The proliferation of space objects is a rapidly increasing source of artificial night sky brightness

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on behalf of

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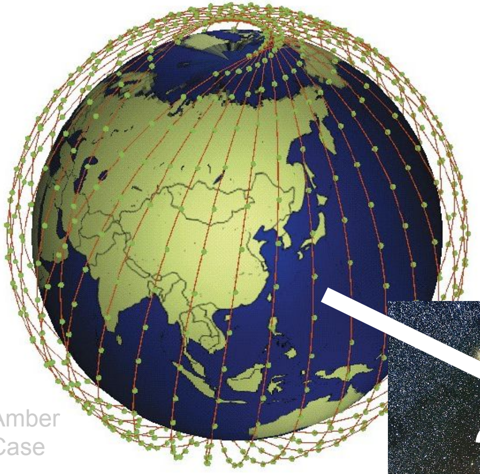
Outline

1. Motivation
2. Theory
3. Model
4. Results
5. Next Steps

1. Motivation

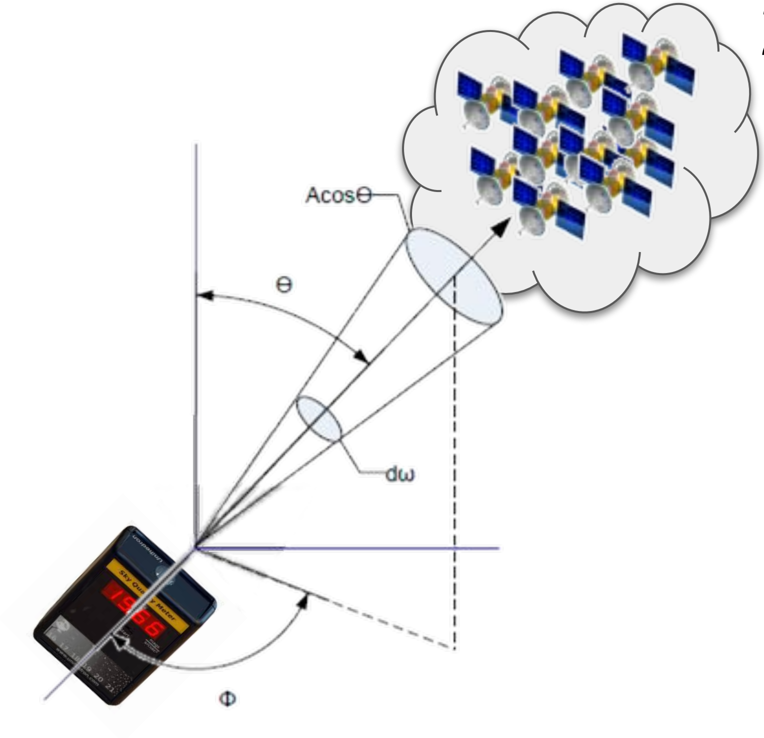


Amber Case

Jeremy Stanley

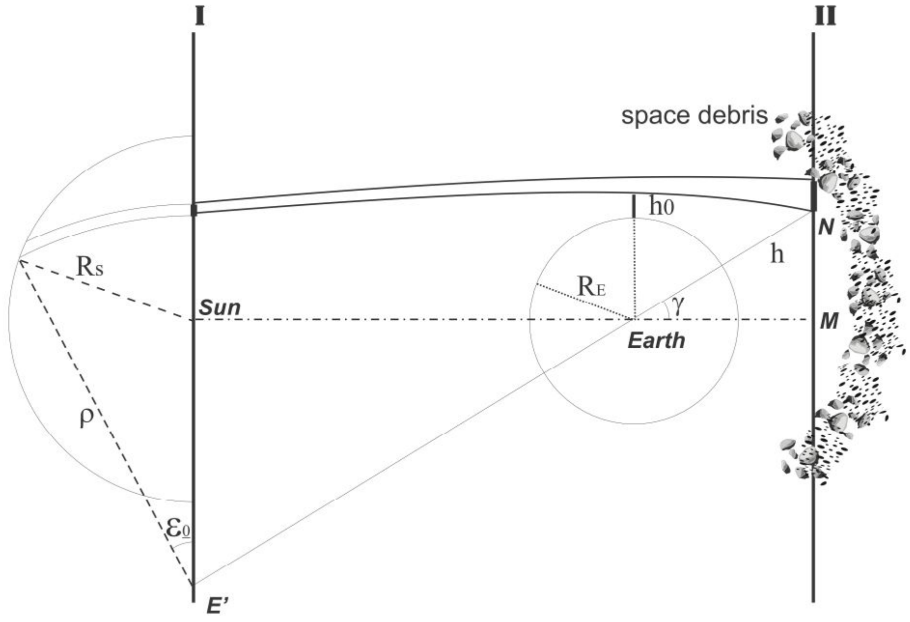
- Artificial satellites are not a new phenomenon, but LEO ‘megaconstellations’ *are* new
- Much of the attention to the problem posed by LEO megaconstellations has to do with the effects of *direct* observations of satellites
- Science question: *by how much does the light reflected from 'space objects' contribute to the overall diffuse brightness of the night sky as seen from the surface of the Earth?*

