POLARIMETRY and ASTROBIOLOGY

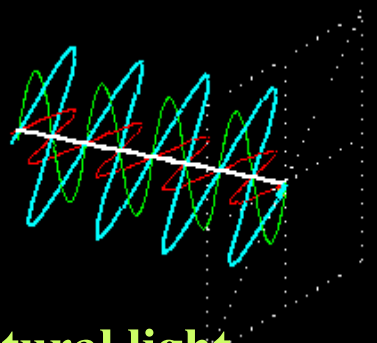
(project supported by NASA Astrobiology Program)

Ludmilla Kolokolova

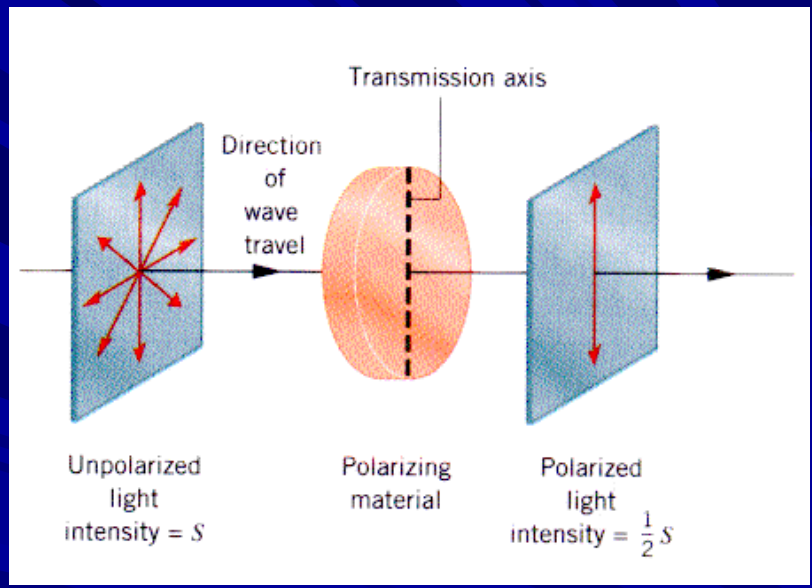
University of Maryland, ASTR695, November 22, 2010

