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

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with

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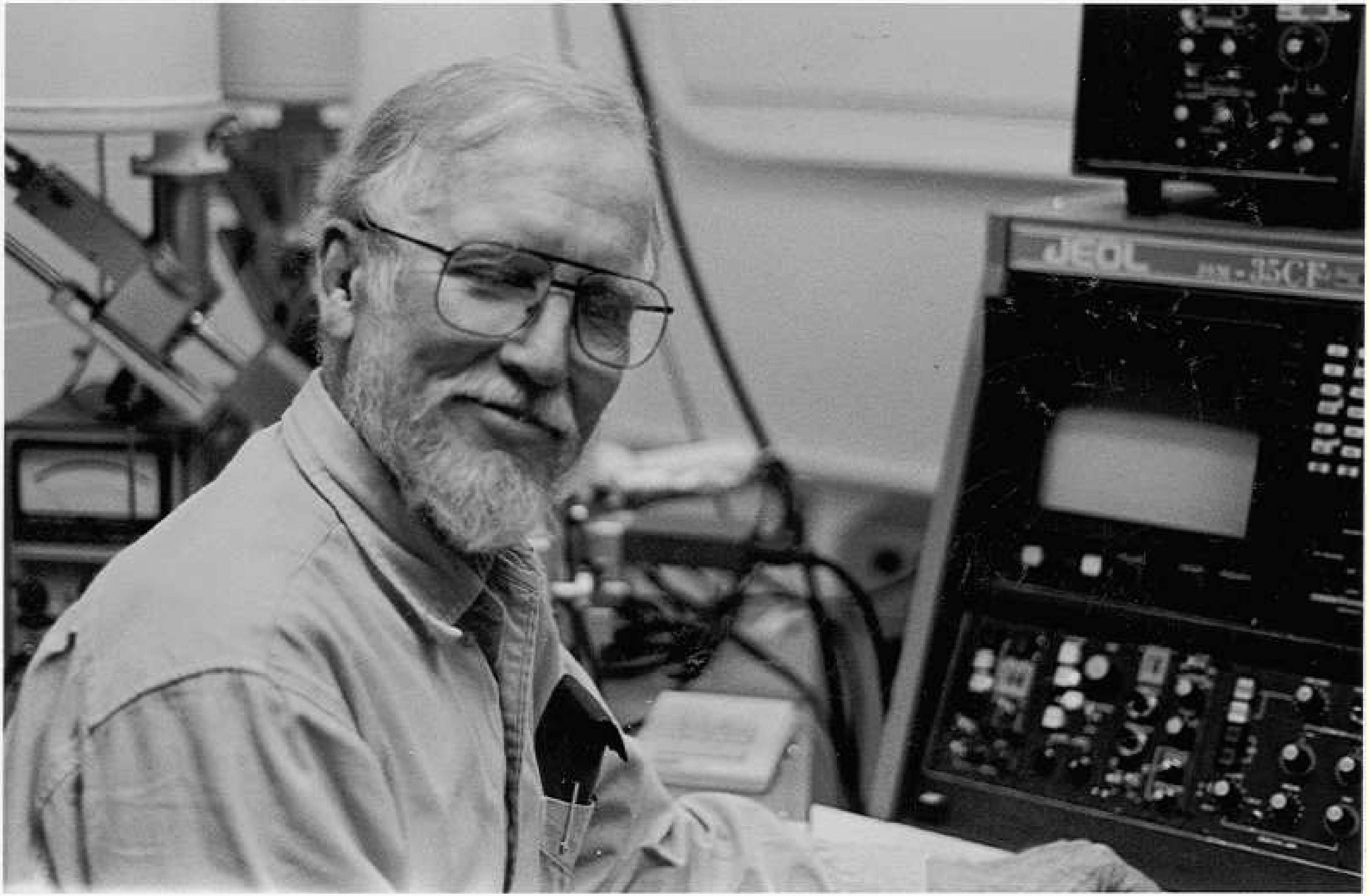
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What is the Zodiacal Light?

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.

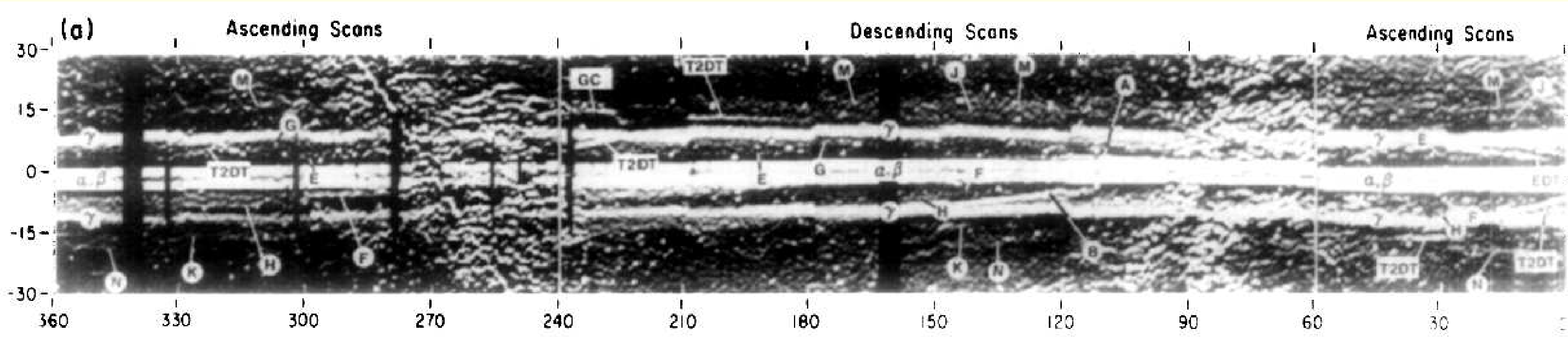
Why Study Interplanetary Dust?

- 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 dust collection 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).

