Dust in the solar system and in other planetary systems

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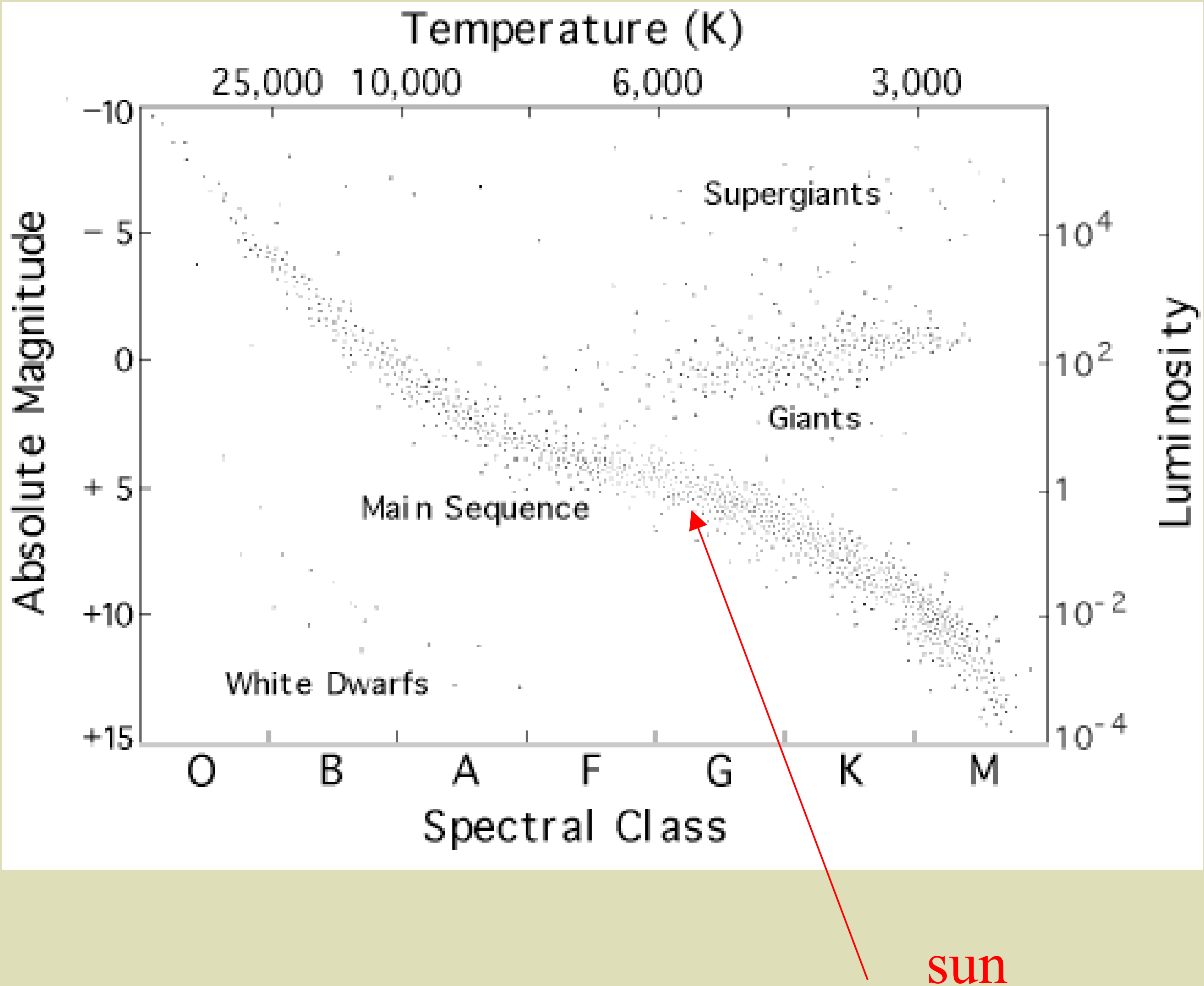
Outline……

Interplanetary medium, dust & small bodies, dust interactions, interstellar dust

Dust in the inner solar system compared to dust in extra-solar planetary systems

Sun & Interplanetary Medium

Hertysprung - Russell diagram to classify stars



Sunspots:

- dark spots on the surface of the sun indicate regions of lower temperature (ca 4500 K) compared to the surrounding temperature (ca 6000 K)
- sunspots have strong magnetic fields and are connected through loops of magnetic field lines
- Emission of particles and radiation from the coronal holes
- lifetime of sunspots ranges from days to months

Magnetic fields:	Sunspots	$B \approx$	4000 Gauss
	Surface of Sun	$B \approx$	3-4 Gauss
	near Earth orbit	$B \approx$	$5 \cdot 10^{-4}$ Gauss
	Surface of Earth	$B \approx$	0.2–0.7 Gauss

Solar Magnetic Field

solar "dynamo"

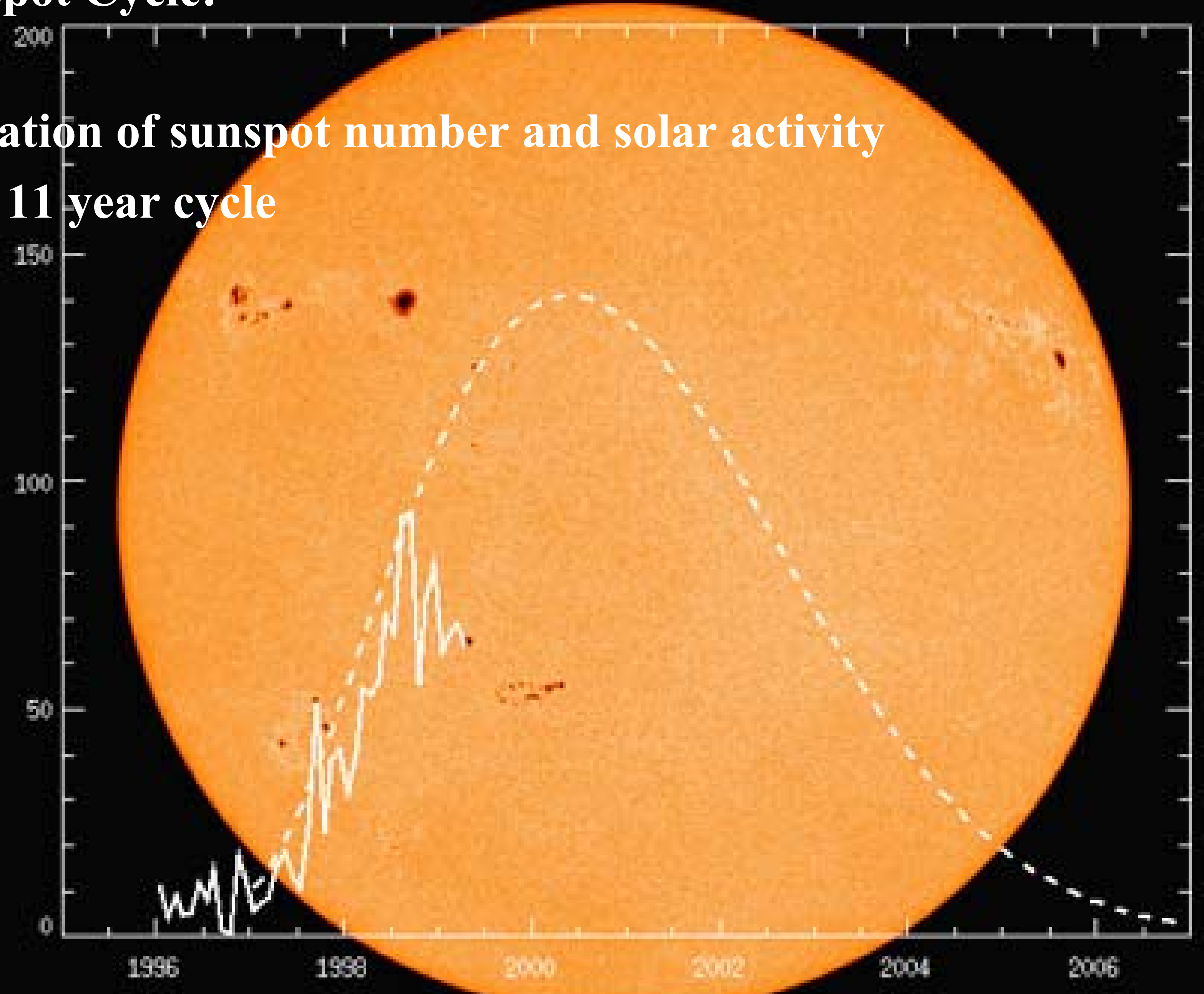
complex structure

tilted dipole plus lots of "perturbations"

Sunspots indicate "magnetic activity" of the Sun that causes reversal of the magnetic field

Sunspot Cycle:

Variation of sunspot number and solar activity over 11 year cycle



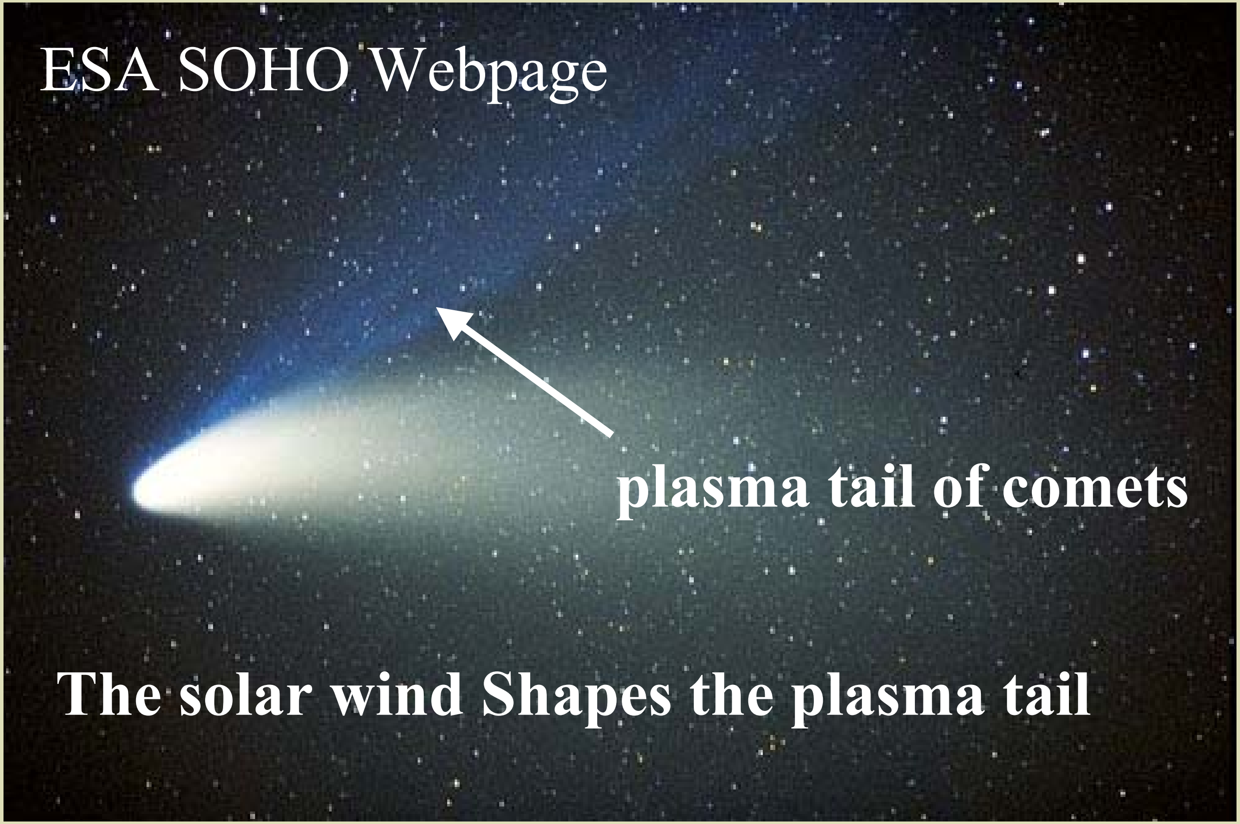
ESA SOHO Webpag

LASCO/SOHO observations of the solar Corona

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

ESA SOHO Webpag

Does the corona expand into the interplanetary medium



Yes, it forms the solar wind !

A close-up view of comet Hale-Bopp taken April 4, 1999 by University of Hawaii astronomers (see David Jewitt's WebPage). **The narrow blue ion tail is shaped by the solar wind and points almost directly away from the Sun**. The diffuse dust tail has a more curved shape, caused by radiation pressure from the force of the light that the dust particles absorb. The dust particles follow trajectories that are a combination of their orbital inertia and the outward push from the sunlight.

Solar wind:

electrons & ions streaming away from the Sun into interplanetary space

First assumptions: originates from expansion of the coronal gas

First "detection": Plasma tail of Comets (Biermann 1951)

Solar wind is accelerated in the solar corona and then streams through interplanetary space with $v \approx$ const.

Solar wind near Earth orbit:

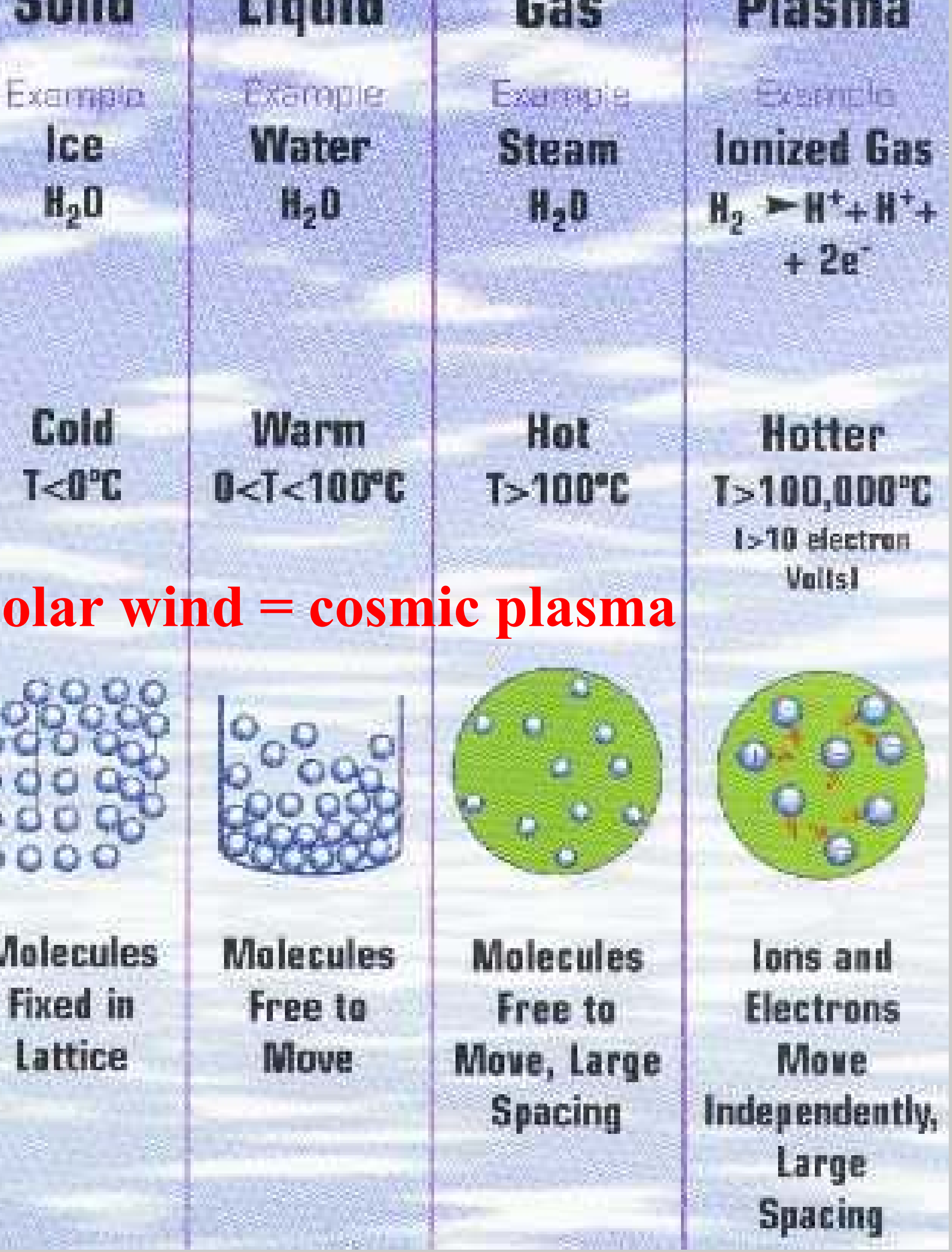
Protons	$n_H =$	5 cm^{-3}
Elektrons	$n_e =$	5 cm^{-3}
Temperature	$T =$	$2 \cdot 10^5$ K
Velocity	$v =$	300-800 km/s
Magnetic field	$B =$	$5 \cdot 10^{-4}$ Gauss

Solar Wind = Cosmic Plasma:

Plasma = hot ionized gas consisting of:
electrons, ions, neutrals

"**quasi-neutral**": number of positive and negative charges in a larger volume (**Debye Sphere**) equals out