Polarimetry

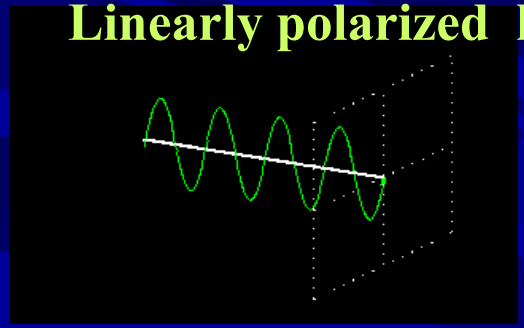
Studies polarization of the light

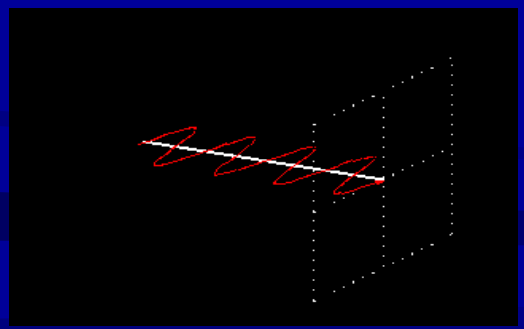


Natural light

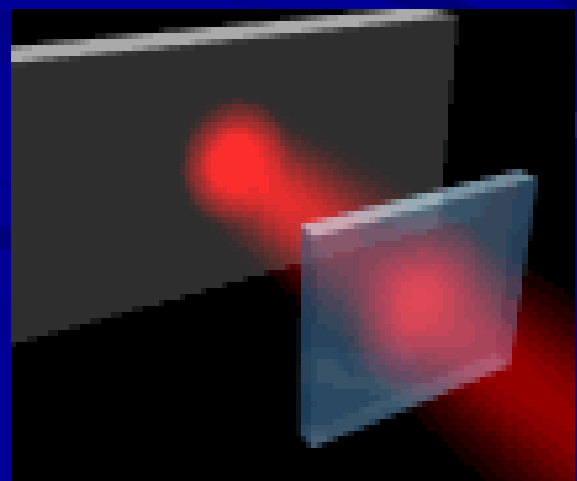


Linearly polarized light

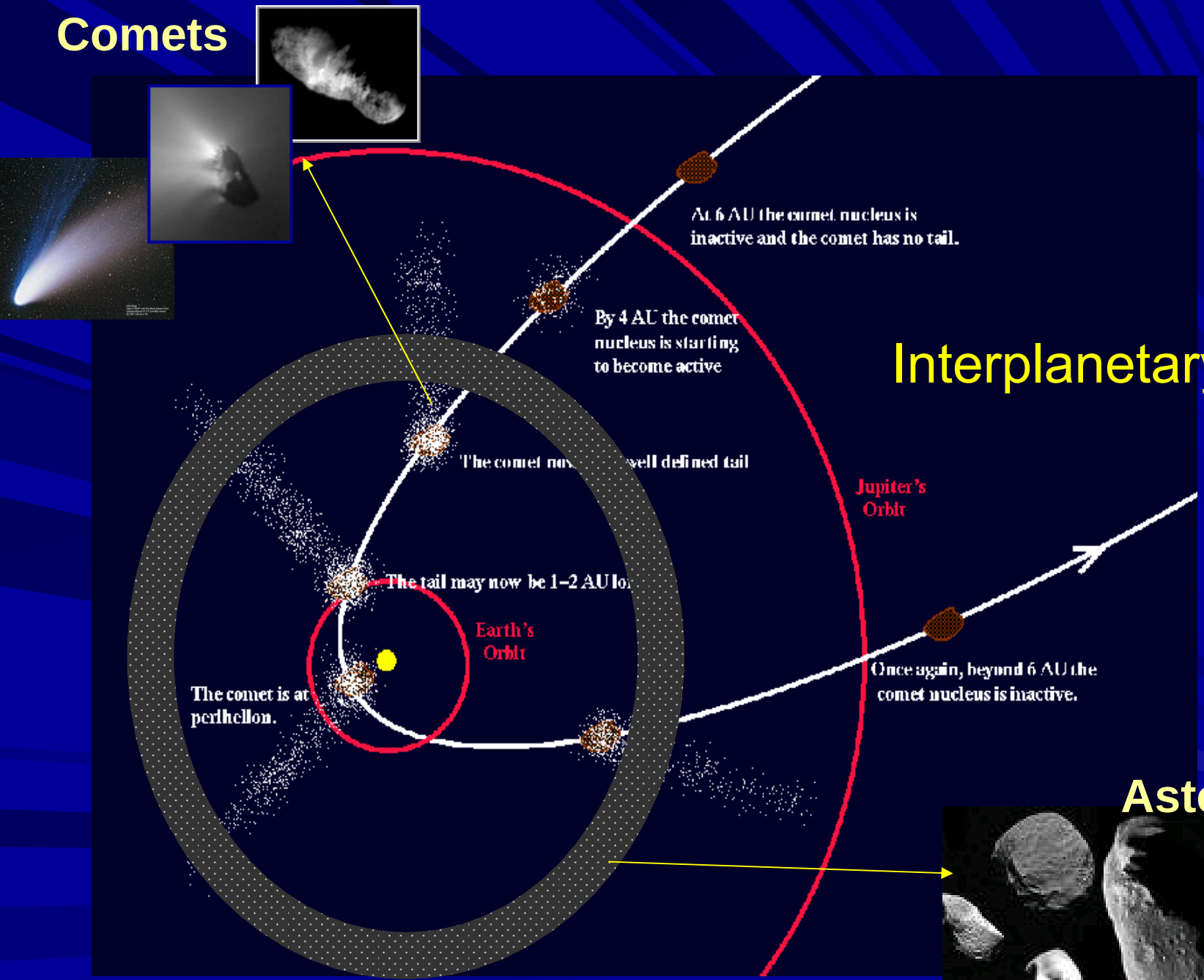




$P = (I_{\perp} - I_{\parallel}) / (I_{\perp} + I_{\parallel})$



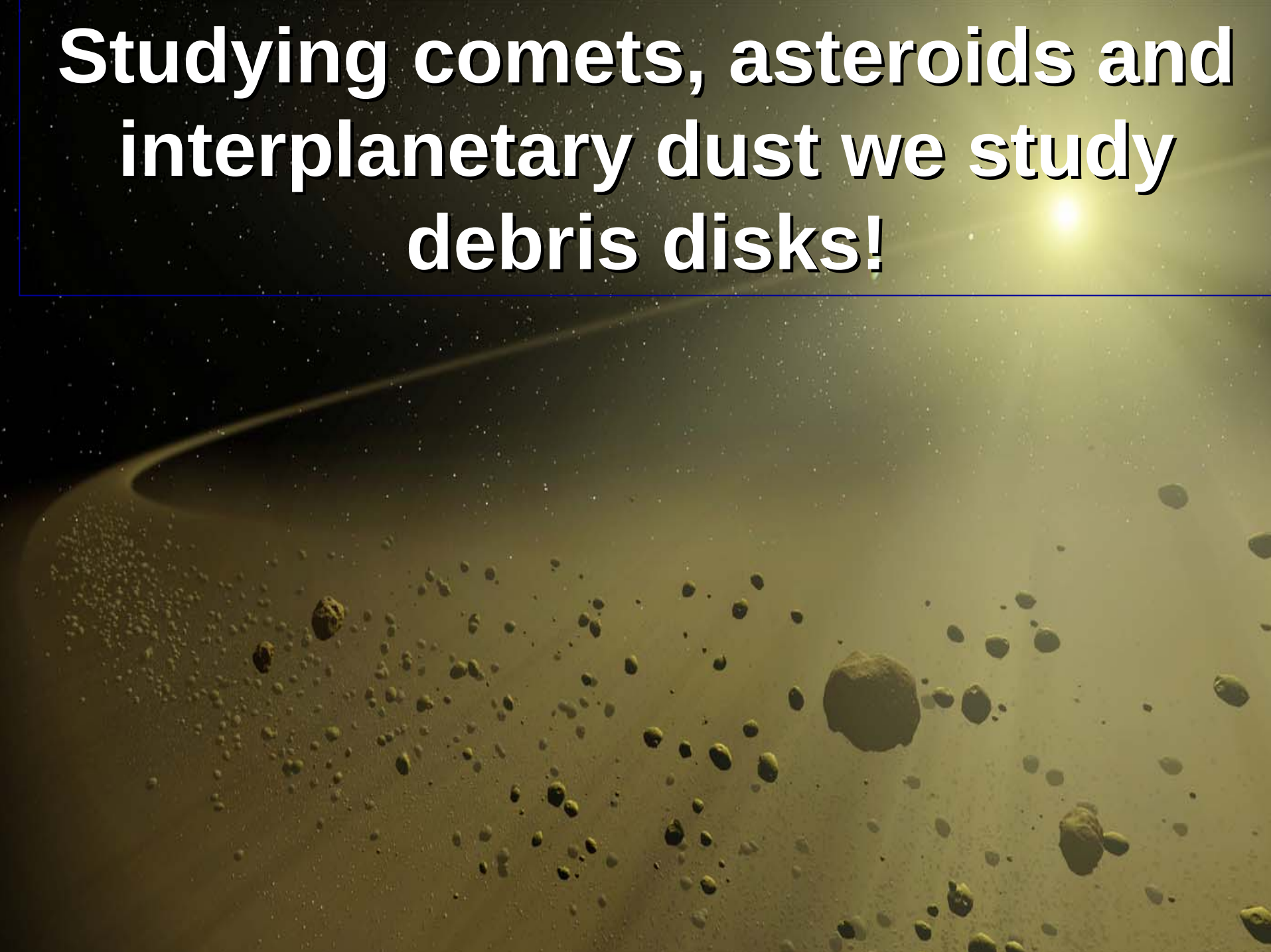
Comets



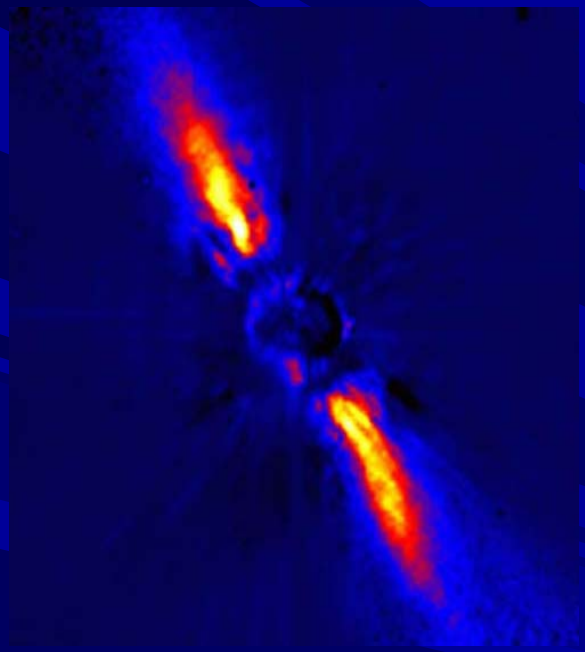
Interplanetary dust

Asteroids

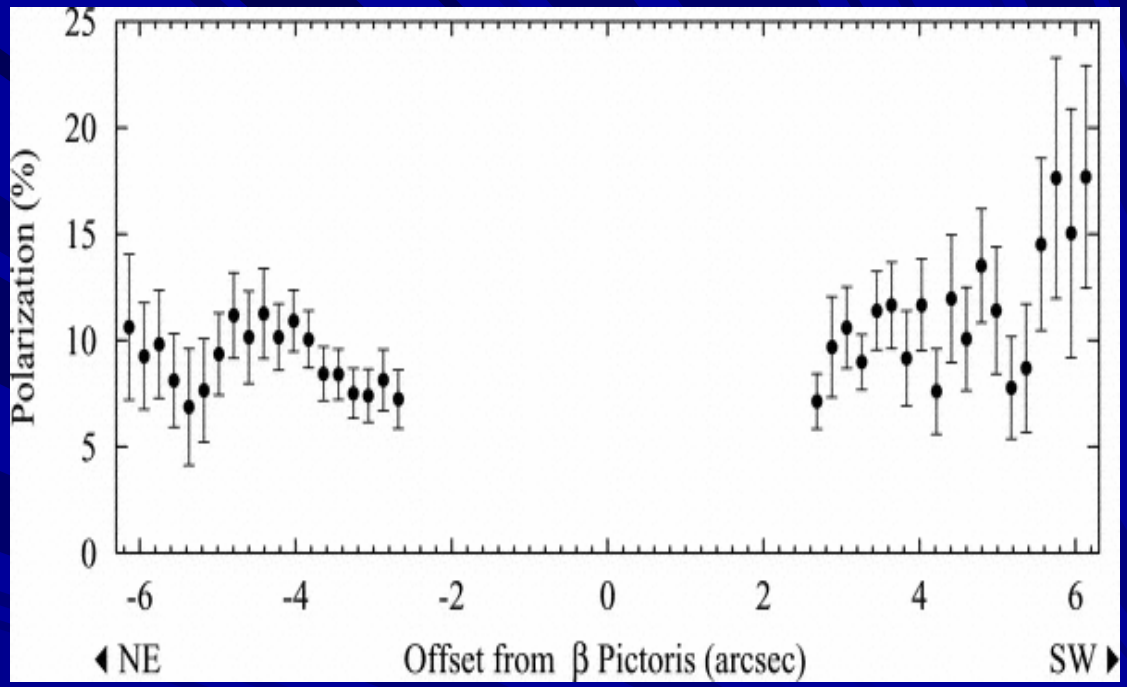
Studying comets, asteroids and interplanetary dust we study debris disks!



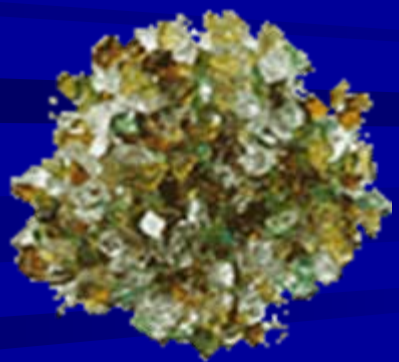
Beta Pictoris Debris Disk

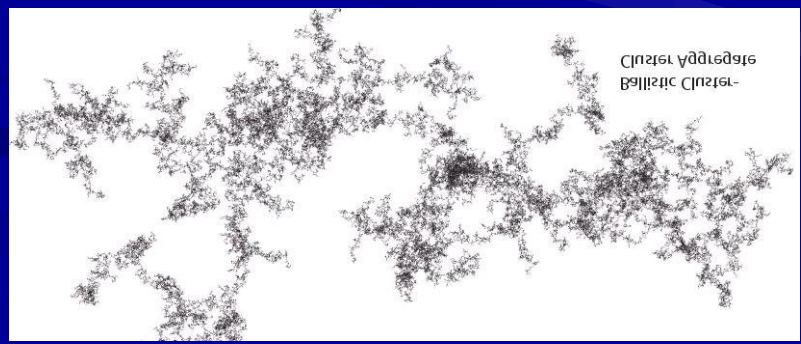


Brightness
(J.-L. Beuzit et al. ESO)

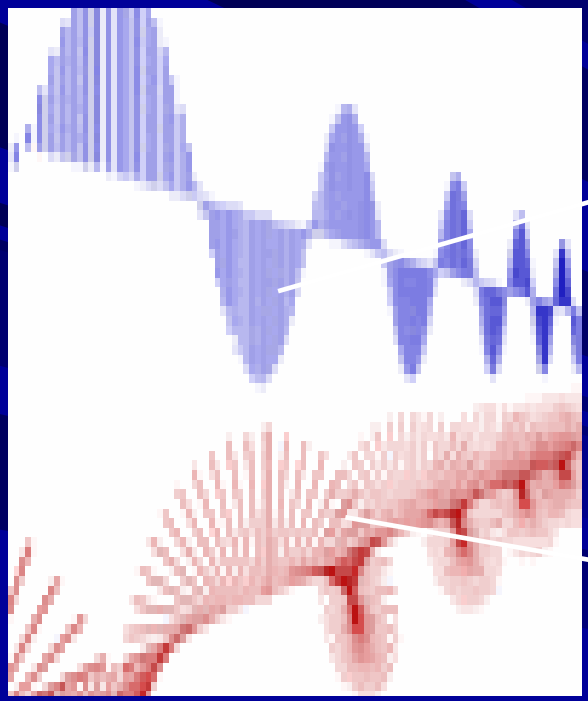


Polarization in *K* band
(Tamura et al., Ap. J., 2006)





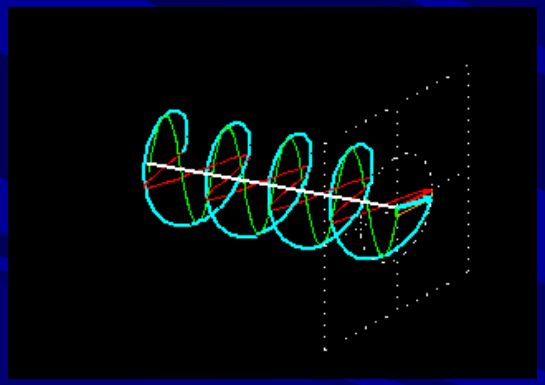
Linear and Circular Polarization

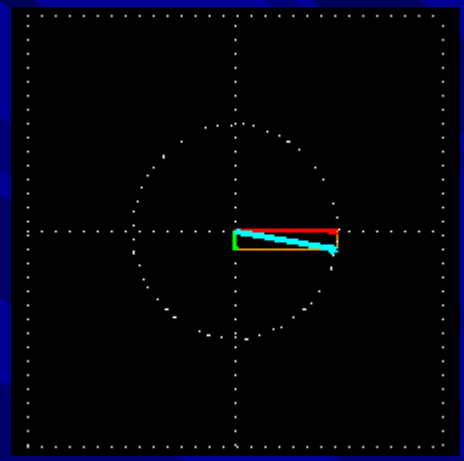


Linearly polarized light

Circularly polarized light

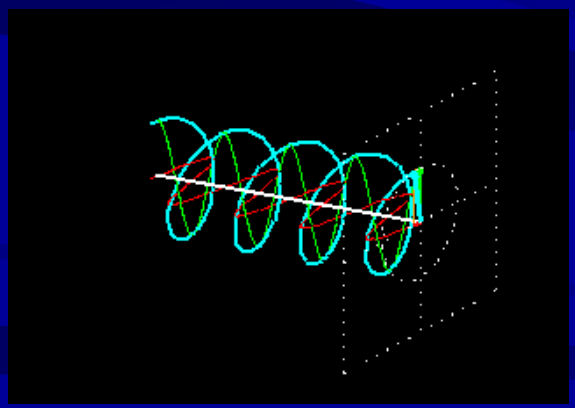
Circular polarization

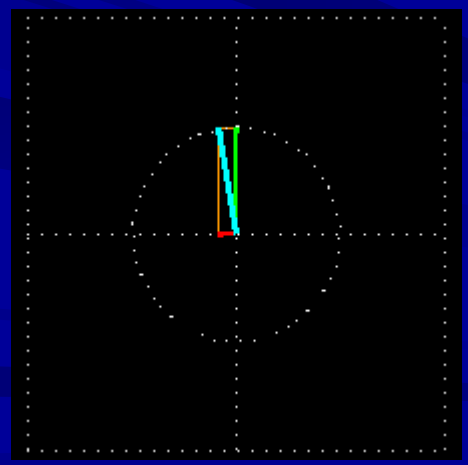




Right-handed

+





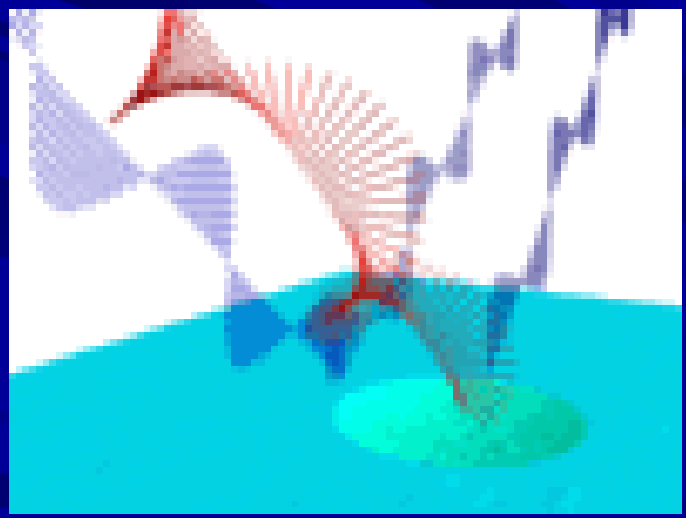
Left-handed

—

$$P = (I_{right} - I_{left}) / (I_{right} + I_{left})$$

What causes circular polarization?