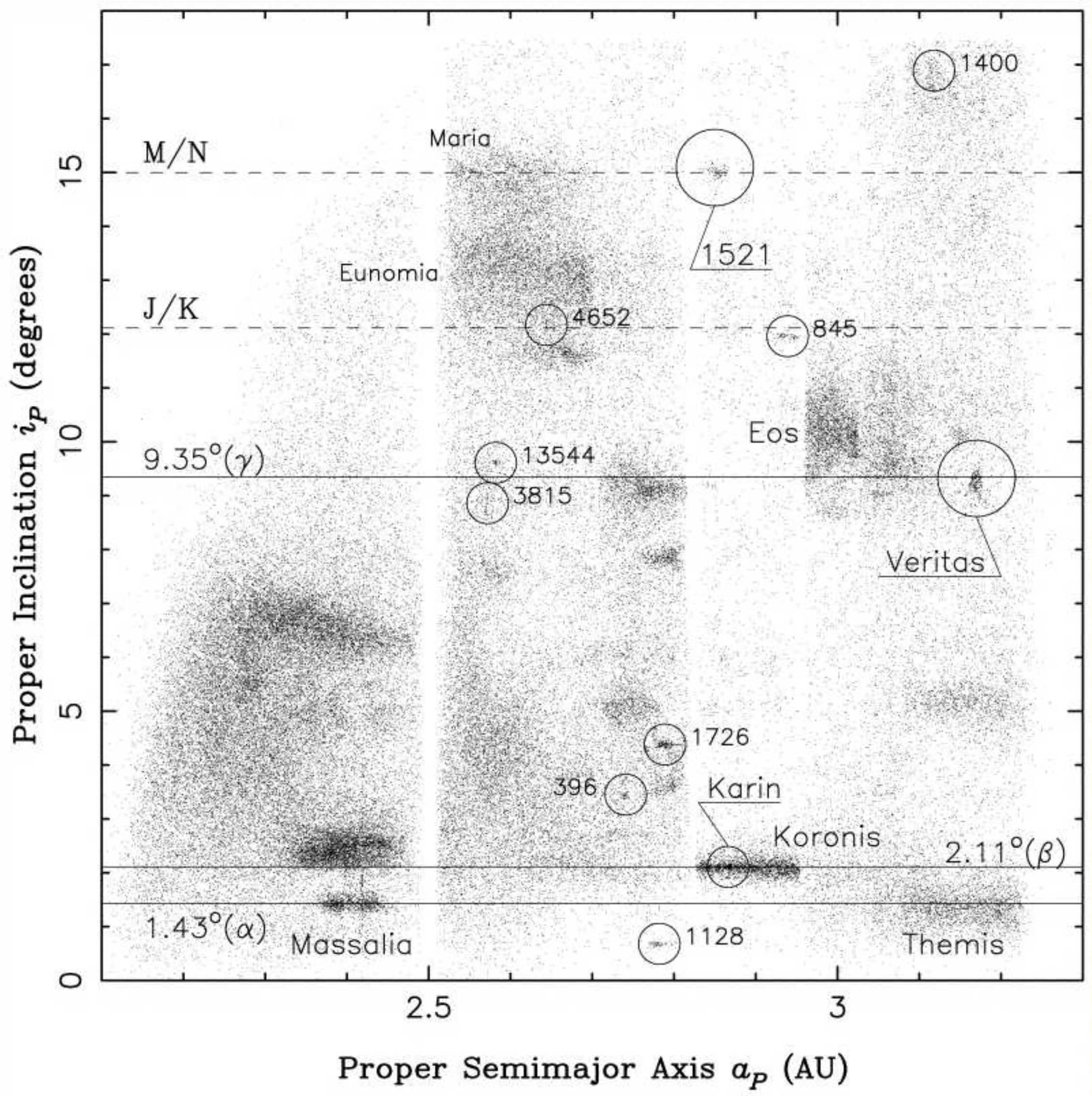
Dust Bands in the Outer Zodiacal Light



IRAS map of ecliptic at $\lambda = 25\ \mu$m by Sykes (1988)

- Dust bands are due to collisions in asteroid *clusters* (e.g., Nesvorný et al 2002, 2003) that inhabit asteroid *families*
  - Veritas asteroid cluster (inside Eos family) has inclinations $i = 9.3^\circ$
    - produces a *pair* of dust bands at latitudes $\beta_{band} = \pm i$
  - Karin cluster (in Koronis family) has $i = 2.1^\circ$ so $\beta_{band} = \pm 2.1^\circ$
  - the $\beta = \pm 1.4^\circ$ bands from the Themis family overlap Koronis bands
- note T2DT= comet Tempel–2's dust trail

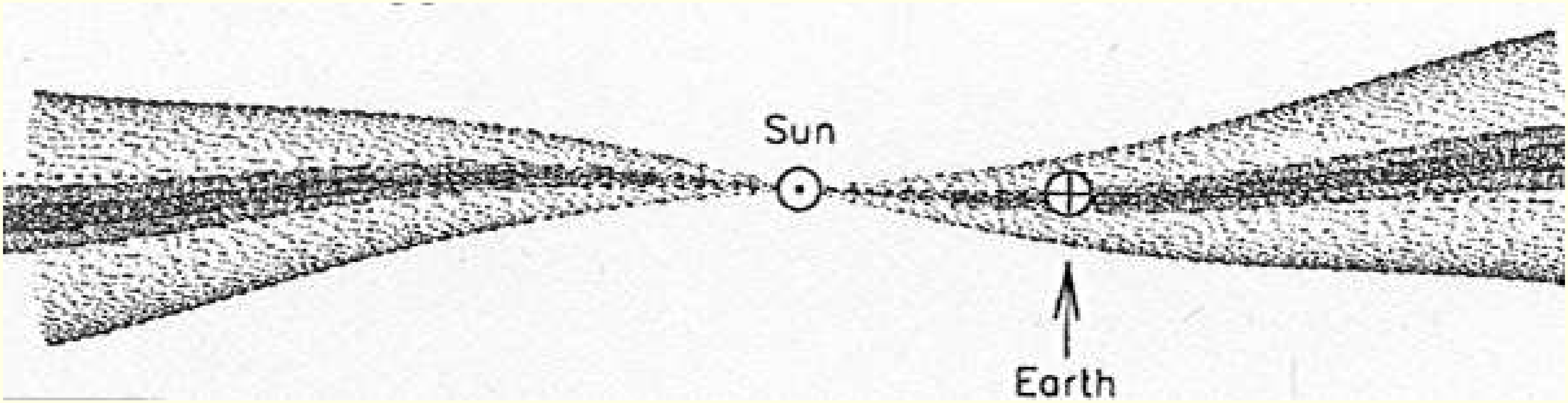
Asteroid Families & Clusters



- an asteroid *family* is a large group of asteroids having common orbit elements (a_p, e_p, i_p), eg, Eos, Koronis, Themis families
  - form via collision $\sim 10^9$ yrs ago
    - $*$ debris' orbit $\sim$ parent's orbit
- a *cluster* is the result of a recent collision $\sim 10^7$ yrs ago, and they have a tight cluster of (a_p, e_p, i_p) (e.g., Nesvorný et al 2002, 2003)

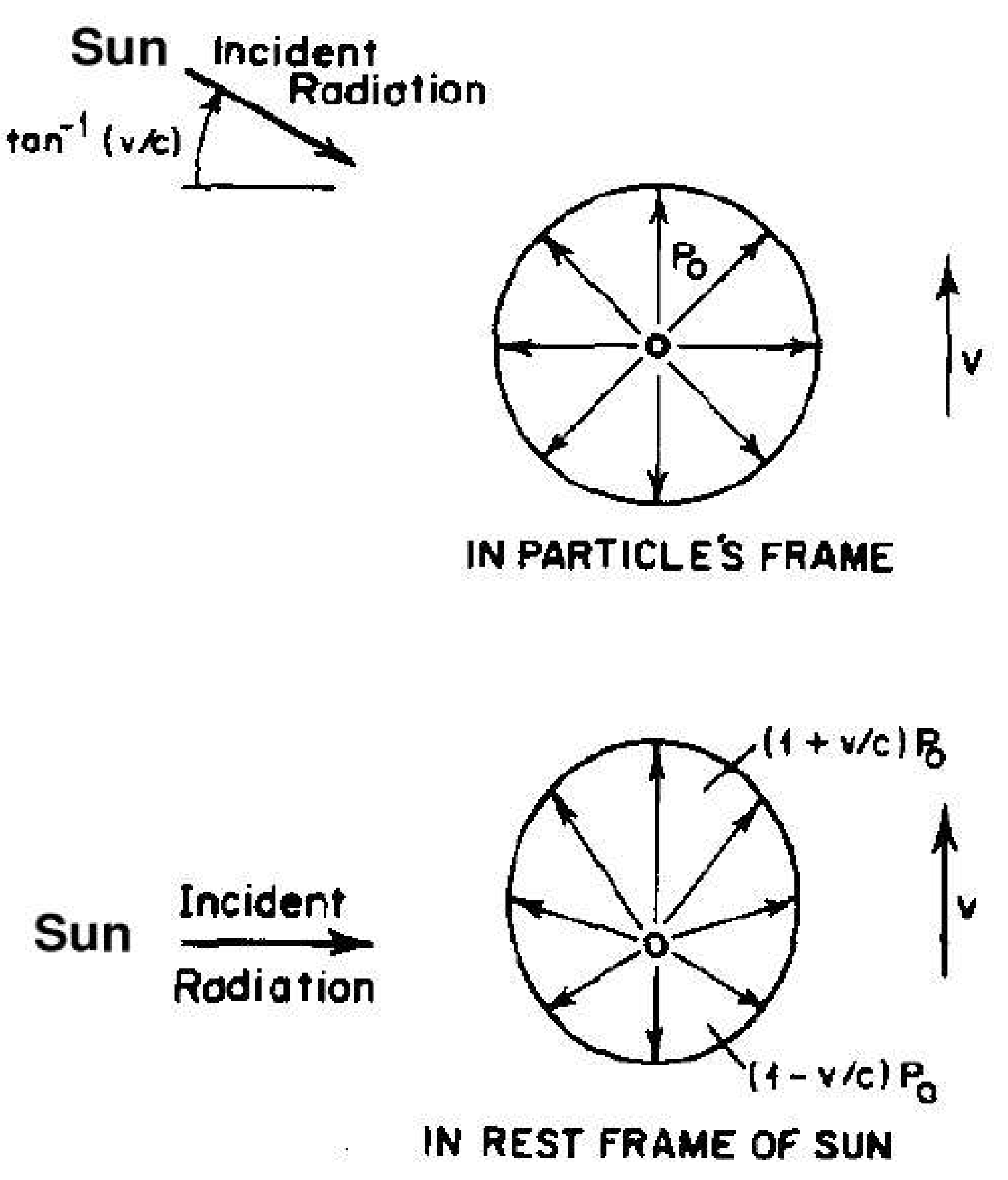
- agreement between cluster inclination i and band latitude β_{band} suggests that cluster asteroids are source of dust bands

