Clementine Observations of the Zodiacal Light and the Dust Content of the Inner Solar System

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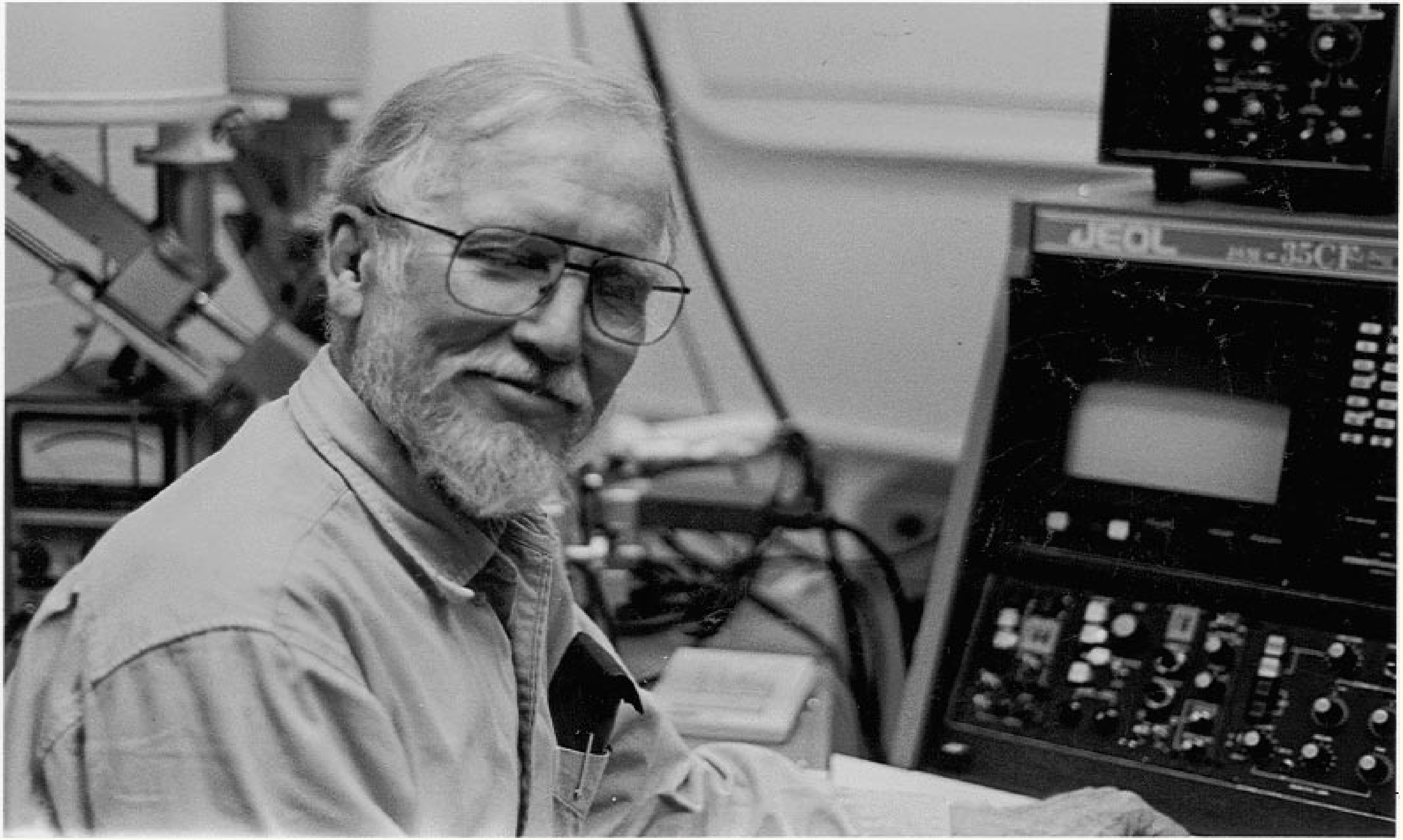

JEOL

photo by Marco Fulle.

The zodiacal light (ZL) is sunlight that is scattered and/or reradiated by interplanetary dust.

The inner ZL is observed towards the sun, usually at optical wavelengths.

The outer ZL is observed away from the sun, usually at infrared wavelengths.

Why Study Interplanetary Dust?

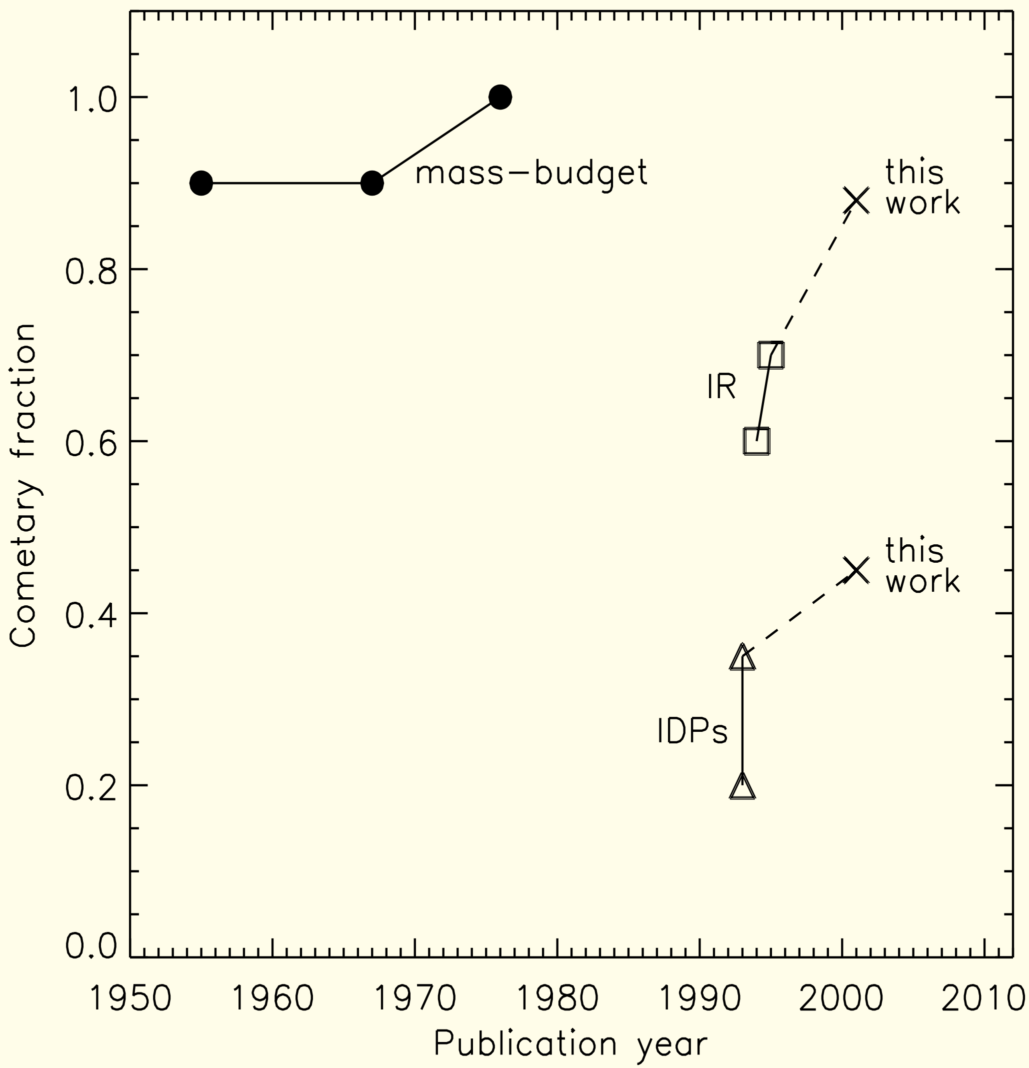
"Someone unfamiliar with astrophysical problems would certainly consider the study of interplanetary dust as an exercise of pure academic interest and may even smile at the fact that much theoretical machinery is devoted to tiny dust grains"

Philippe Lamy, 1975, Ph.D. thesis.