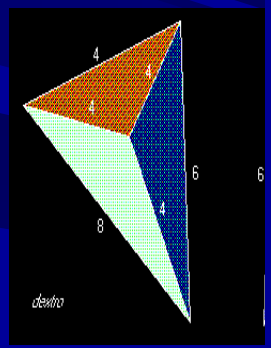
VIOLATION **OF MIRROR SYMMETRY IN THE MEDIUM**



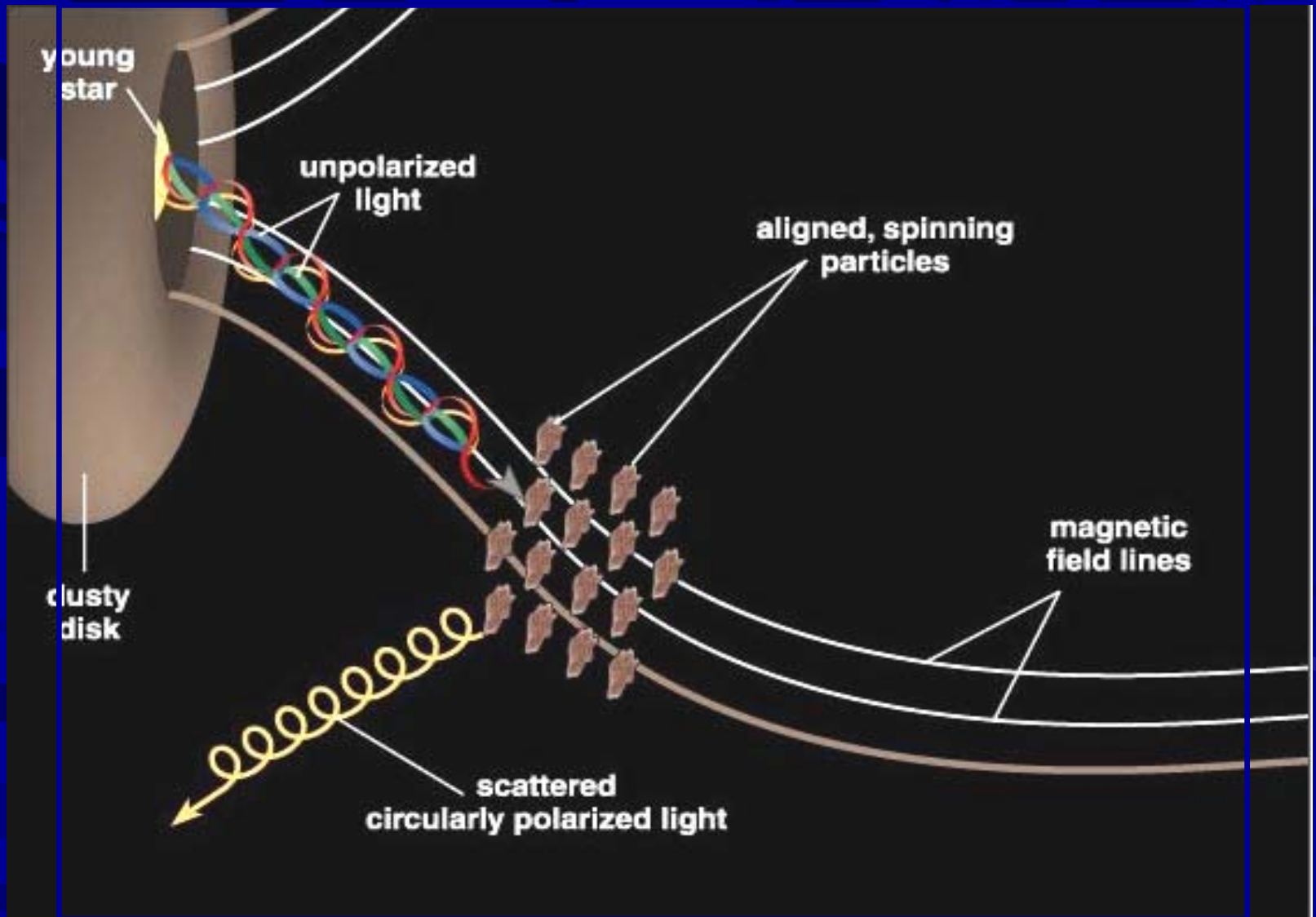
What causes circular polarization?

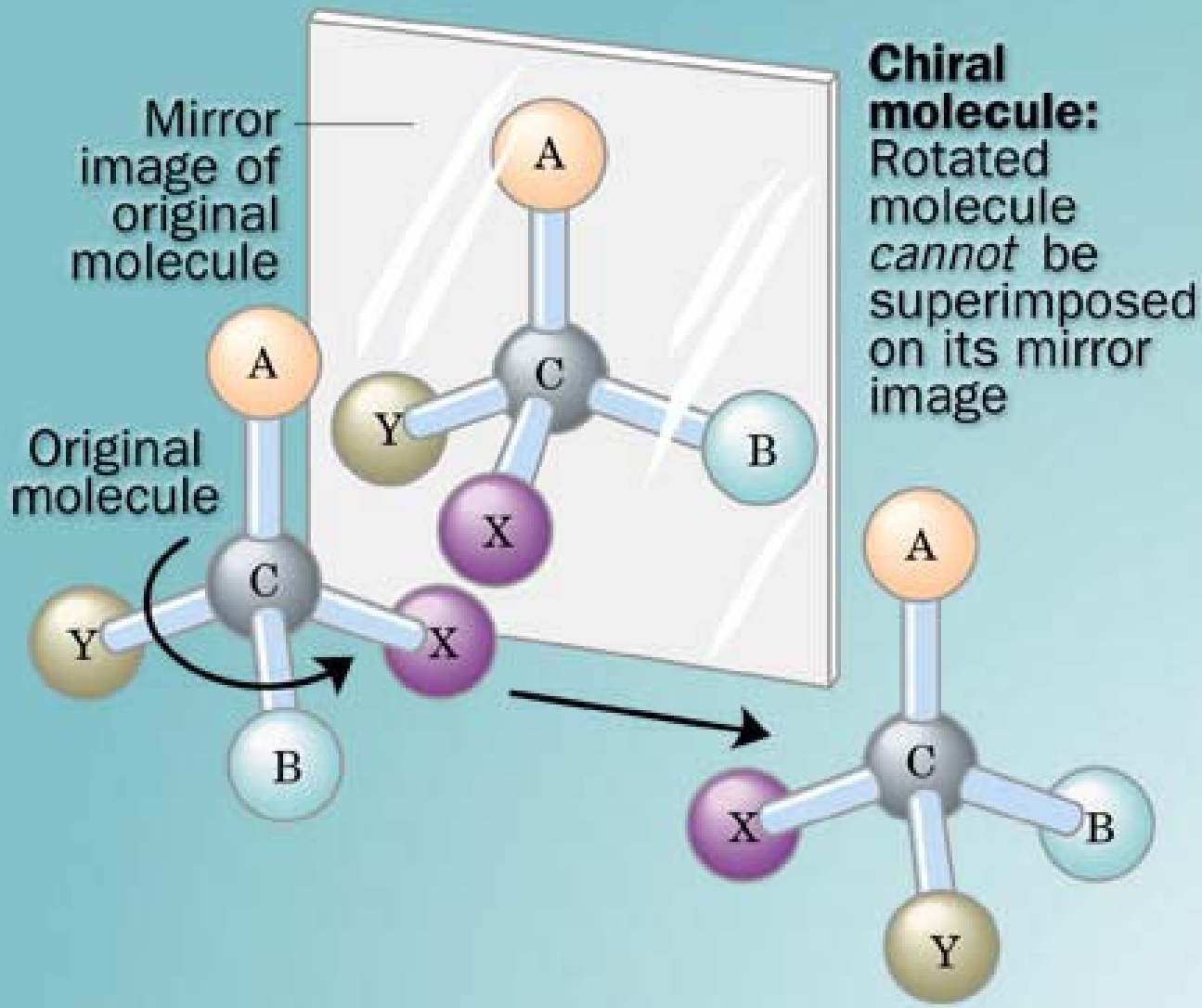
VIOLATION OF MIRROR SYMMETRY IN THE MEDIUM

- Asymmetry in the shape of the particles

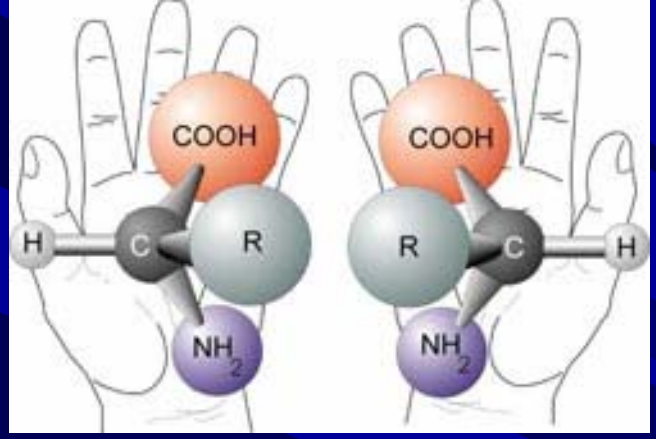


Asymmetry due to alignment of elongated particles in magnetic field




Mirror image of original molecule
Original molecule
Chiral molecule: Rotated molecule *cannot* be superimposed on its mirror image
A
C
Y
B
X
A
C
Y
X
B
A
C
X
B
Y

Chirality



Chirality of organic molecules

Organic molecules that form a chiral pair are called **enantiomers.**

Non-biological organics: equal number of right and left handed molecules

Homochirality

All amino acids of biological origin are left-handed

All sugars of biological origin are right-handed

Origin of homochirality

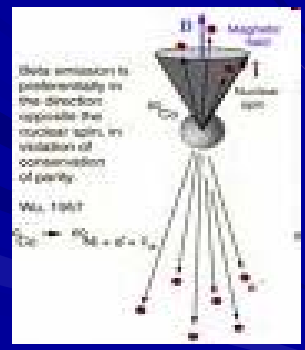
Terrestrial Origin

- ***Quartz crystals as the substrate***
  Quartz crystals are hexagonal and dissymmetric. If organic molecules were replicated on a quartz surface one chirality may dominate. Although there is equal number of left and right handed crystals in the terrestrial quartz.

- ***Clay minerals***
  Reported a small chiral selection by clay minerals. The effects may have been an artifact; this could be due to previous absorption of optically active biomolecules.

- ***Scattering of light by particles in water***
  Synthesis of complex molecules affected by the circularly polarized light from suspended particles in calm shallow waters such as tidal pools. Effect is very small.

