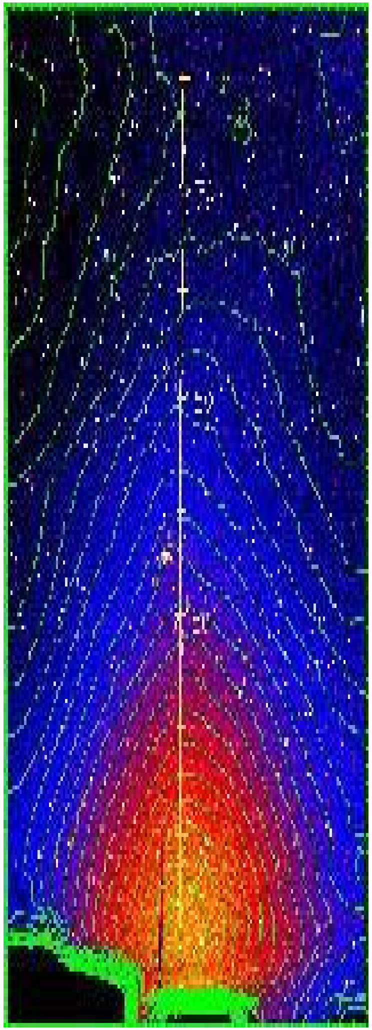
SCATTERING PHASE FUNCTION OF INTERPLANETARY DUST PARTICLES



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Hawaii

04-09-16, KOBE

This work is a result of long collaborations with Prof. Jerry L. Weinberg and Dr. Suk Minn Kwon. Without Archives of the Space Astronomy Laboratory, Snellville, GA, USA this study could not have been made. I am also grateful to Mr. JeongHyun Pyo and some of the WIZARD members for giving me timely supports and ZL images.

ssh at Awaji, 04-09-17

Scattering Characteristics of Cosmic Dusts

- Diffuse Galactic Light

  starlight scattered by interstellar dusts

- Reflection Nebulae
- Comet Tails/ Trails
-
-
- Zodiacal Light (ZL)

  Sunlight scattered by interplanetary dusts (IPDs)

  widest coverage in scattering angle

  Gegenschein : $\Theta = 180°$

Evening ZL taken by M. Ishiguro with WIZARD on March 2 '03

On top of Mauna Kea, Hawaii, h = 4200m

Wide-field Imager of Zodiacal light with ARrray Detector

APOD : Aug 25, 2004

Taken in Namibia, May '04

by Stefan Seip

http://antwrp.gsfc.nasa.gov/apod/

対日照　（ Gegenschein ）　Sep. 18, 1996, 24h48m～25h35m(JST)

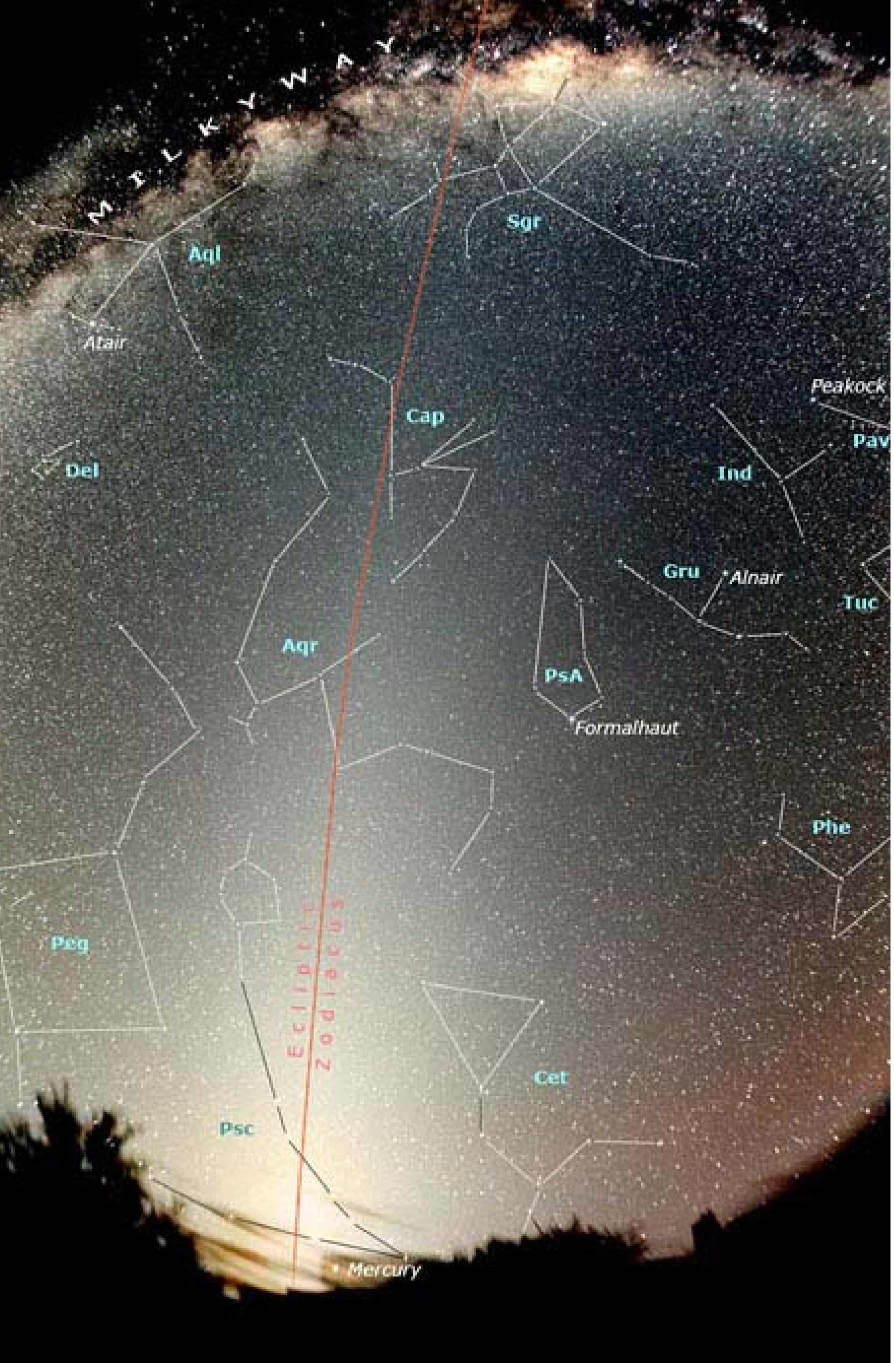
対日照は，東西の黄道光の延長でつながるところ，太陽の位置と正反対の位置に長径20°くらいの広がりを持つ楕円形の非常に淡い光斑として見える現象である．天の川のいちばん淡い部分より，極端に淡いので，これを撮影するのは，たいへん難しい．光害の影響がない，空が澄んでいる場所で観測しなければならない．

この画像は，一見，レンズの周辺減光の特性が現れているように見えるが，そうではない．周辺減光の光むらは，フラットフィールドで補正済みである．左側の明るい星は，土星．

35mm判一眼レフ用広角レンズ（f=20mm，Ｆ3.5／Ｆ5.6に絞る）
冷却ＣＣＤカメラ（武藤工業 CV-16），フィルタ：G-533(V バンド)，露出時間：20分×２
擬似カラー処理，画像範囲：38.365×24.185°，観測場所：乗鞍コロナ観測所

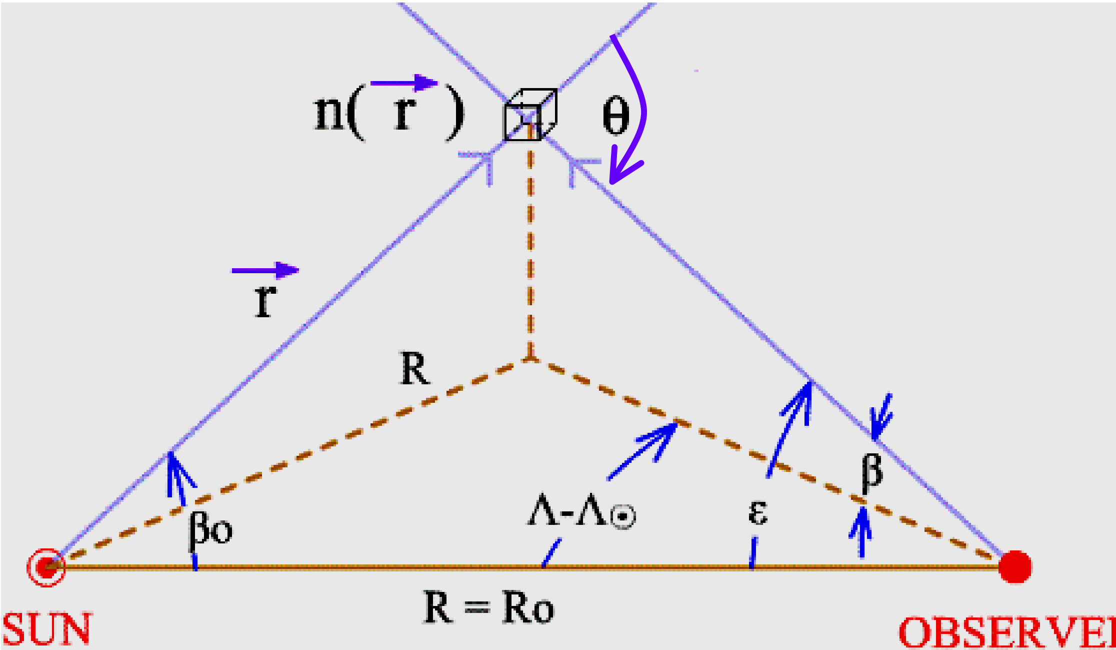
H. Fukushima, D. Kinoshita and J. Watanabe

国立天文台 広報普及室



MILKY WAY
Aql
Atair
Sgr
Cap
Del
Peakock
Pav
Ind
Gru
Alnair
Tuc
Aqr
PsA
Formalhaut
Phe
Peg
Ecliptic
Zodiacus
Cet
Psc
Mercury

ZODIACAL LIGHT BRIGHTNESS INTEGRAL



$$Z\left(\Lambda-\Lambda_{\odot};\beta\right)=\int_{0}^{\infty}F(\vec{r}\,)\,n\left(\vec{r}\,\right)\overline{\sigma}\left(\vec{r}\,\right)\Phi(\Theta,\vec{r}\,)\;dl$$

$F(\vec{r}\,)$: solar flux falling at position $\vec{r}$

$n\left(\vec{r}\right)$: number density of the IPDs at $\vec{r}$

$\overline{\sigma}\left(\vec{r}\,\right)$: mean scattering cross-section

$\Phi(\Theta,\vec{r}\,)$: mean volume scattering phase function

INVERSION of the ZL BRIGHTNESS INTEGRAL

$$Z(\Lambda - \Lambda_{\odot}; \beta) = \int_0^{\infty} F(\vec{r})\, n(\vec{r})\, \overline{\sigma}(\vec{r})\, \Phi(\Theta, \vec{r})\; dl$$

2-D Distribution of ZL Brightness $\Leftarrow$ **OBSERVATION**

- 3-D structure of the IPD cloud complex
- local properties of IPDs in terms of
  - scattering cross-section
  - scattering phase function

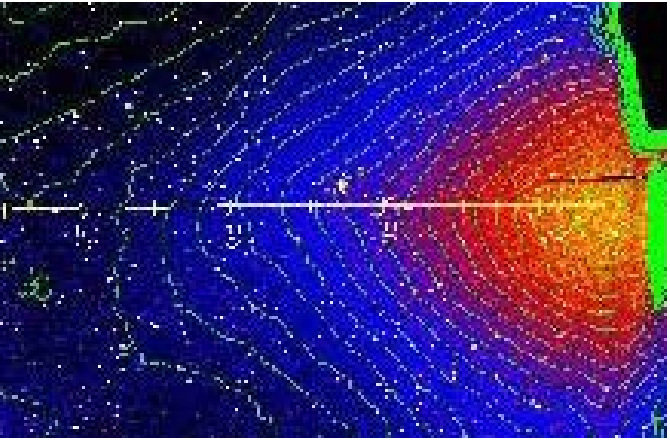
- wavelength dependence of the ZL brightness
  - wavelength dependent scattering properties
  - IPDs are grey in the optical !

