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MODEL CALCULATIONS OF THE F-CORONA AND INNER ZODIACAL LIGHT

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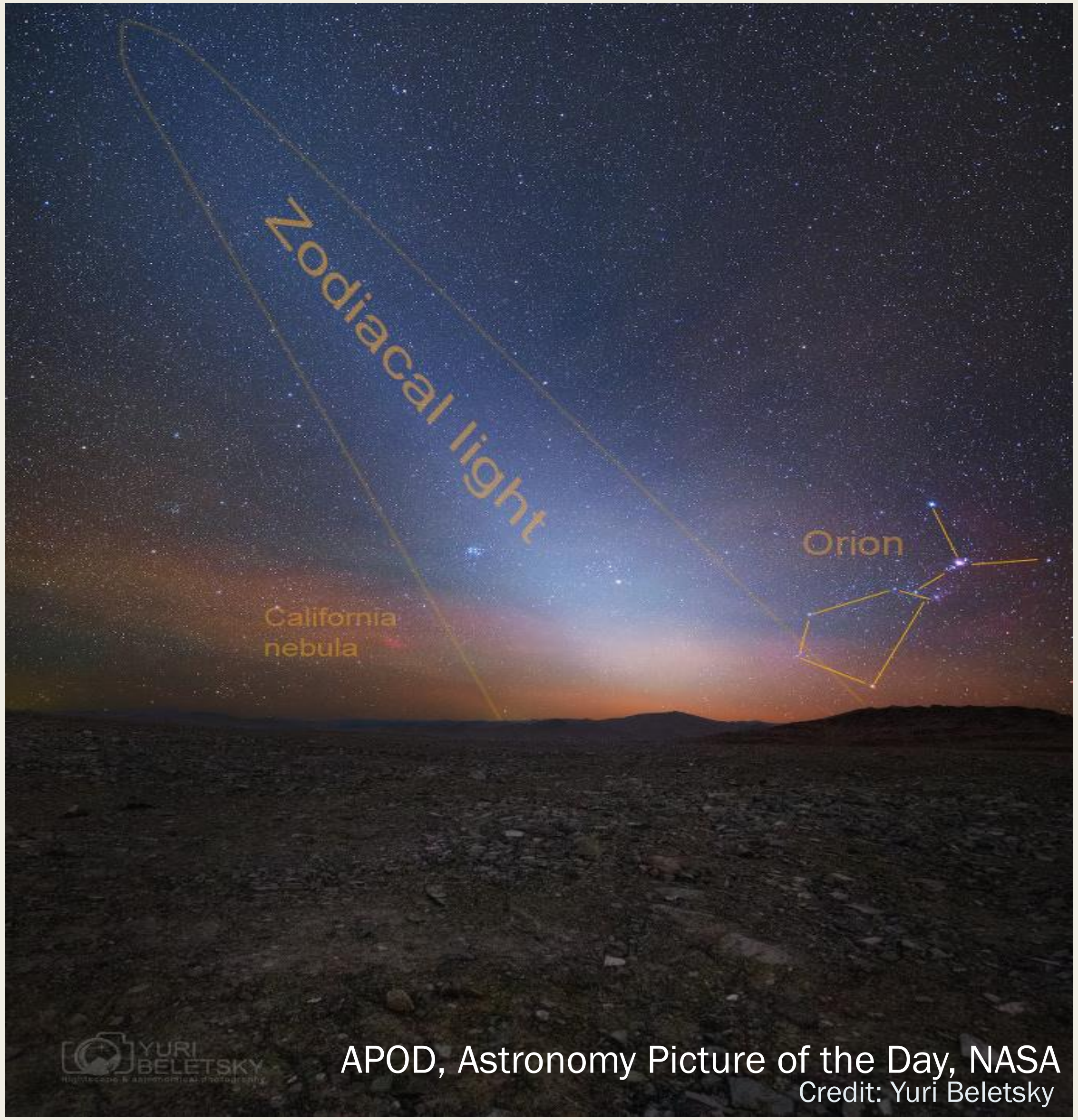
ABSTRACT

The white-light Fraunhofer corona (F-corona) and inner Zodiacal light are generated by interplanetary (Zodiacal) dust particles that are located between Sun and observer. At visible wavelength the brightness comes from sunlight scattered at the dust particles. F-corona and inner Zodiacal light were recently observed from STEREO (Stenborg et al. 2018) and Parker Solar Probe (Howard et al. 2019) spacecraft which motivates our model calculations. We investigate the brightness by integration of scattered light along the line of sight of observations. We include a three-dimensional distribution of the Zodiacal dust that describes well the brightness of the Zodiacal light at larger elongations, a dust size distribution derived from observations at 1AU and assume Mie scattering at silicate particles to describe the scattered light over a large size distribution from 1 nm to 100 µm. From our simulations, we calculate the flattening index of the F-corona, which is the ratio of the minor axis to the major axis found for isophotes at different distances from the Sun, respectively elongations of the line of sight. Our results agree well with results from STEREO/SECCHI observational data where the flattening index varies from 0.45° and 0.65° at elongations between 5° and 24°. To compare with Parker Solar Probe observations, we investigate how the brightness changes when the observer moves closer to the Sun. This brightness change is influenced by the dust number density along the line of sight and by the changing scattering geometry.