"**frozen-in magnetic field**": if the plasma is sufficiently thin then it carries the magnetic field with it (described with models of magneto-hydro-dynamics)



olar wind = cosmic plasma

Plasma
4th state of matter

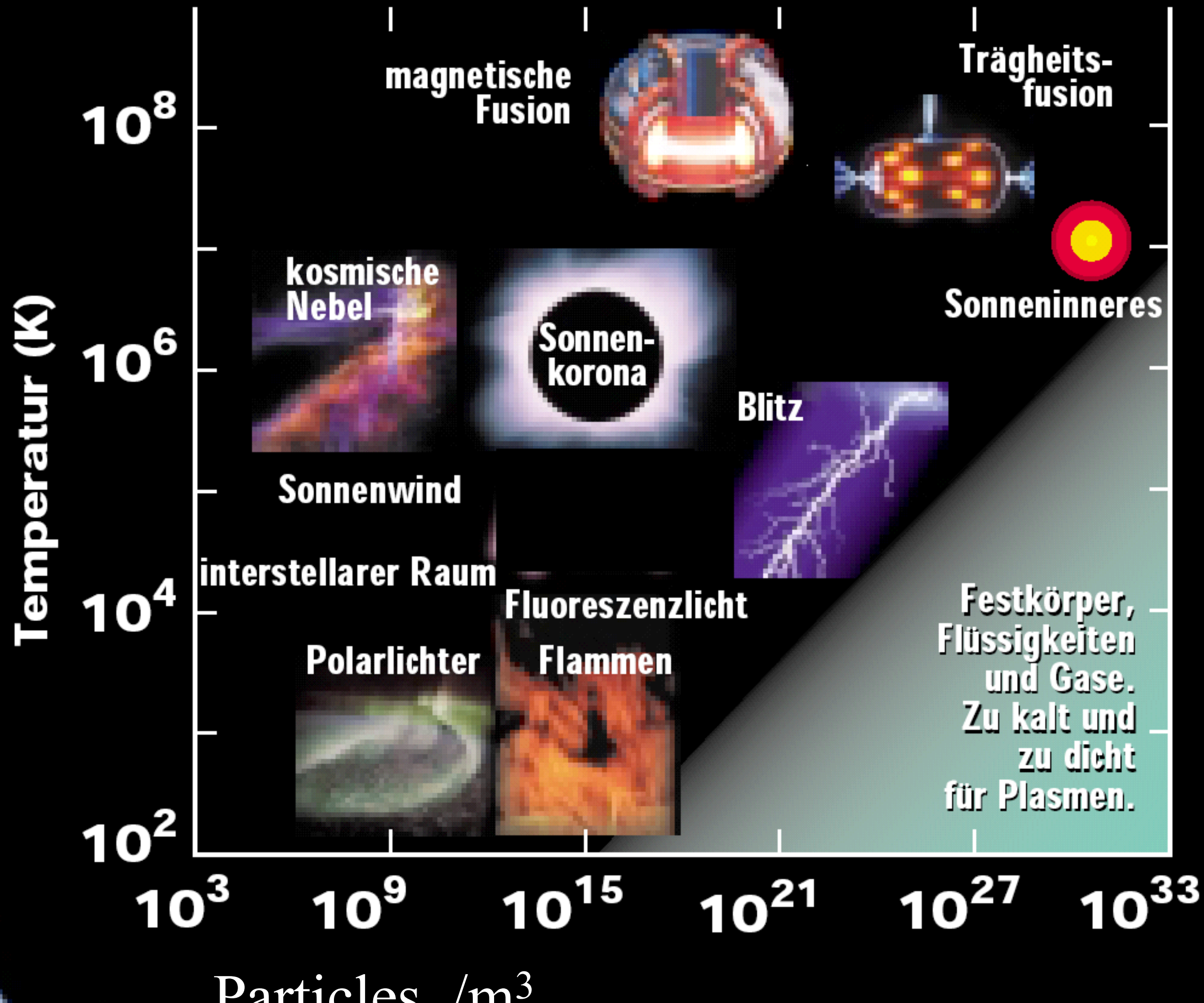
Under certain conditions plasma behaves like fluid that carries the magnetic field with its flow

"Magnetohydrodynamik"
"frozen in magnetic field"

plasma particles are coupled through electric and magnetic fields

EIGENSCHAFTEN TYPISCHER PLASMEN

Plasmen bestehen aus frei beweglichen geladenen Teilchen, d.h. Elektronen und Ionen. Sie entstehen bei extrem hohen Temperaturen, wenn Elektronen vom bis dahin neutralen Atom abgetrennt werden. Sie sind in der Natur und im Universum allgegenwärtig. So bestehen Sterne z.B. vorwiegend aus Plasma. Man bezeichnet Plasmen als den vierten Aggregatzustand, weil sie einzigartige physikalische Eigenschaften aufweisen, die sie von Festkörpern, Flüssigkeiten und Gasen deutlich unterscheiden. Die Temperaturen und Dichten von Plasmen erstrecken sich über einen extrem weiten Parameterbereich.



Components of Solar Wind:

Mainly protons and electrons
Up to 20% Helium - variable
Highly ionized species

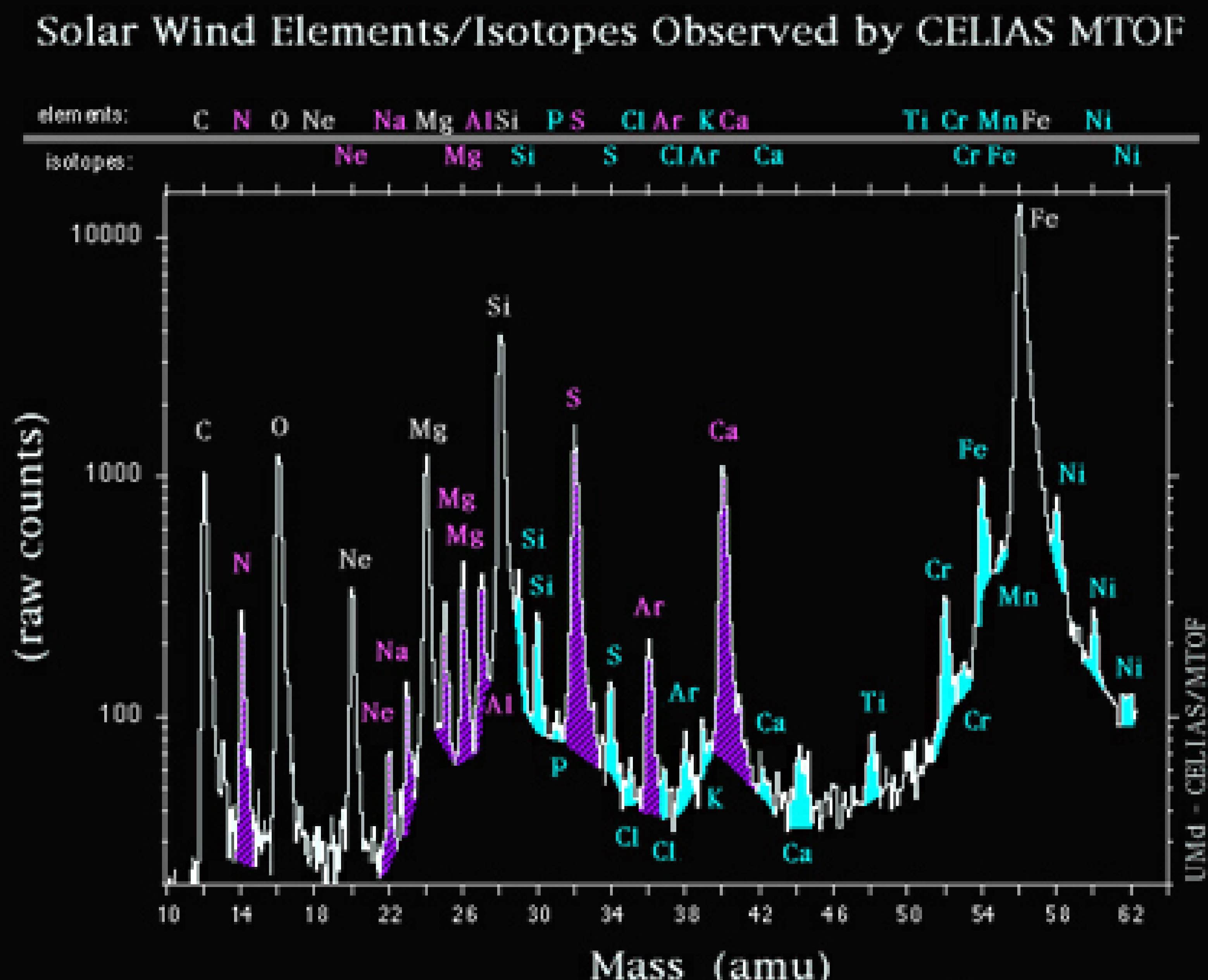
Heavy elements: (> He)

element abundances in the solar wind are similar to those in the solar photosphere

These abundances are the same as the overall solar system

"Cosmic Abundances" or "Solar (photospheric!) Abundances"

Genesis was planned to measure abundances and isotope ratios in solar wind !