ISOLATION Of the ZODIACAL LIGHT

In The OBSERVED NIGHT SKY BRIGHTNESS

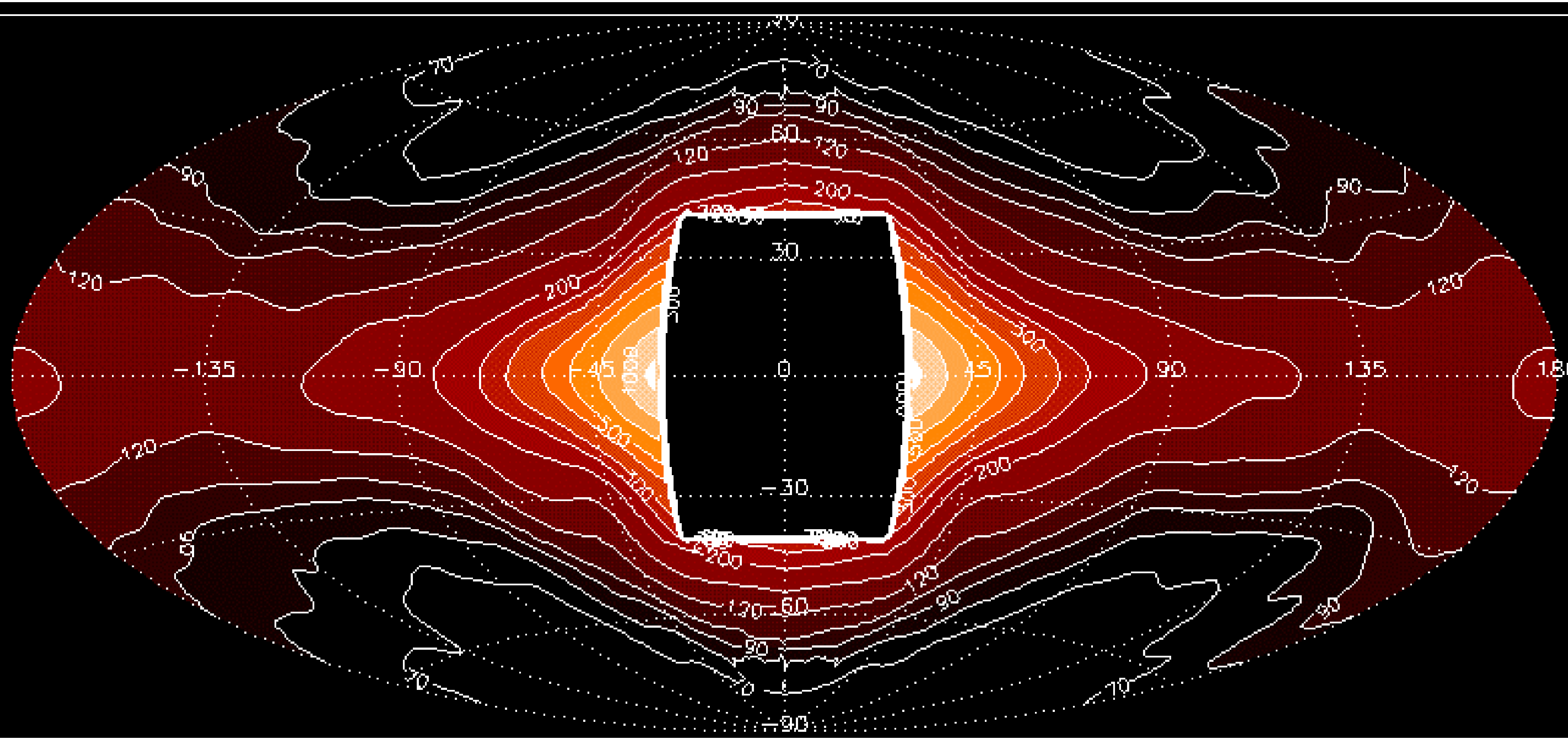
BS = ST + IS + DG + AG + ADL + ZL

- Resolved Bright Starlight
- Integrated or Un-resolved Starlight
- Diffuse Galactic Light
- Airglow Emission
- Atmospheric Diffuse Light
  - diffuse scattered light of IS, DG, AG, and ZL
- Zodiacal Light
- The diffuse sources are of comparable brightness !



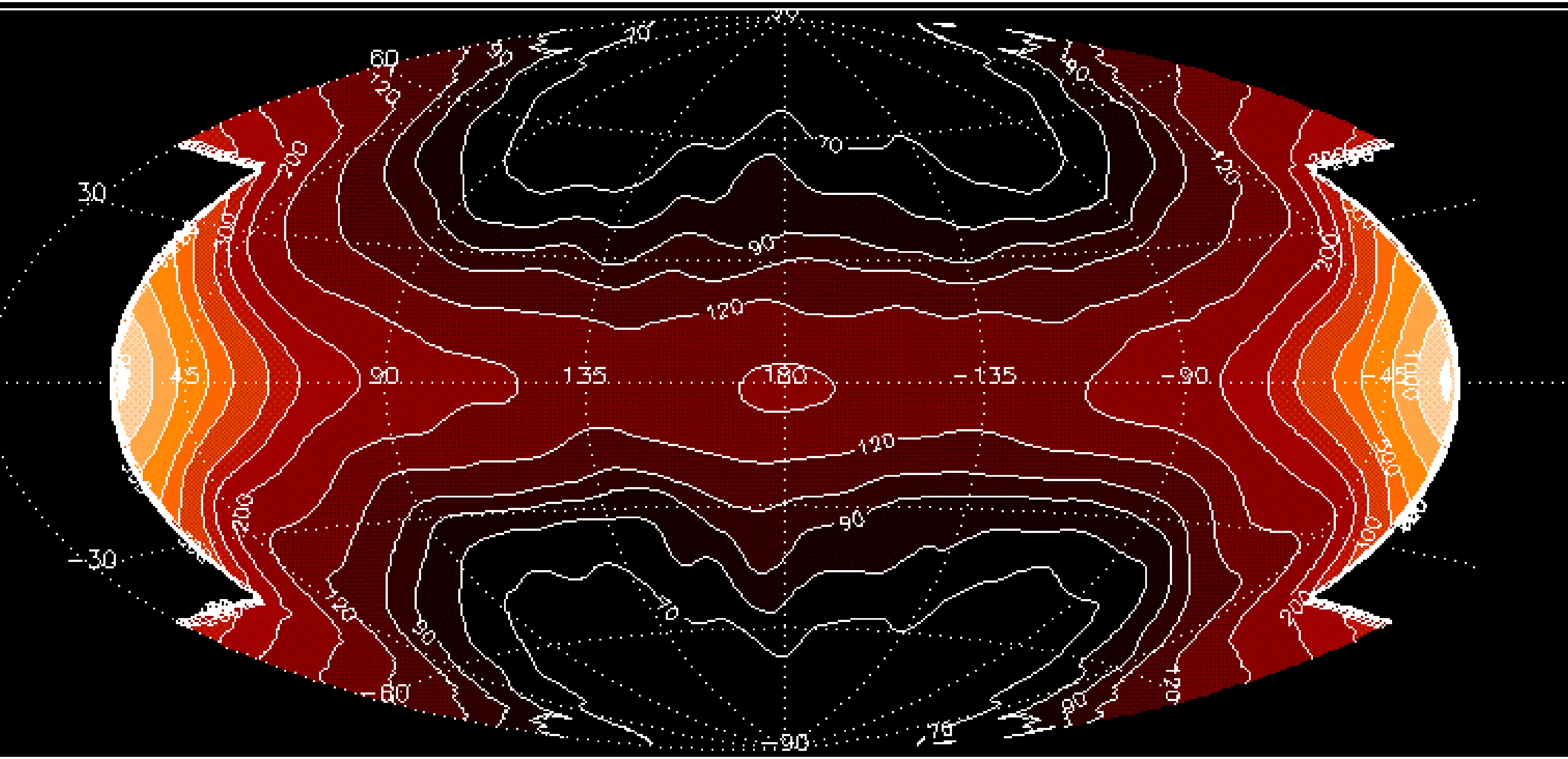
ST, IS, DG, AG, ADL, ZL Brightness Distribution

2-D Distribution of the ZL Brightness



Alt-Azimuth Scans done in 1968 Aug 21/22 with PM Tube on Haleakala, Hawaii, by J.L. Weinberg at 5300 & 5080A

$$Z(\Lambda - \Lambda_{\odot}; \beta) = \int_0^{\infty} F(\vec{r})\, n(\vec{r})\, \overline{\sigma}(\vec{r})\, \Phi(\Theta, \vec{r})\, dl$$