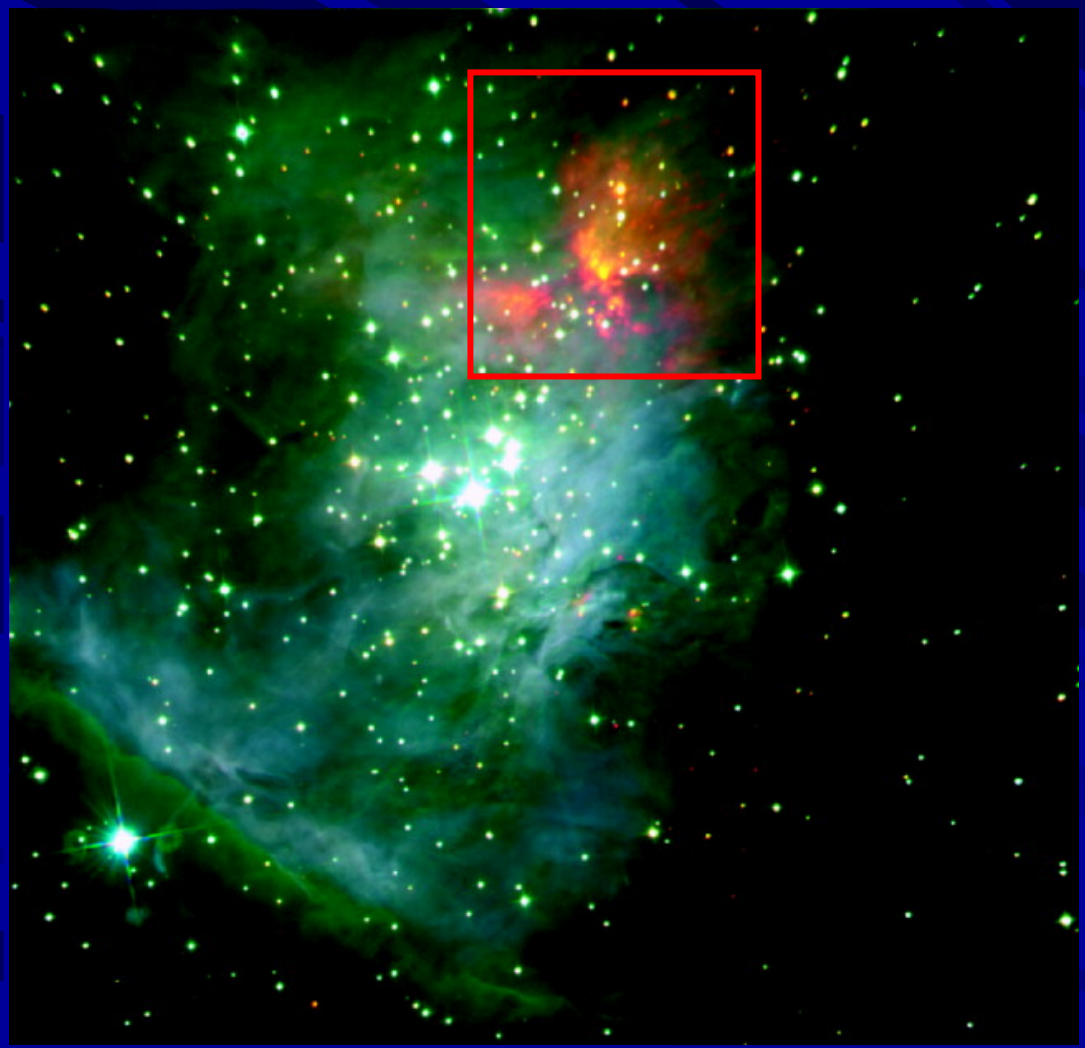
Extraterrestrial origin

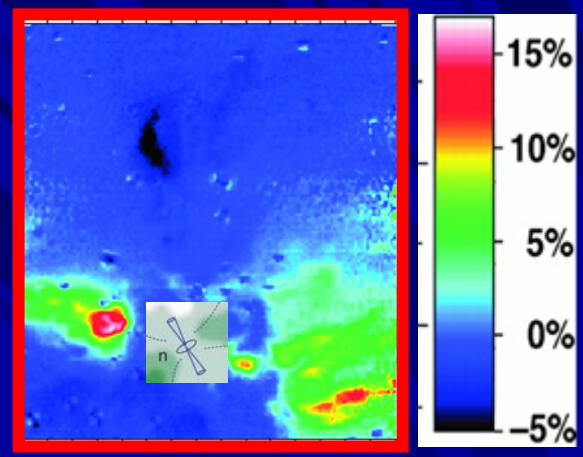


- ***Beta decay and the weak force***
  β-decay is one form of radioactive decay, and it is governed by the *weak force*. This force has a slight handedness, called *parity violation.* β-decay could account for the chirality in living organisms as due to it the energy of L enantiomers is slightly smaller than the energy of D enantiomers of aminoacid. However, the weak force is really weak: the effect would be only one excess L-enantiomer for every 6×10^{17} molecules of a racemic mixture of amino acids.

- ***Asymmetric photolysis in molecular clouds***
  Synthesis of complex molecules is affected by the circularly polarized light of the star

Orion Nebula





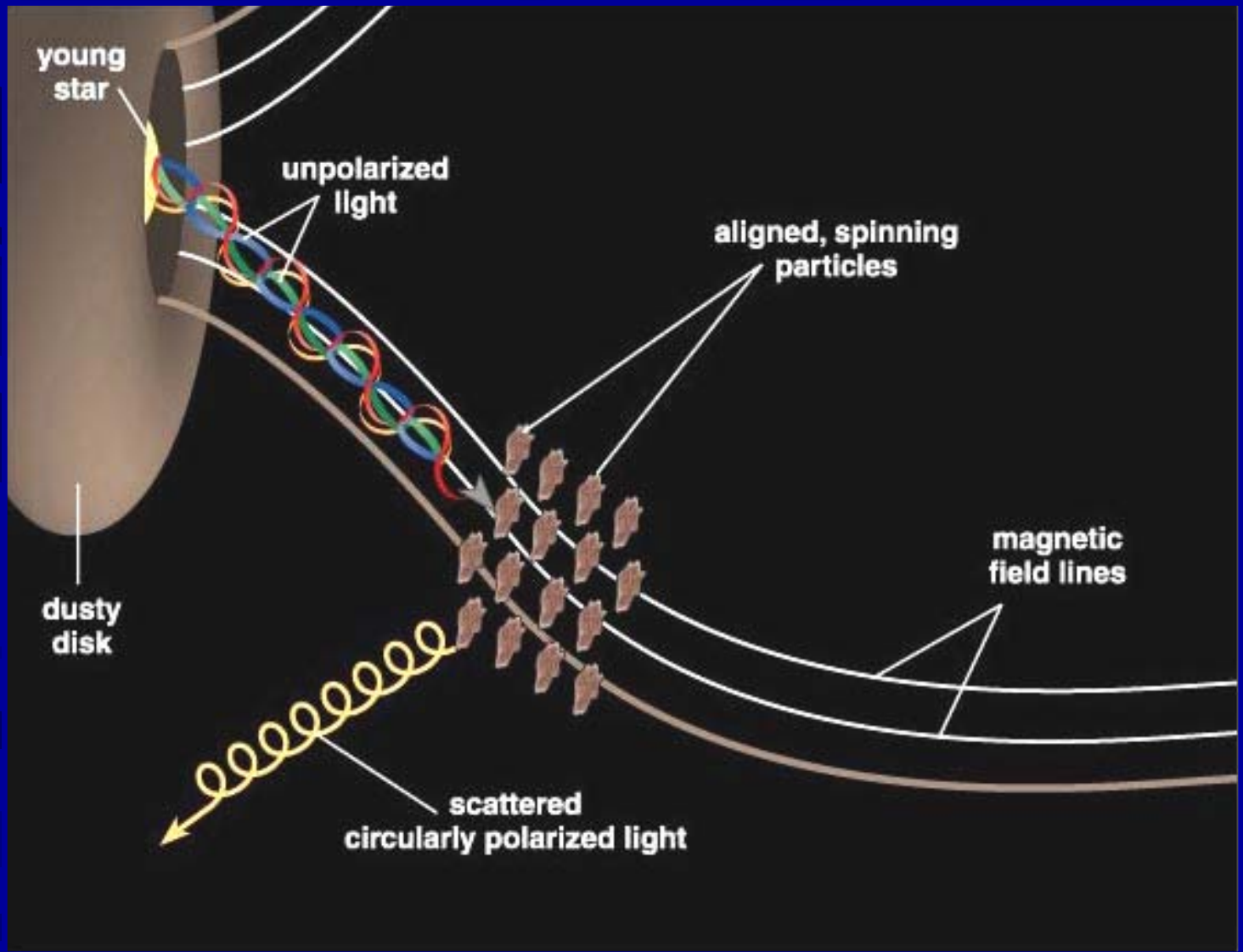
NIR image from Muench et al., 2002

Summary of detections of circular polarization

Object	Mass	Type	CP (λ)
OMC-1	High	OB star	17% (2.2μm)
NGC 6334 V	High	OB star	15% (2.2μm)
HH 135/6	Intermediate	Herbig Ae/Be	15% (2.2μm)
R CrA	Intermediate	Herbig Ae/Be	5% (1.6μm)
GSS 30	Low?	Class I	2% (2.2μm)
Cha IRN	Low?	Class I	1% (1.6μm)
R Mon	High	OB star	0.4% (0.6μm)
GL 2591	High	OB star	< 1% (0.8μm)
PV Cep	Intermediate	Herbig Ae/Be	< 1% (0.8μm)
V633 Cas	Intermediate	Herbig Ae/Be	< 1% (0.8μm)
HL Tau	Low	T Tauri	< 1% (2.2μm)
L1551 IRS5	Low?	Binary YSOs	< 3% (0.8μm)

(Adapted from Clayton et al. 2005)

Alignment of particles by magnetic field in molecular clouds



Circularly polarized light can induce homochirality in organic molecules!

(Bailey et al., 1998; Lucas et al, 2003)

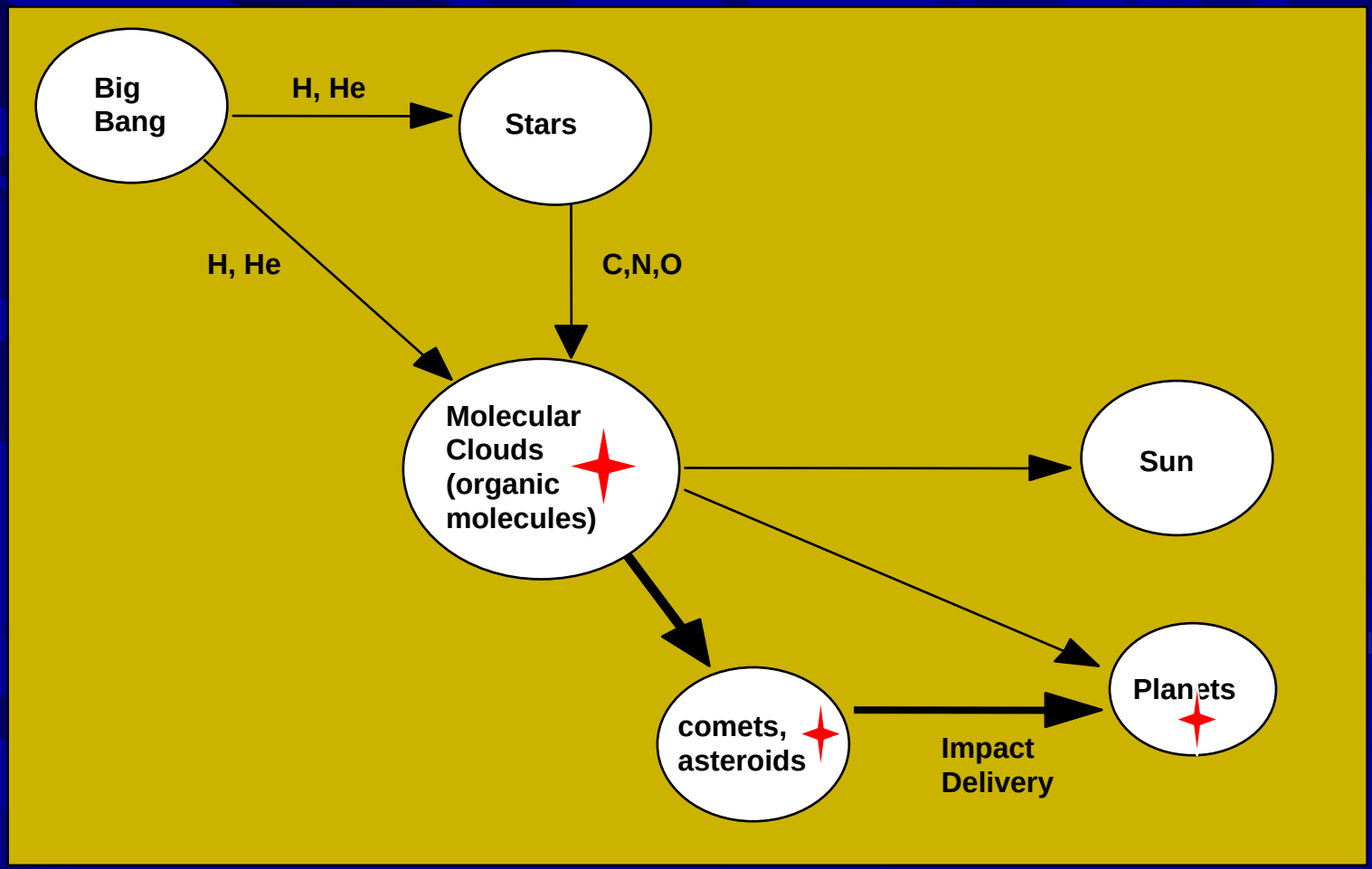
Asymmetric photolysis of amino acids in the cloud or in a protostellar disk:

Exposure to circularly-polarized radiation can induce an enantiomeric excess by destroying one enantiomer more efficiently than the other .

