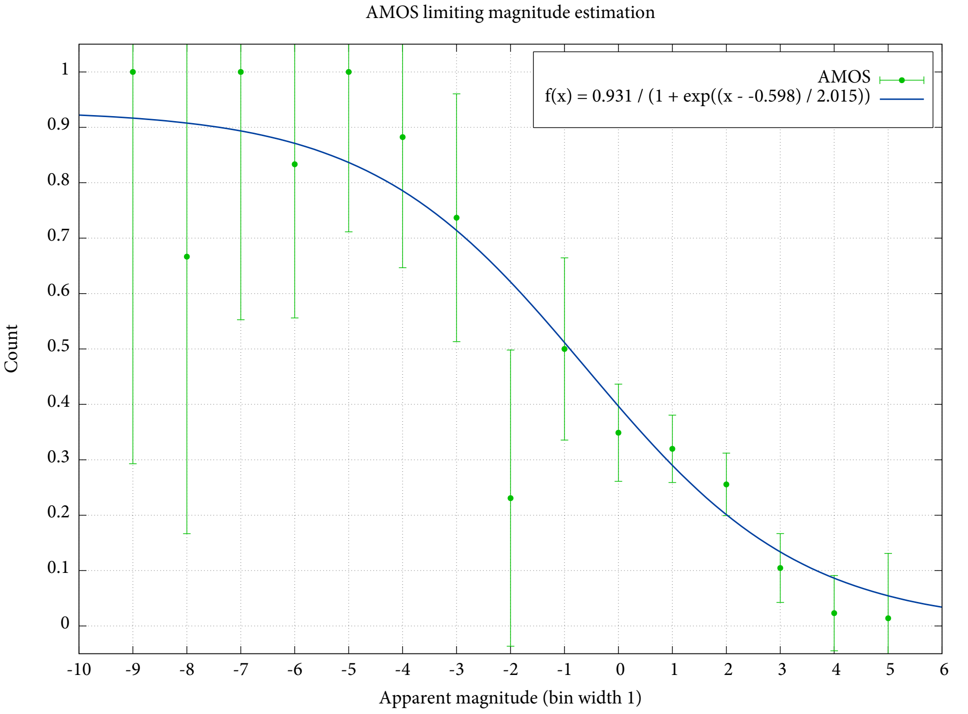
- determine whether a meteor is detected
- magnitude dependence