BACKGROUND

The Fraunhofer or **F- corona** is formed by sunlight scattered at dust particles. F-corona brightness is seen near the Sun and extends at large elongations into Zodiacal light. Zodiacal light is a brightness at the nightsky that occurs during astronomical twilight. F-corona and inner Zodiacal light are best observed from space.



APOD, Astronomy Picture of the Day, NASA
Credit: Yuri Beletsky

MOTIVATION

Parker Solar Probe (PSP) carries an imaging instrument, the Widefield Imager for Solar Probe (WISPR). Observations of the inner Zodiacal light made with WISPR during the first two perihelion passages at 0.16 AU and 0.25 AU suggest that there is possibly a smaller amount of dust in the vicinity of the Sun than was previously asumed (Howard et al., 2019).

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ZODIACAL LIGHT MODEL

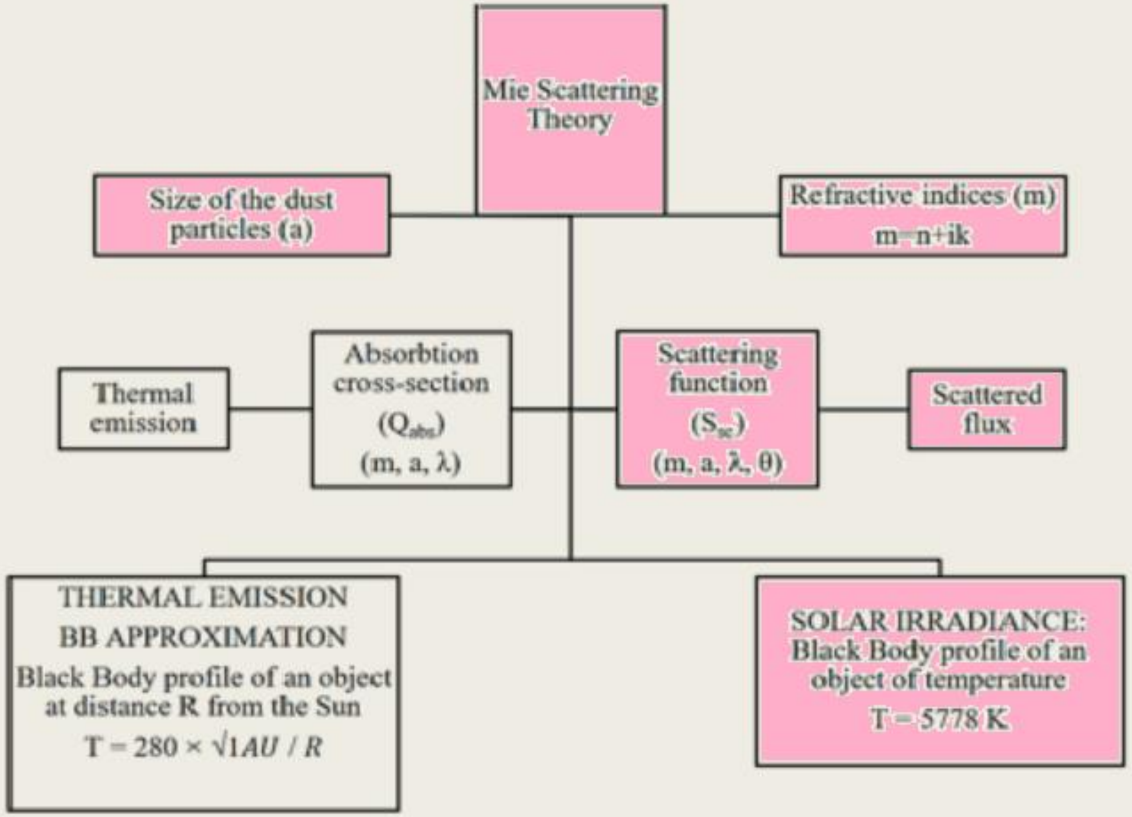
We describe the Zodiacal light by calculating scattered light for particles with a size distribution and index of refraction of silicate. We use Mie scattering and a model assumption on the spatial distribution of dust.