Kwon, Hong & Weinberg 2004, *New Astronomy*, in press

INVERSION of the OBSERVED 2-D ZL DISTRIBUTION for 3-D MODEL of IPD CLOUD

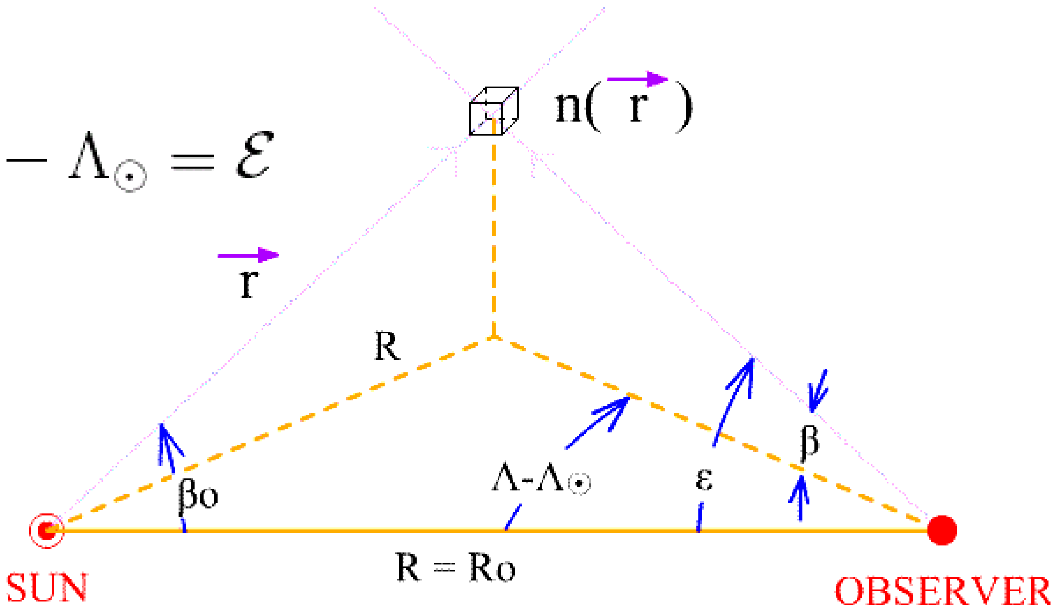
$$Z\,(\Lambda - \Lambda_{\odot};\beta) = \int_0^{\infty} F(\vec{r}\,)\,n\,(\vec{r}\,)\,\overline{\sigma}\,(\vec{r}\,)\,\Phi(\Theta,\vec{r}\,)\;dl$$

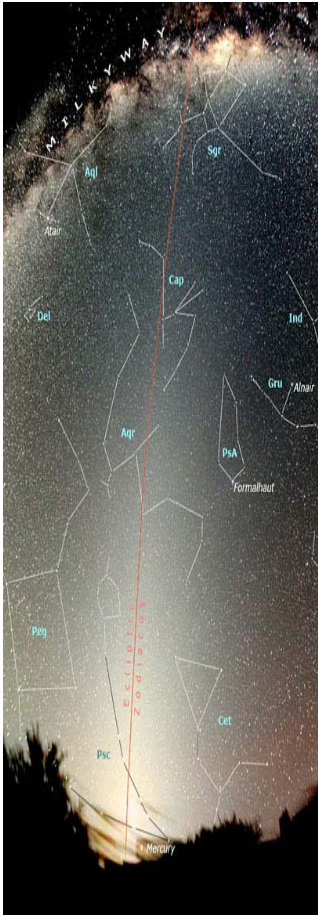
- inaccessible zones in the sky coverage
- temporal changes of the Earth's atmosphere
- annual Modulations in the ZL brightness →
  dcliptic coordinate system may not be the best choice to work with.
- uncertain ADL corrections
- insufficient angular resolution
- mathematically a difficult problem to solve
  - degeneracy
  - sensitive to the input, i.e. ZL
- **A Boot Strap Operation we have to rely on !**

IN-ECLIPTIC ZL BRIGHTNESS

$\beta = 0 \quad ; \quad \Lambda - \Lambda_\odot = \mathcal{E}$

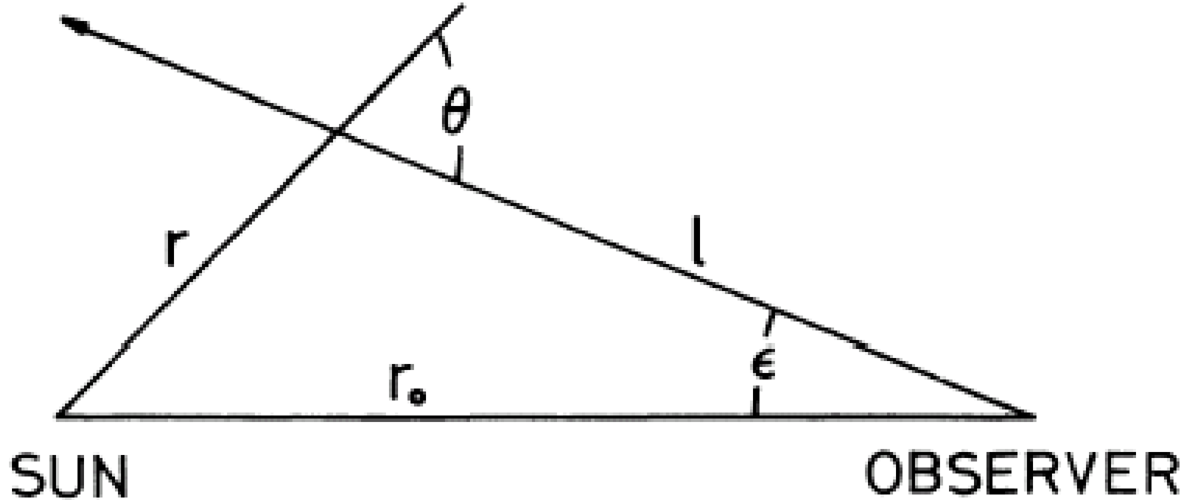
$\nu \approx 1$





$$Z(\mathcal{E}) = \int_0^\infty F_o \left(\frac{R_o}{R}\right)^2 n_o \left(\frac{R_o}{R}\right)^\nu \overline{\sigma}\, \Phi(\Theta)\, dl$$

$$Z(\mathcal{E}) = \frac{F_o n_o R_o \overline{\sigma}}{\sin^{\nu+1}\mathcal{E}} \int_{\mathcal{E}}^{\pi} \Phi(\Theta) \sin^\nu \Theta \, d\Theta$$



$$\frac{R_\mathrm{o}}{R} = \frac{\sin\Theta}{\sin\mathcal{E}} \quad ; \quad dl = R_\mathrm{o}\,\frac{\sin\mathcal{E}}{\sin\Theta}\,\frac{d\Theta}{\sin\Theta}$$

INVERSION of the IN-ECLIPTIC ZL DISTRIBUTION for the IPD SCATTERING PHASE FUNCTION $\Phi\ (\Theta)$

$$Z\,(\Lambda - \Lambda_{\odot};\beta) = \int_0^{\infty} F(\vec{r})\,n\,(\vec{r})\,\overline{\sigma}\,(\vec{r})\,\Phi(\Theta,\,\vec{r})\;dl$$

$$Z\,(\mathcal{E}) = \frac{\zeta\,\overline{\sigma}}{\sin^{\nu+1}\mathcal{E}}\int_{\mathcal{E}}^{\pi} \Phi(\Theta)\sin^{\nu}\Theta\,d\Theta, \quad \text{with } \zeta \text{ being } F_{\rm o}\,R_{\rm o}\,n_{\rm o}$$

Local properties have been replaced by Global simplifications.

power-law distribution is introduced for density distribution ν

spatial uniformity is assumed for σ and $\Phi(\Theta)$

Only the in-ecliptic ZL brightness is utilized as the input data.

Z (Λ-Λsun, β) $\Rightarrow$ Z(Λ-Λsun, β=0)

An Integral Equation for $\Phi(\Theta)$ with observationally known $Z(\varepsilon)$!

Why Are We Interested in the Scattering Phase Function Φ (Θ) ?

- Optical Properties of the IPDs

  characteristic size, composition, and structures/lab exp

- Vertical Density Stratifications of the IPD cloud

$$Z\,(\Lambda - \Lambda_{\odot}; \beta) = \int_0^{\infty} F(\vec{r}\,)\, n\,(\vec{r}\,)\, \overline{\sigma}\,(\vec{r}\,)\, \Phi(\Theta, \vec{r}\,)\; dl$$

$$\Phi(\Theta, \vec{r}) \simeq \Phi(\Theta)\ ; \quad \overline{\sigma}(\vec{r}) \simeq \overline{\sigma}\ ; \quad n(\vec{r}) \simeq n(R)\mathcal{H}(\beta_{\circ})$$

$$Z\,(\Lambda - \Lambda_{\odot}; \beta) \simeq \overline{\sigma} \int_0^{\infty} F_{\circ} \left(\frac{r_{\circ}}{r}\right)^2 n\,(R)\, \mathcal{H}(\beta_{\circ})\, \Phi(\Theta)\; dl$$

- 3-D Model of the IPD cloud !

  But we haven't come to the 'promised land' yet.

DIFFERENTIAL INVERSION with IN-ECLIPTIC ZL

$$Z\left(\mathcal{E}\right) = \frac{\zeta\,\overline{\sigma}}{\sin^{\nu+1}\mathcal{E}} \int_{\mathcal{E}}^{\pi} \Phi(\Theta)\sin^{\nu}\Theta\, d\Theta$$

Take derivative of Z(ε) with respect to solar elongation :

$$\Phi\left(\Theta\right) = -\frac{1}{\zeta\,\overline{\sigma}} \left[(\nu+1)\, Z(\mathcal{E}) \cos\mathcal{E} + \sin\mathcal{E}\, \frac{\partial}{\partial\mathcal{E}} Z(\mathcal{E}) \right]_{\mathcal{E}=\Theta}$$

Replace the integral by a quadrature sum :

$$Z\left(\mathcal{E}_i\right) = \frac{\zeta\,\overline{\sigma}}{\sin^{\nu+1}\mathcal{E}_i} \sum_{\Theta_j=\mathcal{E}_i}^{\pi} W_{ij} \sin^{\nu}\Theta_j\, \Phi(\Theta_j)\, \Delta\Theta_j$$

⇒ Upper triangular system of linear equations

⇒ Backward substitution yields Φ(Θ)

An INTEGRAL METHOD of INVERSION :

H-G REPRESENTATION of the SCATTERING PHASE FUNTION for IPDS

- employ a parametric function for $\Phi(\Theta)$ in the brightness integral
- synthesize $Z_{syn}(\varepsilon)$ and construct its residual from $Z_{obs}(\varepsilon)$
- optimize the parameter set by minimizing the residual
- Henyey-Greenstein Function

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ing is now available. We have carried out our computations, using a phase function of the form

$$\Phi(\alpha) = \frac{\gamma(1 - g^2)}{4\pi} \frac{1}{(1 + g^2 - 2g \cos \alpha)^{3/2}} . \qquad (2)$$

The phase angle is α, defined as the deviation of the ray from the forward direction; γ is the spherical albedo; the parameter g measures the asymmetry of the phase function, according to the expression