2. Theory



- Objects at or below the threshold of detection as discrete sources still contribute light in the sky, especially for detectors that "see" relatively large solid angles
- Analogy: detection of integrated starlight by wide-field photometers commonly used to record night sky brightness (e.g., SQM)
- This applies even to the much narrower fields of view of telescopes for (very small) objects below the noise level in digital images

3. Model

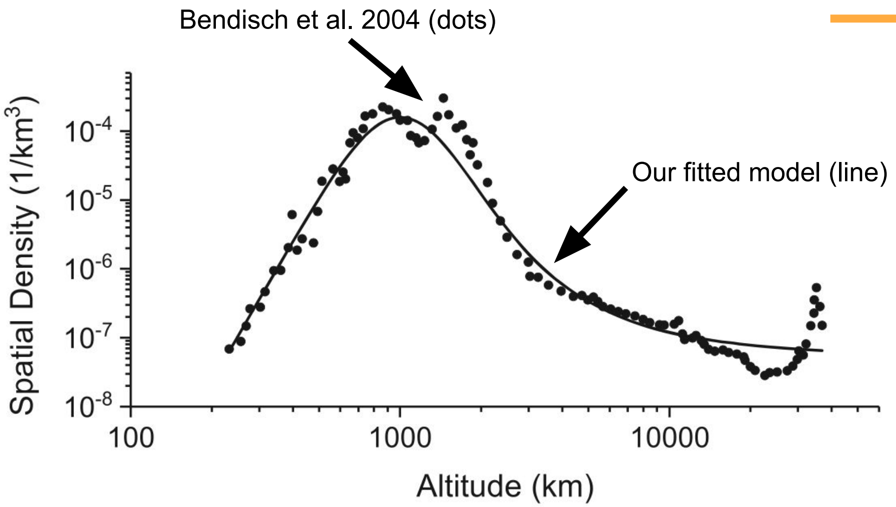


Assumptions

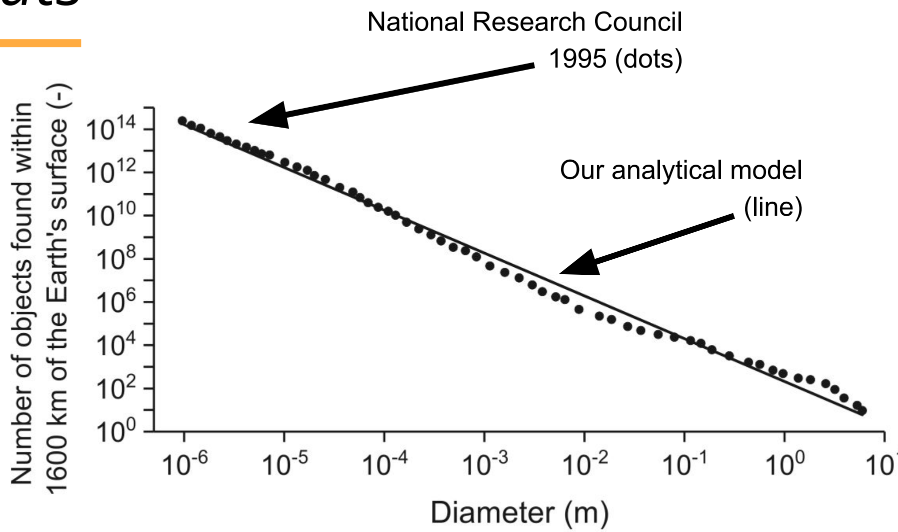
- Space objects are uniform in spatial distribution and only illuminated by the Sun
- The number of objects is large
- Geometric optics with Mie scattering applies
- Irregularly shaped objects of volume *V* are replaced by spheres of radius [*V**3/(4π)]^(1/3)
- Illuminated fraction of objects is ½ [1+cos θ], where θ is the phase angle
- Number/size distribution of objects follows published models
- Size distribution applies to all orbital altitudes