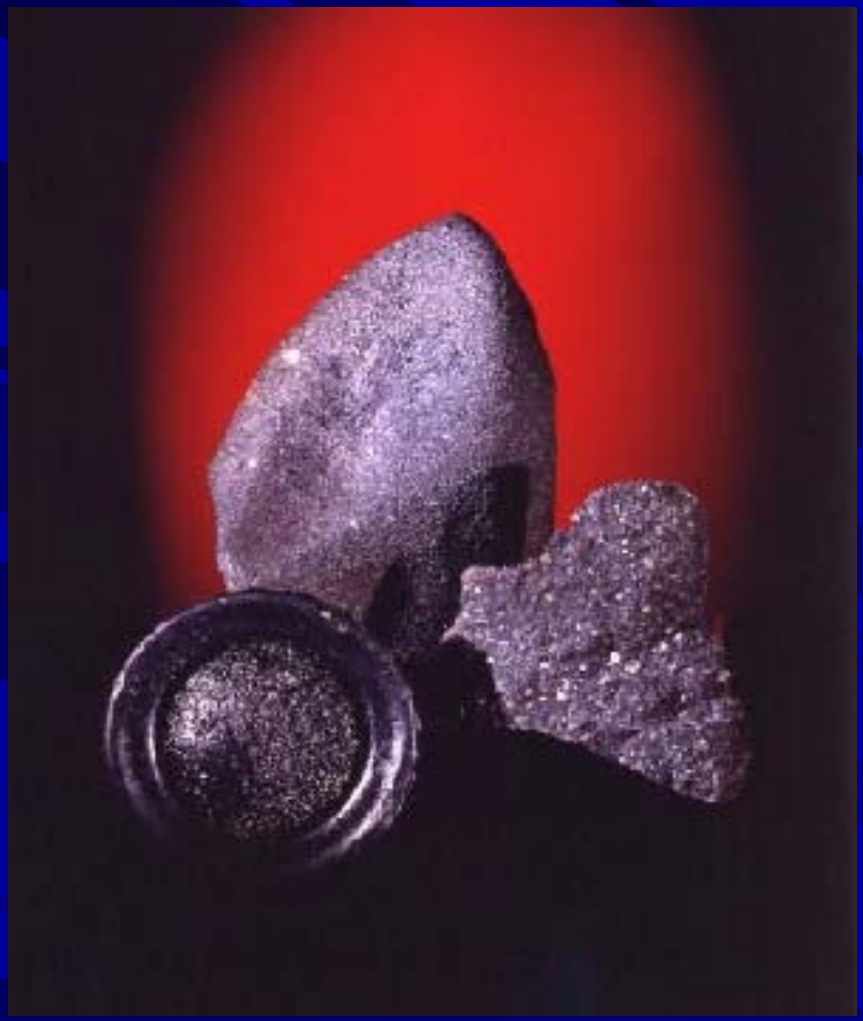
Confirmed by laboratory experiments (Nuevo et al. 2003, 2004).

Homochirality in the terrestrial bio-organics may have an astrophysical origin.

Circular polarisation could imprint chiral asymmetry in interstellar molecules before or during the formation of the Solar System.



Homochiral Organics in Meteorites!



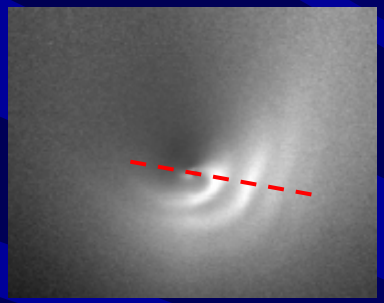
The Murchison meteorite fell in Murchison, Victoria, on 28 September 1969. A total of ~100kg of material was collected from the impact site.

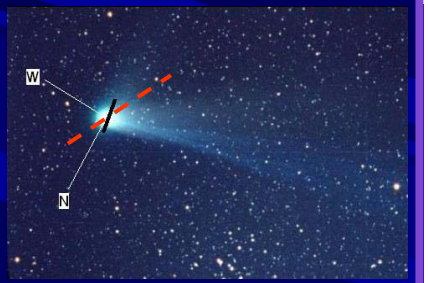
Murchison meteorite contained a wide variety of organic compounds including many amino acids (more than 100 have now been identified).

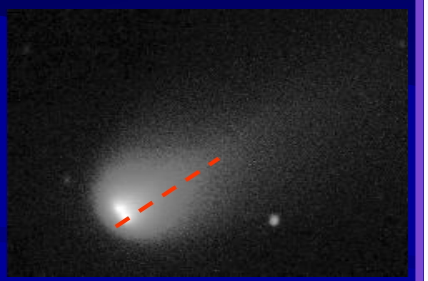
Engel et al. (1982, 1990, 1997) find large enantiomeric excesses (up to 50%) in common protein amino acids such as alanine, while Cronin and Pizzarello (1997) find enantiomeric excesses (of 2-15%) in several a-methyl amino acids.

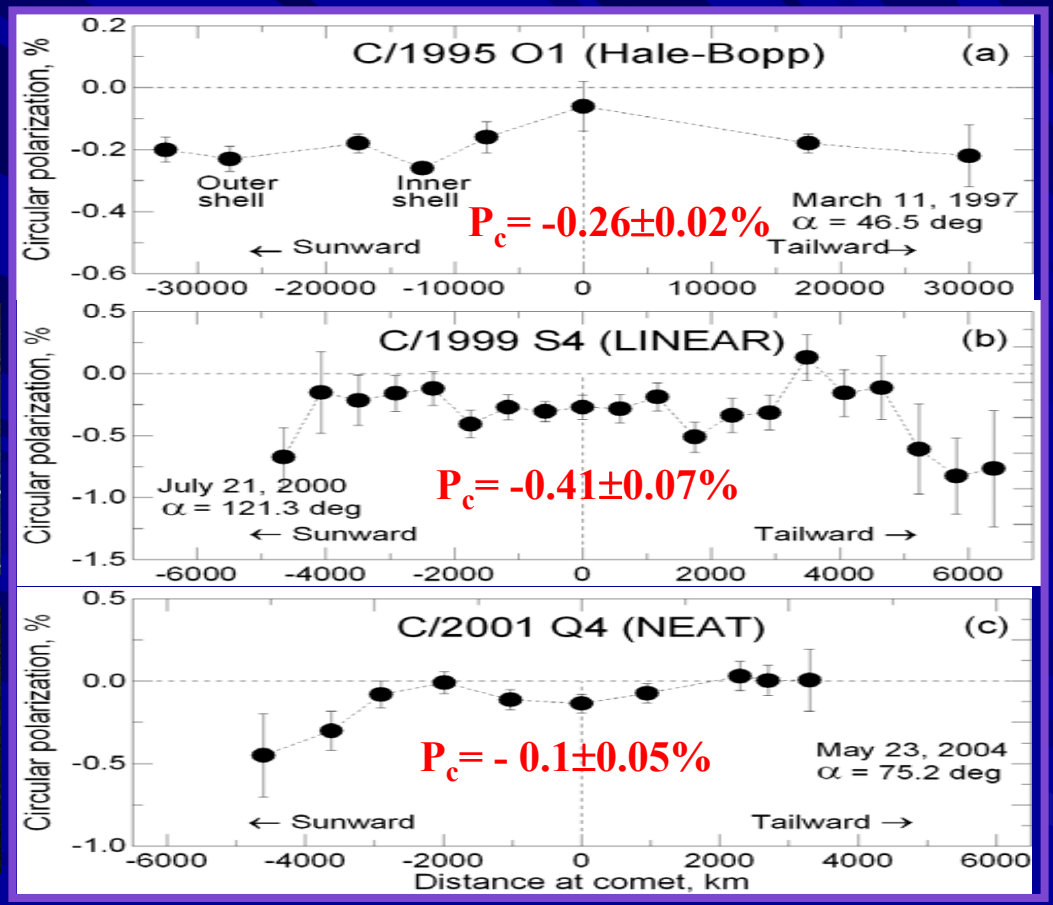
This was confrimed for meteorite Murray (Pizzarello & Cooper, 2001)

Circular polarization in comets









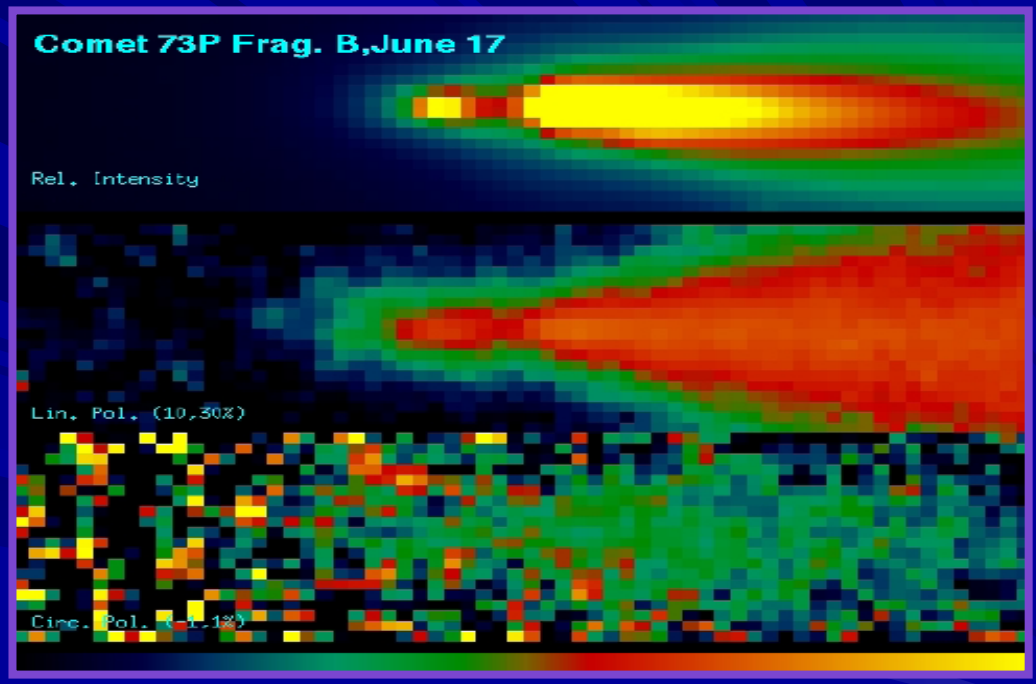
Hale-Bopp [Rosenbush et al. 1997];

S4 (LINEAR) [Rosenbush et al. 2007b];

Q4 (NEAT) [Rosenbush et al. 2007a].