- Dust are samples of small bodies that formed in remote niches throughout the solar system, and they place constraints on conditions in the solar nebula during the planet–forming epoch.
  - dust from asteroids tell us of solar nebula conditions at $r \sim 3$ AU
  - dust from long–period Oort Cloud comets tell us of nebula conditions at $5 \lesssim r \lesssim 30$ AU
  - dust from short–period Jupiter–Family comets tell us of conditions in the Kuiper Belt at $r \gtrsim 30$ AU

- IF the information carried by dust samples (collected by U2 aircraft, Stardust, spacecraft impact experiments, *etc.*) are indeed decipherable, then their mineralogy will inform us of nebula conditions and its history over $3 \lesssim r \lesssim 30$ AU.

- However interpreting this dust requires understanding their *sources* (asteroid & comets), their *spatial distributions*, transport mechanisms, and sampling biases (e.g., certain sources may be more effective at delivering dust to your detector than other sources).



The Perceived Abundance of Asteroidal & Cometary Dust Grains vs. Time:

an oversimplified and incomplete history of interplanetary dust studies.

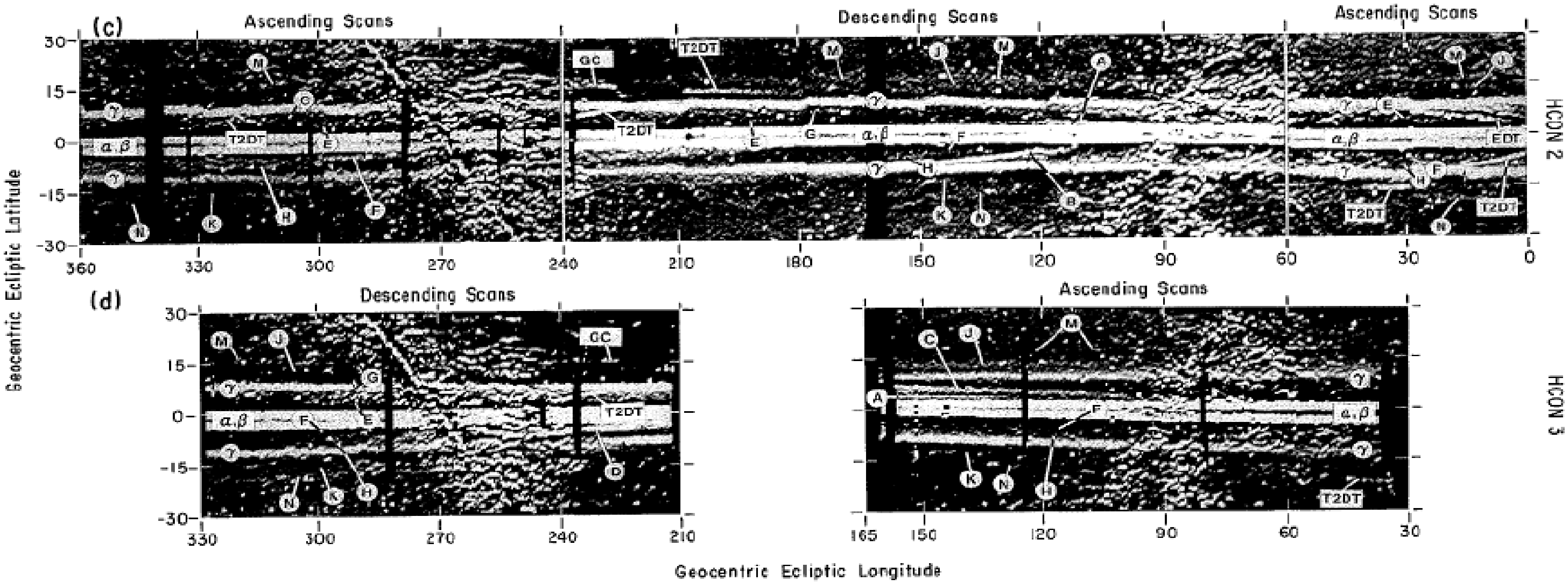


FIG. 1—*Continued*

SYKES (*see* 334, L57)

Dust bands are due to collisions among Themis–family asteroids ($i = 1.4^\circ$), Koronis family ($i = 2.1^\circ$), and Eos ($i = 9.4^\circ$) (Dermott *et al.* 1984).

Note also the dust trails from comets Encke & Tempel 2.