Dust Bands are *Sheets* of Dust



- asteroids in dense clusters recollide, generates dust having $i = i_{cluster}$
- giant planet's *secular perturbations* cause the dust orbits to precess differentially, which shears out the dust into a *torus* about Sun
- Poynting–Robertson drag causes dust slowly spiral sunwards
- a dust grain's vertical motion is oscillatory,
  so dust is densest at the higher latitudes where their vertical velocity is lowest
  - an observer sees pair of dust bands at latitudes $\beta_{band} \sim \pm i_{cluster}$

PR drag is due to absorption & reradiation of Solar γ



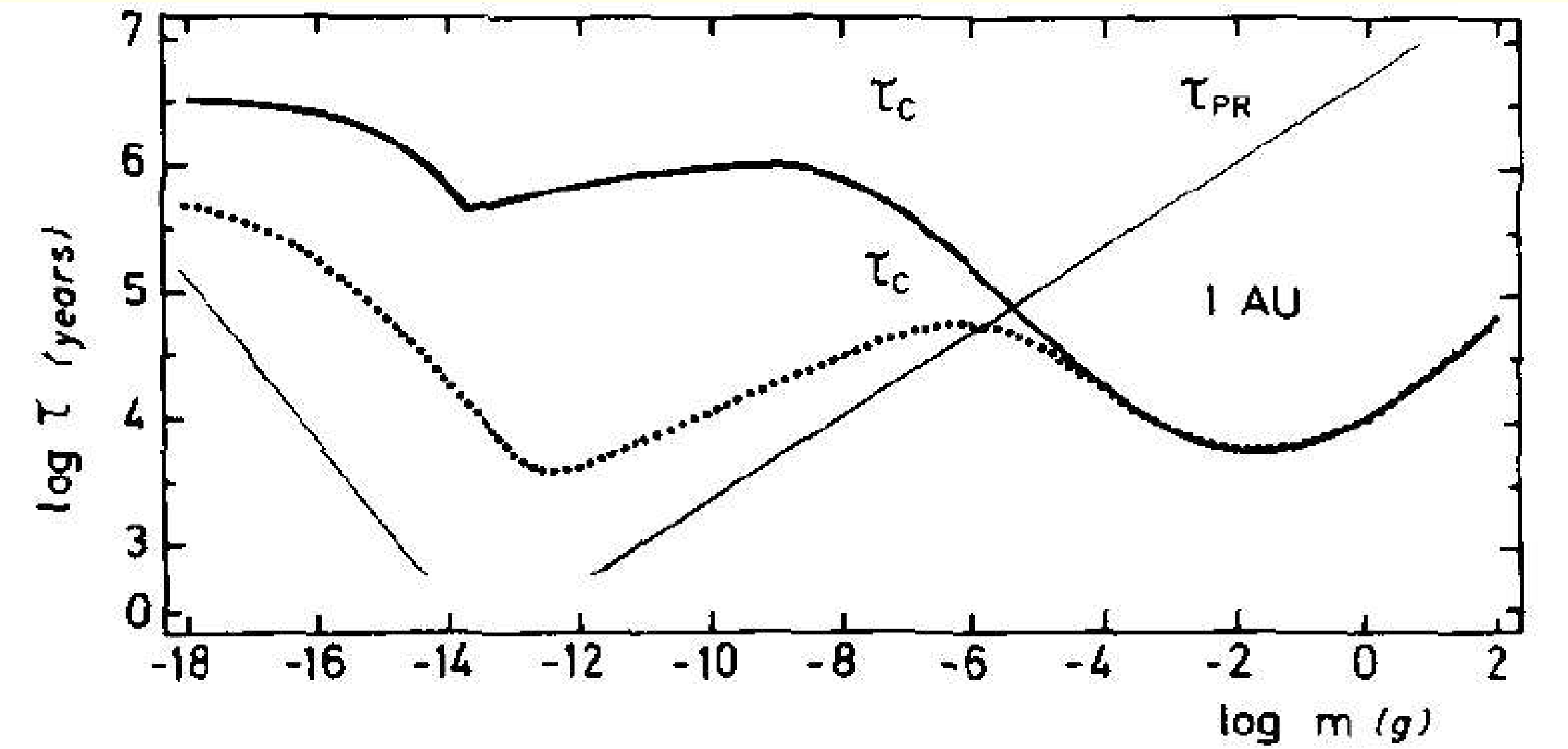
from Burns, Lamy, & Soter (1979)

Consider a grain in a circular orbit about Sun

- in the grain's rest frame, the Sun is forward of left
  - the grain absorbs incident solar radiation,
  - reradiates isotropically
- in the Sun's rest frame, the grain's radiation field is slightly forward–throwing
  - since photons carry momentum, p–conservation implies a backward kick on the grain $\Leftarrow$PR drag
- this is PR drag $\propto$ dust area/mass $\propto R^{-1}$

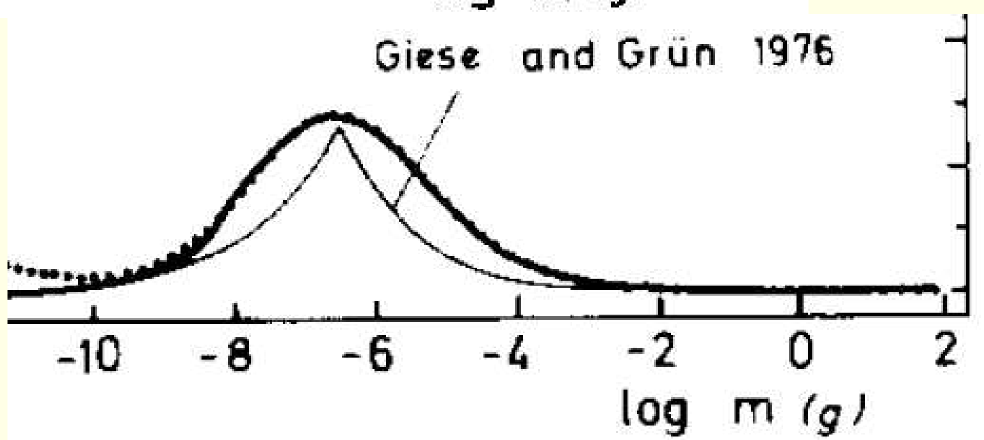
Dust Lifetimes & Sizes

- PR drag preferentially destroys smaller dust since orbit decay timescale $\tau_{PR} \propto R$
- dust–dust collisions fragments the larger grains since collision lifetime $\tau_{col} \propto R-1$
- this confines grain radii to $1 \lesssim R \lesssim 300\ \mu$m