ESA SOHO Webpag

Main Components of Solar Wind:

Protons H^+ and electrons e^-

Up to 20% **He^+ - variable**

Plus

Heavy elements: (> He)

Ionisation by collisions with electrons in the corona

collision rates are low in the interplanetary medium

$\Rightarrow$

The abundance of charge states (Fe^{10+}, Fe^{11+}, Fe^{12+}……) of solar wind ions depends on time variation of coronal temperature

(high temperature = high kinetic energy of electrons and ions = frequent collisions = high charge states)

ESA SOHO Webpage

charge

Solar Wind = Cosmic Plasma:

Plasma = hot ionized gas consisting of:
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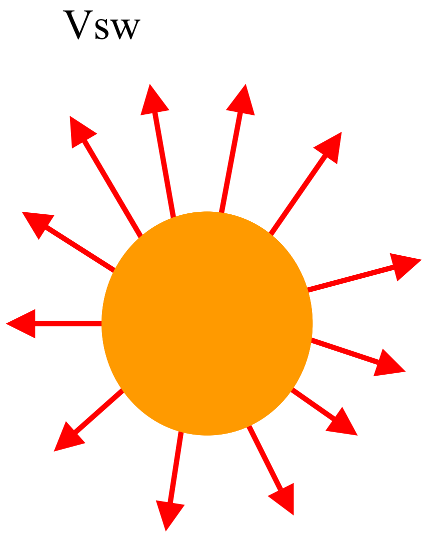
"quasi-neutral": number of positive and negative charges in a larger volume (**Debye Sphere**) equals out

"frozen-in magnetic field": if the plasma is sufficiently thin then it carries the magnetic field with it (described with models of magneto-hydro-dynamics)

⇒Sector structure of the interplanetary magnetic field

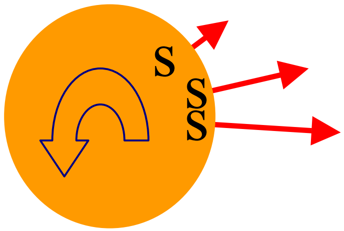
Sector structure of interplanetary magnetic field



Solar Wind Flow radially outward carries magnetic field from surface of sun

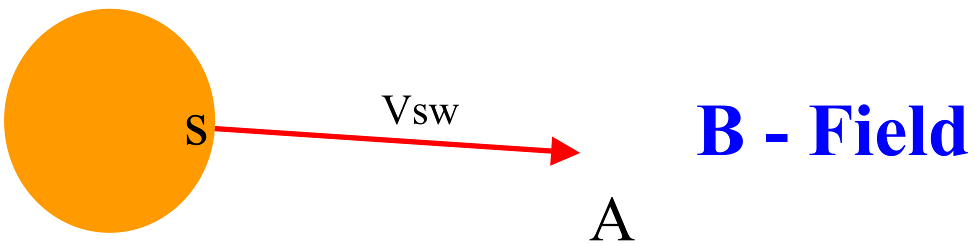
Sector structure of interplanetary magnetic field

Consider solar wind flow from surface element S with magnetic field B !



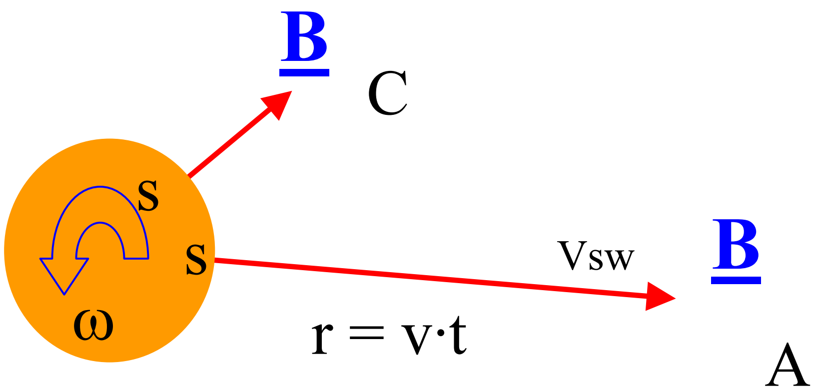
All plasma packages emitted from point S have the same B-Field direction but S moves with rotation of the sun!

Sector structure of interplanetary magnetic field



Solar wind: radially streaming with v ≈ const., carries magnetic field **B' from point S** at solar surface radially **outward to point A**

Sector structure of interplanetary magnetic field

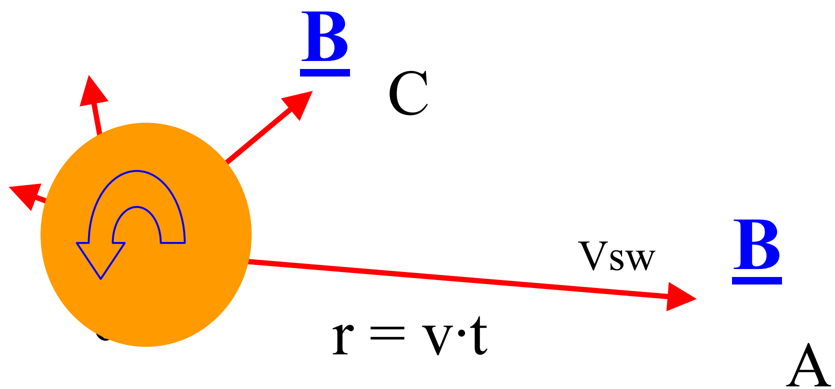


After time t, this plasma "parcel" has moved by $r = v \cdot t$

Rotation of the sun by $\Phi = \omega \cdot t$ so that **point S now emits plasma into direction SC**

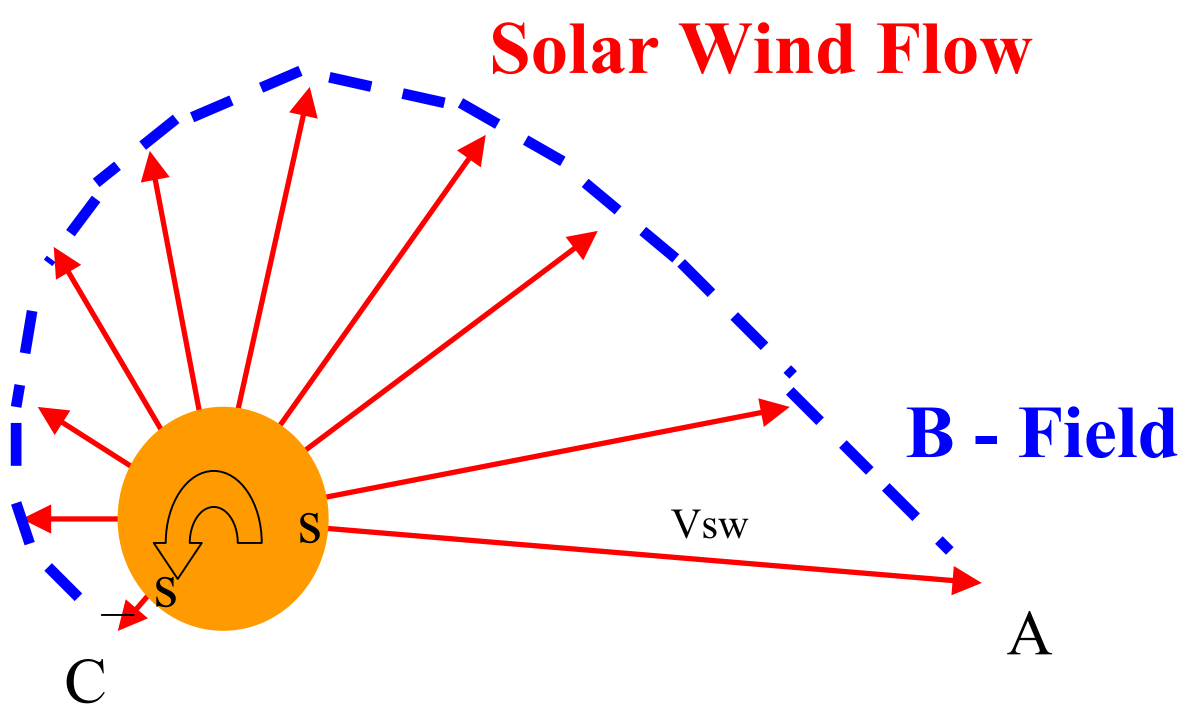
Sector structure of interplanetary magnetic field

$\underline{\mathbf{B}}(C) = \underline{\mathbf{B}}(A) = \underline{\mathbf{B}}(S)$



Points A and C have same magnetic field stemming from same surface element of the Sun. **The are connected through a line described by r = v/ω · Φ (equation for Archimedian Spiral) of all plasma elements that originate from the same surface element of the Sun.**