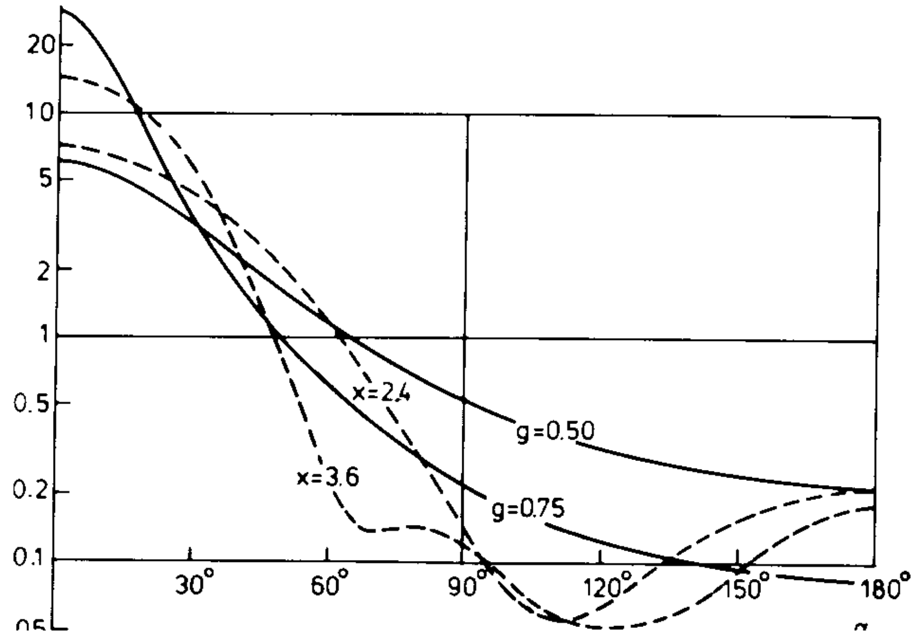
Henyey-Greenstein Function

$$\phi_{\rm HG}(\Theta\,;\,g) \equiv \frac{1}{4\pi}\frac{1-g^2}{(1+g^2-2g\cos\Theta)^{3/2}}$$

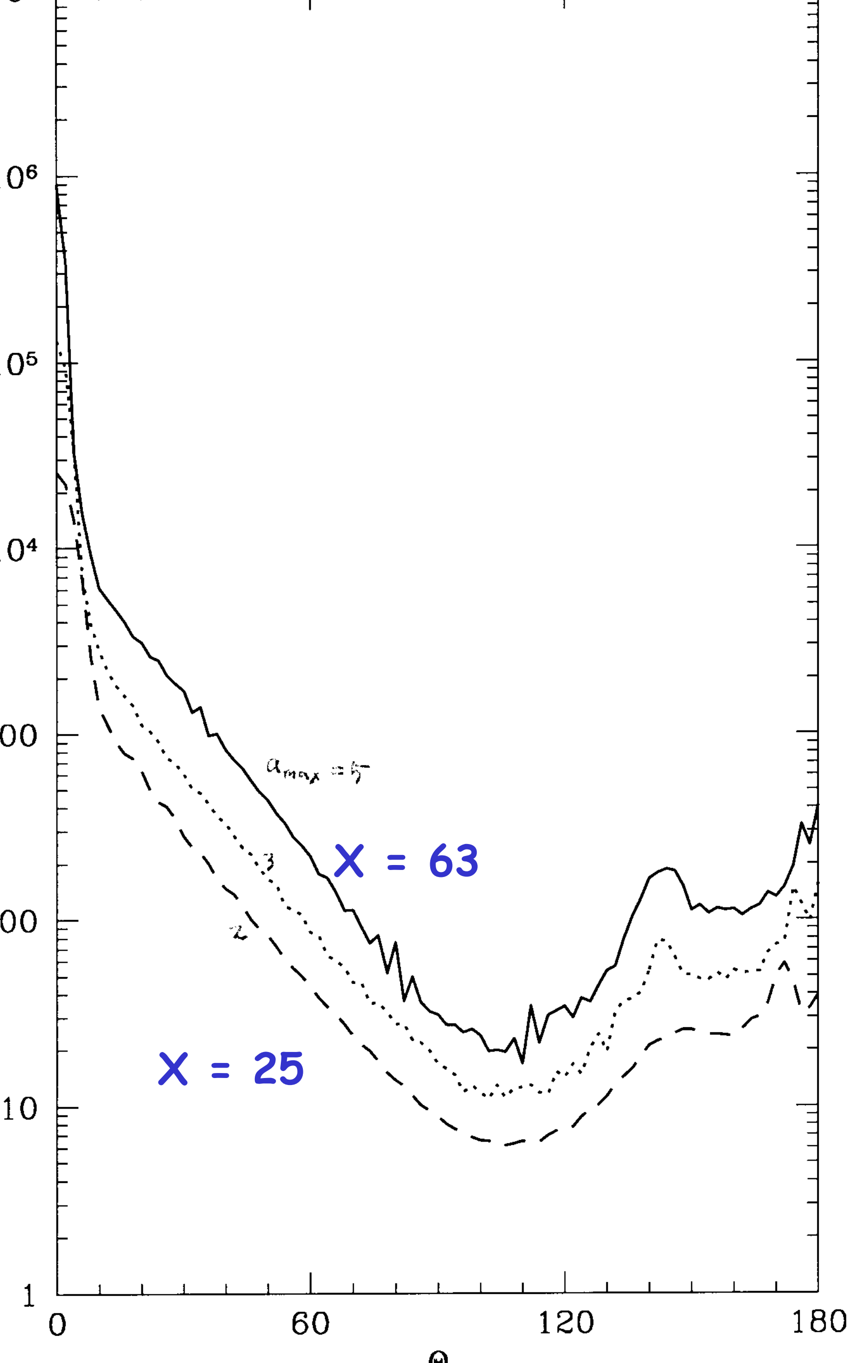
$$1 = \frac{1}{2}\int_{-1}^{1} \phi_{\rm HG}(\Theta\,;\,g)\,d(\cos\Theta)$$

$$g = \frac{1}{2}\int_{-1}^{1} \phi_{\rm HG}(\Theta\,;\,g)\,\cos\Theta\,d(\cos\Theta)$$

$$f \equiv \frac{1}{2}\int_{0}^{1} \phi_{\rm HG}(\Theta\,;\,g)\,d(\cos\Theta)$$



$$\phi_{\rm HG}(0) = \frac{1+g}{(1-g)^2}\;;\;\phi_{\rm HG}(\pi) = \frac{1-g}{(1+g)^2}\;;\; f = \frac{1+g}{2g}\left[1-\frac{1-g}{(1+g^2)^{1/2}}\right]$$



Characteristics of $\Phi(\Theta)$

- an example of phase function

  m = 1.33; λ = 0.5 μm
  collection of water droplets with size distributed over some range

- a very sharp diffraction peak

  $\Theta \leq 180°$/size parameter x

- strongly forward-throwing part
- more-or-less isotropic middle
- backward enhancement

$$\Phi(\Theta) = \sum_{k=1}^{3} w_k \, \phi(\Theta\,;\; g_k) \quad \text{with condition} \quad \sum_{1}^{3} w_k = 1$$

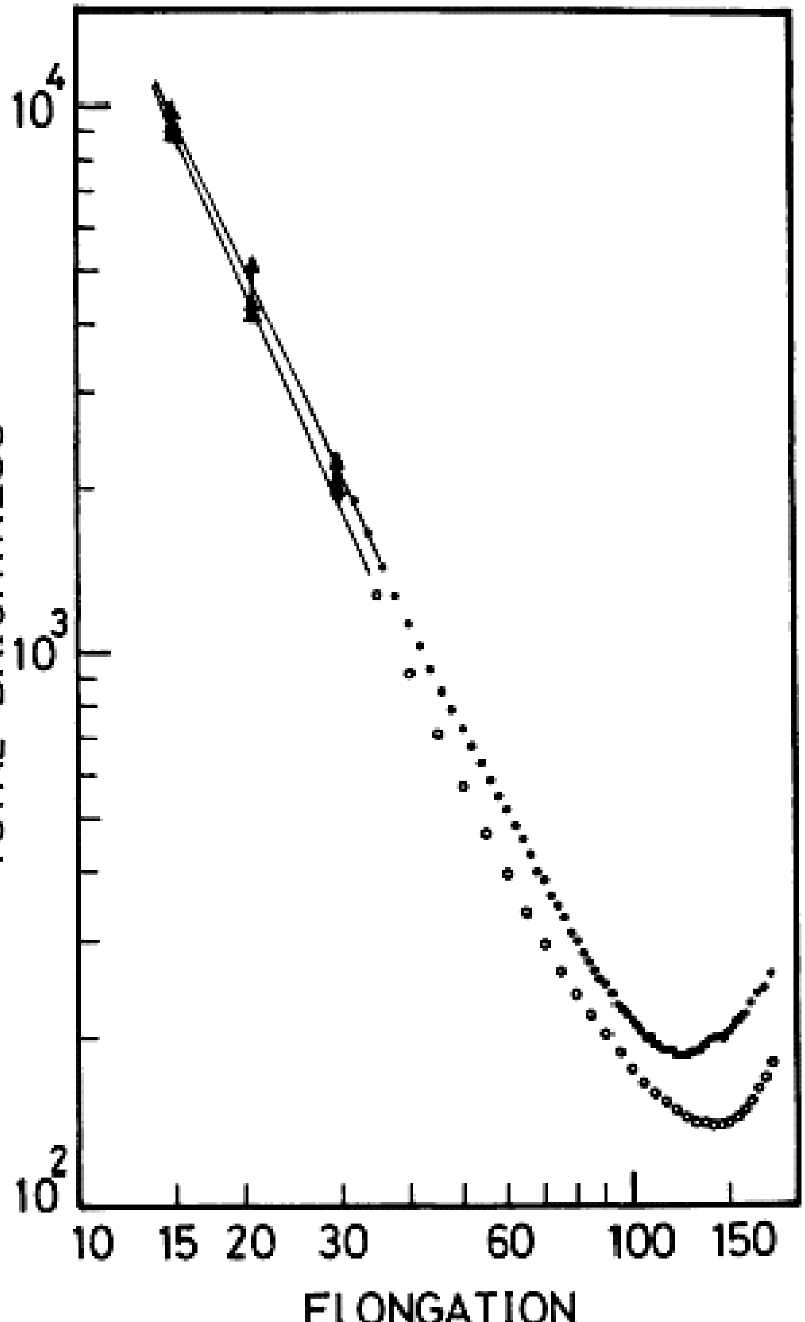
a five parameter representation

$$Z(\mathcal{E}) = \frac{\zeta\,\overline{\sigma}}{\sin^{\nu+1}\mathcal{E}} \sum_{k=1}^{3} \int_{\mathcal{E}}^{\pi} w_k \phi_{\mathrm{HG}}(\Theta; g_k)\, \sin^{\nu}\Theta \, d\Theta$$