- **Number density:** n ~ mass−7/6

- **Mass** = 4/3 ρ π a^3

$$n \sim R^{-1} \quad \text{and} \quad n \sim a^{-7/2}$$

- **Dust radii:** 1nm-100µm



Coloured boxes of flow chart describe elements of the Zodiacal light model used here. Other parts descibe thermal emission which is negligible in visible light.

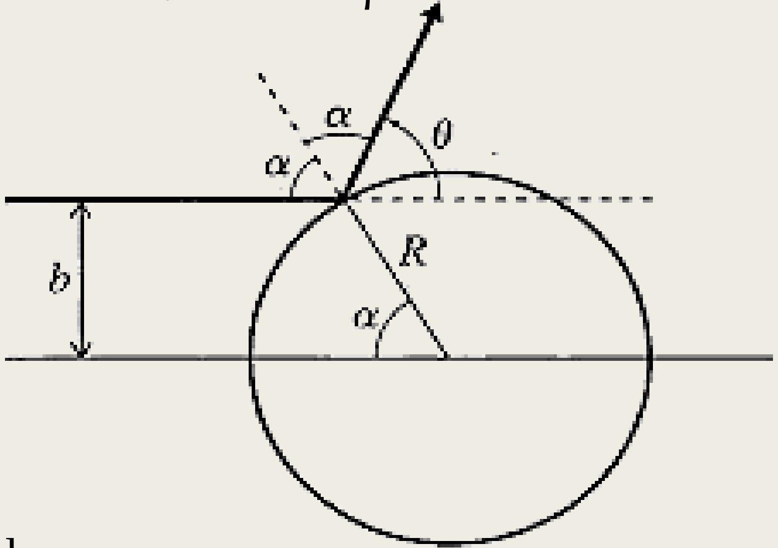


Figure 1: Scattering angle

LINE OF SIGHT INTEGRAL

The flux formulas integrated over the size distribution $n_a(a)$, from Grün et. al., 1985 are the following:

$$I_{sc}(R, \lambda, \theta) = F_{Sol}(R) \times S_R[\lambda, \theta(R)]$$

$$S_R[\lambda, \theta(R)] = \frac{\int_{1\,nm}^{1\,\mu m} S(a, \lambda, \theta) \times n_a(a) \times da}{\int_{1\,nm}^{100\,\mu m} n_a(a) \times da}$$

Scattered flux

$$I_{sc}^{LOS} = \int_0^{\infty} F_{sol}(R) \times S_R[\lambda, \theta(R)] \times n_R(R) \times dx$$

- **B_λ :** Planck's Law, describing the emission of the grain of dust in the Black Body approximation at temperature T
- **F_{Sol} :** Solar irradiance, modelized using Planck's Law for a body at temperature at distance R (1AU) from the Sun (5778K)
- **S_R :** Scattering function
- **I_{sc} :** Scattered flux
- x : Distance of the dust from the Earth
- **λ :** Wavelength
- **$n_a(a)$** : Number density as a function of size of the particles
- **$n_R(R)$** : Number density as a function of distance (1AU)
- **θ (R) :** Scattering angle as a function of distance (1AU)