$$D(m; f, m_0, \omega) = \frac{f}{1 + e^{\frac{m - m_0}{\omega}}}$$

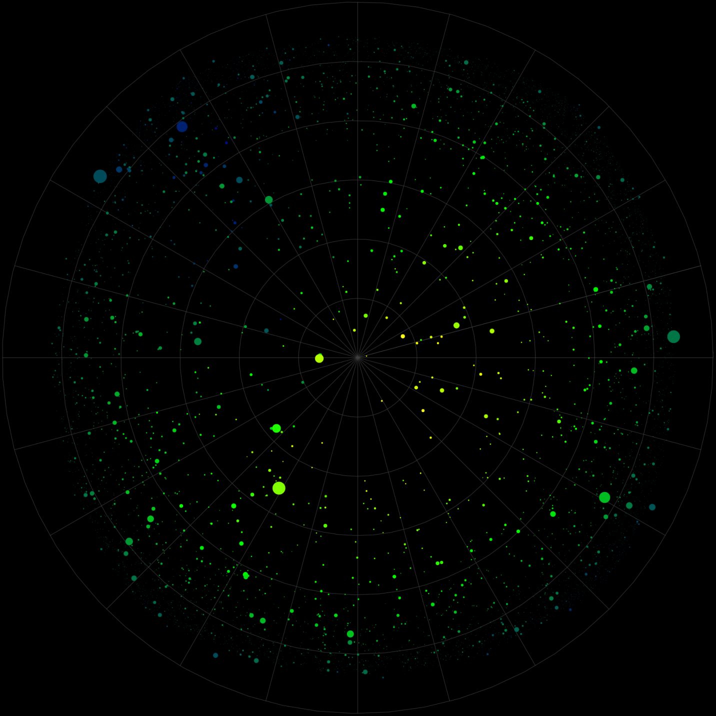
- altitudinal dependence

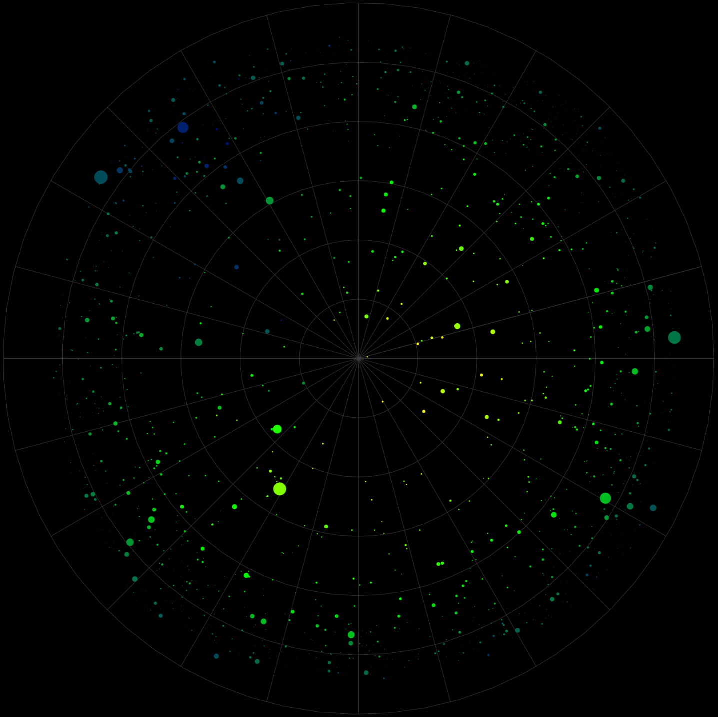
$$A(\theta; \alpha) = (\sin\theta)^{\alpha}$$

- we need to establish values of parameters f, m_0, ω, α
- assume the effects are **independent**



AMOS limiting magnitude estimation
AMOS
f(x) = 0.931 / (1 + exp((x - -0.598) / 2.015))
Count
Apparent magnitude (bin width 1)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6





Asmodeus

What is it

All-**S**ky **M**eteor **O**ptical **D**etection **E**fficiency **S**imulator

- a suite of five **Python** scripts
- implements the described model

Evaluation

- we processed one model night
  - Perseids 2016 (August 11–12)
  - observed from **Tepličné** (48.6822° N, 19.8580° E, 700 m)
  - seven hours (19:00 – 02:00 UTC)
  - mass index $s = 1.8$, later varied
- 100000 meteoroids are generated