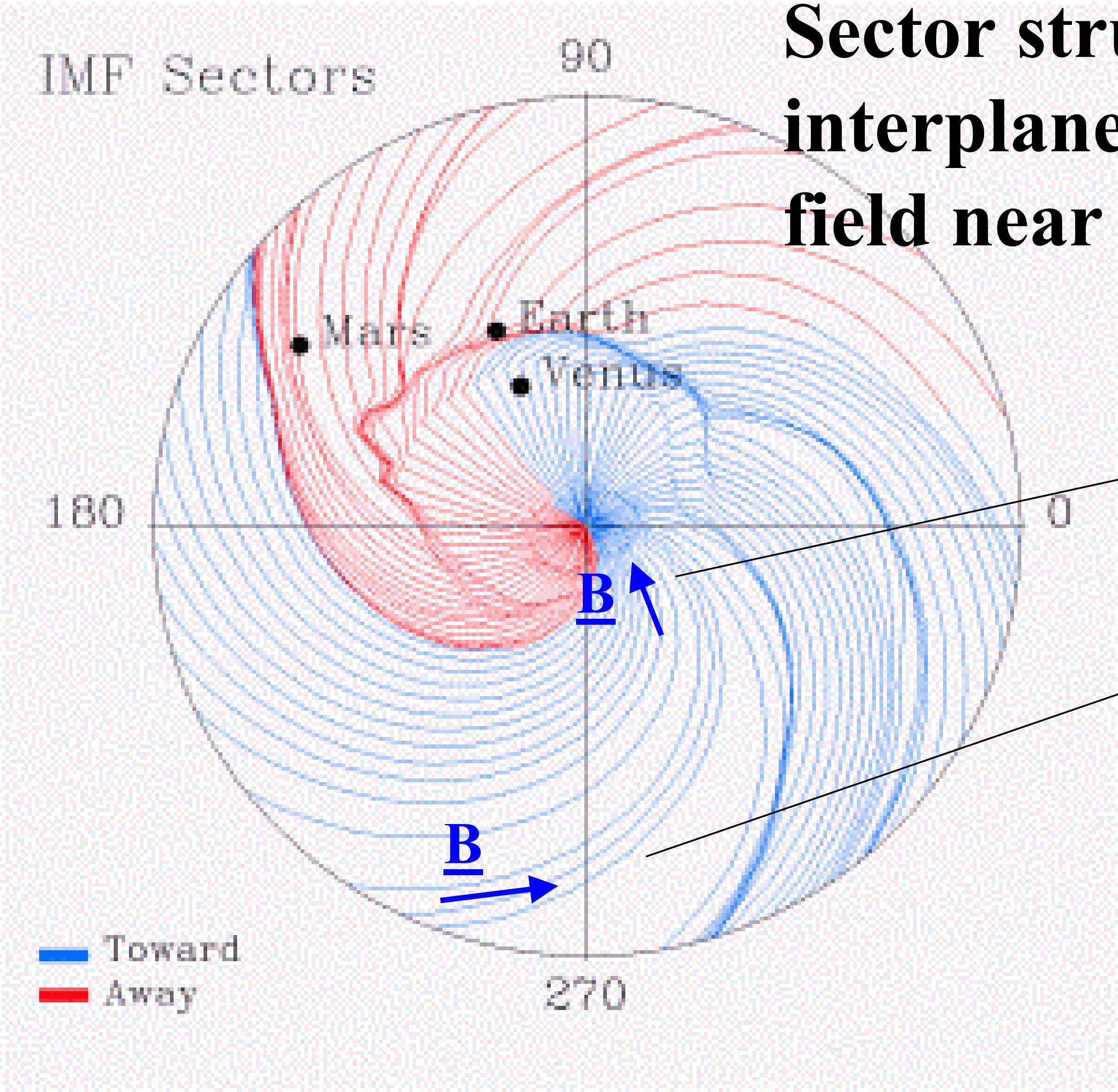
Sector structure of interplanetary magnetic field



The Archimedian Spiral (connecting line described by $r = v/\omega \cdot \Phi$) moves radially away from the Sun.

View from solar pole on structure
near ecliptic ≈ solar equatorial plane

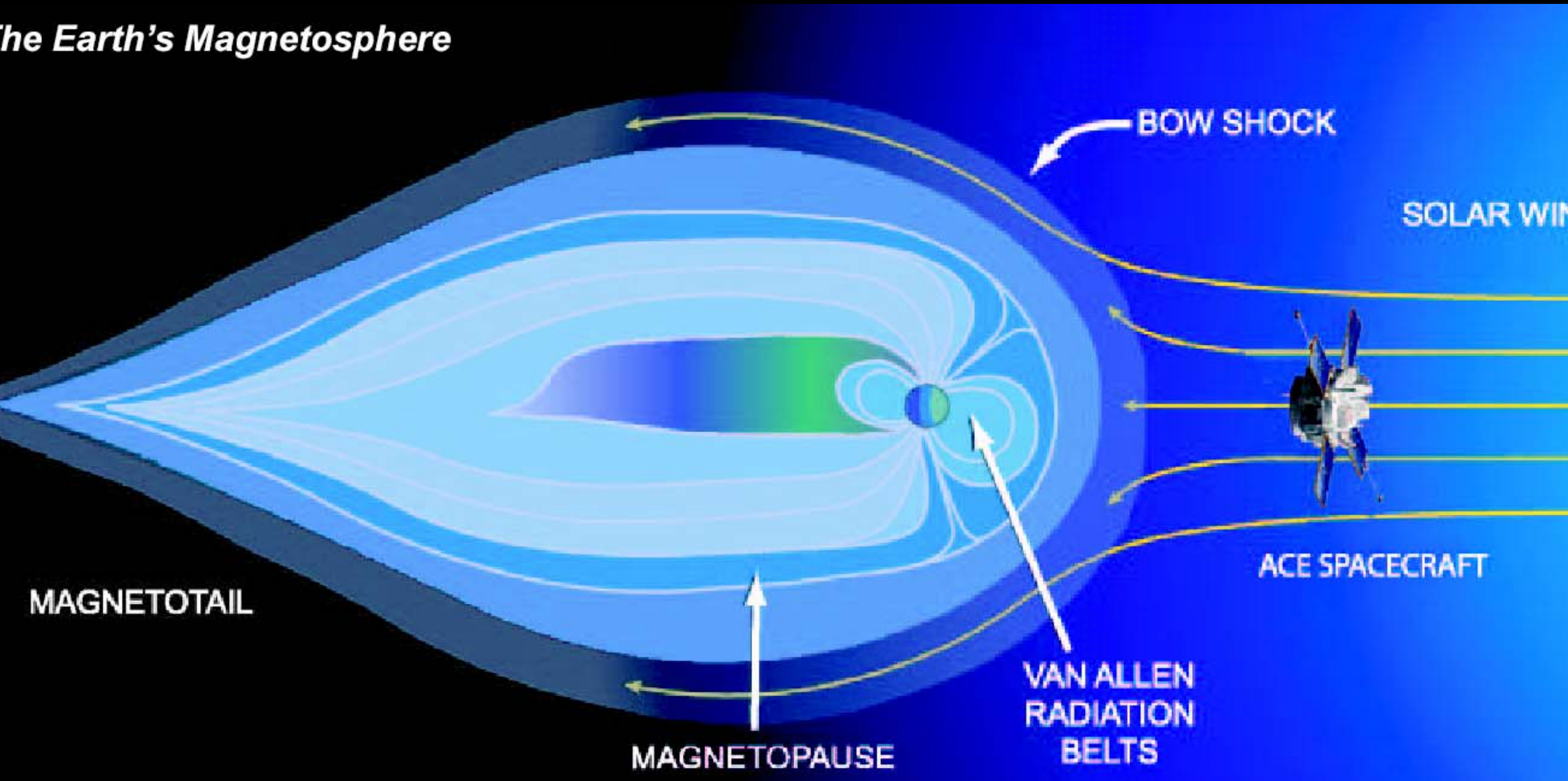
Sector structure of the interplanetary magnetic field near ecliptic



Near the Sun
$\underline{B} \approx B_r$

large distance:
$\underline{B} \approx B_\Phi$

Magnetosphere of the Earth: Earth magnetic field shields us against solar wind (compare to two fluids…)



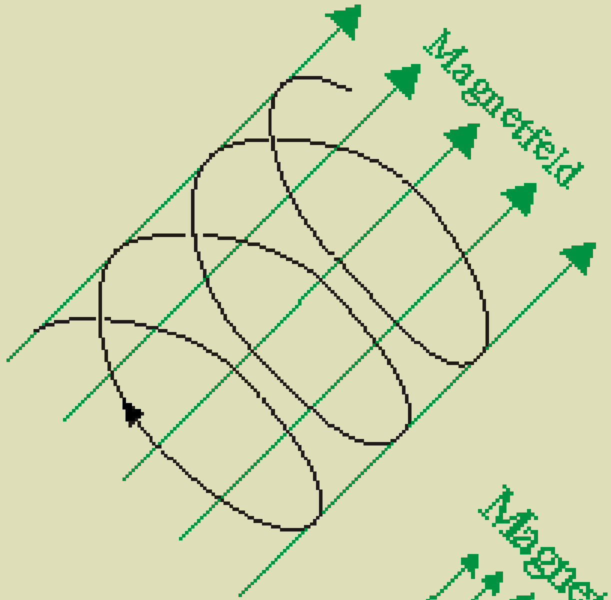
Space weather !

Van-Allen radiation belts:
Example for charged particle in B-field
= “magnetic bottle”

NASA ACE Webpage

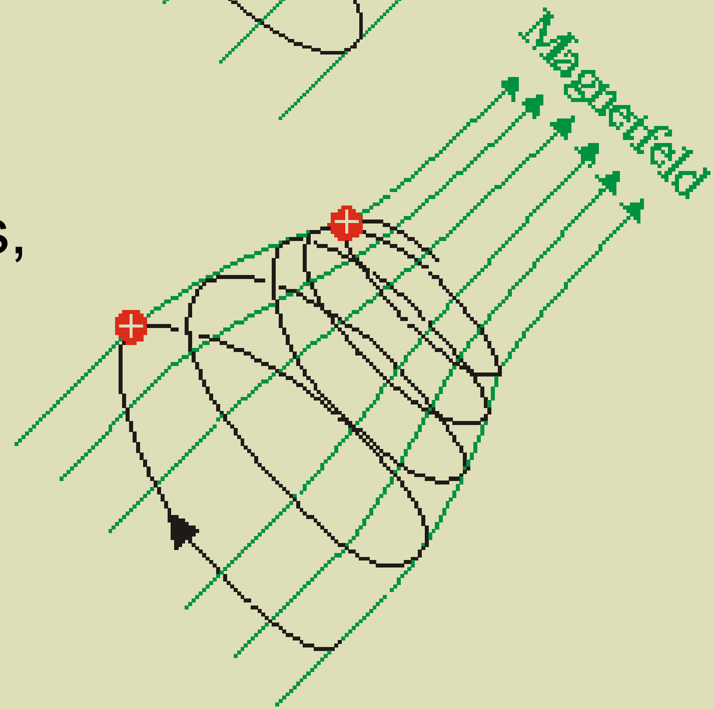
Magnetic Bottle

Charged particles that encounter non-parallel the field lines of a homogeneous magnetic field move in a cork-screw shaped orbit.