3-D LINE OF SIGHT INTEGRAL

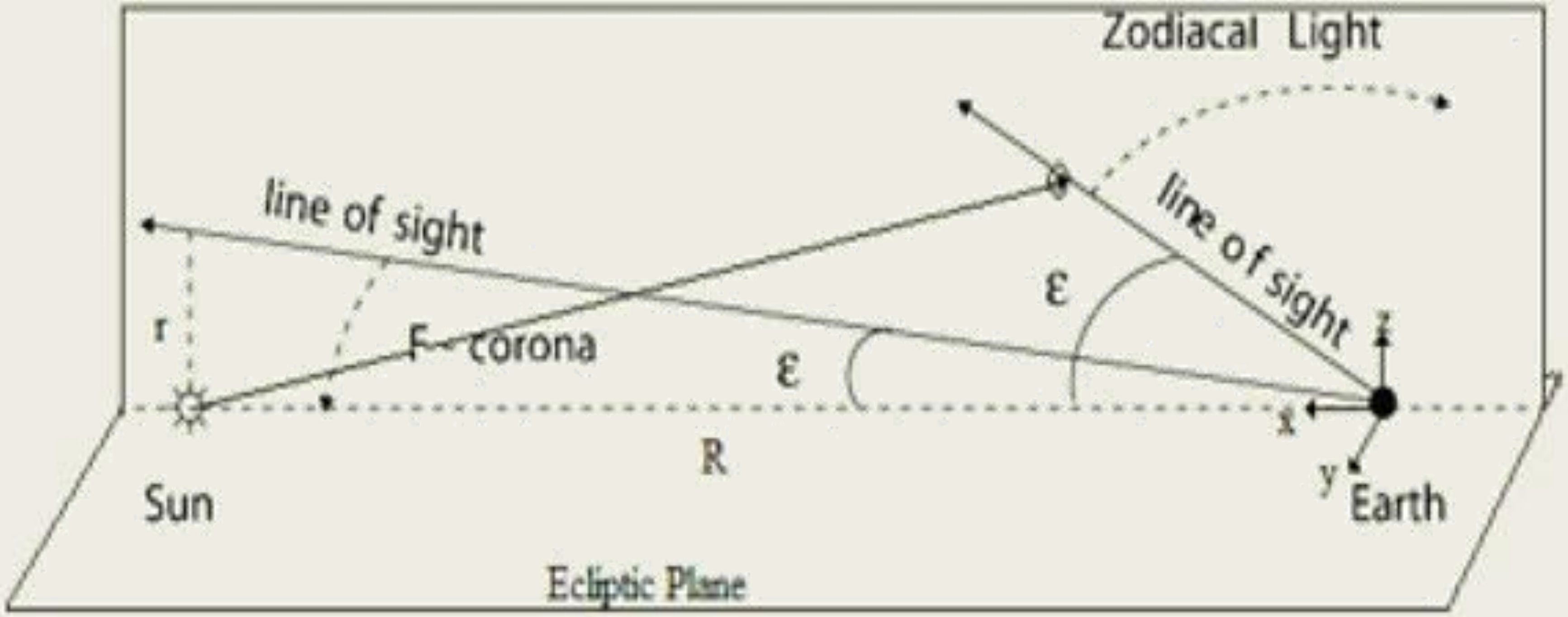


Figure 2: Basic geometry:

- **E,** Earth;
- **S**, Sun;
- **ε :** Elongation
- **r :** position vector;

R, heliocentric distance of the observer in the ecliptic plane.
Shown is line of sight in a plane perpendicular to the ecliptic.

3-D LINE OF SIGHT INTEGRAL AND MODELS

The observed brightness **$I(\lambda - \lambda_\odot, \beta)$** of the Zodiacal light can be explained with different models of the three-dimensional number density distributions of interplanetary dust.

In most cases it is assumed that **$n(r)$** (number density) can be given as a product **$n \sim r^{-\nu} f(\beta_\odot)$,** where **$f(\beta_\odot)$** depending on the heliocentric ecliptic latitude **$\beta_\odot = \arcsin (z/r)$** mainly defines the concentration of dust out of the symmetry plane. The power law **$r^{-\nu}$** determines the change of **n** within the symmetry plane (**$\beta_\odot = 0$**), where **f(βsun) = 1** by definition.

We use cosine model for our simulation and for the Cosine model; ν = 1.3, k = 0.15, γc = 28)

→ **$n = n_0 r^{-1.3} [0.15 + 0.85 \cos 28\, \beta_\odot]$**, Giese et al., 1986.

and for the brightness calculation you can see the integral below:

$$I(\varepsilon, \beta, R) = F_\odot \mathrm{R}_0 n_0 \left(\frac{\mathrm{R}}{\mathrm{R}_0} sin\varepsilon\right)^{-(\nu+1)} \int_\varepsilon^\pi \bar{\sigma}(\theta) f(\beta_\odot) \mathrm{sin}\nu\theta \, d\theta$$

(Giese and von Dziembowski, 1969)

- **R_0 :** Distance between the Sun and the Earth
- **$F_\odot$:** Solar irradiance
- **σ :** Scattering function
- **θ** : Scattering angle
- **ε** : Elongation