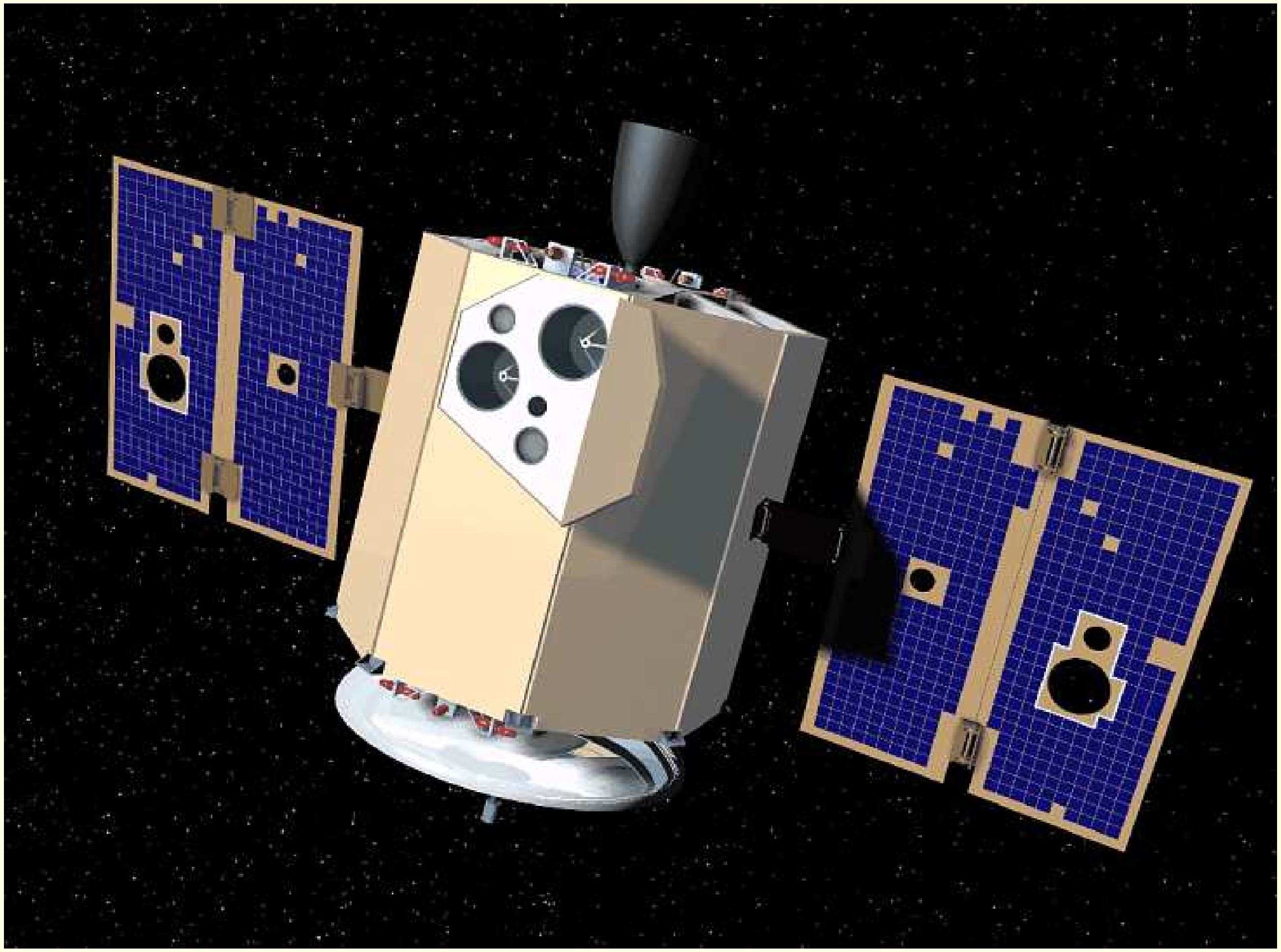


from Grün *et al.* (1985)

- competition between collisions & PR drag confines the dust size distribution to $1 \lesssim R \lesssim 300\ \mu$m



Clementine



Quote of the Day: “We don’t need a lot of fancy Ph.D’s to build a spacecraft.”

Lt. Col. Pedro Rustan,
Clementine program manager

- DoD spacecraft,
  orbited the Moon in 1994
- cover story:
  - map metals in the lunar surface
  - search for water–ice in shadowed polar craters
- secret mission:
  - test Star Wars hardware
  - autonomous navigation system
    - failed *en route* to Geographos

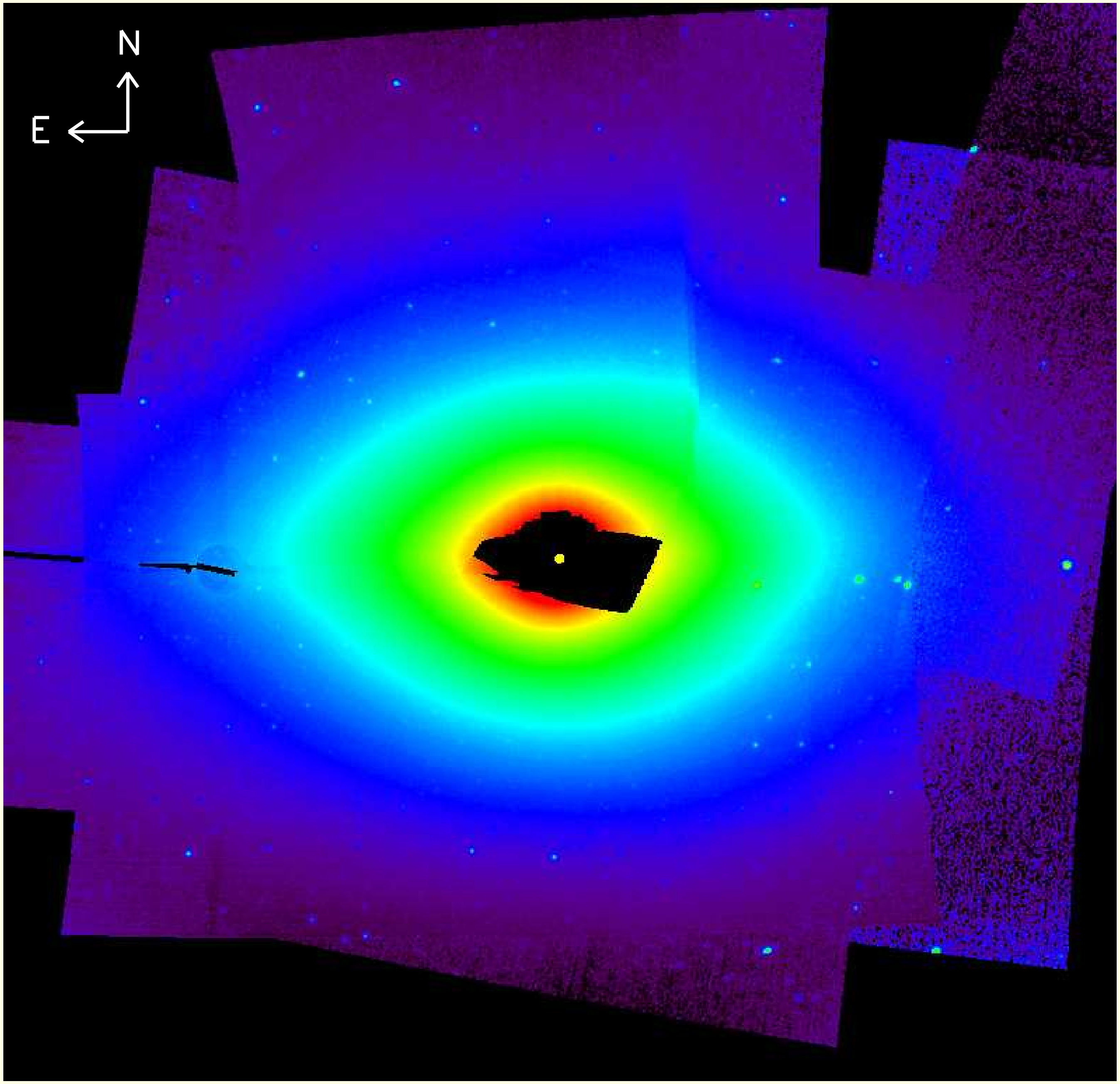
The Star Tracker Camera

- Hundreds of optical images of the inner ZL were acquired by wide–angle star tracker cameras that are ordinarily used for spacecraft navigation—*not for science*.