3. Model

Inputs



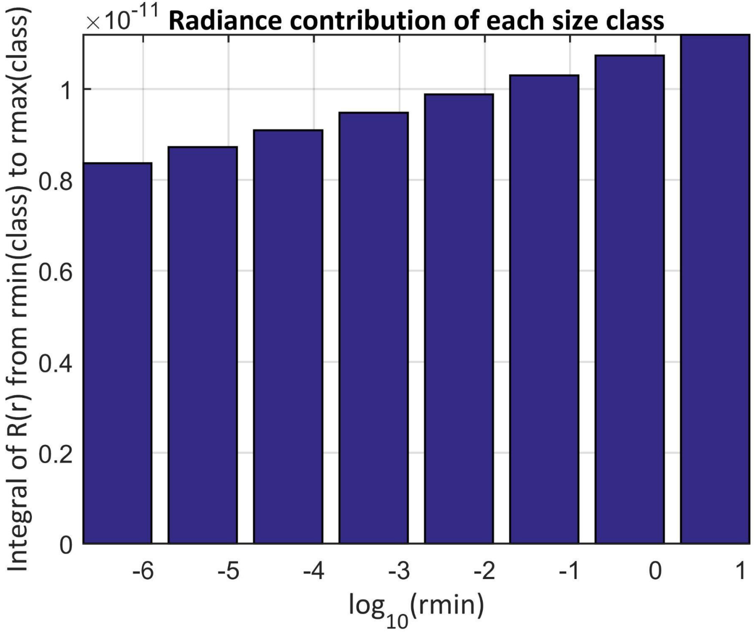
Spatial distribution of LEO objects



Size distribution of LEO objects

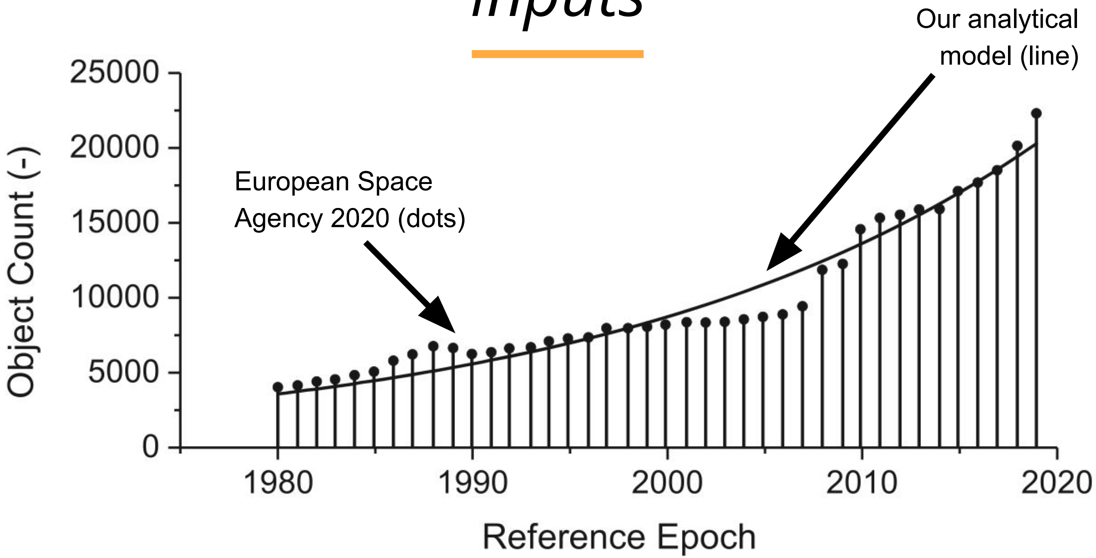
3. Model

If the object size distribution density is a power law with exponent –2 (pretty close to our fit), then all log decades contribute exactly the same amount of sky radiance.



3. Model

Inputs



Total number of LEO objects

3. Model

Calculations

Solar spectral irradiance

$$E_\lambda(\gamma) = 2b_{0,\lambda} \int_{\gamma - R_S}^{\gamma + R_S} T_\lambda^{Ext}(\rho)\, \epsilon_0(\rho)\, \mathrm{d}\rho = b_{0,\lambda} \pi R_S^2$$

Volume scattering coefficient

$$k_\lambda(h) = \pi \int_0^\infty r^2 n(r,h)\; Q_{\lambda,sca}(r)\, \mathrm{d}r$$

Spectral radiance along the line of sight

$$L_\lambda(z) = \frac{e^{-\tau_\lambda / \cos z}}{\cos z} E_{0,\lambda} \int_{h_1}^\infty \frac{P_\lambda(\theta)}{4\pi} k_\lambda(h)\, \mathrm{d}h$$

Spectral radiance in the zenith

$$L_\lambda(z) = \frac{E_{0,\lambda} e^{-\tau_\lambda}}{2} \int_{h=h_1}^\infty \int_{r=0}^\infty r^2\, n(r,h)\, \mathrm{d}r\, \mathrm{d}h$$