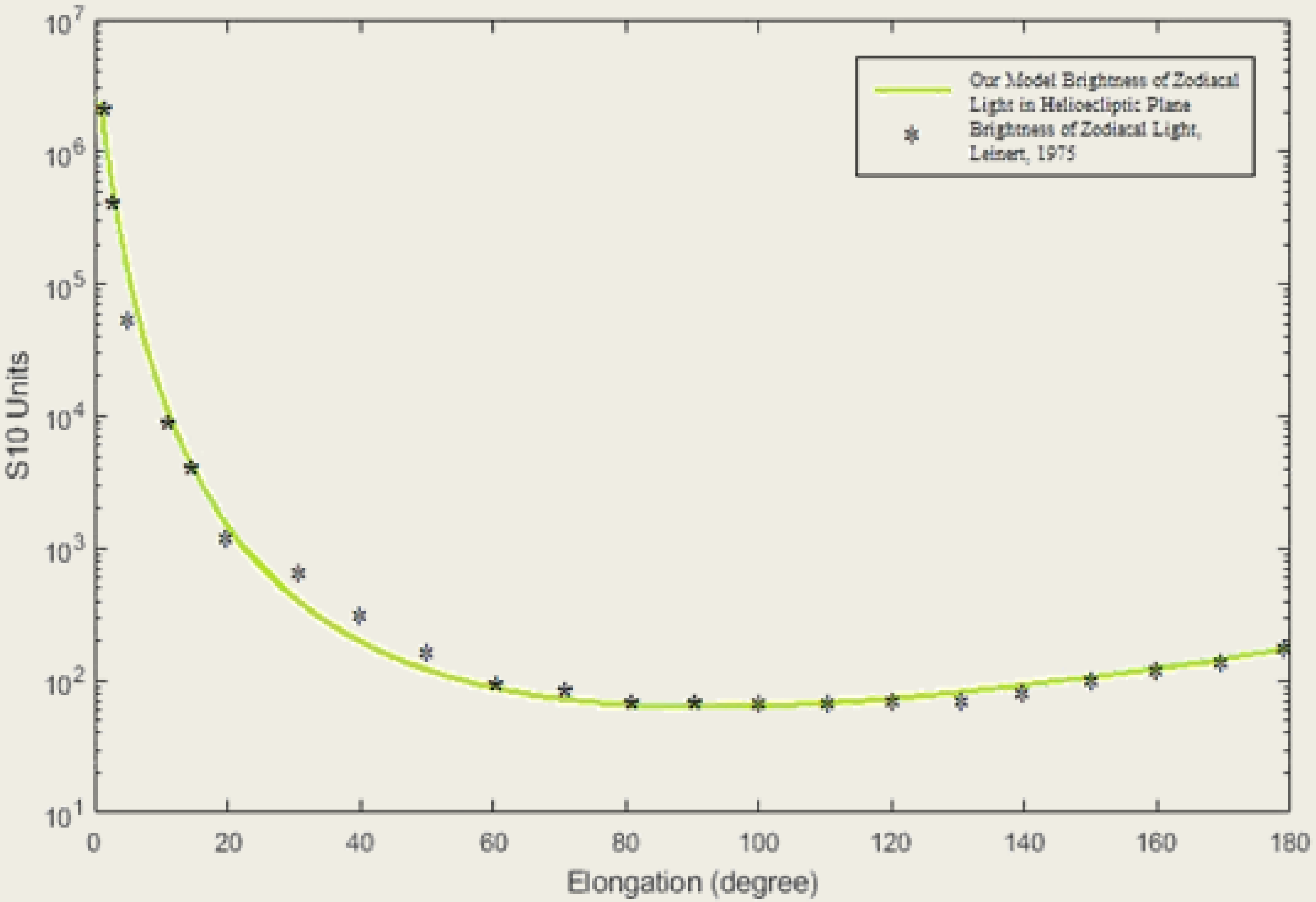
No distinction is made here between the ecliptic and the symmetry plane of the dust cloud (x,y,z)(s).

CALCULATED BRIGHTNESS

Figure 3. Brightness of F-corona and Zodiacal light in the helio-ecliptic plane.

Solid line shows calculations using equations given in slide 7 (normalized to 10^2 S10 at 90°).

The symbols show observational data compiled by Leinert (1975, Table 3).