- 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...

Mosaic of Inner ZL



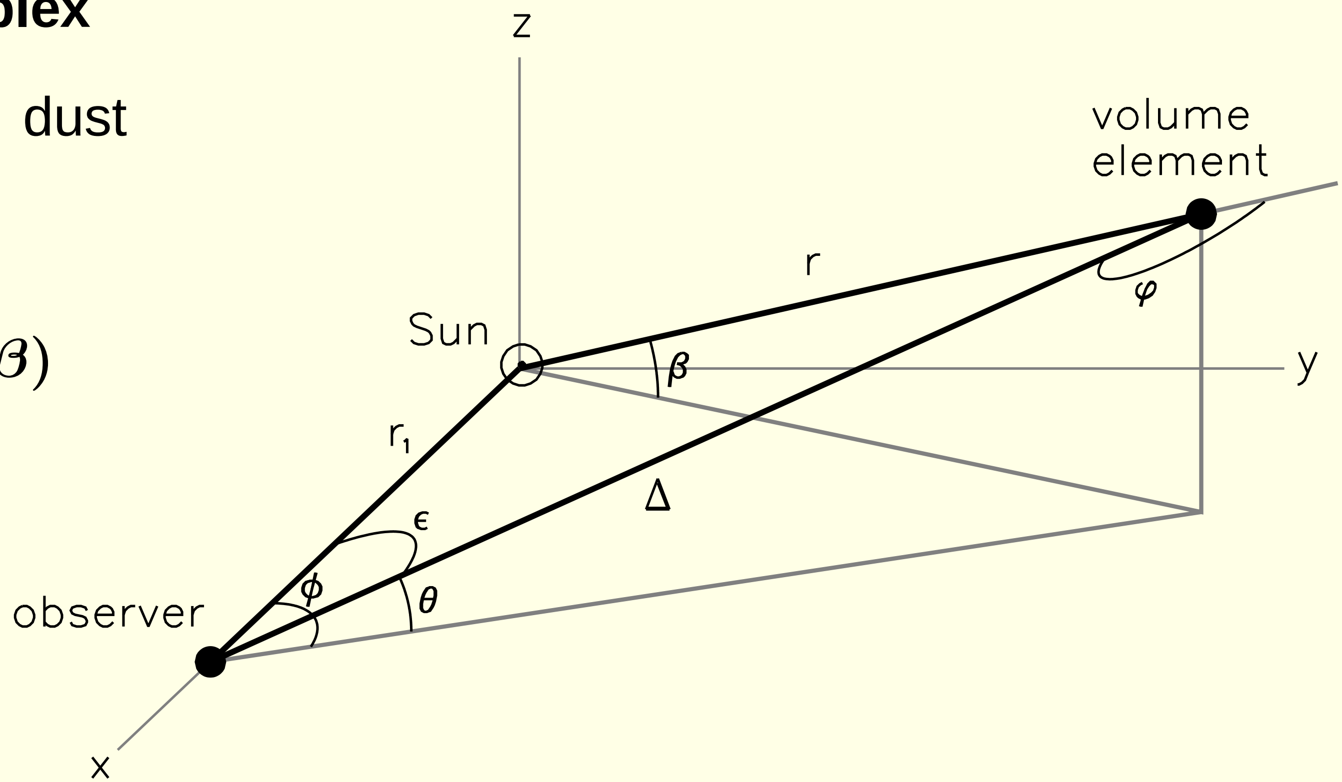
- observed 7 distinct fields over 2 months
- 'edges' are due to light pollution by V & $\oplus$
- several planets drift across the field: V,S,M,M,S, & Mer.
- unique map of IZL:
  - hard to observe from ground
  - few spacecraft are bold enough to try
- integrated $m_V = -8.5$
  - $\mathbf{m_V}$(full Moon) $= -12.7$
  - m_V(Venus) ≥ -4.6

A Simple Model of the Interplanetary Dust Complex

- assume the density of dust cross section varies

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

where $h(\beta) =$ dust latitude distribution



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

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

where a=dust albedo, $B_\odot$=mean solar brightness, and $\psi(\phi)$= empirical phase law for dust (Hong 1985, Lamy & Perrin 1986)

Making a synthetic image of a model dust complex

- the dust surface brightness Z varies as

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

- the unknown dust latitude distribution $h(\beta)$ depends upon its unknown 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 $g(i) \propto \sin(i)$.

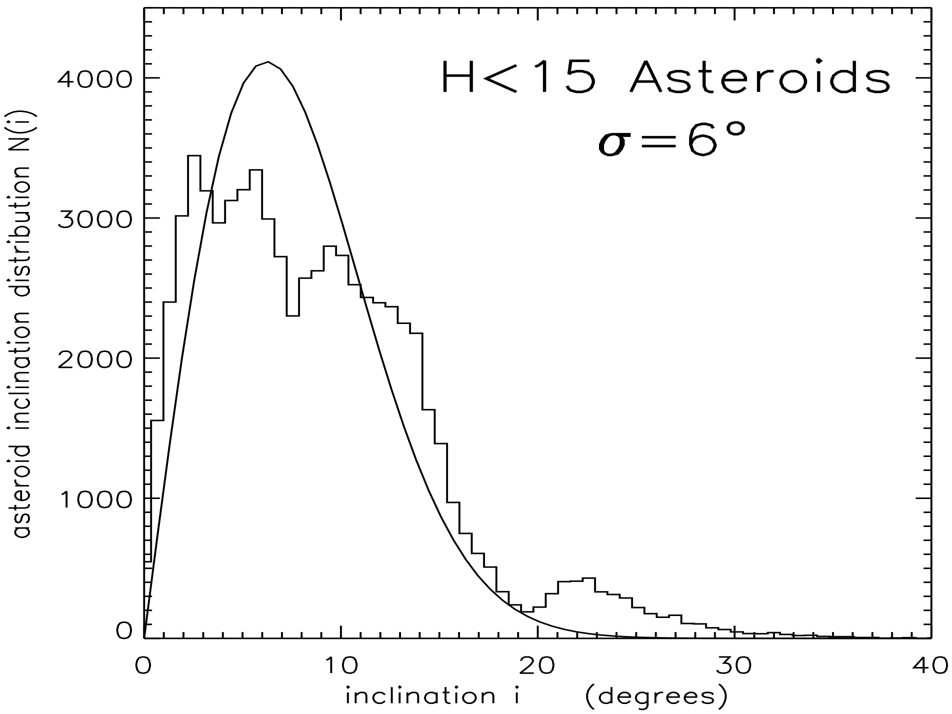
- if I knew the dust inclination distribution $g(i)$, then...
  - I could calculate the dust latitude distribution $h(\beta)$
  - then calculate a model dust surface brightness map Z_{model} for comparison to $Z_{observed}$