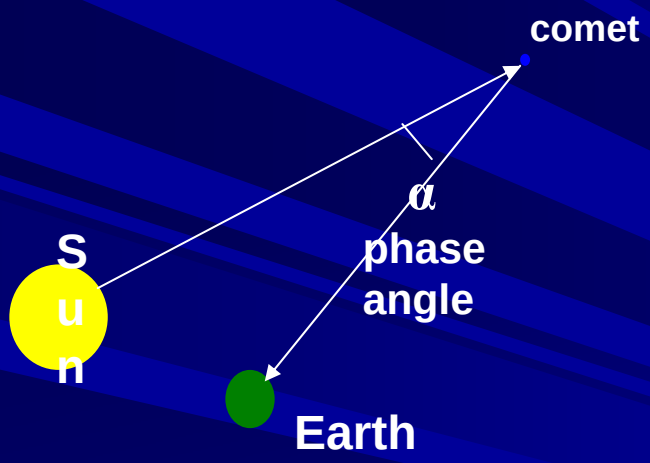
Circular polarization in comet Schwassmann-Wachmann 3

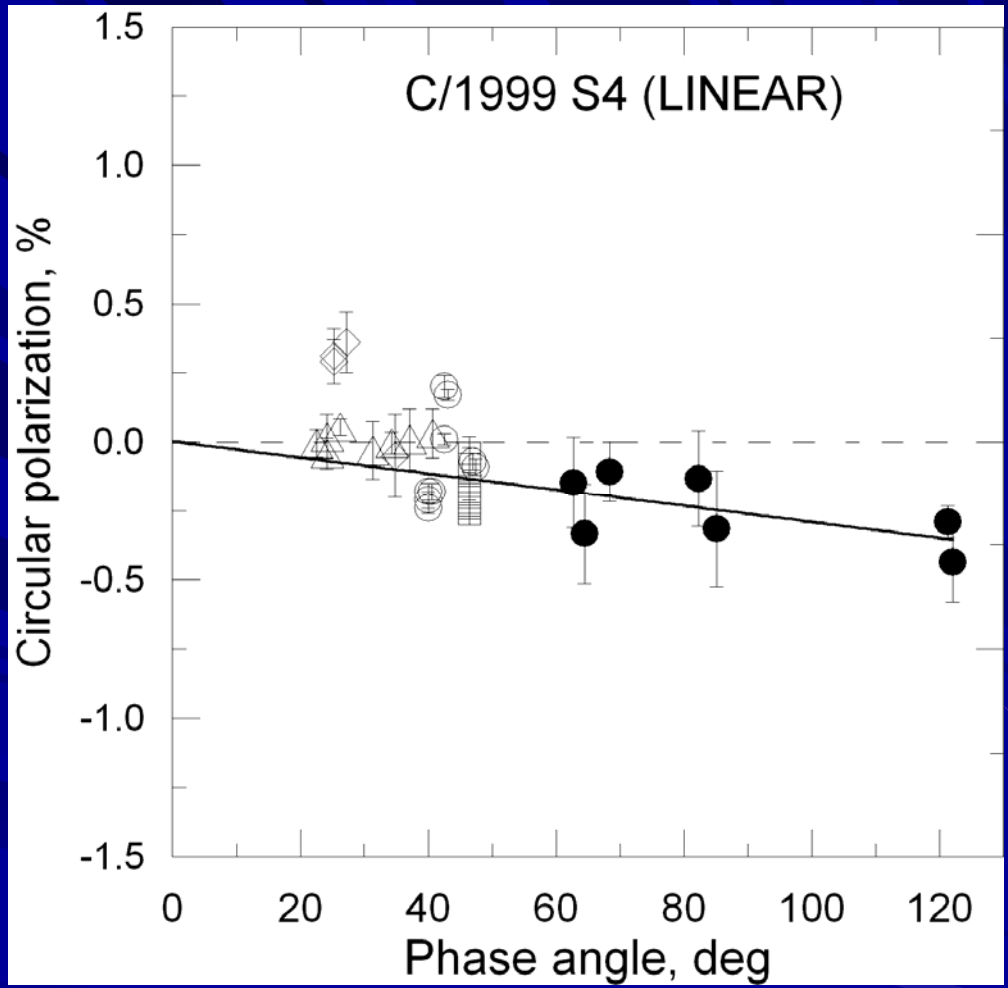
$P_c = -0.2 \pm 0.2\%$



The brightness (top), linear (middle) and circular (bottom) polarization for comet SW3-B obtained with FORS by ESO SW3 team [Tozzi et al. 2006] on June 17, 2006.

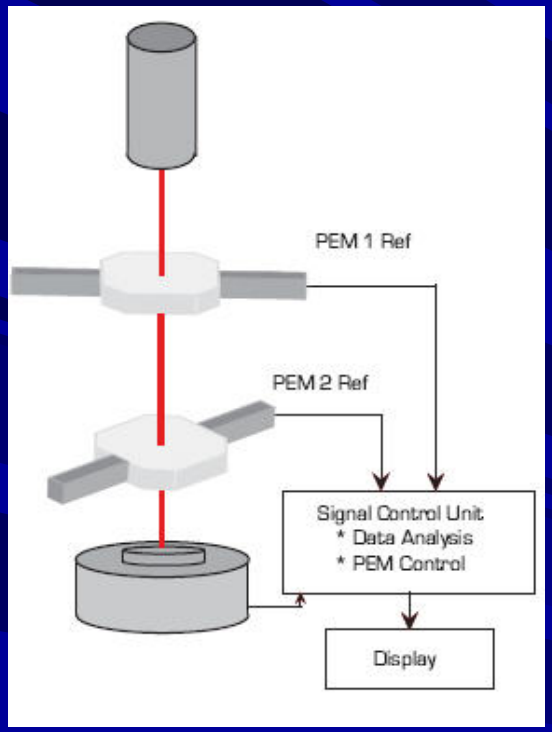
PHASE DEPDENDENCE OF CIRCULAR POLARIZATION

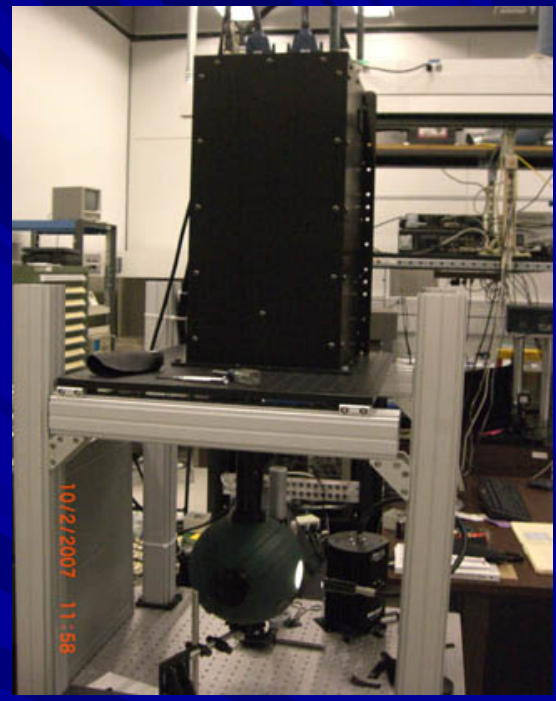




Composite phase-angle dependence of circular polarization
for comets C/1999 S4 (LINEAR), 1P/Halley, and C/1995 O1 (Hale-Bopp).

Hinds Instruments, Series II/FS42-47 dual photoelastic modulator (PEM) precision optical polarimeter

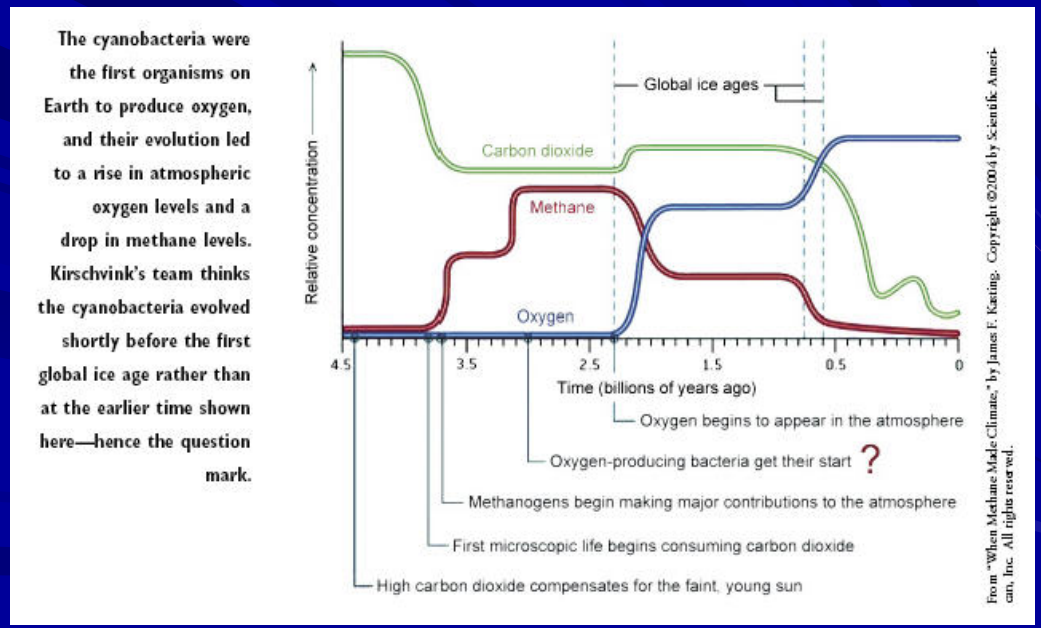




- **Circular polarization degree of 10^{-4} be measurable in the presence of linear polarization of degree 0.03 and that the polarimeter be tunable from 400 nm to 800 nm.**
- The long wavelength cut-off was designed to extend beyond chlorophyll's red edge at 700 nm while covering the important absorption bands in the optical spectrum.
- Configure to allow transmission and reflection experiments, solids, liquids or powders.
- The entire system is controlled by a dedicated PC
- The equipment is hosted at NIST in the optical metrology department.

Cyanobacteria

- Cholorphyll-based photosynthetic prokaryotes
- Ancient fossil record, possibly to >3.5 billion yr
- Primary agent for rise of oxygen in primitive Earth atmosphere
- Abundant: marine, fresh water, on rock, in rock, soil, symbiosys
- Hardy, adaptable and diverse
- Unicellular; colonial



Cyanobacteria are thought to be responsible for the rise of oxygen in the Earth's atmosphere about 2.5 billion yr ago.

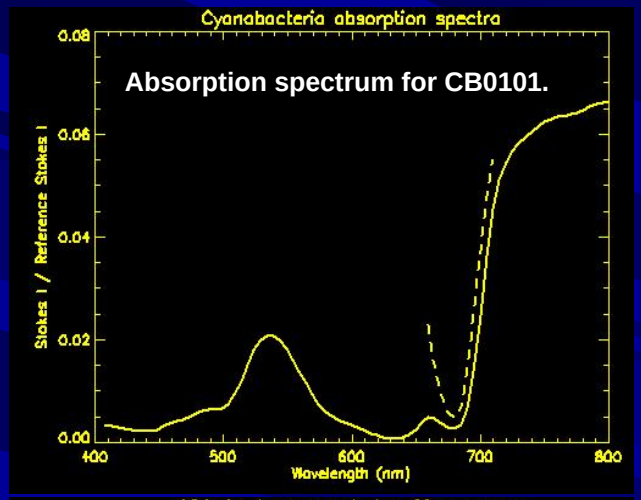
From Kasting, reproduced in Kirschvink "Red Earth, Green Earth, Black Earth, White Earth"

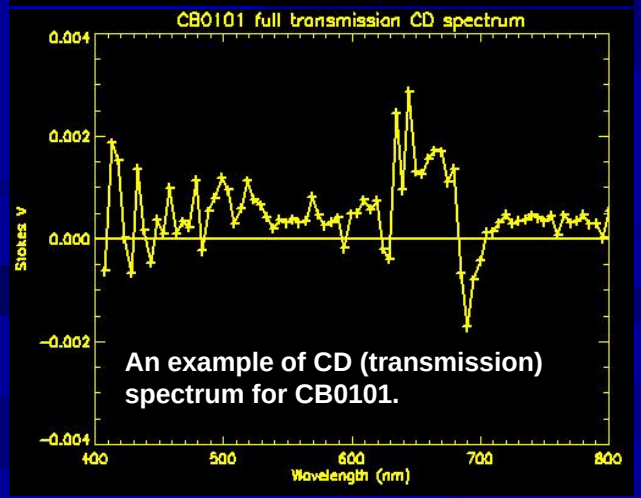
Cyanobacteria: ***synechococcus*** WH7805, CB0101

Above, configuration shown for transmission experiment.

Below, centrifuged and resuspended samples of *Cyanobacterium synechococcus* CB0101 (left) and WH7805 (right). Approximately 10^{12} cells per original 500 ml culture, approx $1/10^{th}$ used.