FLATTENING INDEX

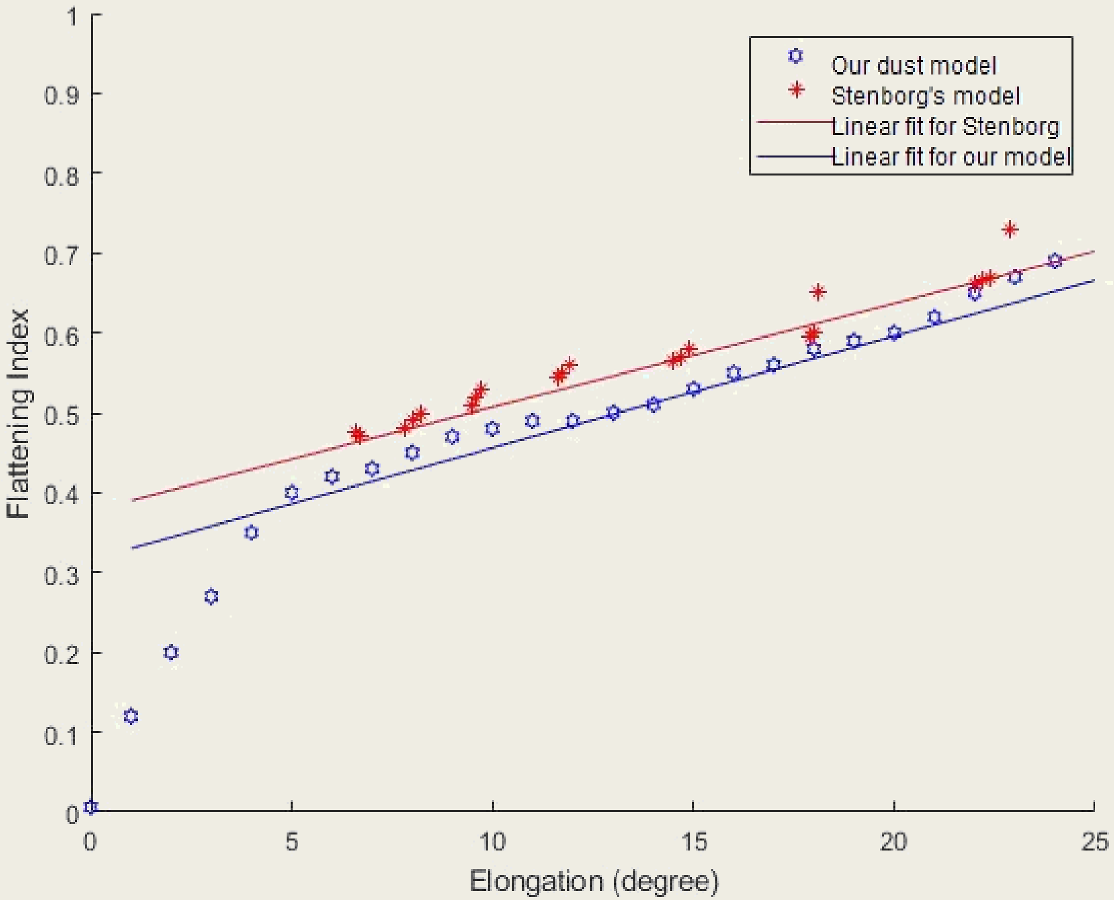


Figure 4. Flattening index of calculated inner Zodiacal light in comparison to results by Stenborg et al. 2018 results for **STEREO-A SECCHI/HI-1 images**

Flattening index, ϵ_f is the ratio of the minor axis to major axis of the corona / inner Zodiacal light (cf. Koutchmy & Lamy, 1985):.

$$\epsilon_f = R_{eq} / R_{pol} - 1$$

Flattening index changes with the angular distance (elongation) from the Sun and it increases with decreasing elongation.

Figure 4 shows the flattening indices derived for calculated brightness in comparison to those derived from STEREO observations (Stenborg et al., 2019).

The flattening index derived from the calculated brightness and that derived from STEREO observations show similar behavior in the interval of the STEREO results.