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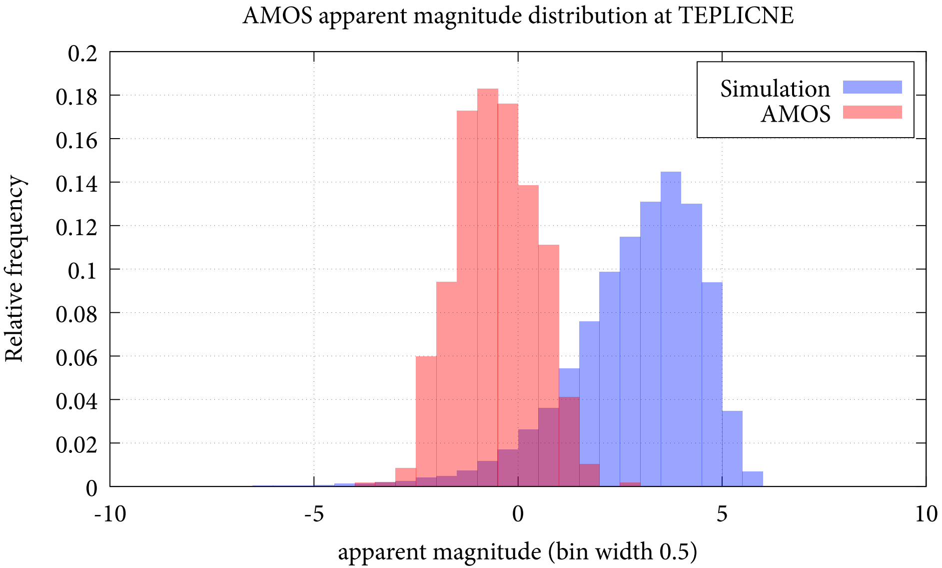
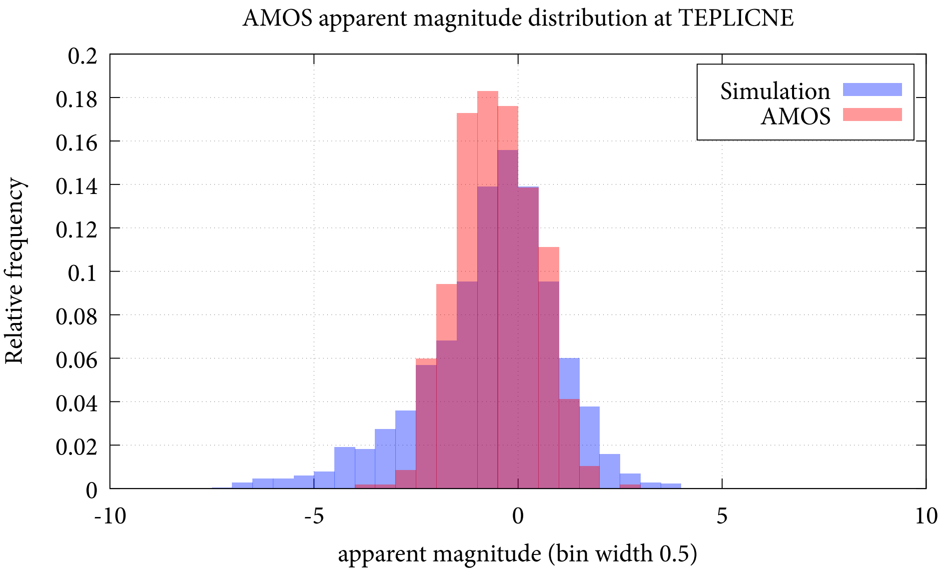

AMOS apparent magnitude distribution at TEPLICNE
Simulation
AMOS
Relative frequency
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
-10
-5
0
5
10
apparent magnitude (bin width 0.5)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10

Magnitude DPF

$$D(m; f, m_0, \omega) = \frac{f}{1 + e^{\frac{m - m_0}{\omega}}}$$

- a wide range of parameter combinations was searched
- fill factor f does not contribute any information