How Asteroid Families Produce Dust Band Pairs

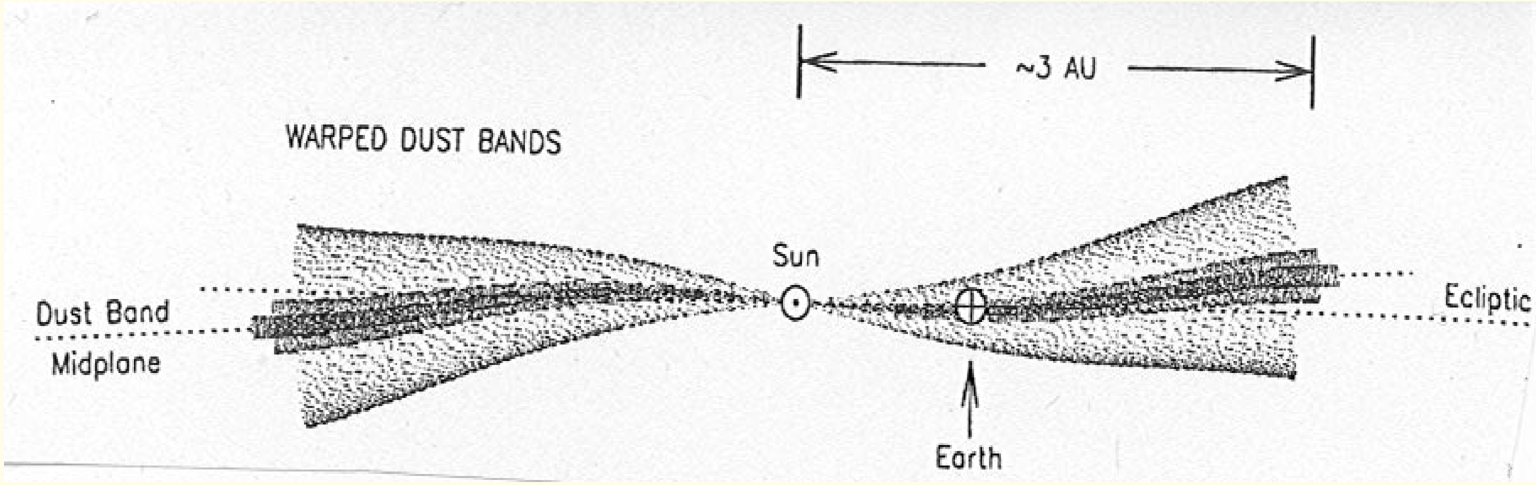


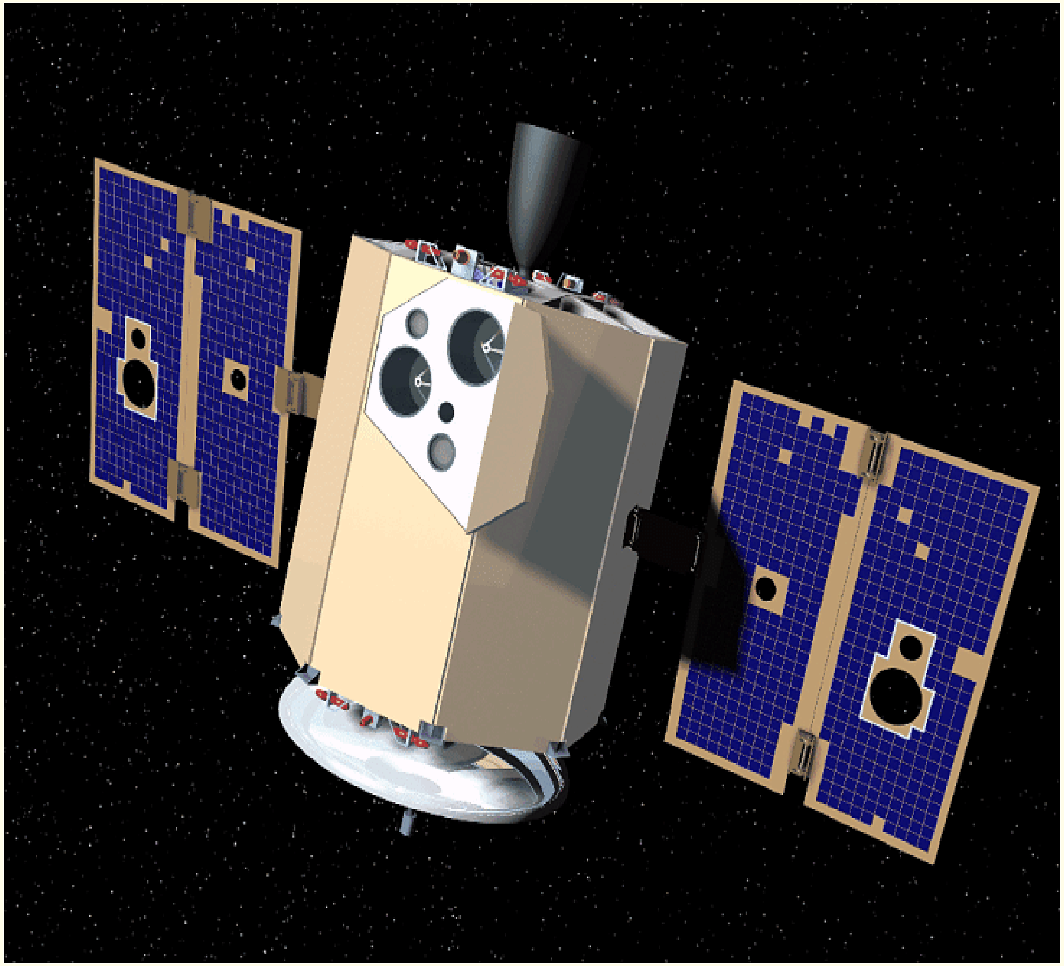
figure from Kortenkamp *et al.* (2001)

Asteroids in a family are fragments of a larger parent body having common (a, e, i), which leads to frequent collisions among members.

Collisions generate dust which spirals sunwards due to Poynting–Robertson drag, producing a sheet of dust having an angular thickness $\sim 2i$.

The grain's vertical motion is oscillatory, so they are densest at the higher latitudes where their vertical velocity is lowest $\Rightarrow$ pair of dust bands at latitude $\pm i$.

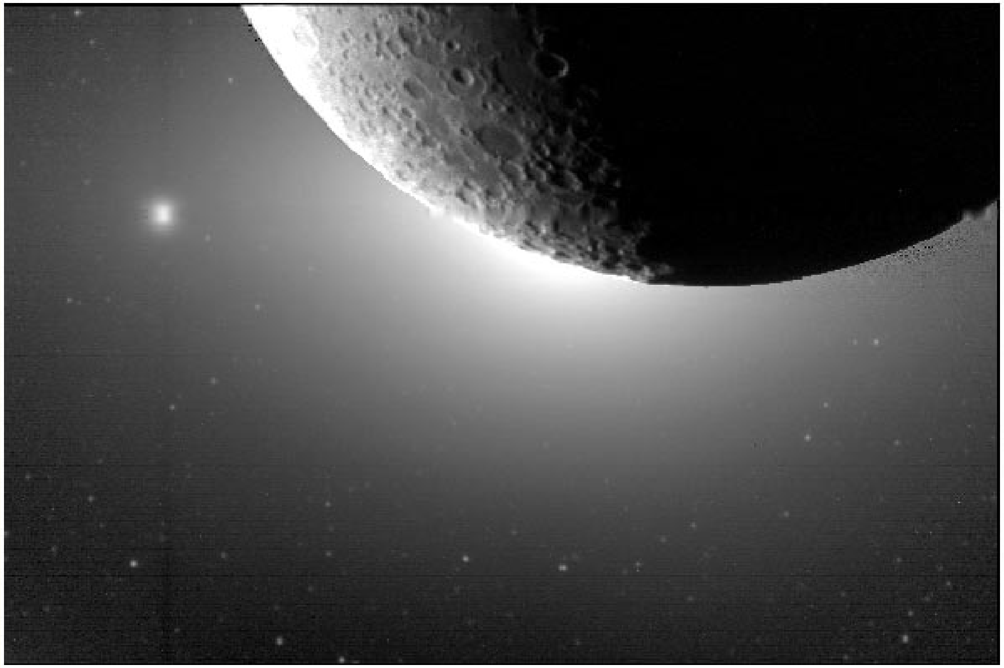
This dust sheet is also warped by the giant planets' secular gravitational perturbations.



Clementine Observations of the Inner Zodiacal Light

"We don't need a lot of fancy Ph.D's to build a spacecraft."