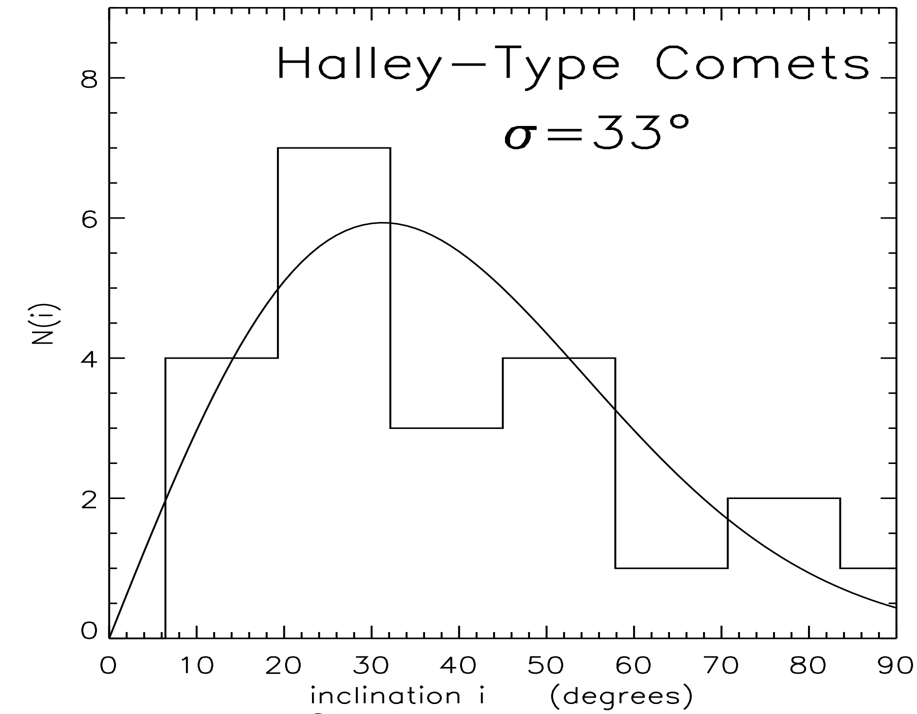
- although I don't know $g(i)$, I can make a plausible guess...
- assume that the dust inclination distribution $g(i)$
  is identical to the sources of interplanetary dust: asteroid and comets

asteroid Mathilde

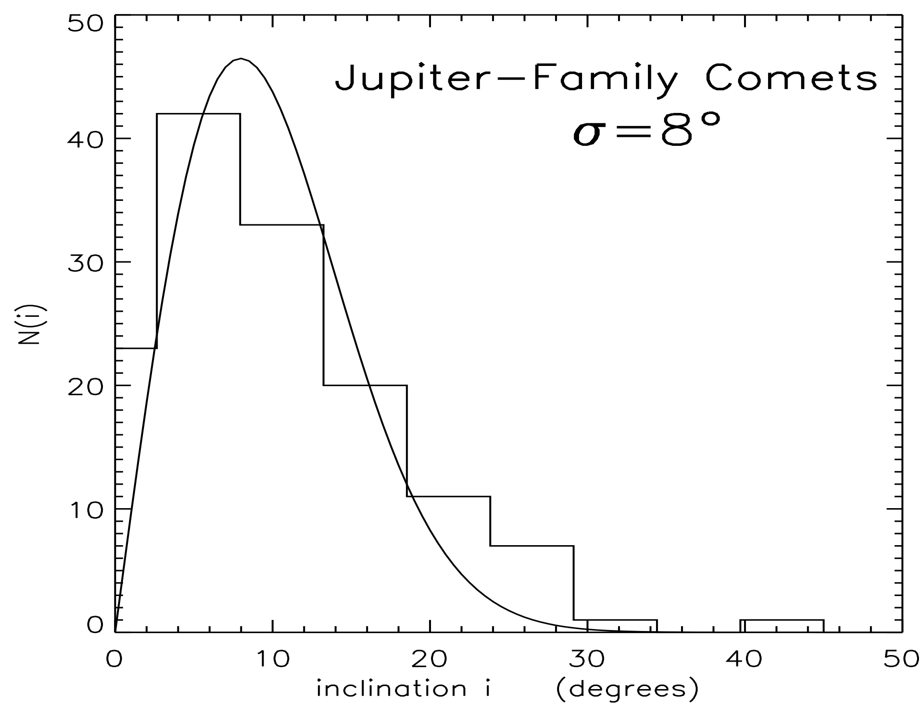
comet Wild–2

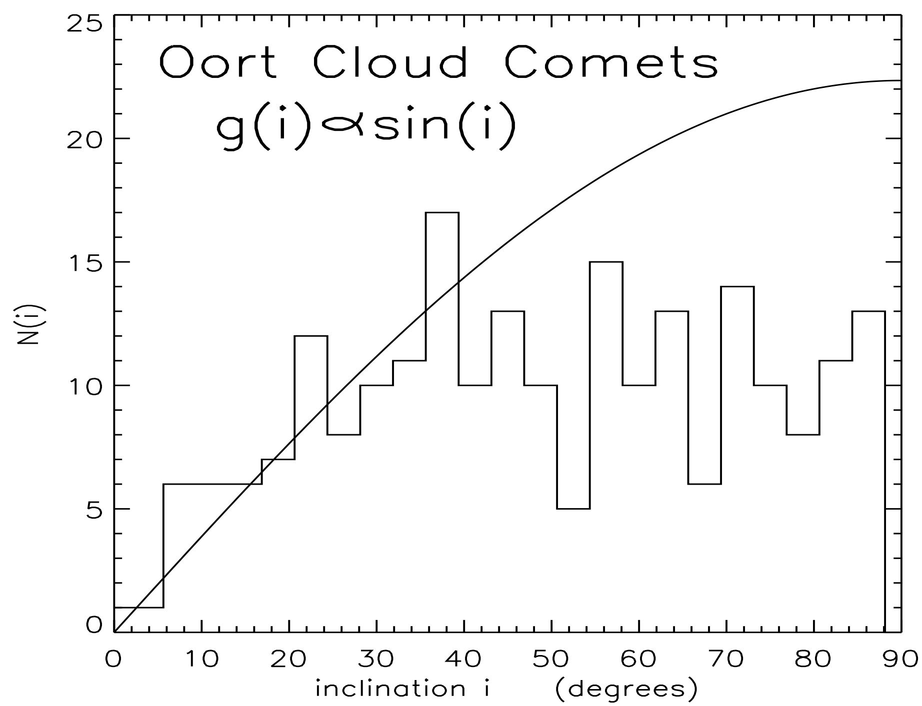
- I can then calculate $h(\beta)$ and Z_{model} and
  test the model by comparing to $Z_{observed}$





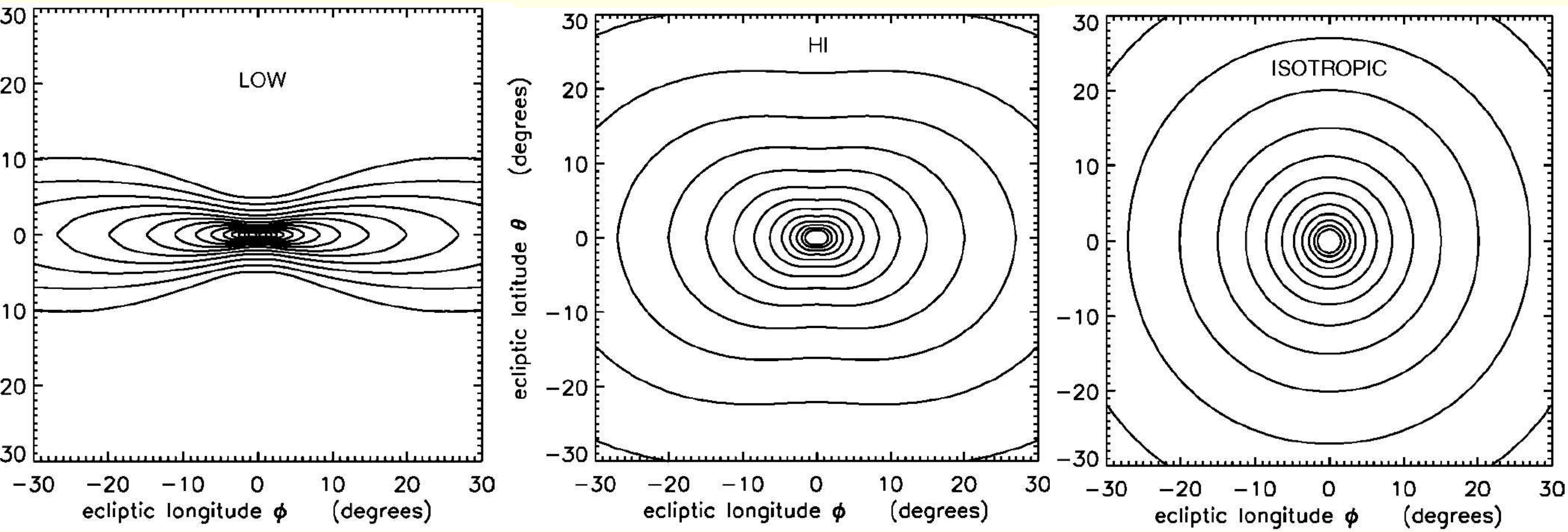
ansatz: $g_j(i) \propto \sin(i) \exp[-(i/\sigma_j)^2/2]$