For the case of $\nu = 1$ this becomes

$$Z(\mathcal{E}) = \frac{\zeta_1\,\overline{\sigma}_1}{\sin^2\mathcal{E}} \sum_{k=1}^{3} \frac{w_k}{4\pi} \frac{1-g_k}{g_k} \left[\frac{1+g_k}{(1+g_k^2 - 2g_k\cos\mathcal{E})^{1/2}} - 1 \right].$$

A closed form of integral with $\nu = 1$ makes an evaluation of the brightness integral very easy. An optimization of H-G parameters becomes a simple matter.



filled circles: 5300Å, Hawaii, Weinberg '63

open circles: 5000Å, Tenerife,

Dumont & Sanchez '75

triangles: 3 λs, Rocket, Leinert et al. '76

eclipse data ε below 15° excluded

diffraction dominated part/ Bessel J_1

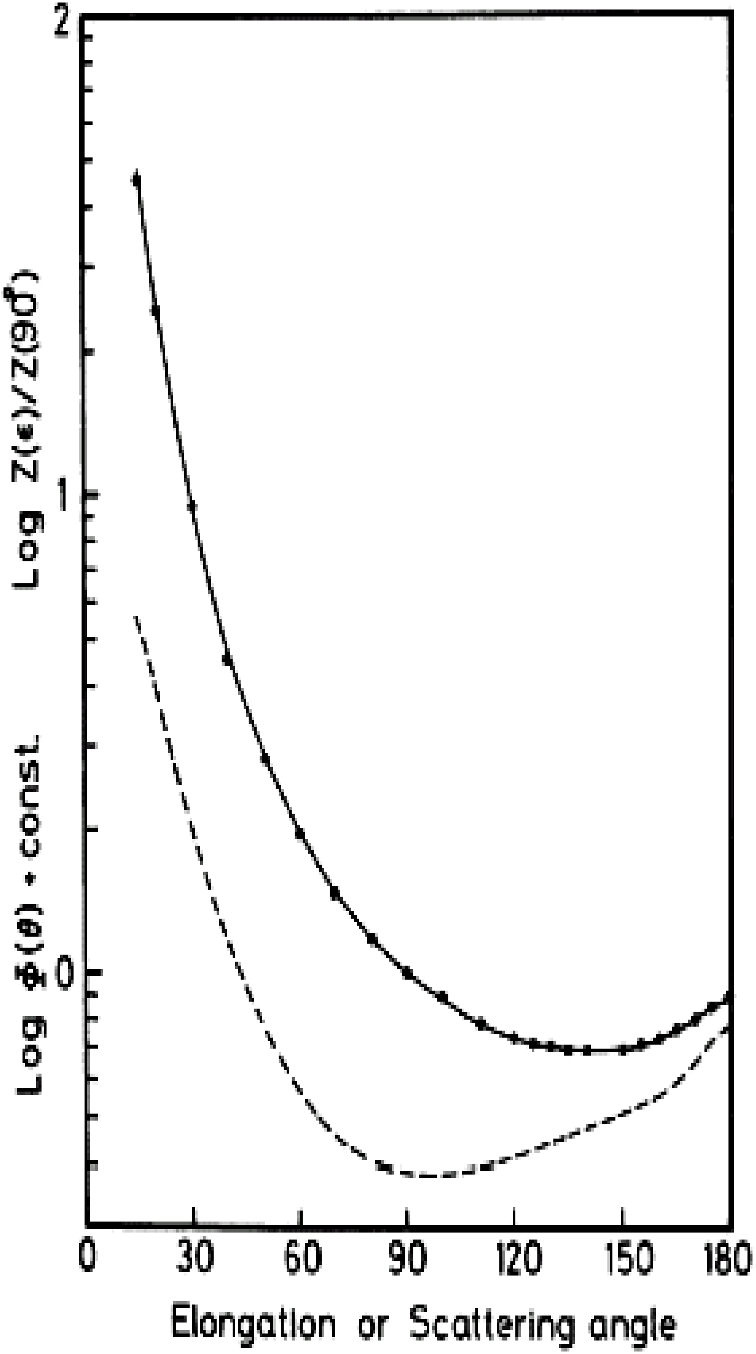
better than H-G

Lamy & Perrin '85; Mann '92;

Davidson et al.'95

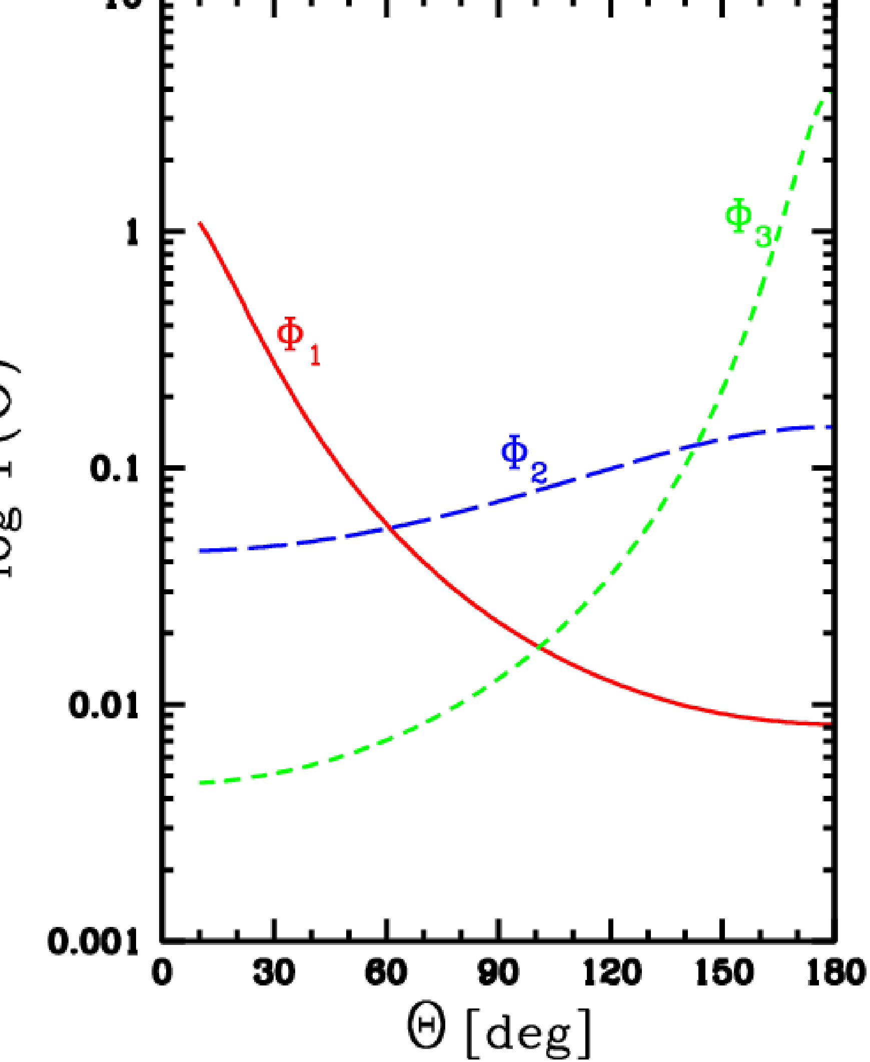
in total 23 points selected along the ecliptic

- Would the integral method give us a 'stable' solution?
- Would then this method 'discriminate' the open circle data from filled one?



- Random errors with relative amplitude less than 5% give us essentially the same combination of asymmetry factors.
- The Hawaii data result in an unsatisfactory combination of asymmetry factors.

⇒ The H-G integral method is robust but sensitive.



Henyey-Greenstein parameters for $\Phi_1(\Theta)$

Asymmetry factors g_k	0.70	−0.20	−0.81
Weights w_k	0.665	0.330	0.005
$\zeta_1 \bar{\sigma}_1$ in $S_{10}(V)_\odot$ sr		$4.61\ 10^3$	

Generalize $\Phi_1(\Theta)$ to $\Phi_\nu(\Theta)$ with ν Other than 1

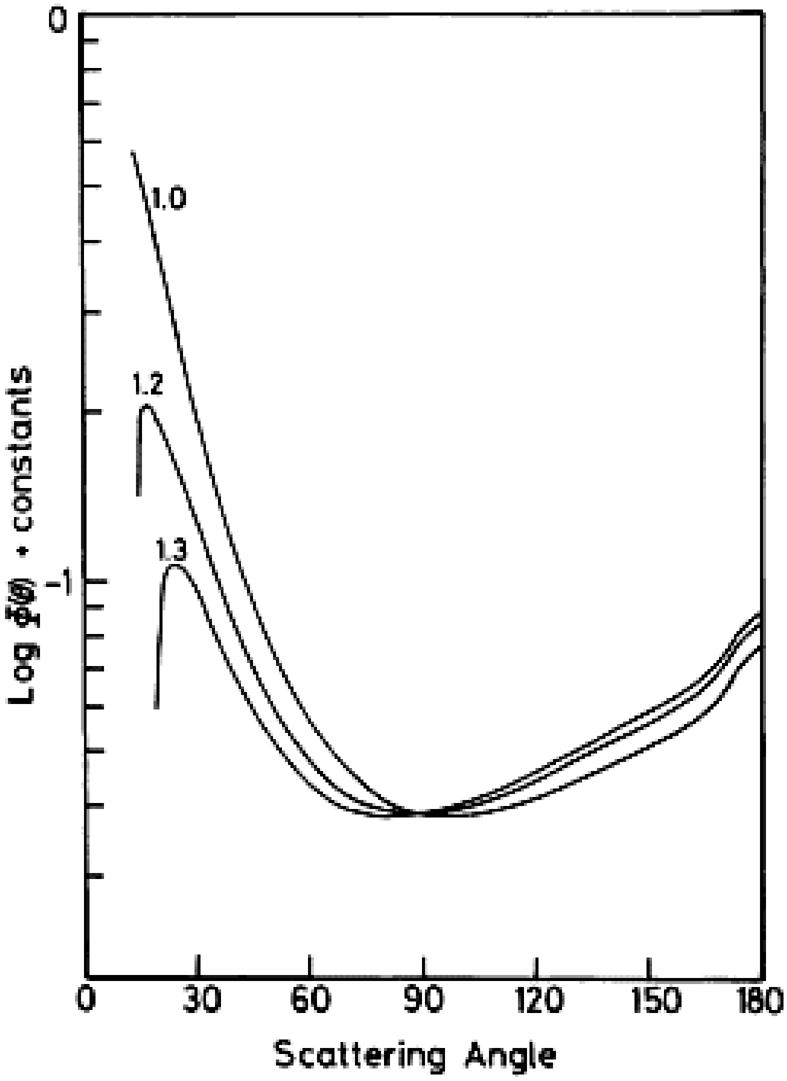
$$\Phi\left(\Theta\right) = -\frac{1}{\zeta\,\overline{\sigma}}\left[\left(\nu+1\right)Z(\mathcal{E})\cos\mathcal{E} + \sin\mathcal{E}\,\frac{\partial}{\partial\mathcal{E}}\,Z(\mathcal{E})\right]_{\mathcal{E}=\Theta}$$