Lt. Col. Pedro Rustan,
Clementine program manager

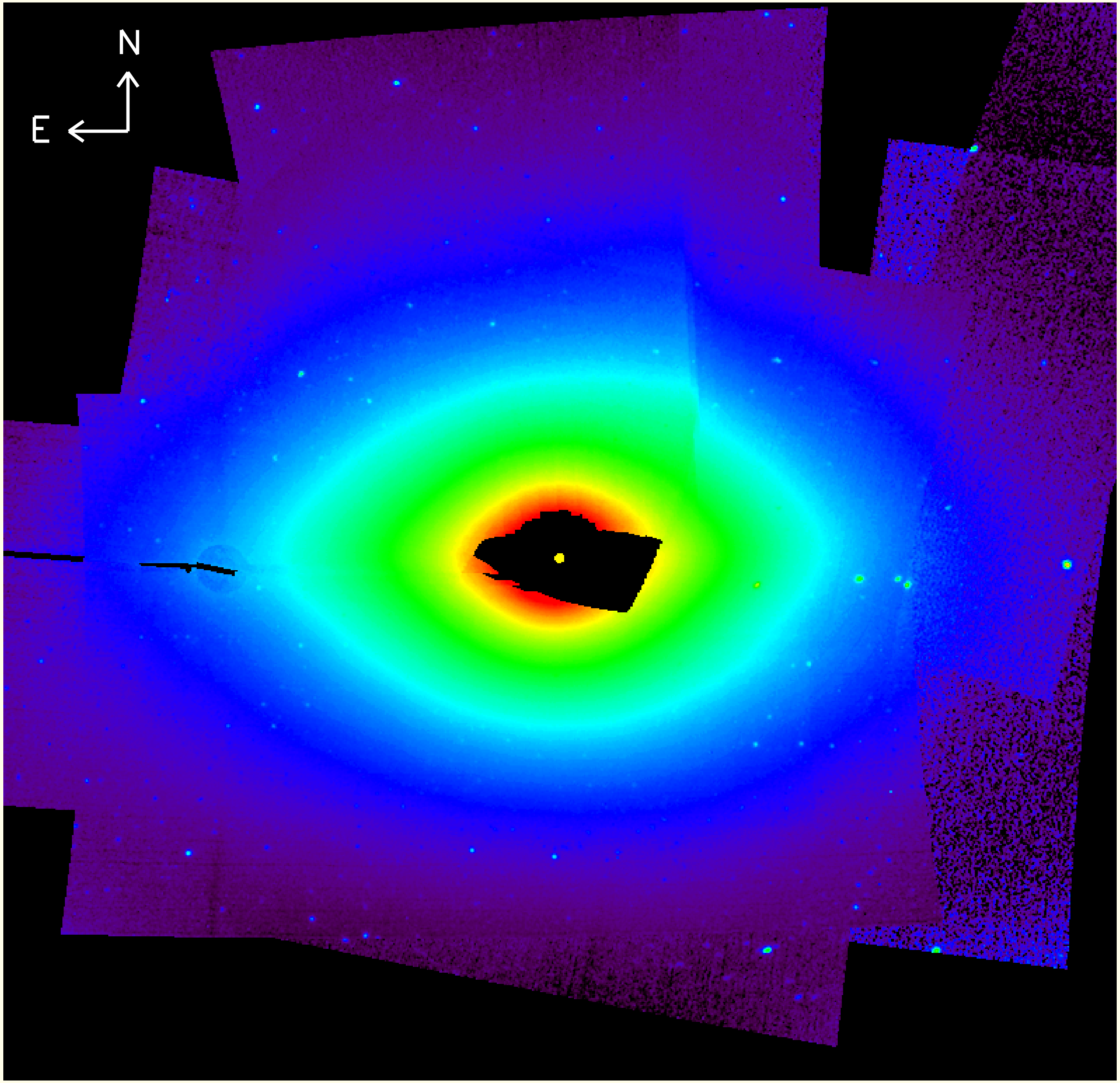


The Star Tracker Camera

Hundreds of optical images of the inner ZL were acquired by wide–angle star tracker cameras that are ordinarily used for spacecraft navigation.

With the Moon occulting the Sun, the inner ZL was observed over elongations of $2^\circ < \epsilon < 30^\circ$, or $10R_\odot < r <$ Venus.

Lots of instrumental issues: no shutter!, dark–current subtraction, flatfielding, calibrating...



Clementine observed
7 distinct fields

Observed several planets:
V,S,M,M,S,Mer.

integrated $m_V = -8.5$

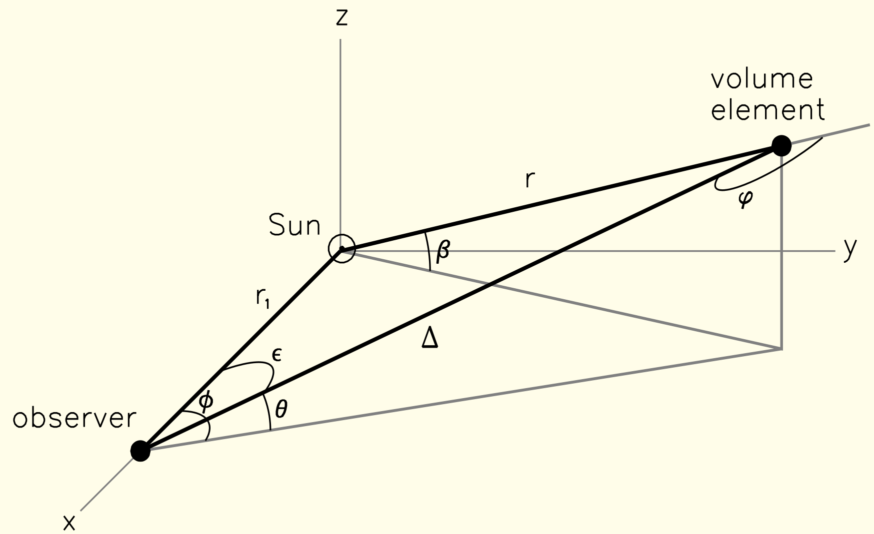
Note:
m_V(full Moon) $= -12.7$,
m_V(Venus) ≥ -4.6

A Simple Model for Interplanetary Dust

assume the density of dust cross section varies as

$$\sigma(r,\beta) = \sigma_1 \left(\frac{r}{r_1}\right)^{-\nu} h(\beta)$$

then the ZL surface brightness is (Aller *et al* 1967):



$$Z(\theta,\phi) = \frac{a\sigma_1 r_1}{\sin^{\nu+1}\epsilon} \left(\frac{\Omega_\odot}{\pi\ \text{sr}}\right) B_\odot \int_\epsilon^\pi \psi(\varphi) h(\beta(\varphi)) \sin^\nu(\varphi) d\varphi$$

where a=dust albedo, $B_\odot$=mean solar brightness, and $\psi(\phi)$=Hong's (1985) empirical phase law for dust.