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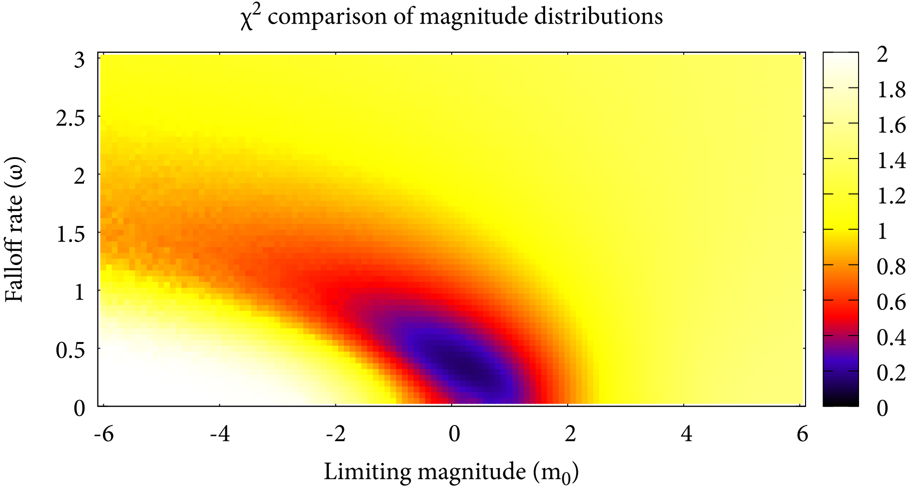
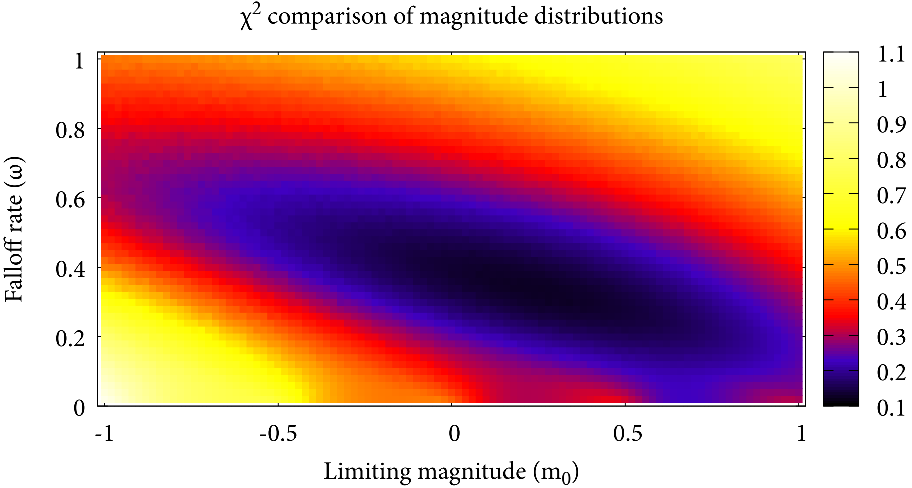
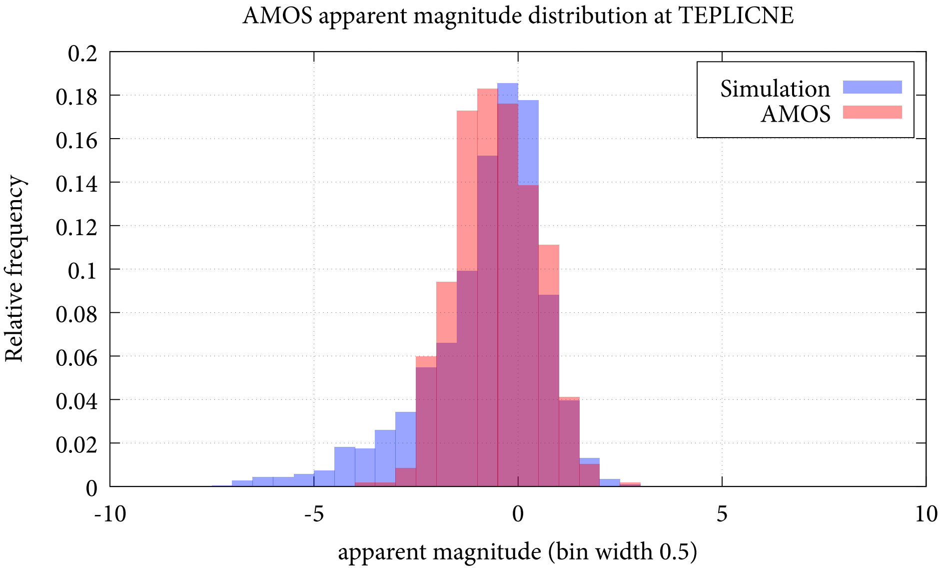
- find values of parameters where χ^2 is minimal
- account for statistical noise



χ^2 comparison of magnitude distributions
Falloff rate (ω)
Limiting magnitude (m_0)
0
0.5
1
1.5
2
2.5
3
-6
-4
-2
0
2
4
6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2