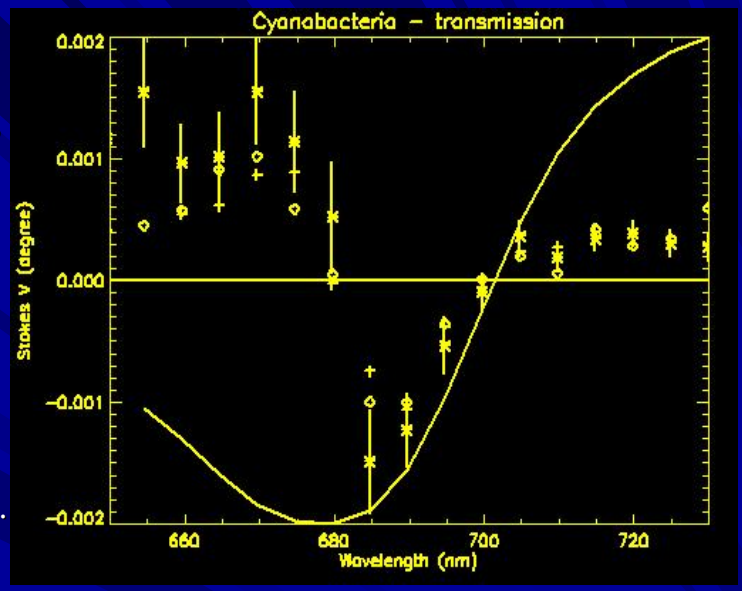
Cyanobacteria ***synechococcus*** WH7805, CB0101: results





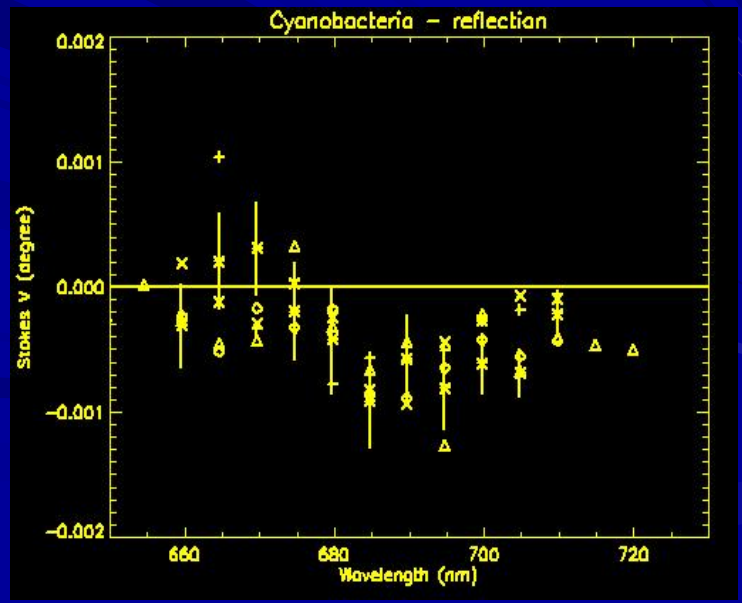
Chlorophyll absorption region of spectrum showing CD transmission with (scaled) absorption overlaid.

Note circular polarization sign flip at absorption maximum.



CP reflection spectrum for multiple scans of both CB0101 and WH7805.

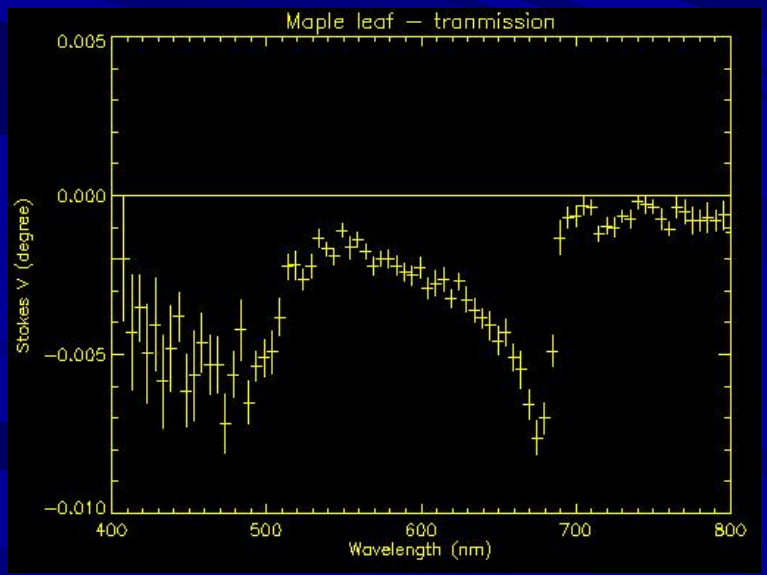
Upper and lower plots have same y-axis scale +/- 0.2%.

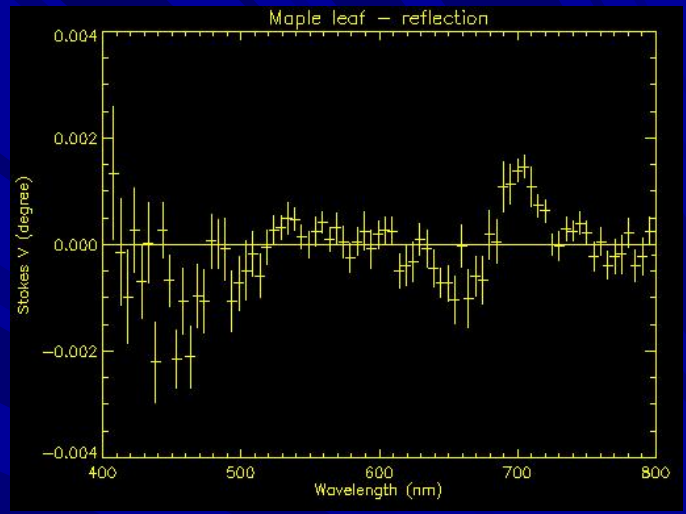


More Experimental Results

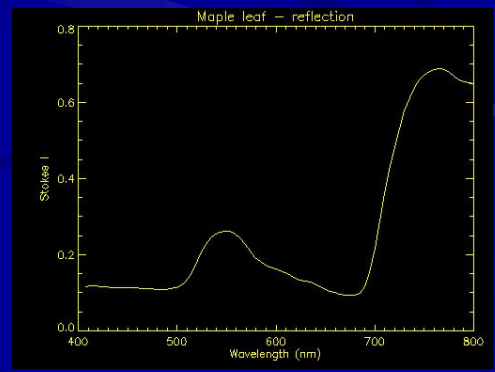
- Maple leaf

Below, CP in transmission, +0.5%, -1%. Strong features in vicinity of chlorophyll absorption peaks.



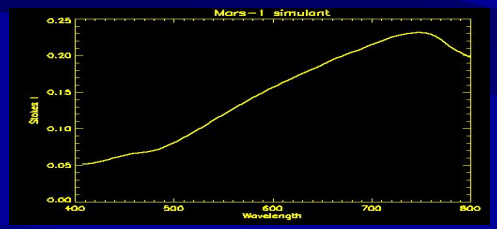


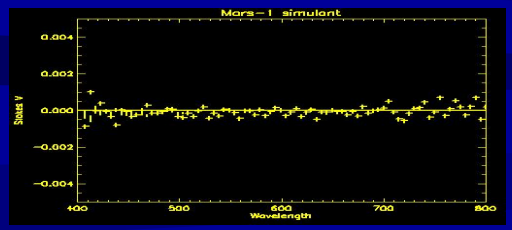
Above, CP in reflection, y-scale +/- 0.4%. Significant features co-located with CD features. Amplitude ≈1/3 CD, rise location coincides, sign flip.



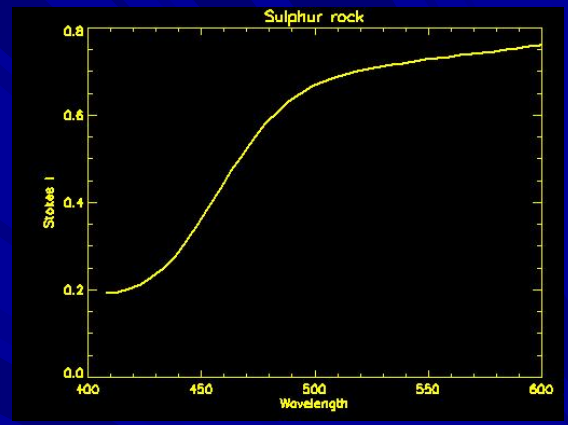
Mineral controls

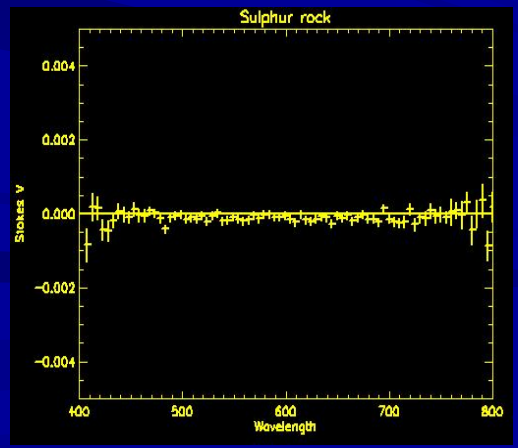
JSC-12 Mars regolith simulant

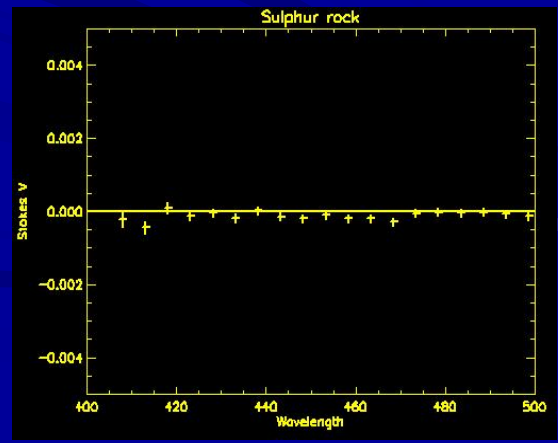




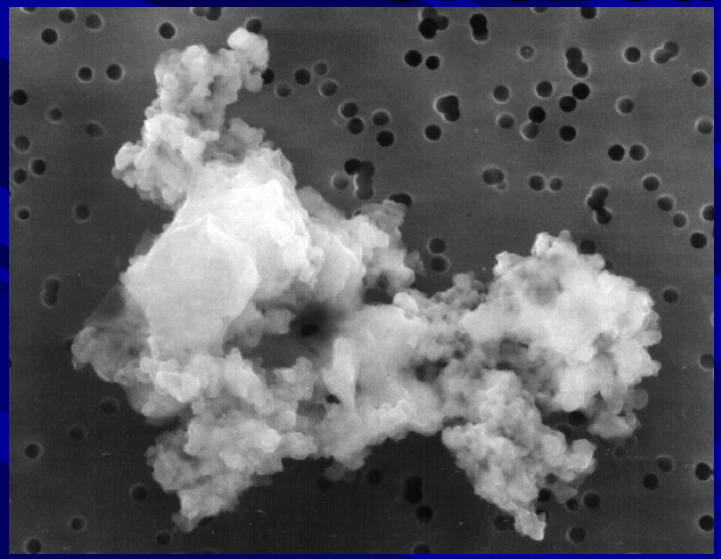
Example: single sulfur rock shows strong “edge”; no definitive polarization.

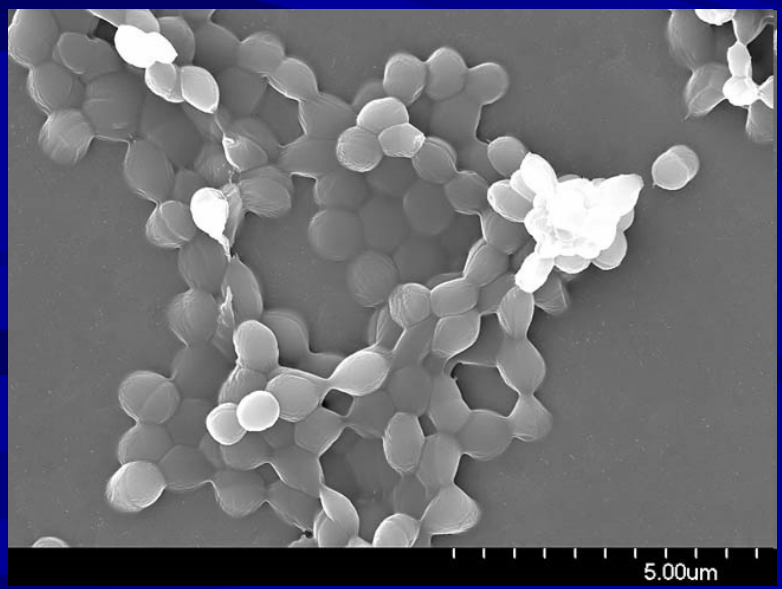






Can we increase the calculated values of circular polarization?