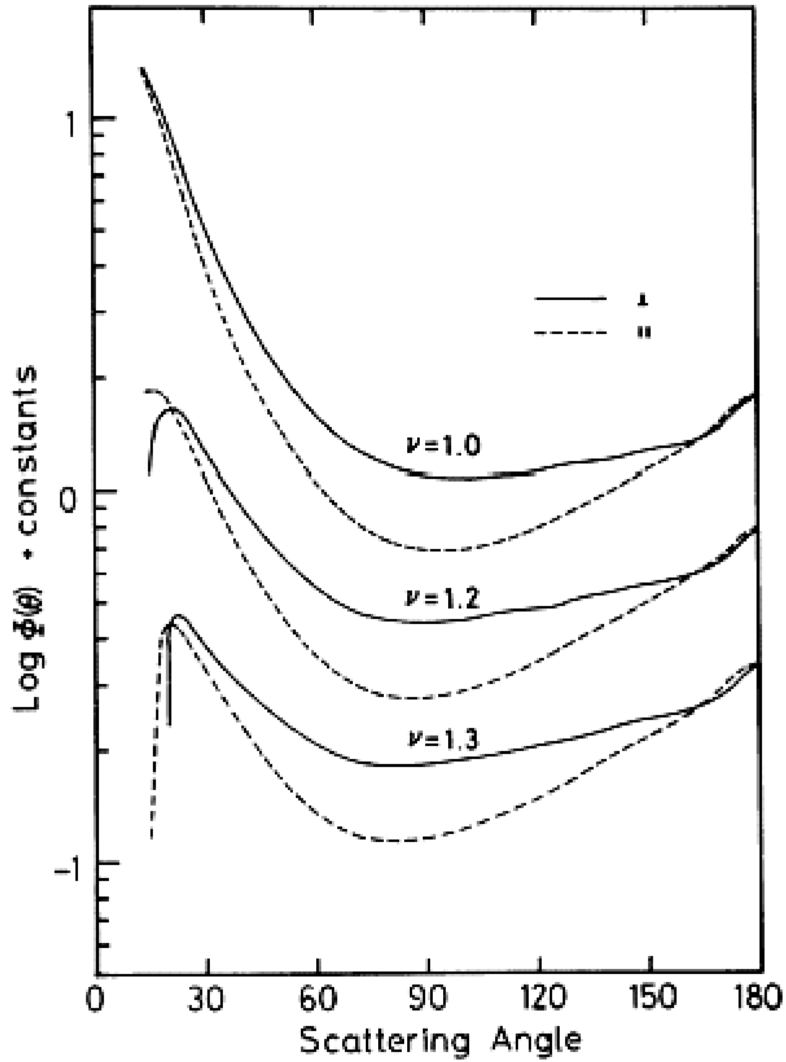
$$\Phi_\nu\left(\Theta\right) = -\frac{1}{\zeta_\nu\,\overline{\sigma}_\nu}\left[\left(\nu+1\right)Z(\mathcal{E})\cos\mathcal{E} + \sin\mathcal{E}\,\frac{\partial}{\partial\mathcal{E}}\,Z(\mathcal{E})\right]_{\mathcal{E}=\Theta}$$

$$\Phi_1\left(\Theta\right) = -\frac{1}{\zeta_1\,\overline{\sigma}_1}\left[\left(1+1\right)Z(\mathcal{E})\cos\mathcal{E} + \sin\mathcal{E}\,\frac{\partial}{\partial\mathcal{E}}\,Z(\mathcal{E})\right]_{\mathcal{E}=\Theta}$$

Consequently we have

$$\Phi_\nu\left(\Theta\right) = \frac{\zeta_1\,\overline{\sigma}_1}{\zeta_\nu\,\overline{\sigma}_\nu}\left[\Phi_1\left(\mathcal{E}\right) - \left(\nu-1\right)\cos\mathcal{E}\,\frac{Z(\mathcal{E})}{\zeta_1\overline{\sigma}_1}\right]_{\mathcal{E}=\Theta}$$





The Tenerife+Rocket data imposes too strict a constraint upon the power-law exponent for the IPD density distribution: $\nu \leq 1.15$

New ISOLATION Of ZODIACAL LIGHT

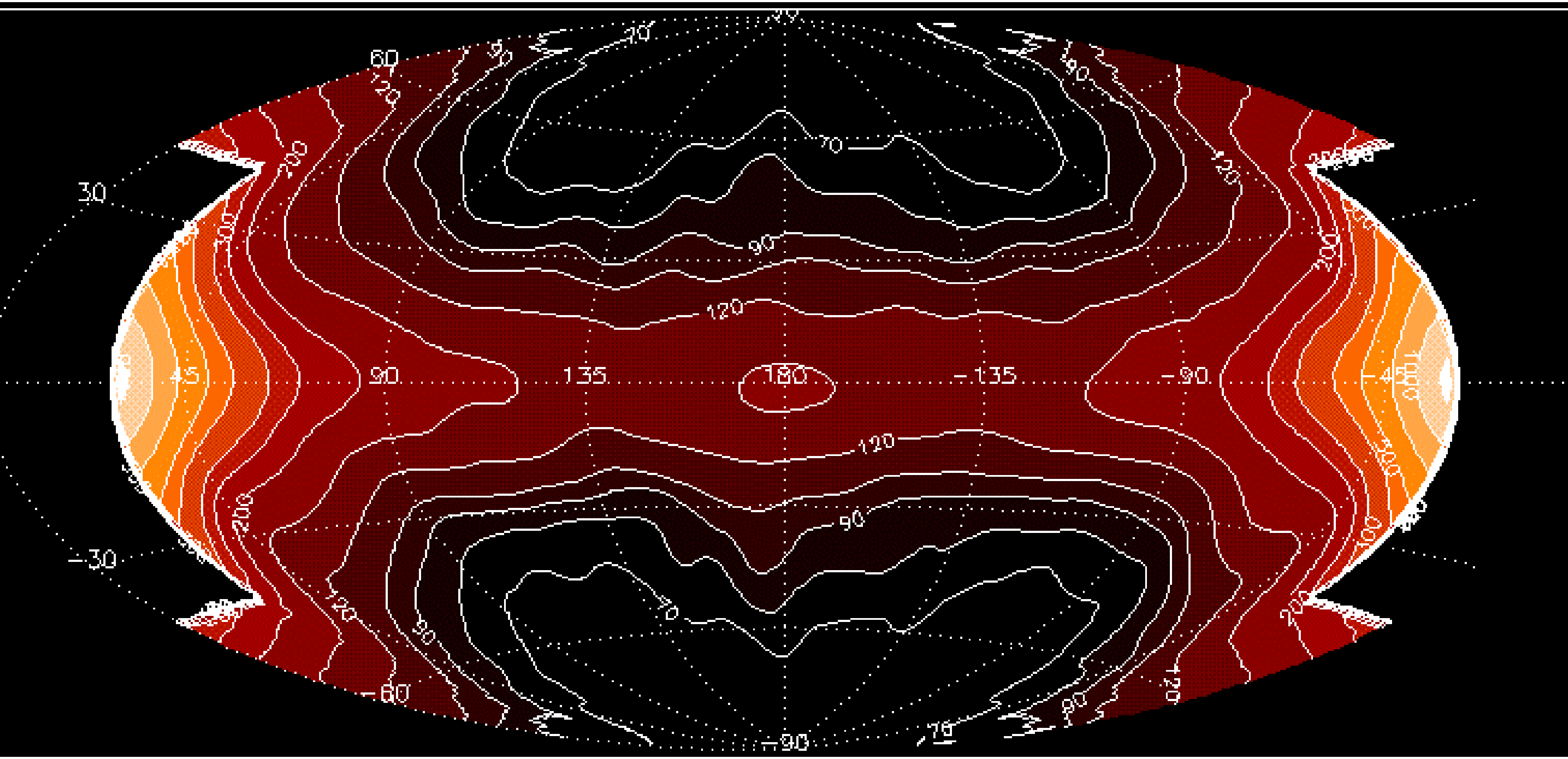
In the OBSERVED NIGHT SKY BRIGHTNESS

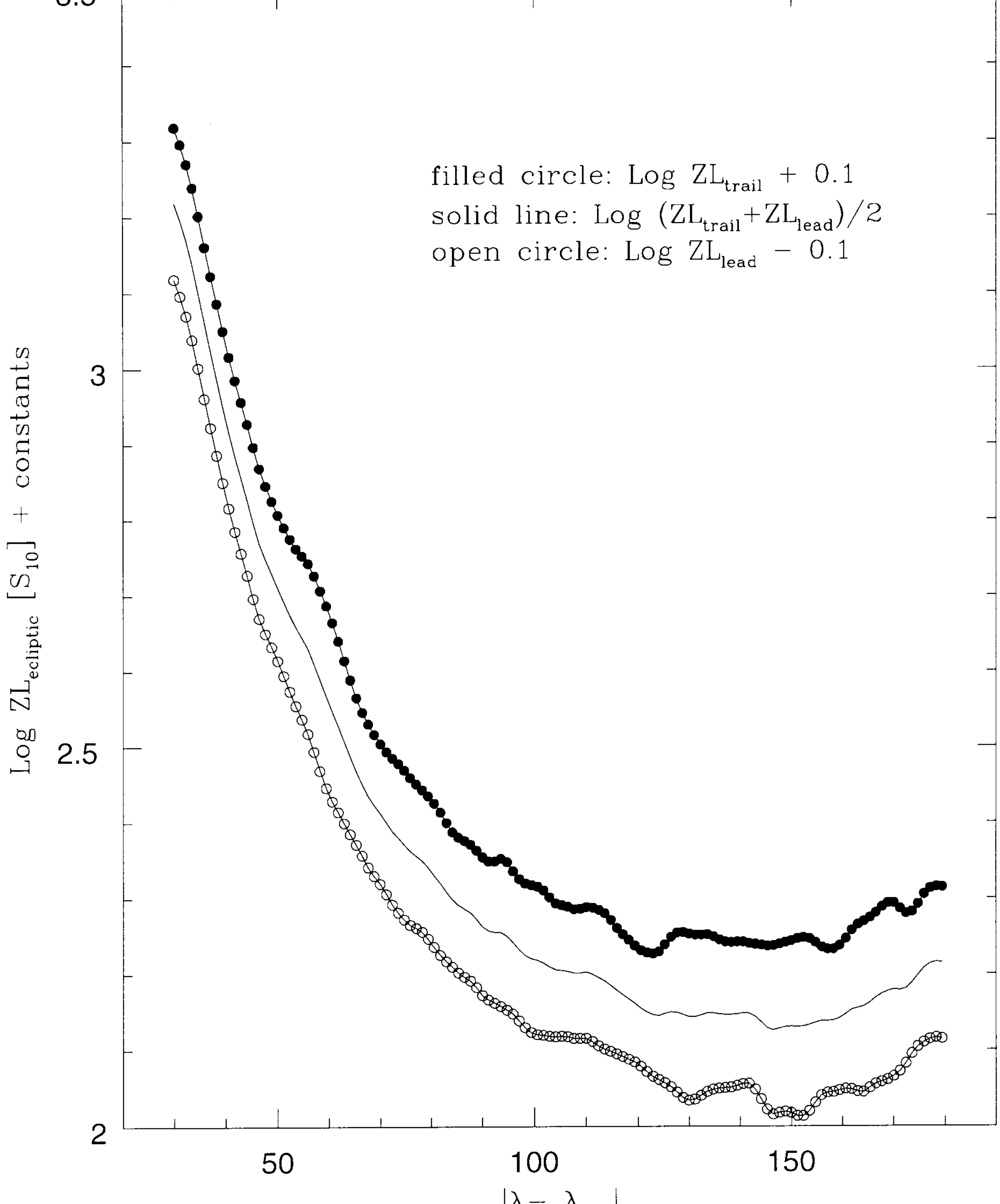
BS = ST + IS + DG + AG + ADL + ZL

- Resolved Bright Starlight /catalogues
- Integrated or Un-resolved Starlight/Pioneer Obs.
- Diffuse Galactic Light /Pioneer Observations
- Airglow Emission /modeling with van Rhijn function
- Atmospheric Diffuse Light/multiple scattering
  - Quasi-Diffusion Method
  - The 'effective tau' by Dumont turns out to be a partial success.