χ2 comparison of magnitude distributions
Falloff rate (ω)
Limiting magnitude (m0)
0
0.2
0.4
0.6
0.8
1
-1
-0.5
0
0.5
1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1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Relative frequency
0.2
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apparent magnitude (bin width 0.5)

Mass index s

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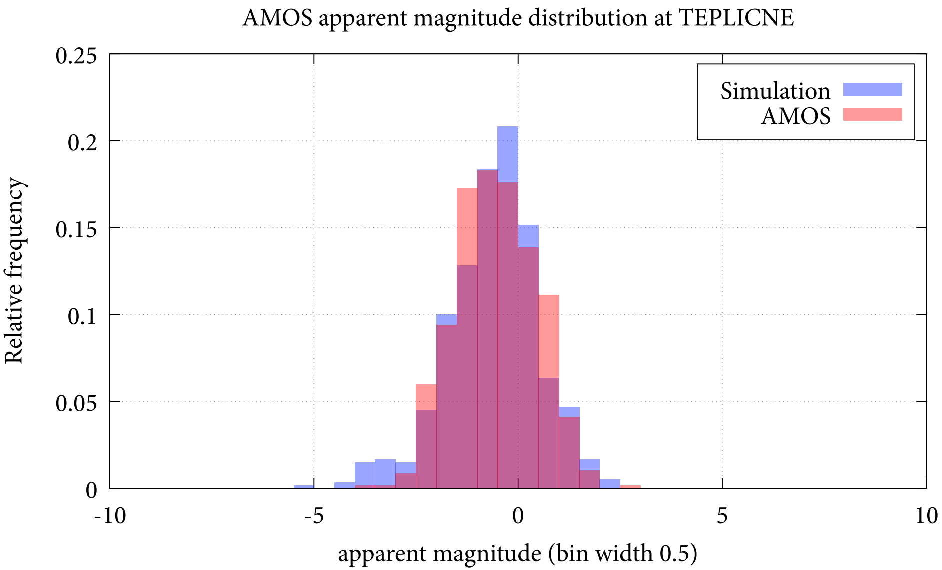
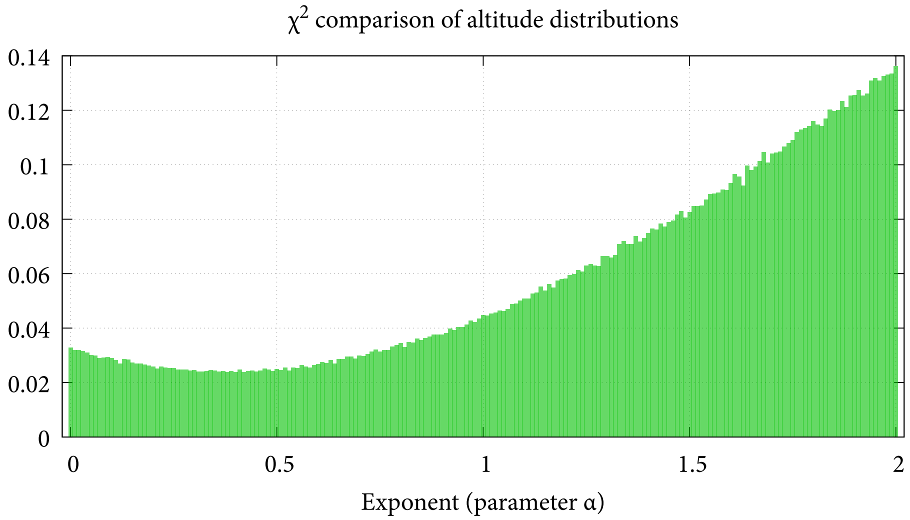
- a natural reaction is to try another value of s
    - a full range 1.6 – 2.8 was tried
- best fit for $s = 2.15$
- no value below 2 is consistent with observations