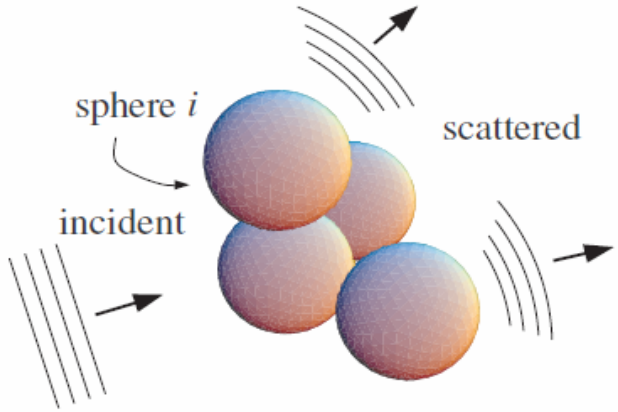




Considering
- realistic comet particles (aggregates)
- colonies of bacteria

should increase circular polarization due to interaction between constituents of the aggregate (similar to the effect of multiple scattering)

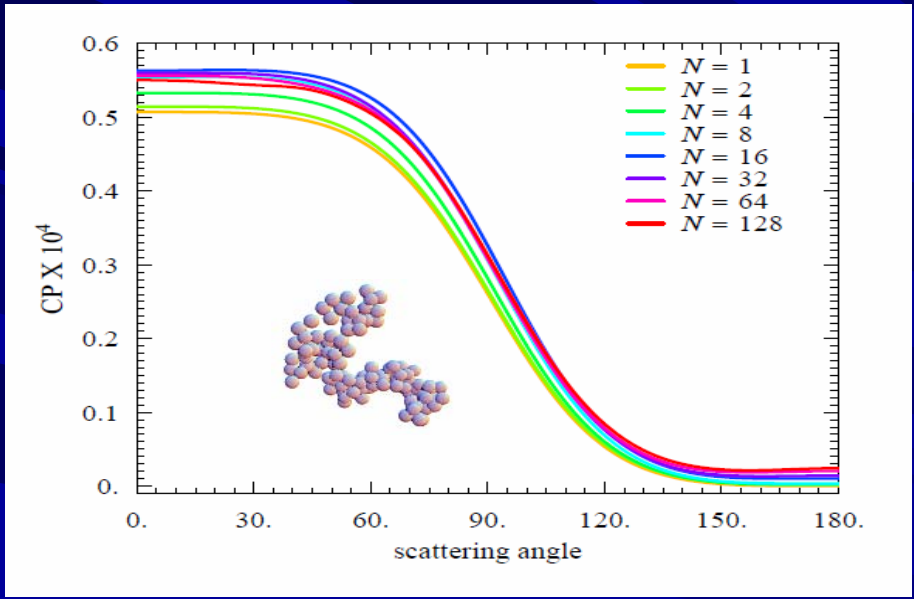
T-matrix code of aggregates of spherical particles made of optically active materials

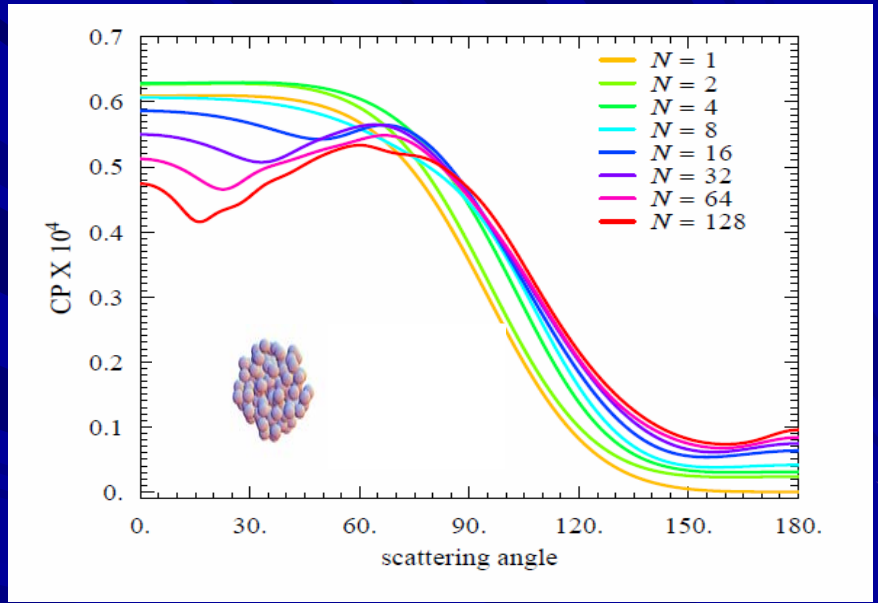


$$\mathbf{E}_{sca} = \sum_{i=1}^{N} \mathbf{E}_{sca,i}$$

$$\mathbf{E}_{sca,i}(\mathbf{r}) = \sum_{n=1}^{n} \sum_{m=-n}^{n} \sum_{p=1}^{2} a_{mnp}^{i} \, \mathbf{N}_{mnp}^{(3)}(\mathrm{k}\,(\mathbf{r} - \mathbf{r}_i))$$

Results for fractal aggregate
(mirror-symmetric pair was considered)



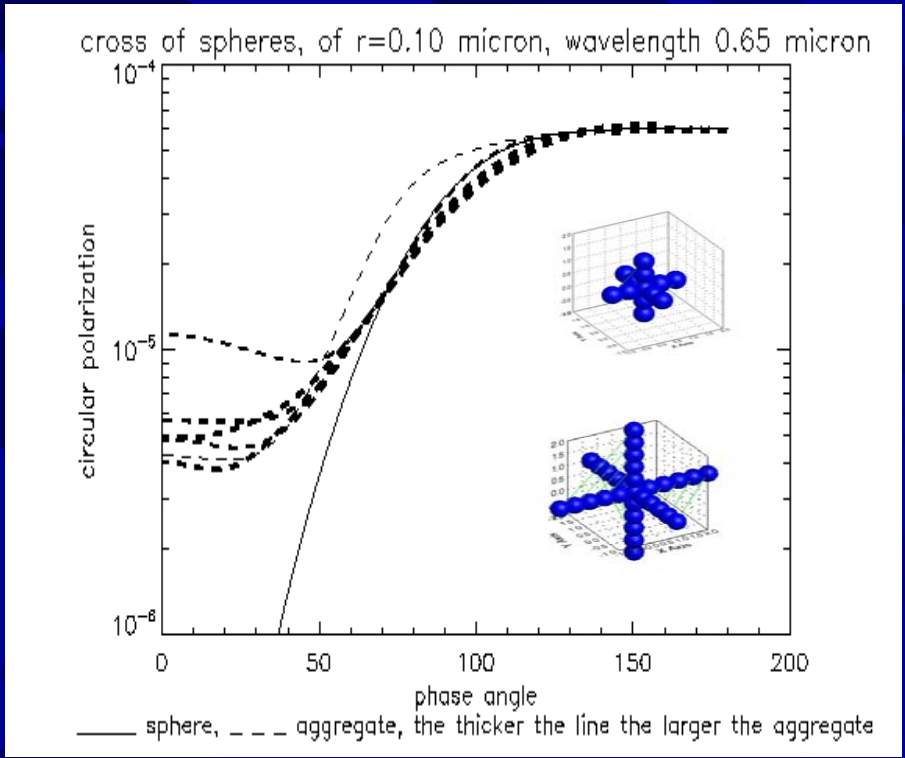


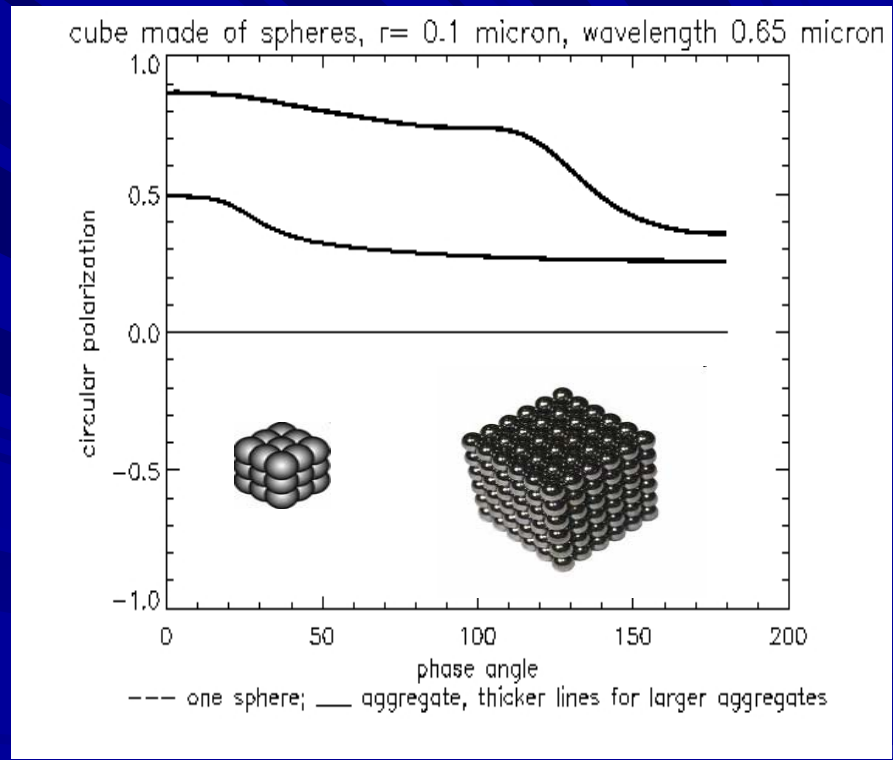
Circulars birefringence for amino acids (Mason, 1982): difference in the refractive index for the left and right circular polarization 3×10^{-6}.

Circular dichroism of amino acids (Schreier et al., 1995): the difference in the imaginary part of the refractive index on the order of 1×10^{-8}.

We considered that only 10% of the material is optically active (i.e. is represented by chiral molecules).

Effect of porosity





What next?

Short-term goal: optimize the remote-sensing technique, make it more efficient

- More laboratory studies, need to complete current study to assess connection between absorption and circular dichroism
- Field/airborne studies: robust precision polarimeter to characterize terrestrial environments in reality; oceans, forests, desert…
- More observations of comets, Earthshine, and solar-system objects that may harbor life (Mars, Europa, Titan)
- Theoretical modeling of circular polarization from aggregates containing organics with enanitomeric excess to simulate observations and laboratory measurements

Long-term goal:

- Develop an element in space exploration toolbox to study solar-system objects and extra-solar planets

Collaborators

- *Space Telescope Science Institute, MD*
- *National Institute of Standards, MD*
- *Auburn University, AL*
- *Max Planck Institute of Solar System Research, Germany (ESO, Chile)*
- *University of Hertfordshire, UK (Gemini Observatory, Hawaii, Chile)*
- *Center for Planetary Sciences. Kobe University, Japan*
- *Main Astronomical Observatory, Ukraine (Crimean observatory)*
- *Osservatorio Astrofisico di Arcetri, Firence (Canaries Island telescopes)*
- *Armach Observatory, Ireland*

Structure of Deep Impact ejecta cloud based on studying the shadow of the cloud (one more project, supported by NASA PMDAP)