Evidently there are 3 source populations having distinct inclination distributions:

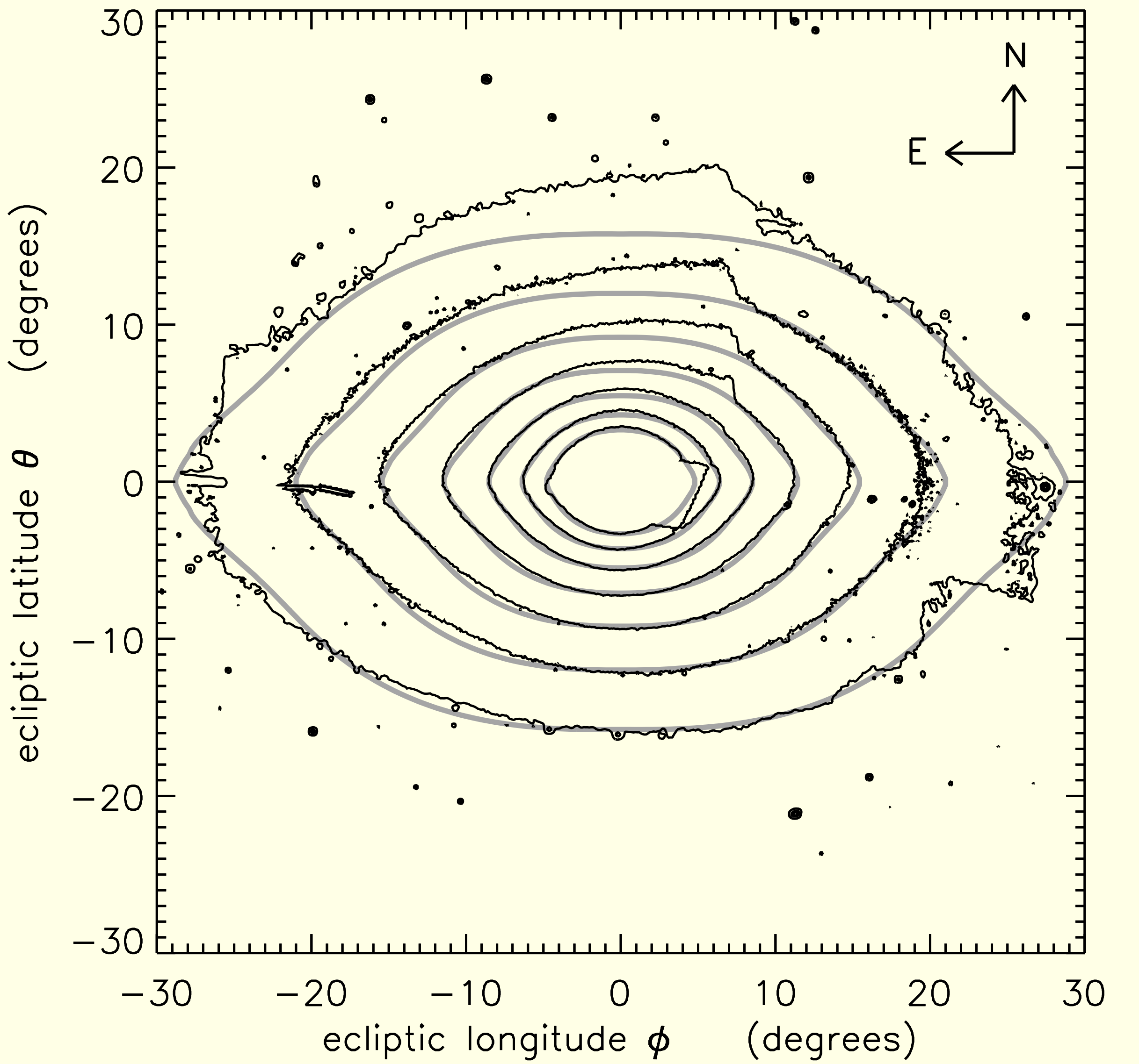
- low–i population (asteroids + JFCs) with $\sigma_{low} \simeq 7^\circ$
- high–i population (HTCs) with $\sigma_{high} \simeq 33^\circ$
- isotropic population (OCCs) with $g(i) \propto \sin i$



Fit Synthetic ZL Map to the Observed Map

Co–add 3 populations & seek best fit to the observed ZL map:

- 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 $f_{iso} = 0.05 \pm 0.02$
- $a\sigma_1 r_1 = (1.2 \pm 0.1) \times 10^{-8}$ $\Rightarrow a \sim 0.1$



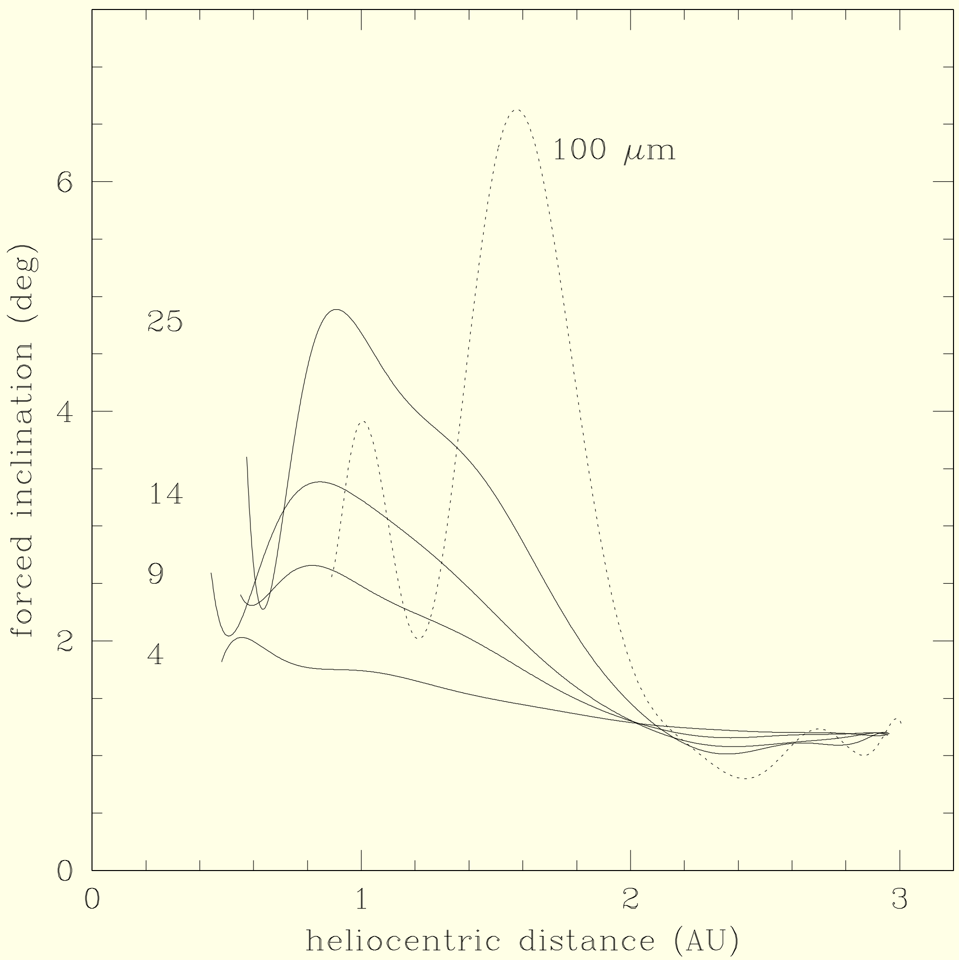
The f_j are the population's fractional contribution to the dust cross–section density σ at $r = 1$ AU *in the ecliptic plane*

- the low–$\mathbf{i}$ population (asteroids & JFC's) is confined to latitudes $\beta \lesssim 20^\circ$
- 90% of this dust above $\beta \gtrsim 20^\circ$ is in comet–like orbits (e.g., HTCs and OCCs)

One Important Caveat!