Lorentz force $\underline{F} = q \cdot \underline{v} \times \underline{B}$

If the magnetic field is heterogeneous, then the radius of the cork-screw shrinks until the particles turns its direction of motion



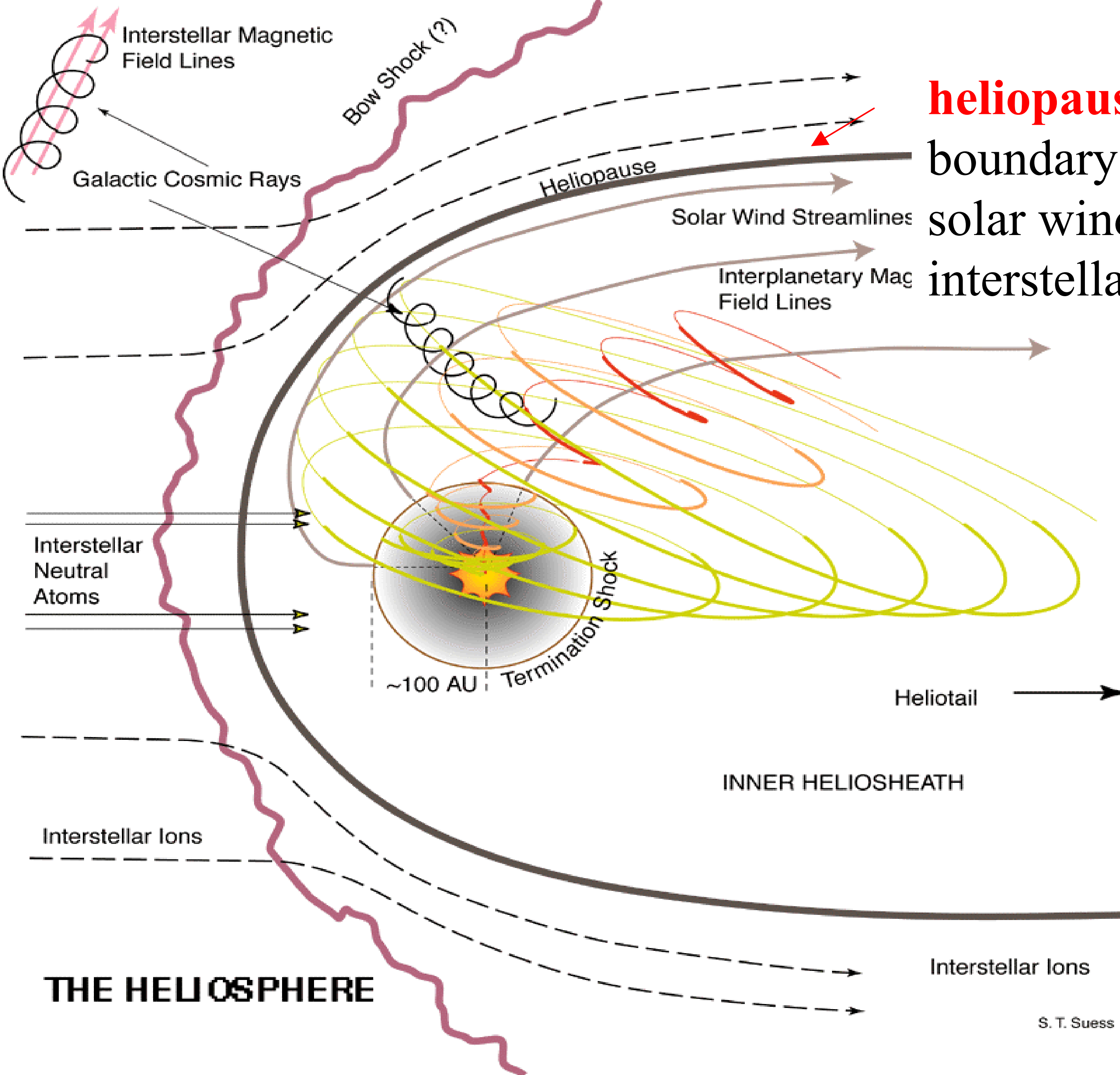
<u>Reflection of charged particles at heterogeneities in the B-field</u>

Reflection = Acceleration

The Heliosphere

- Region around the Sun that is filled with solar wind plasma
- Shielded against interstellar medium