MODEL BRIGHTNESSES

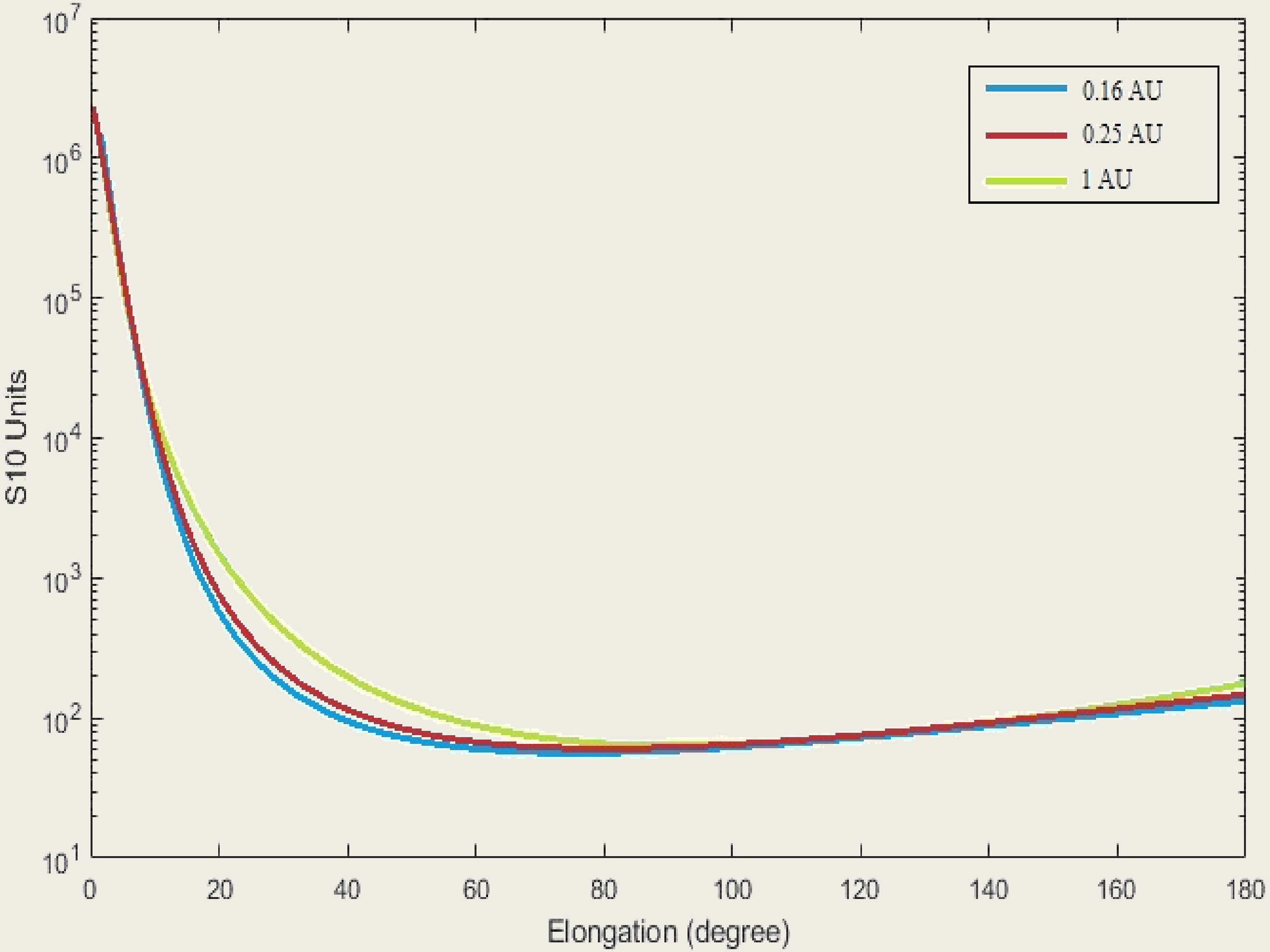


Figure 5. Normalized values of calculated F-corona and Zodiacal light brightness for different distances between Sun and observers, brightness values normalized at 90 degree.

Here we calculate the F-Corona and Zodiacal light brightness as seen from the distances of first two perihelion passes of PSP. To illustrate the influence of the scattering function, we show results normalized to value at 90° elongation (Figure 5).

The remaining difference in brightness slopes shows the influence that the change in scattering geometry has on the brightness, best seen at 15° to 80° elongation.