- These findings are valid provided asteroid dust does not have its i pumped up at resonances with the giant planets
- might happen as PR drag causes dust to drift across resonances
- initially low i asteroid dust might masquerade as high i comet dust!
- resonant i–excitation is only important for large $R \gg 100\ \mu$m grains that drift *slowly* drift through resonances
- However most of the zodiacal light is reflected by grains with $R \lesssim 200\ \mu$m, so $\Delta i \lesssim 5°$
  - this unmodeled effect is not very important...

from Grogan *et al* (2001)⟶



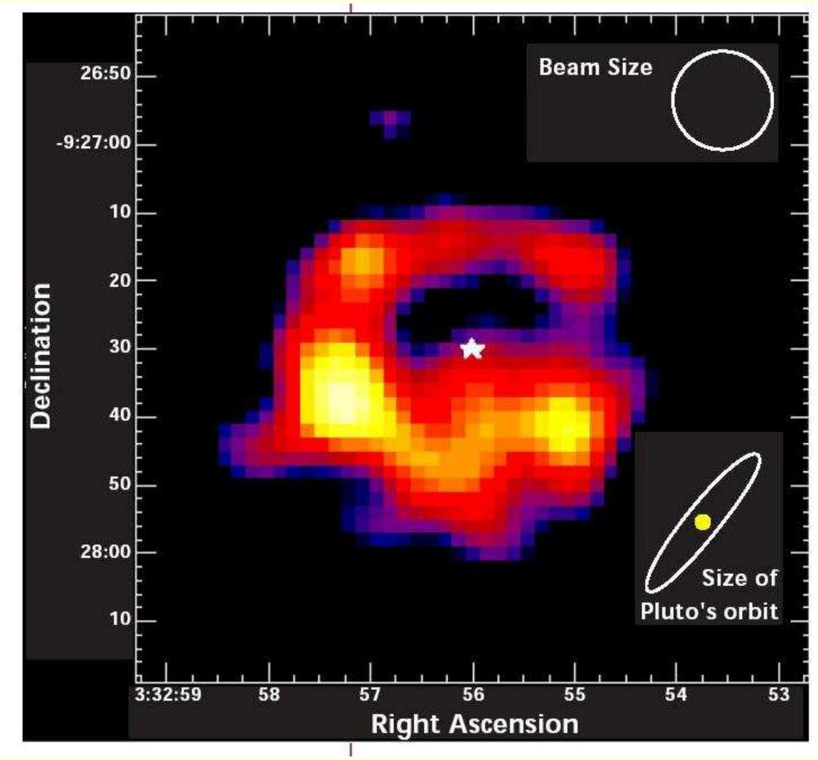
Extrapolate these Findings Outwards

The total dust cross section is

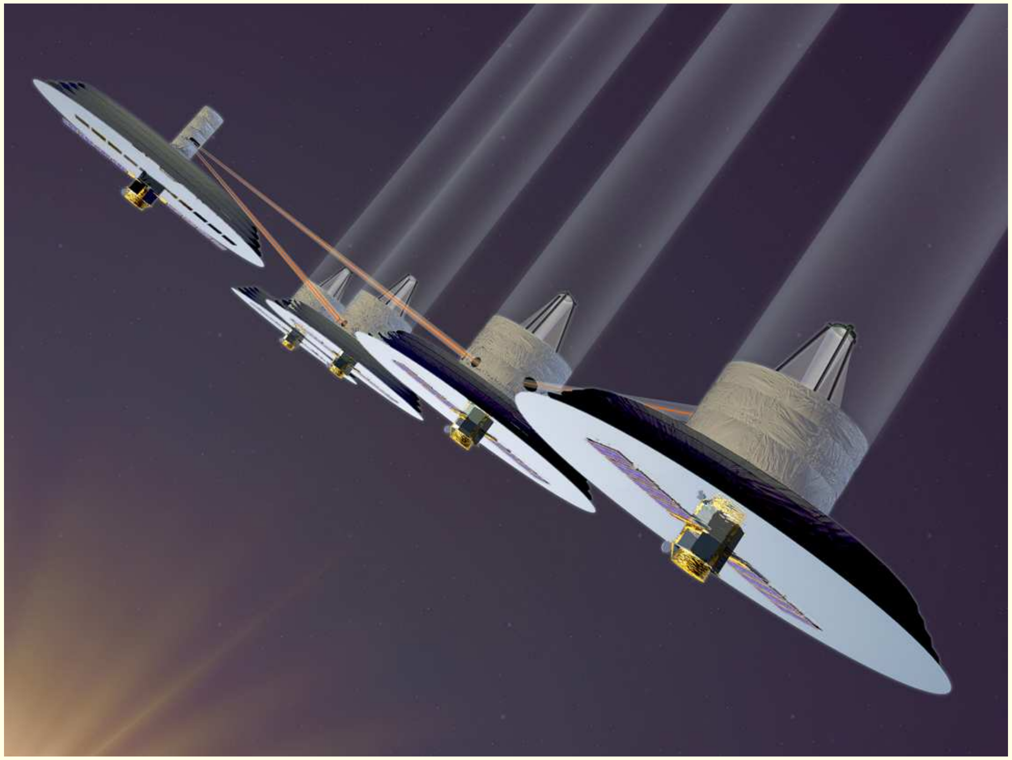
$$\Sigma = \int \sigma(r,\beta)dV$$

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

$\Rightarrow$ if asteroids & comets are common features in *extrasolar* planetary systems, their dust will make planet–hunting via direct imaging more difficult...



Dust @ Epsilon Eridani at $\lambda = 850\ \mu$m (Greaves et al 1998)



Terrestrial Planet Finder (proposed)

Estimate the Mass of Dust in the Inner Solar System

Again, the total dust cross section is

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

So Σ_{low}(3.3 AU) $= 6.8 \times 10^9$ km^2
$=$ the cross–section of asteroid + JFC dust out to asteroid belt

The total mass of this dust is

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

which is the mass equivalent of a $\mathbf{D} \sim 10$ km asteroid.

$\Rightarrow$ the 2^{nd} brightest thing in the Solar System does not amount to much mass.

Boldly Extrapolate out to the Oort Cloud

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

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

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

That dust is ultimately stripped from the Sun by the local interstellar gas and dust that flows around the outer edge of the Solar System.

comet Hale–Bopp (Dave Schleicher)

Summary of Conclusions

- at most $\mathbf{45\%}$ of the dust cross section in the ecliptic at $\boldsymbol{r = 1}$ 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 $\boldsymbol{D \sim 12}$ km asteroid.
  - if similar amounts of dust are common in the terrestrial zones of *extra–solar* planetary systems, then this dust represents one of the main challenges facing efforts to detect exoplanets via direct imaging (e.g., TPF)...

- nearly the dust at high latitudes in the Solar System, $\boldsymbol{\beta > 20^\circ}$, are in comet–like orbits.
  - when you consider all the dust orbiting interior to a $\boldsymbol{r = 1}$ AU sphere, at least $\mathbf{90\%}$ are in comet–like orbits
  - these findings are valid provided resonant inclination excitation is unimportant, which is likely a safe assumption for the small $\boldsymbol{R \lesssim 200\ \mu}$m that live in the interplanetary dust complex