⇒ ZL is newly determined over almost the entire sky that can be reached by ground-based observations with 2° resolution.

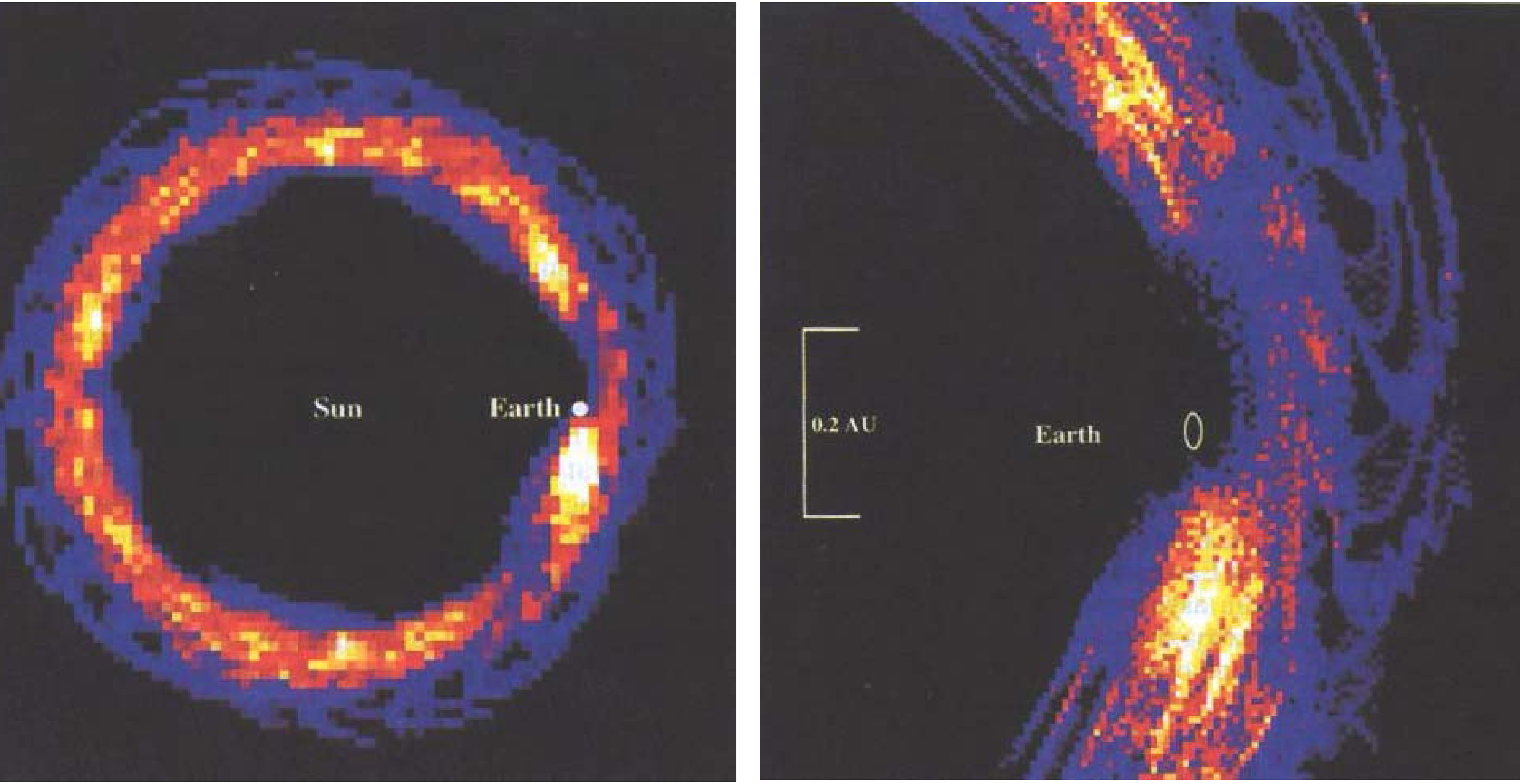
Kwon, Hong & Weinberg 2004, *New Astronomy*, in press





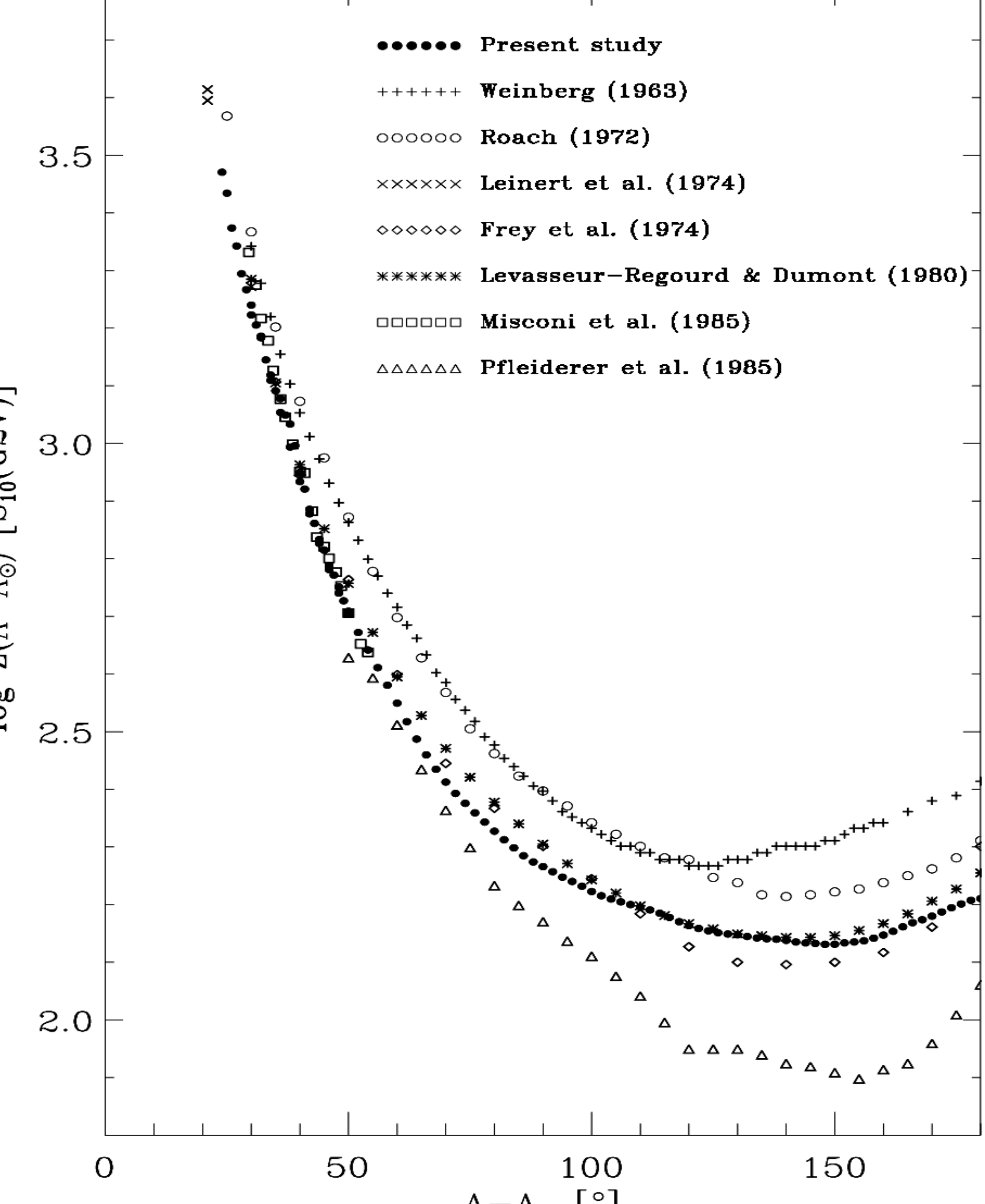
filled circle: Log ZL$_{trail}$ + 0.1
solid line: Log (ZL$_{trail}$+ZL$_{lead}$)/2
open circle: Log ZL$_{lead}$ − 0.1
Log ZL$_{ecliptic}$ [S$_{10}$] + constants
3
2.5
2
50
100
150