F-CORONA INTENSITIES

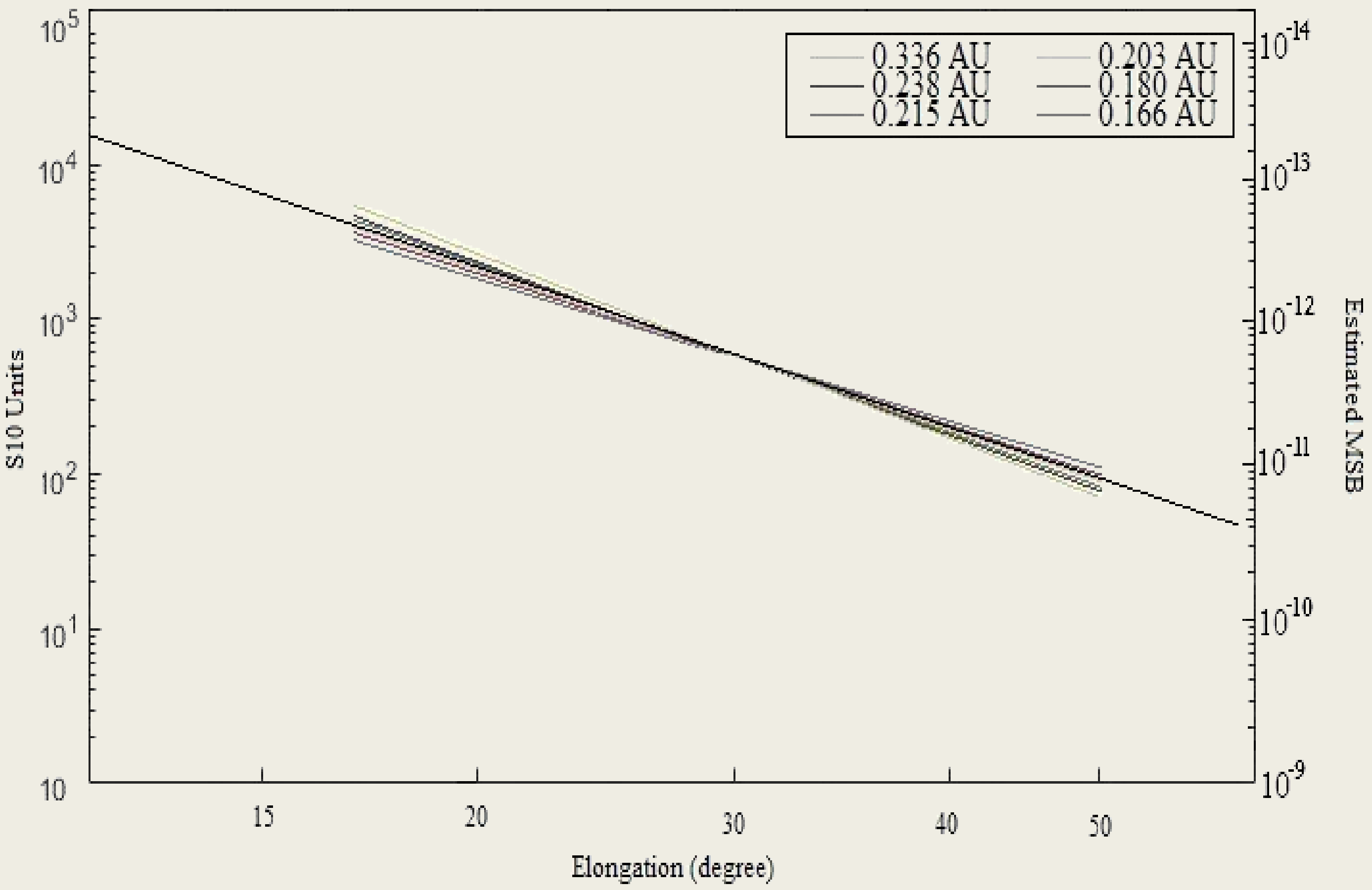


Figure 6. Calculated F-Corona brightnesses from our model for six different distances as a function of elongation normalized at the same value at 30° elongation.

Howard et al. 2019 calculated the brightness from WISPR-I for the five heliocentric distances as a function of elongation normalized at the same value at 30° elongation.

To compare our results with their model results based on observational data we simulated various brightnesses and we assume that the brightness at 30° is 5×10^{-11} MSB which we estimate from their figure in the paper.

Black solid line in the figure describes linear fit to the F-corona intensities for elongations in the figure (n=2.83).

DISCUSSION

We have shown that a brightness model that is consistent with (ground-based) Zodiacal light observations at larger elongations and with the dust size distribution measured at 1AU can well describe the shape of the outer F-corona at elongations from 6° to 25° recently observed from 1 AU with STEREO.

Using the same model to calculate the brightness for varying distances between Sun and observer, we find that the brightness is influenced by the variation of the number density along the line of sight and also by the scattering geometry that changes.

The slope of the brightness with elongation that we calculate is different from the slope observed from PSP. A possible explanation is that the dust number density in the inner solar system is smaller than assumed in our model. Another factor that influences the brightness slope is the volume scattering function which depends on the dust size distribution (and material composition).

In future work, we will study the influence of reduced dust density near the Sun and the influence of dust size distribution. We will also investigate the influence that the assumed model of the three-dimensional dust number density distribution has on the brightness.

REFERENCES

A. LI & J.M. GREENBERG - A Unified Model of Interstellar Dust - 1997, “Astronomy and Astrophysics” .

C.F. BOHREN & D.R. HUFFMAN - Absorption and Scattering of Light by Small Particles, Wiley-VCH.

C. LEINERT - Zodiacal Light : A Measure of the Interplanetary Environment,1975.

E. GRÜN, H.A. ZOOK, H. FECHTIG & R.H. GIESE - Collisional Balance of the Meteoric Complex - 1985.

R.A. HOWARD, and 25 co-authors - 2019: Near-Sun observations of an F-corona decrease and K-corona fine structure, Nature 576, 232–236

R. H. GIESE, B. KNEISSEL, AND U. RITTICH - Three-Dimensional Models of the Zodiacal Dust Cloud: A Comparative Study, 1986. ICARUS 68, 395-411.

R. H. GIESE, C. V. DZIEMBOWSKI - Suggested zodiacal light measurements from space probes, 1969. Planetary and Space Science 17(5):949-956.

S. KOUTCHMY, & P. LAMY - The F-Corona and the Circum-Solar Dust Evidences and Properties [G. Nikolsky Memorial Lecture], 1985. International Astronomical Union Colloquium, 85, 63-74.

STENBORG, G., HOWARD R. A., and STAUFFER J. R. - 2018: Characterization of the White-light Brightness of the F-corona between 5° and 24° Elongation, Astrophysical. Journal. 862: 168.

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