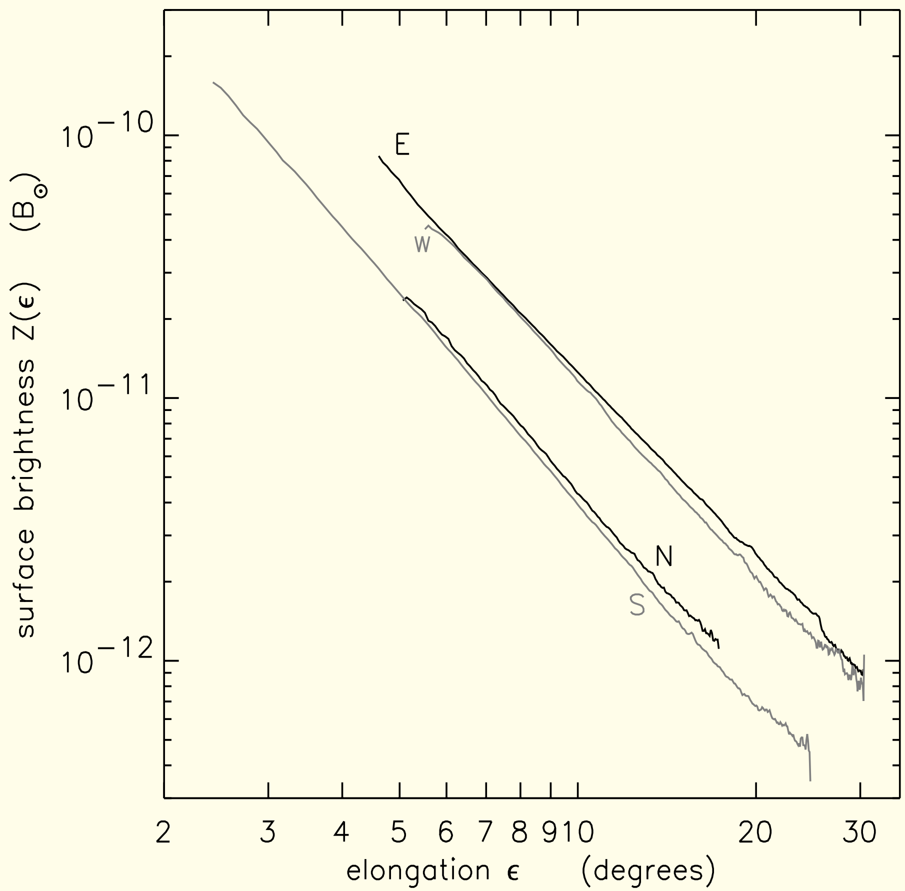
Dust Variations in the Ecliptic

Note that $h(\beta) = 1$ in the ecliptic, so

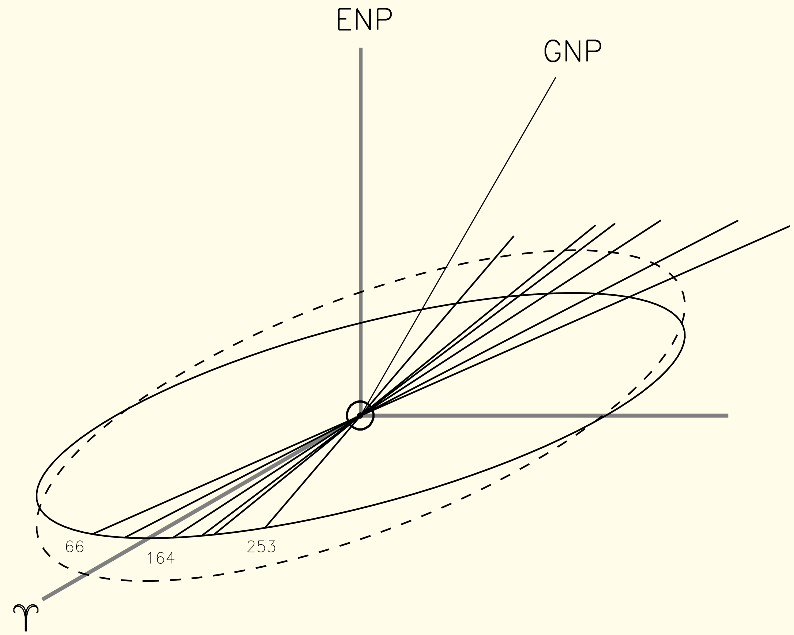
$$Z(\epsilon) \rightarrow 1.8 \times 10^{-5} \frac{a\sigma_1 r_1}{\sin^{\nu+1} \epsilon} B_\odot$$

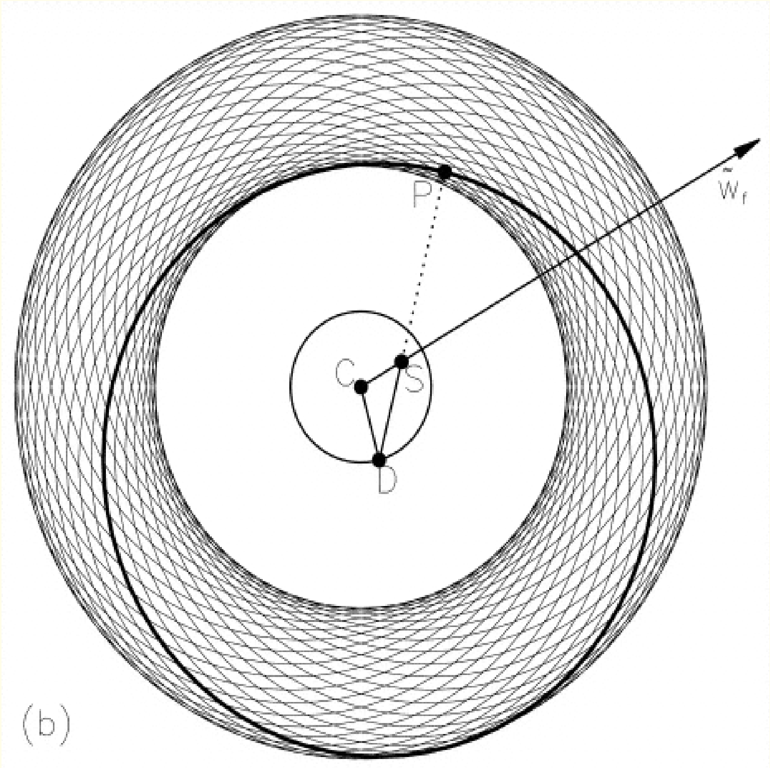
$\Rightarrow a\sigma_1 = 7.8 \times 10^{-22}$ cm^2/cm^3
$\Rightarrow \nu = 1.45 \pm 0.05$.

Adopting $\sigma_1 = 4.6 \times 10^{-21}$ cm^2/cm^3 (Grün *et al.* 1985),
$\Rightarrow a = 0.17$ within a factor of 2?



Note also the North–South and East–West asymmetries.





The N–S asymmetry is likely due to the $i = 3^\circ$ tilt of the dust midplane detected by Helios (Leinert *et al* 1980).

The E–W asymmetry is probably due to ‘pericenter glow’ (Dermott *et al*).

Tilt and pericenter glow are due to the secular part of the giant planets’ gravitational perturbations.

The Dust Vertical Variations

Recall that the dust surface brightness Z varies as

$$Z \propto \int_{\epsilon}^{\pi} \psi(\varphi) h(\beta(\varphi)) \sin^{\nu}(\varphi) d\varphi$$

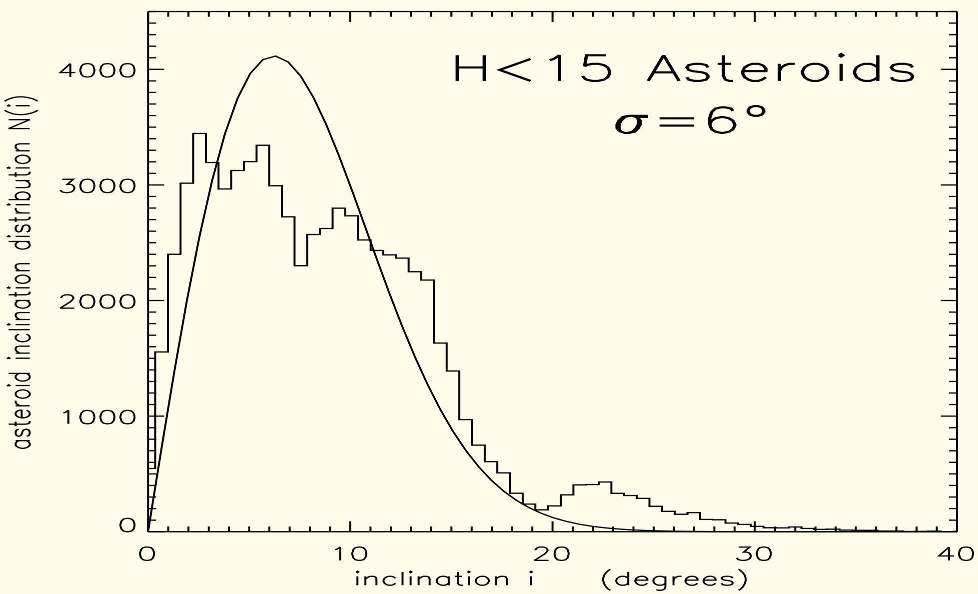
where the latitude distribution $h(\beta)$ depends upon the dust inclination distribution $g(i)$:

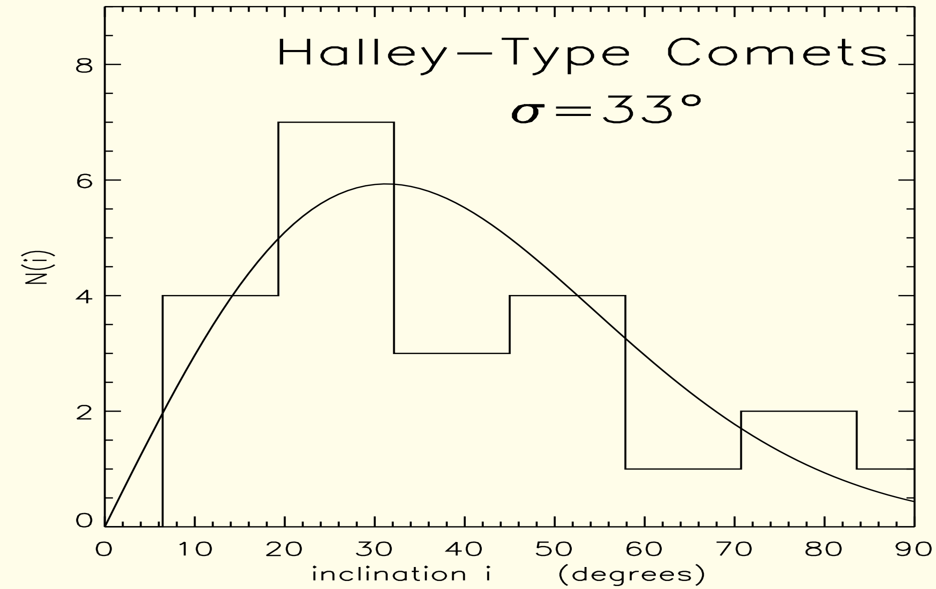
$$h(\beta) = \int_{\beta}^{\pi/2} \frac{g(i)di}{\sqrt{\sin^2 i - \sin^2 \beta}}.$$

Note: an isotropic dust shell has $g(i) \propto \sin(i)$.

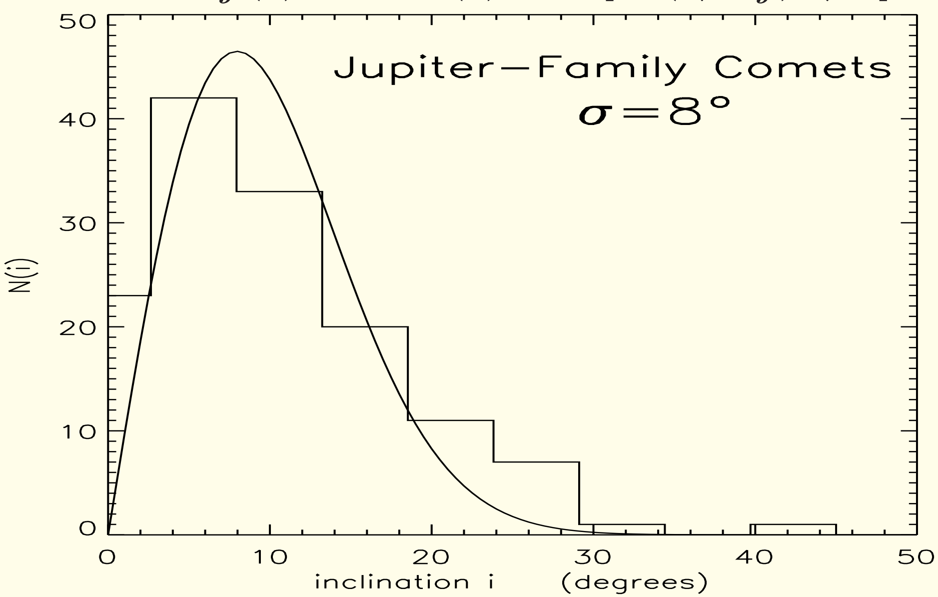
Inferring the Dust Vertical Distribution

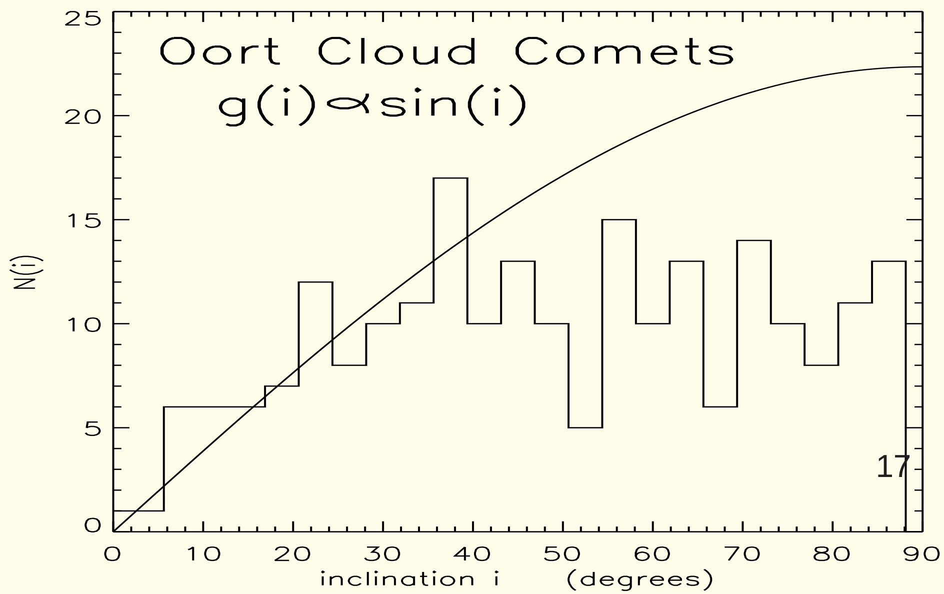
- specify a trial inclination distribution $g(i)$
  - assume the dust have $g(i)$ similar to their sources (e.g., asteroids & comets).
- compute latitude distribution $h(\beta)$ and the surface brightness Z_{model}
- compare to $Z_{observed}$





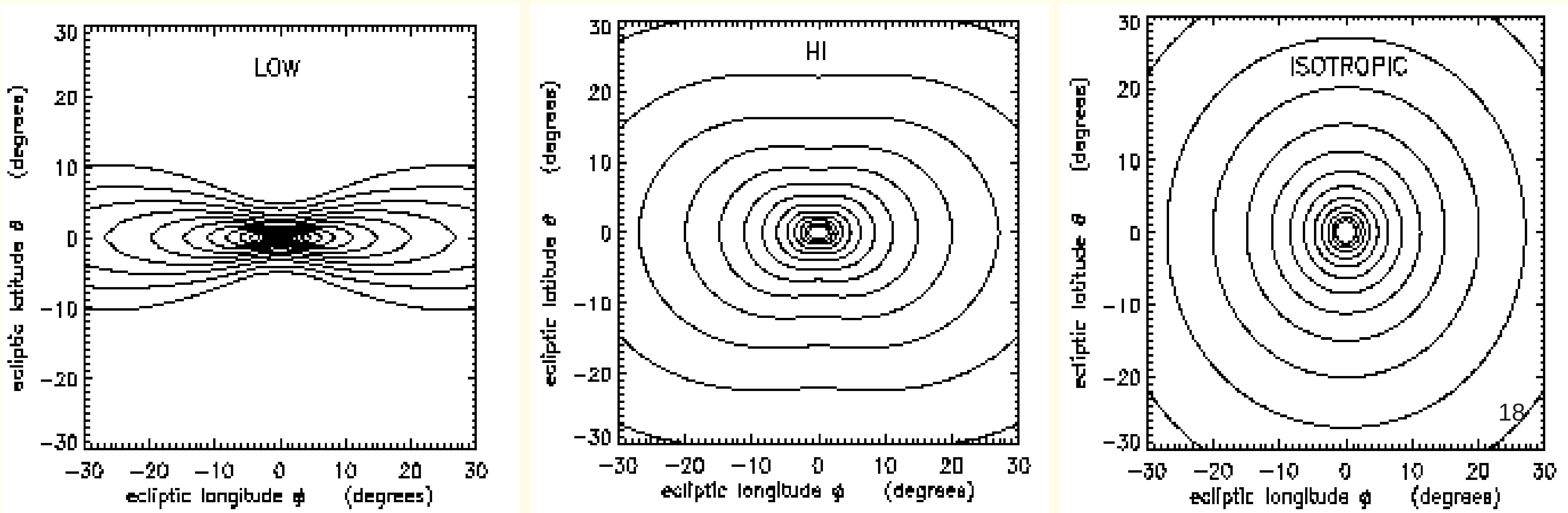
ansatz: $g_j(i) \propto \sin(i)\exp[-(i/\sigma_j)^2/2]$