3. Model

Calculations

Average scattering cross section of objects

$$\sigma = 2\pi \int_{5\times10^{-7}\ \mathrm{m}}^{5\ \mathrm{m}} r^2 R(r)\mathrm{d}r$$

Luminance from all space objects in the zenith

$$L = \sigma\alpha \frac{E_{0,vis}}{4\pi} \int_{2\times10^{5}\ \mathrm{m}}^{4\times10^{7}\ \mathrm{m}} H(h)\mathrm{d}h$$

$$= \frac{E_{0,vis}\alpha}{2} \int_{5\times10^{-7}\ \mathrm{m}}^{5\ \mathrm{m}} r^2 R(r)\mathrm{d}r \int_{2\times10^{5}\ \mathrm{m}}^{4\times10^{7}\ \mathrm{m}} H(h)\mathrm{d}h$$

4. Results

Luminance from all space objects in the zenith (as of the late 1990s) $\approx \alpha\, 7.2\ \mu\mathrm{cd\,m}^{-2}$

(We take the average albedo $\alpha \approx 0.5$ following Krutz et al. 2011.)

Luminance from all space objects in the zenith (now) $(7.2\alpha) \times 4.5\ = 16.2\ \mu\mathrm{cd\,m}^{-2}$

(We take the ESA estimate for the factor increase in space objects since the 1990s: 4.5)

4. Results

How does this compare to other sources?

Natural night sky (starlight, airglow): ~200 μcd m^{-2}

Yuri Beletsky / ESO

Anthropogenic skyglow: up to ~300000 μcd m^{-2}

Fernando Tomás

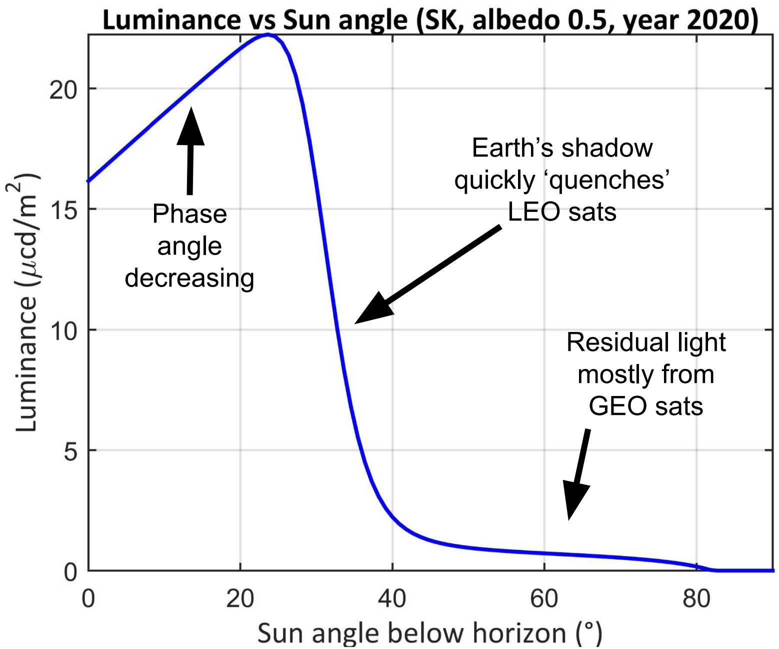
4. Results

How does this compare to light pollution standards?

CIE Joint Technical Report 001 (1980)
"Guidelines for minimizing urban sky glow near astronomical observatories"

Artificial skyglow should contribute no more than 10% additional brightness beyond the natural background airglow at a zenith angle of 45º.

4. Results



What about twilight?

- Luminance contribution at the zenith increases steadily after sunset, peaks at a solar depression angle of ~22°–23° and declines
- Earth's shadow height reaches lowest significantly populated orbital altitudes around this time
- Illuminated fraction of sats seen from the ground increases during this time until objects move into Earth's shadow ("quenching")

Much more about this coming up in Oli Hainaut's talk!

5. Next Steps

Limitations of this study

- We did not account for any launches since 2019; results are *status quo ante* before the megaconstellation era began
- The number distribution of space objects as a function of size likely undercounts smaller objects, results are under-estimates
- Model assumes uniform characteristics for all objects; real world is more complicated
- We only accounted for night sky brightness in the human visual band
- We did not include atmospheric scattering
- Experimentally validating the model predictions is difficult

How to improve on it

- Update model with better estimates of space object population characteristics
- Use estimates of, e.g., albedo and BRDF from observations
- Account for non-uniform spatial distribution of satellites

How the community can help

Make absolute measurements of NSB and compare with models of the natural night sky and/or monitor changes in NSB on time-scales of order of a few years

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