AMOS apparent magnitude distribution at TEPLICNE
Relative frequency
0.25
0.2
0.15
0.1
0.05
0
-10
-5
0
5
10
apparent magnitude (bin width 0.5)
Simulation
AMOS

Altitudinal DPF

$$A(\theta; \alpha) = (\sin\theta)^{\alpha}$$

- only a simple 1D fit
- a very well defined minimum at $\alpha = 0.4$


χ2 comparison of altitude distributions
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.5
1
1.5
2
Exponent (parameter α)

Results

Total flux

Finally, we may calculate the total flux

- simulation is run again with AMOS's **optimal DPF parameters**

$$A(\theta) = (\sin\theta)^{0.4}$$

$$D(m) = \frac{0.93}{1 + e^{\frac{m+0.1}{0.35}}}$$

- the number of meteors is **scaled** to match observations

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- the number of meteors is **scaled** to match observations

- 135 000 particles per 1 000 000 $\mathrm{km^2\,h}$
- 0.338 kg per 1 000 000 $\mathrm{km^2\,h} \approx 43\ \mathrm{kg\,h^{-1}}$ over entire Earth
- all particles in size range 1 mm – 1 m

Comparison to known values

- results consistent with recent estimates
  - **Blaauw et al., 2016**: 98 000 particles per 1 000 000 km^2 h
  - **Molau, 2017**: 47 000 particles per 1 000 000 km^2 h (but up to 6.5^m)
- high fraction of small particles ($s = 2.15$)

- more precise evaluation is needed
- a larger observational dataset would also help

Conclusion

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- we have designed and implemented the simulation

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  - correct geometry and luminance data and statistic
  - observations **comparable** to real data
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- flux values are not perfect
  - we were able to estimate the flux
  - a good fit was found

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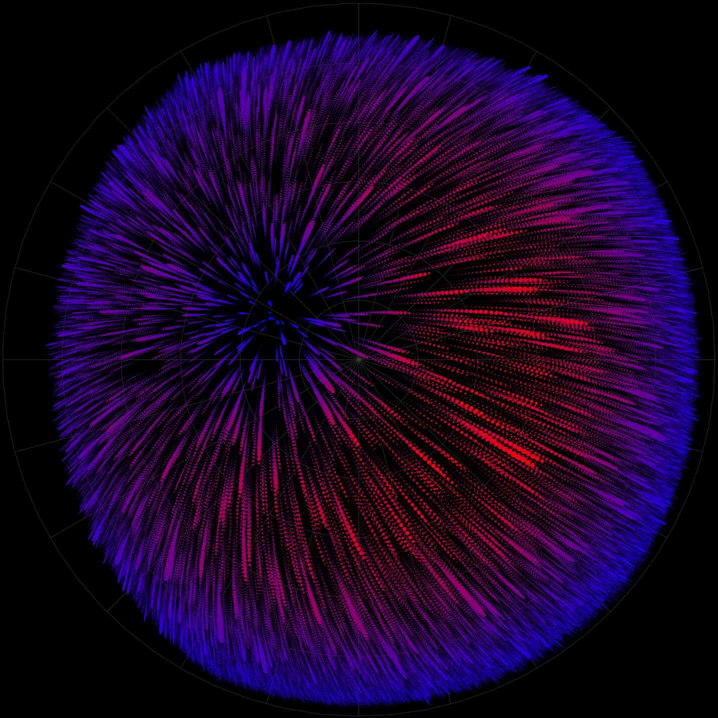
- it is a **surprisingly good** method
  - correct geometry and luminance data and statistic
  - observations **comparable** to real data
  - and the results are aesthetically pleasing
- flux values are not perfect
  - we were able to estimate the flux
  - a good fit was found
  - mass index seems to be much higher than known values
  - a much larger observational dataset is needed



Thank you for your attention

The scientist is not a person who gives the right answers, he's one who asks the right questions.

Claude Lévi-Strauss
Le Cru et le Cuit, 1964

References

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