Evidently there are 3 source populations having distinct inclination distributions:

- low–i population (asteroids + JFCs) with $\sigma_{low} \simeq 7^{\circ}$
- high–i population (HTCs) with $\sigma_{high} \simeq 33^{\circ}$
- isotropic population (OCCs) with $g(i) \propto \sin i$



Fitting the Observations

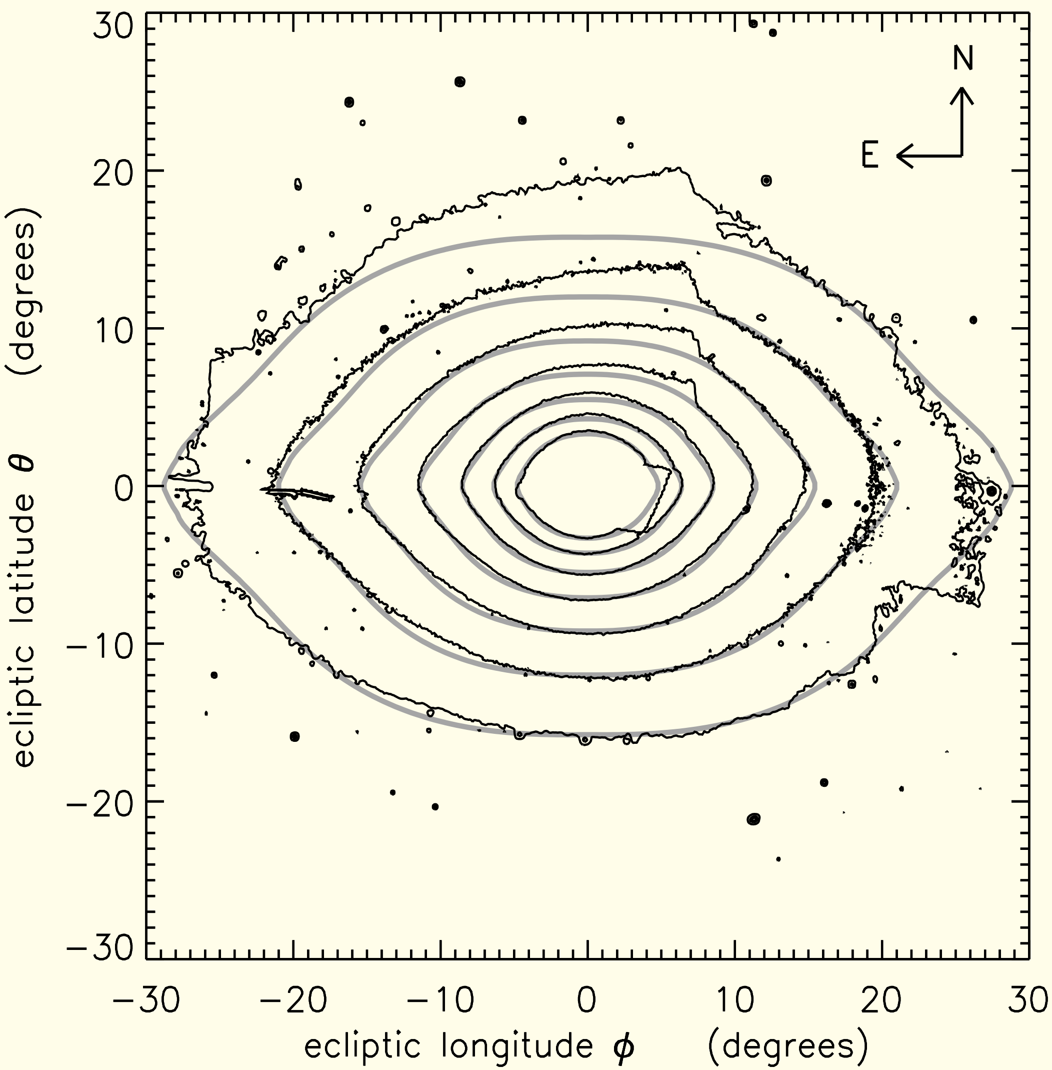
Parameters for the best fit:

- low–i: $\nu_{low} \simeq 1.0$ and $f_{low} = 0.45 \pm 0.13$.

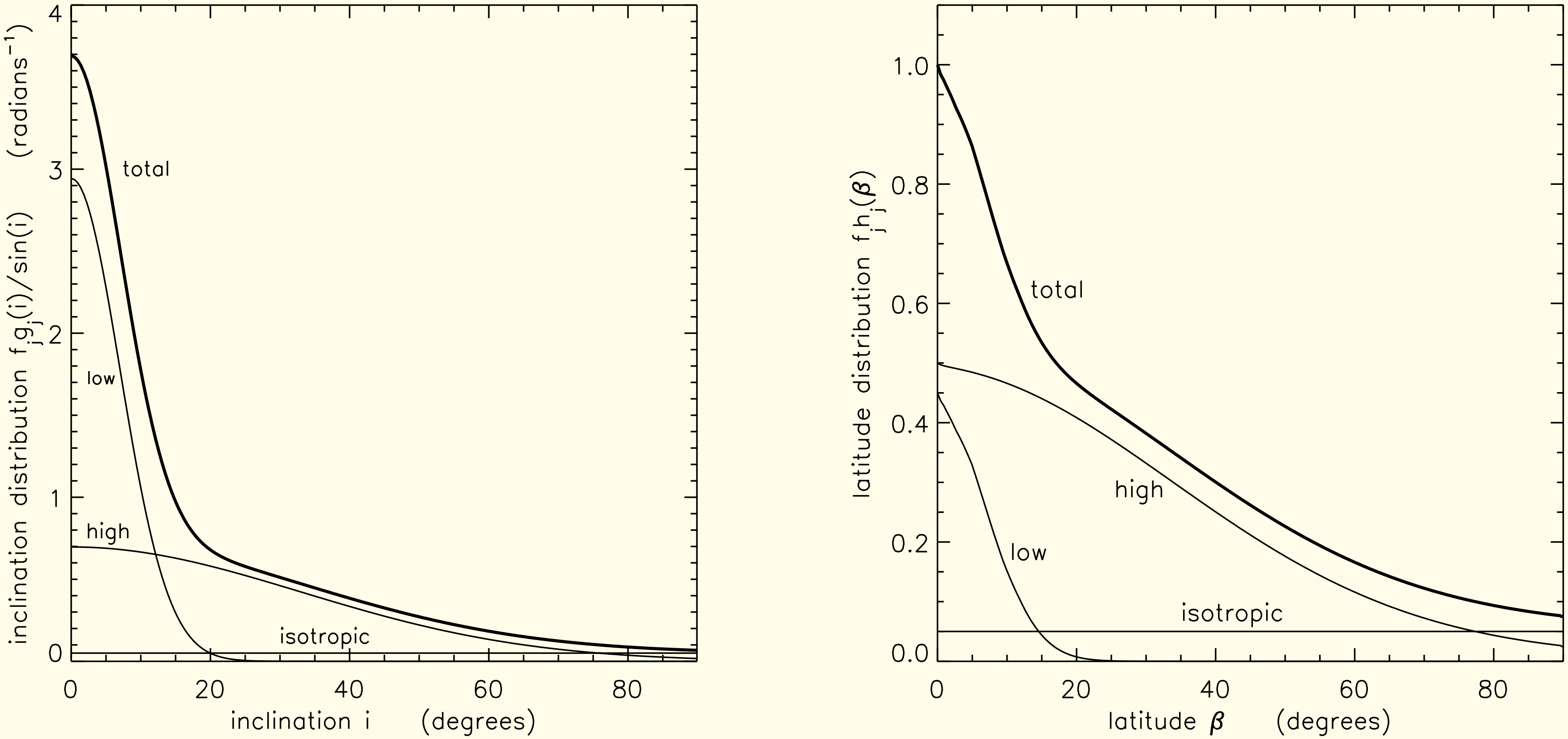
- high–i: $\nu_{high} \simeq 1.45$ and $f_{high} = 0.50 \pm 0.02$.