Circumsolar Dust Ring
of the Earth's Mean Motion Resonance



Dermott et al. 1994

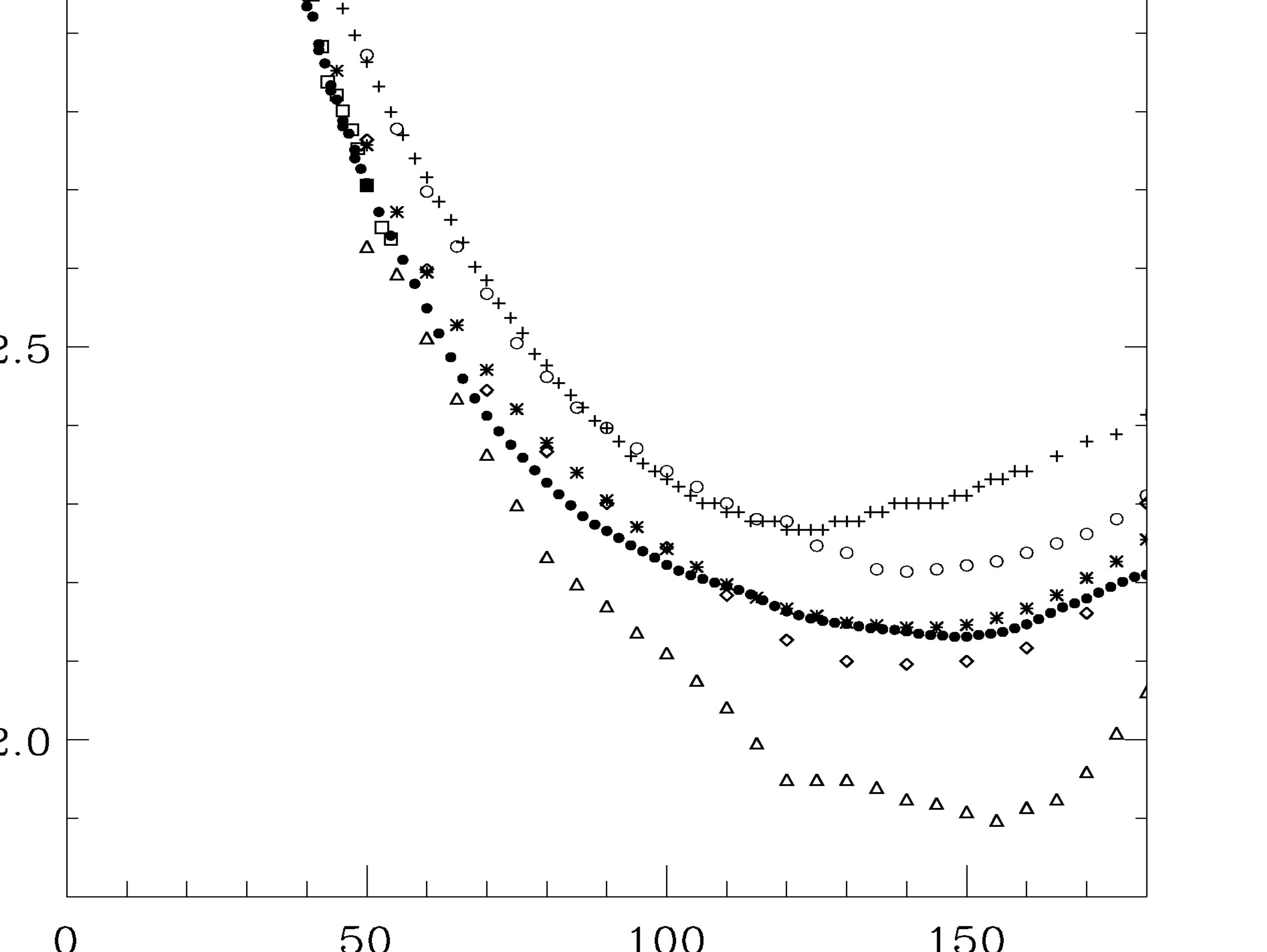
The In-Ecliptic ZL BRIGHTNESS



A remarkable agreement is found with L-R&D '80.

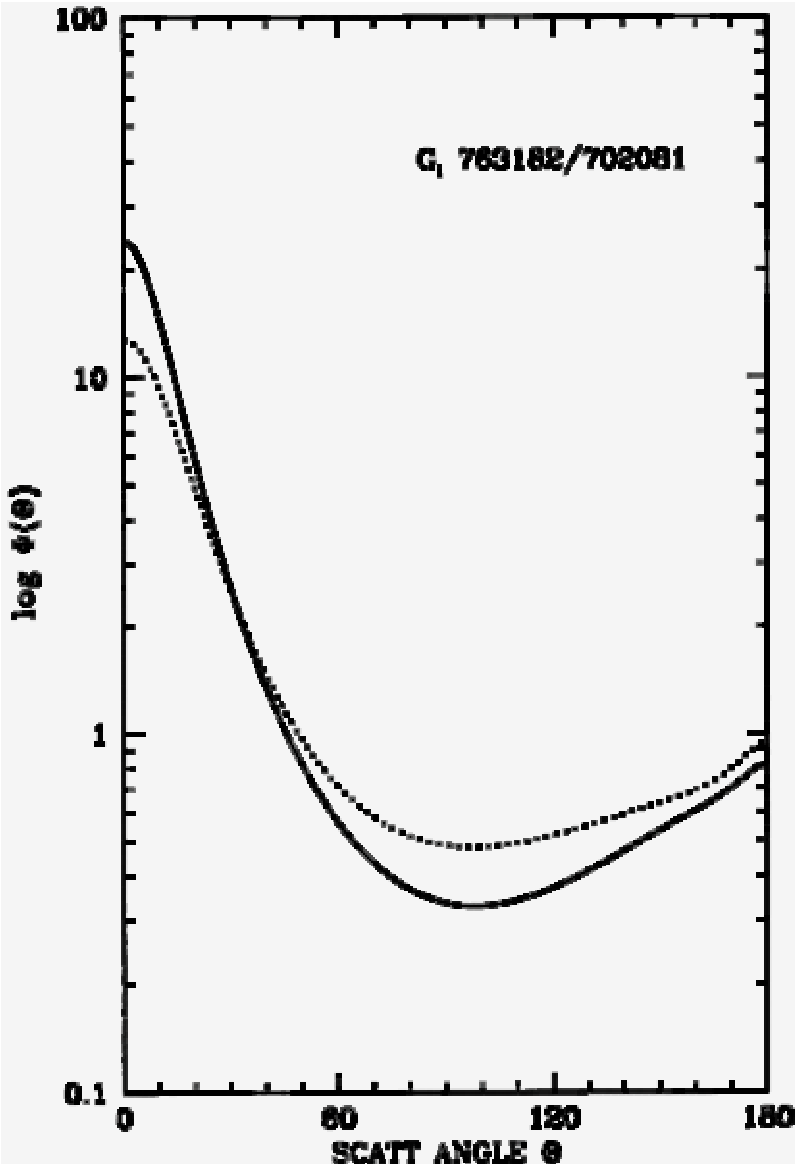
An agreement from two totally different approaches !

Yet, there exist subtle differences between the two.



2.5
2.0
0
50
100
150

New DETERMINATION OF MEAN VOLUME SCATTERING PHASE FUNTION FOR IPDs

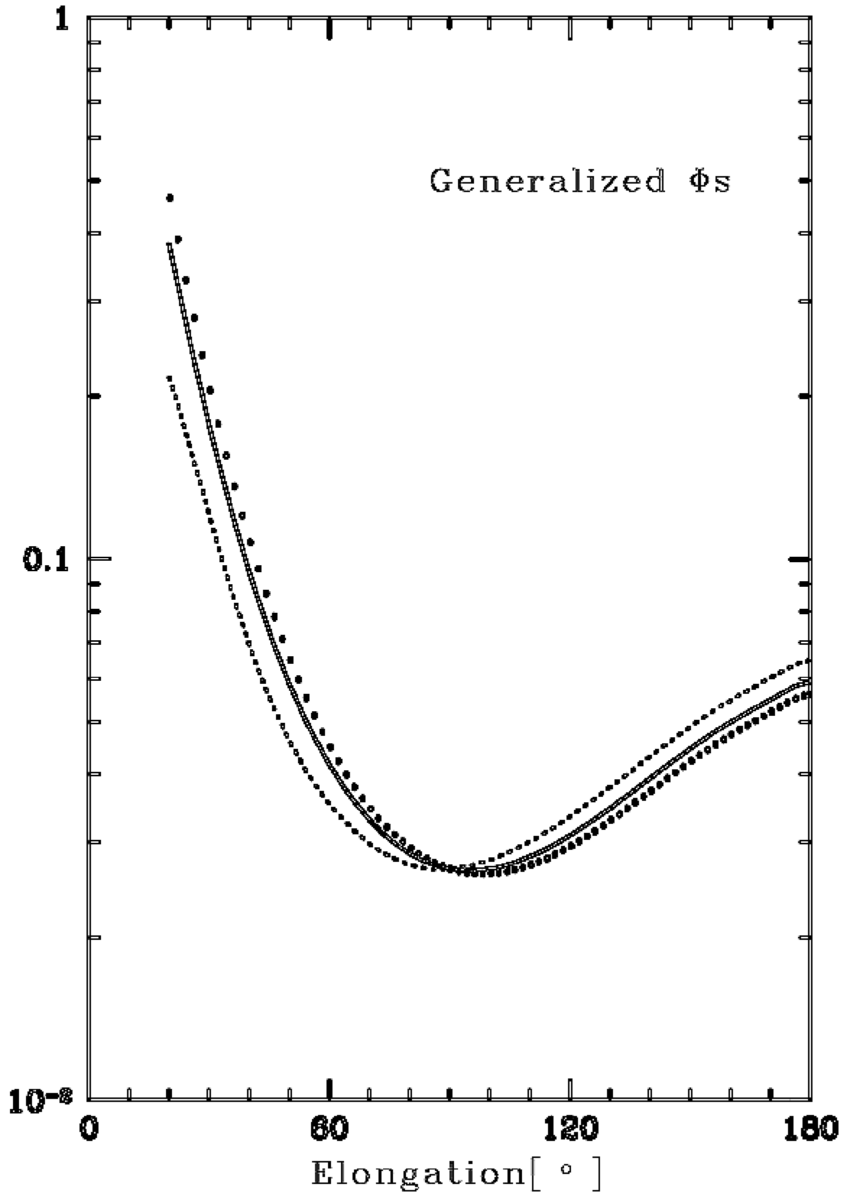


dotted; Tenerife data

solid ; newly reduced Haleakala data

g_k	+ 0.76	- 0.31	- 0.82
w_k	0.785	0.214	0.001

This is a preliminary result.



Generalized to

ν = 1.1, 1.2, and 1.3

no turn over at small scattering angle

$$Z\left(\mathcal{E}\right)=\frac{\zeta\,\overline{\sigma}}{\sin^{\nu+1}\mathcal{E}}\int_{\mathcal{E}}^{\pi}\Phi(\Theta)\sin^{\nu}\Theta\,d\Theta$$

DISCUSSION and CONCLUSION

- Next step inversion is to be done with ZL taken along the maximum density plane, and also over geoecliptic latitudes.

$$\cos \varepsilon = \cos (\Lambda - \Lambda_{\bullet}) \cos \beta$$

- Origin of the structures seen in the ZL distribution

Δ ZL $\Leftarrow$ $\Delta n(r)$; MMR, tilt of max density plane

asteroid/comet debris

$\Delta\Phi(\Theta)$; ones in large elongation angles

polarization reversal at ~152°

- How to disentangle them ?

an improvement in spatial resolution with WIZARD

type instruments by direct imaging

laboratory scattering experiments/ dynamical simulations

comparison of ZL and ZE distributions over large sky area

We saw subtle difference in the ZL brightness between L-R&D and KHW at the middle solar elongation angles. This has removed the abrupt turn-over at small scattering angles, which demonstrates consistency between the newly reduced ZL and the resulting $\Phi(\Theta)$.

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