- isotropic: $\nu_{iso} \simeq 2.0$ and $f_{iso} = 0.05 \pm 0.02$.

- $a\sigma_1 r_1 = (1.2 \pm 0.1) \times 10^{-8}$



The Inferred Inclination & Latitude Distributions



Since $f_{low} = 45\% \Rightarrow$ at most 45% of the ecliptic dust cross section is contributed by asteroids (plus and unknown contribution by JFCs).

But at latitudes $\beta > 15^\circ$, 90% of the dust is from HTCs and OCCs

Caveat

These findings are valid provided the effects of *resonant inclination–pumping* are modest.

This is clearly important for grains with radii $R \gtrsim 100\ \mu$m.

However most of the zodiacal light is reflected by grains with $R \lesssim 100\ \mu$m.

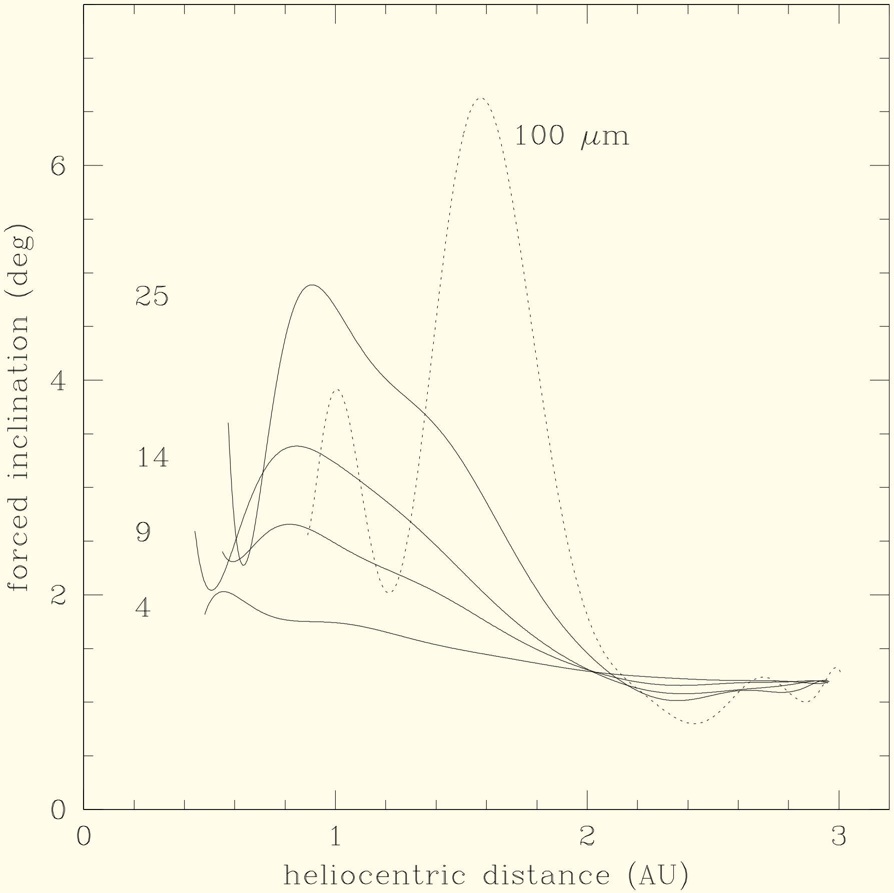


Figure from Grogan *et al* (2001)

Extrapolate these Findings to the Asteroid Belt

The total dust cross section is

$$\Sigma = \int \sigma(r, \beta) dV$$

so $\Sigma_{total}(\text{2 AU}) = 1.6 \times 10^{10}$ km$^2 \simeq 50 \times \Sigma(\text{terrestrial planets})$.

Also, $\Sigma_{low}(\text{3.3 AU}) = 6.8 \times 10^9$ km^2 so

$$M_{low}(\text{3.3 AU}) \sim \rho R_c \Sigma_{low} \sim 2 \times 10^{18} \left(\frac{\rho}{\text{2.5 gm/cm}^3}\right) \left(\frac{R_c}{100\ \mu\text{m}}\right) \text{ gm}$$

which is the mass equivalent of a $D \sim 12$ km asteroid.

Boldly Extrapolate out to the Oort Cloud

Oort Cloud comets travel out to $a \sim 10^4$ AU, and the extrapolated mass of their dust is of order

$$M_{iso} \sim 10^{19} \left(\frac{\rho}{1\ \text{gm/cm}^3}\right) \left(\frac{R_c}{1\ \mu\text{m}}\right) \left(\frac{a}{10^4\ \text{AU}}\right)\ \text{gm}$$

(albeit *very* uncertain), which has a mass equivalent to a $D \sim 30$ km comet.

Stellar Dust Tails?

This Oort Cloud dust fills a volume $a \sim 10^4$ AU across.

This dust is ultimately stripped from the Sun by the local flow of interstellar gas and dust, forming a *stellar dust tail*.

comet Hale Bopp, courtesy Dave Schleicher

Conclusions

- at most 45% of the dust cross section in the ecliptic at $r = 1$ AU is due to dust in asteroid–like orbits (but this estimate also includes dust from JFCs). The mass of this dust is equivalent to a $D \sim 12$ km asteroid.

- at least 90% of the dust interior to a $r = 1$ AU sphere is in comet–like orbits

- these findings are valid if inclination–pumping is modest (which is likely).
  - however the preferred solution would be to simultaneously fit a *dynamic* (rather than a *static*) dust model to the IRAS & Clementine observations.

- also, the Sun lies at the center of a $a \sim 10^4$ AU–wide cloud of dust generated by OCCs. This dust is steadily removed by interstellar gas & dust flow, possibly forming a stellar dust tail.