heliopause boundary between solar wind and interstellar plasma



Energetic Particles in the Interplanetary Medium

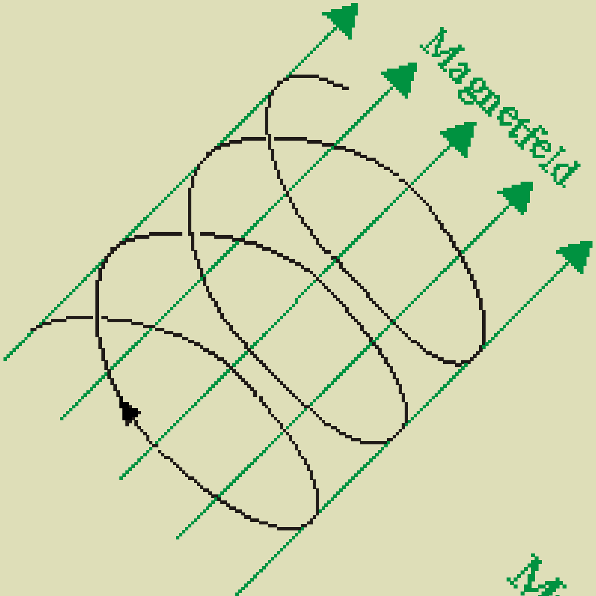
Generation of energetic particles

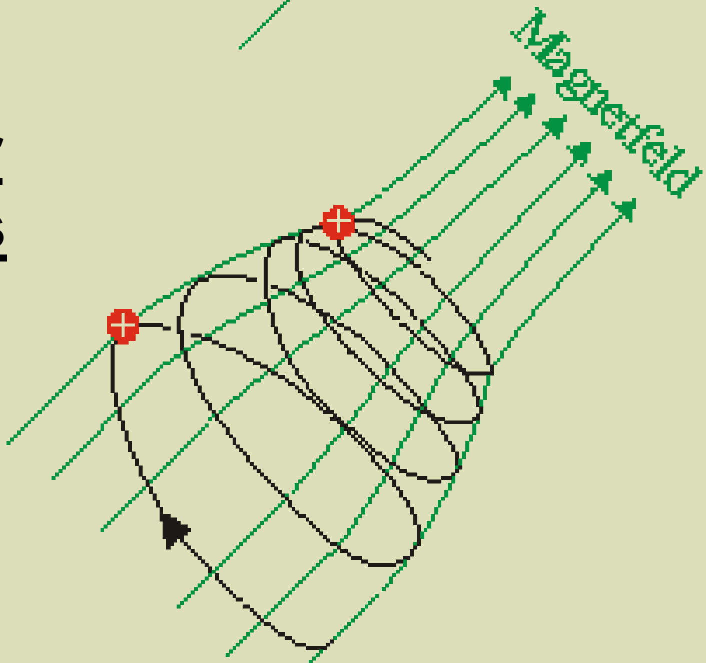
Magnetic Bottle

Lorentz force $\underline{F} = q \cdot \underline{v} \times \underline{B}$

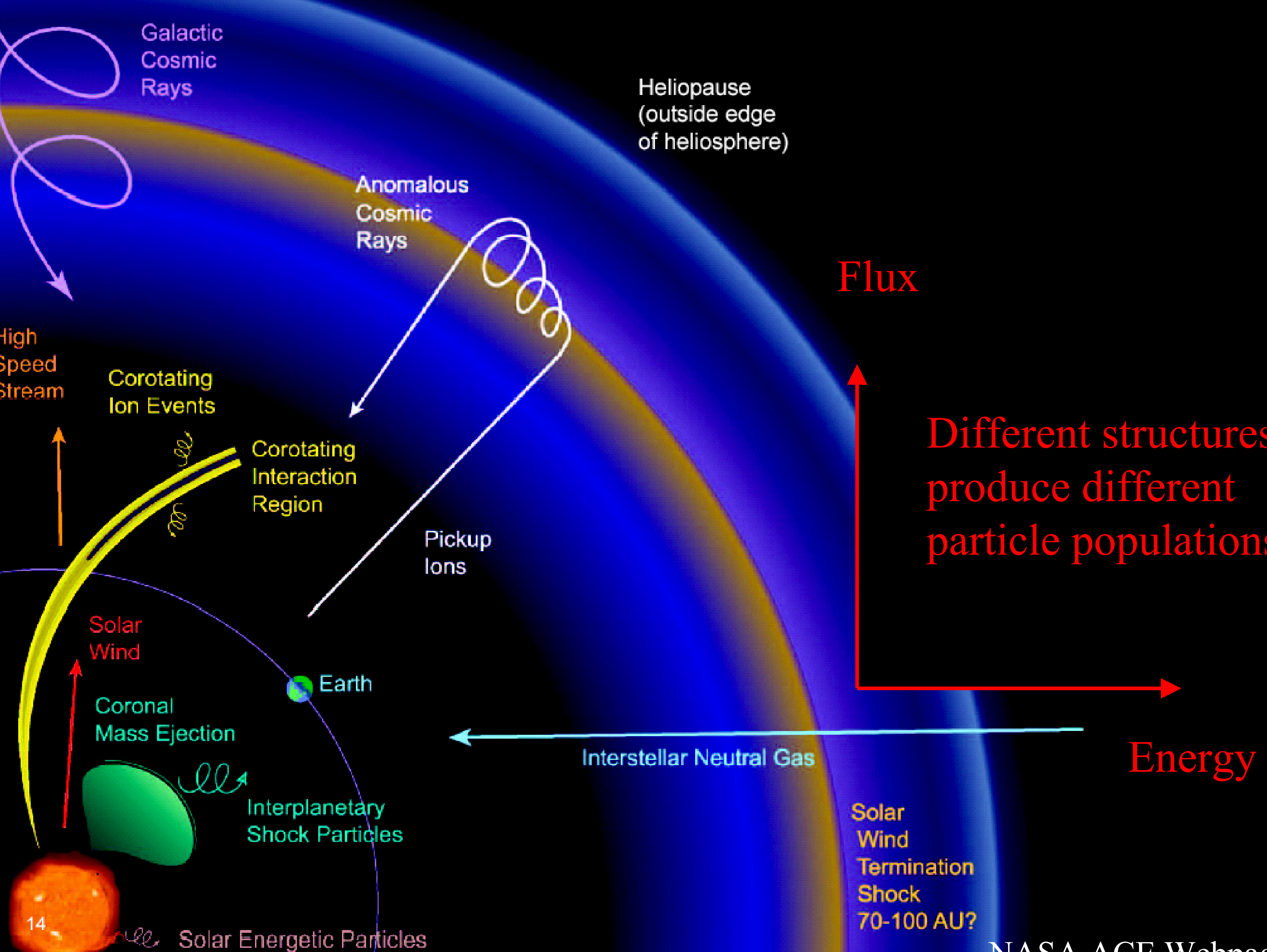
<u>Reflection of charged particles at heterogeneities in the B-field</u>

<u>n the interstellar medium and solar ystem - acceleration of anomalous nd galactic cosmic rays</u>

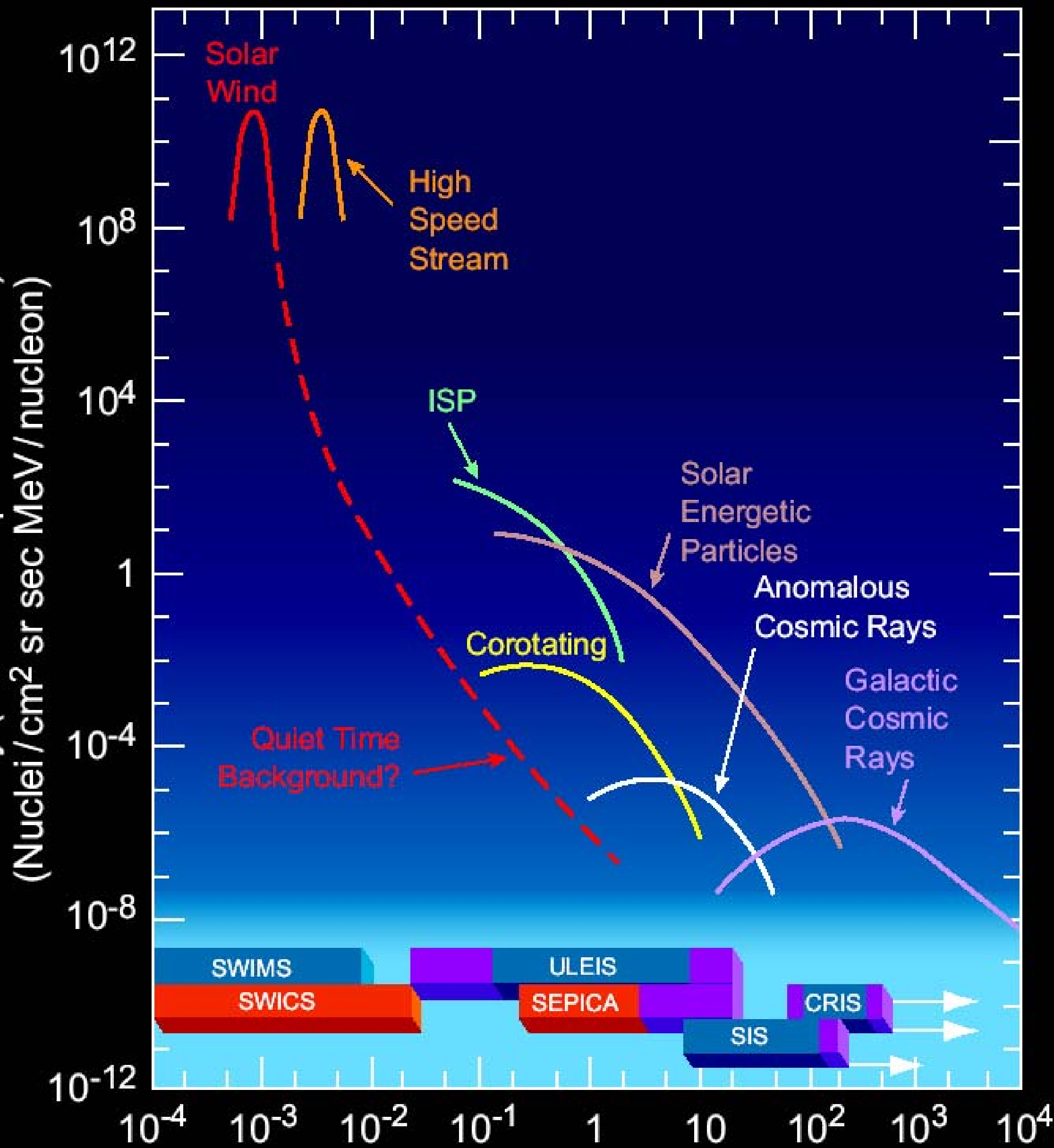




Particles are accelerated at he plasma boundary layers


Galactic
Cosmic
Rays
Heliopause
(outside edge
of heliosphere)
Anomalous
Cosmic
Rays
Flux
High
Speed
Stream
Corotating
Ion Events
Different structures
produce different
particle populations
Corotating
Interaction
Region
Pickup
Ions
Solar
Wind
Earth
Coronal
Mass Ejection
Interstellar Neutral Gas
Energy
Interplanetary
Shock Particles
Solar
Wind
Termination
Shock
70-100 AU?
Solar Energetic Particles

Typical Energy Spectra



Energetic particles in the interplanetary medium (measured during NASA ACE Mission)

NASA ACE Webpage

Interplanetary medium components:

Solar wind plasma streaming outward
which carries magnetic field

Energetic particles in random directions

Solar **photons**

Few **neutral atoms**

From Dinner Discussion with Yuichi Nakagami and Katsuyuki Noguchi I learnt a Japanase Saying:

... Translated „Gathering Dust makes a big mountain“

CHIRI MO TSUMOREBA YAMATO NARU.

„Many a little makes a mickle“

Negative/Positive:

Accumulation of small efforts leads to large progress !

Small Bodies:

Asteroids (up to 1000 km)*

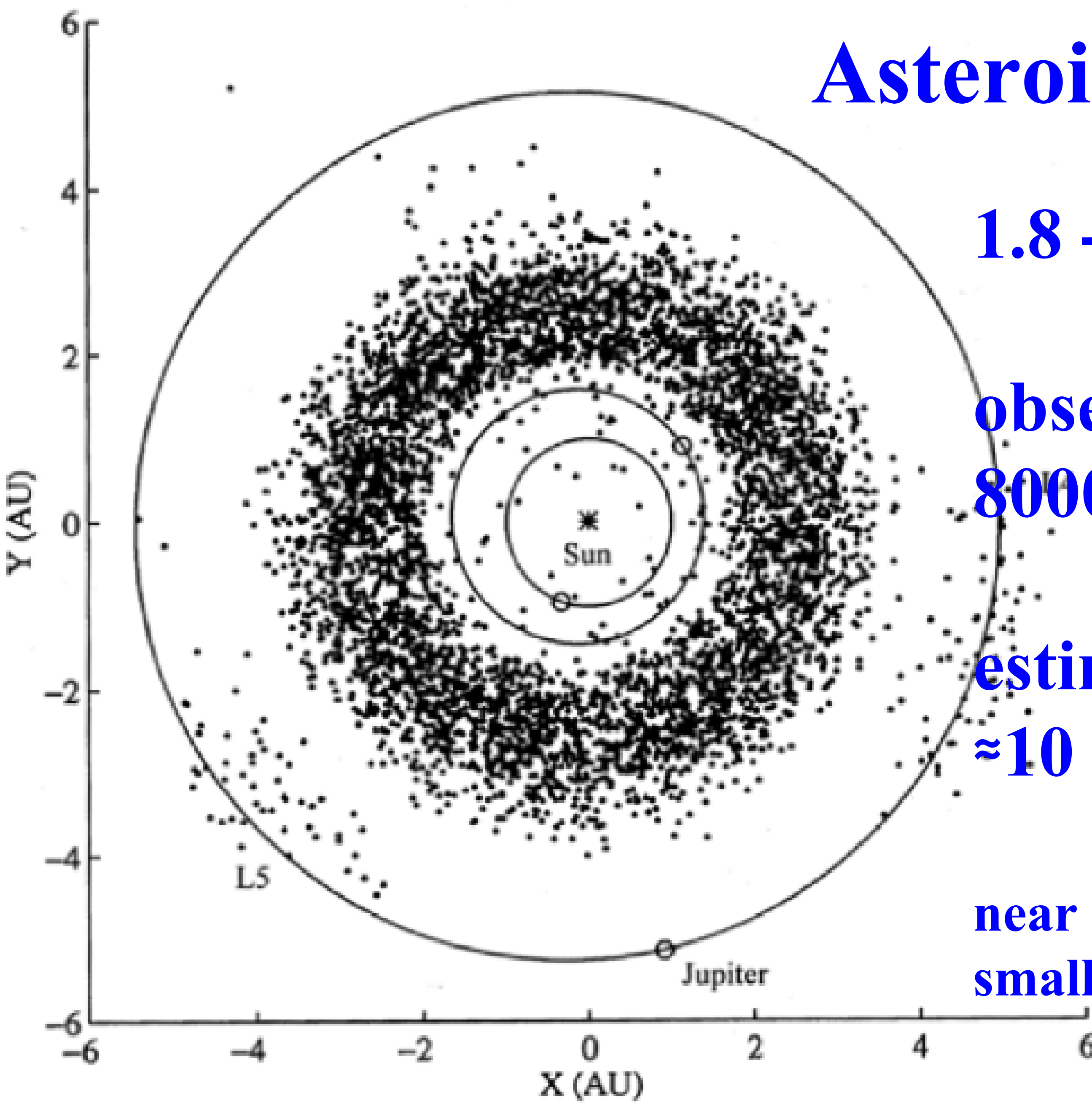
Comets (up to 10 km)

Meteoroids (mm to m)

Micrometeoroids (= dust < mm)

* Direct detection

Asteroid Ida with moon Dacty



Asteroids:

1.8 - 5.2 AU

observed:
8000 Objects

estimated:
≈10 000 Objects

near ecliptic orbits
small eccentricity orbi

Comets

Classification of Comets by orbit

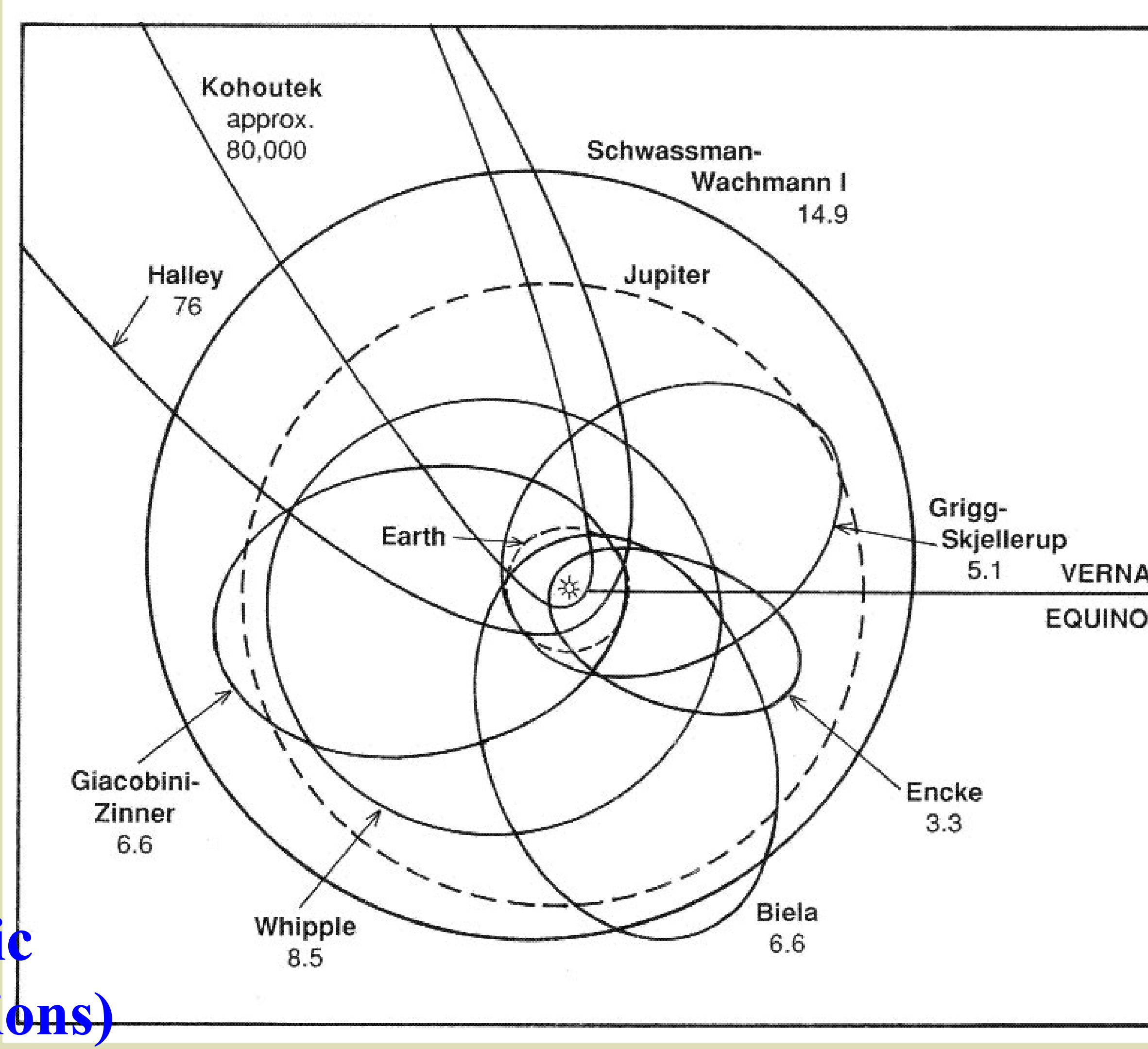
hort-period comets:

elliptical orbits
close to ecliptic
(low inclination)

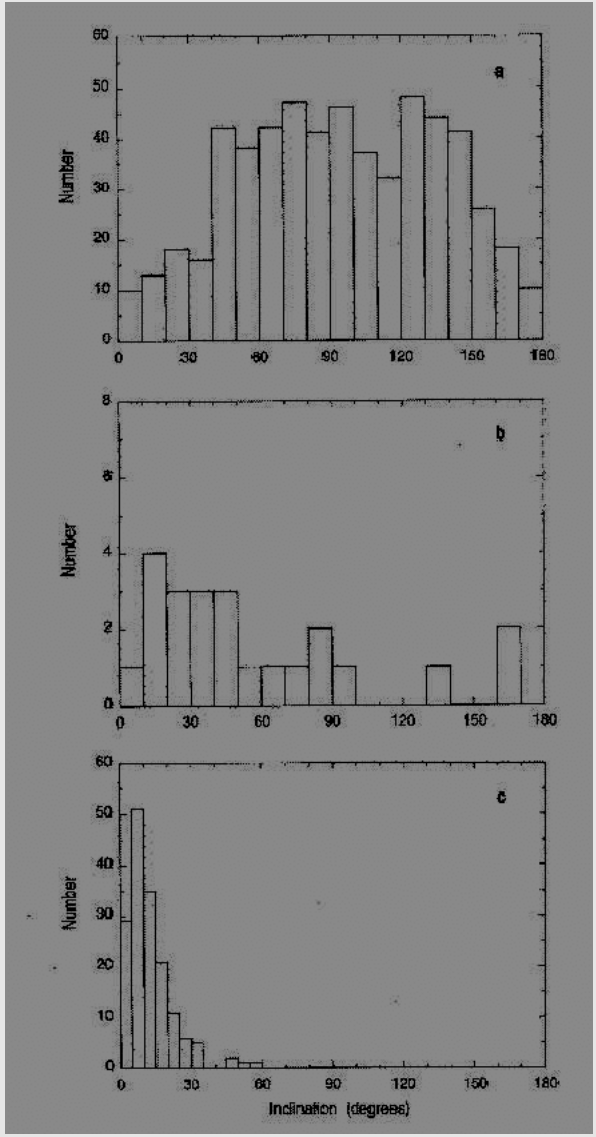
upiter family or
Halley-type comets

Long-period comets:

hyperbolic orbits
in & out of ecliptic
(random inclinations)



Orbits of Comets



Orbital Period, P

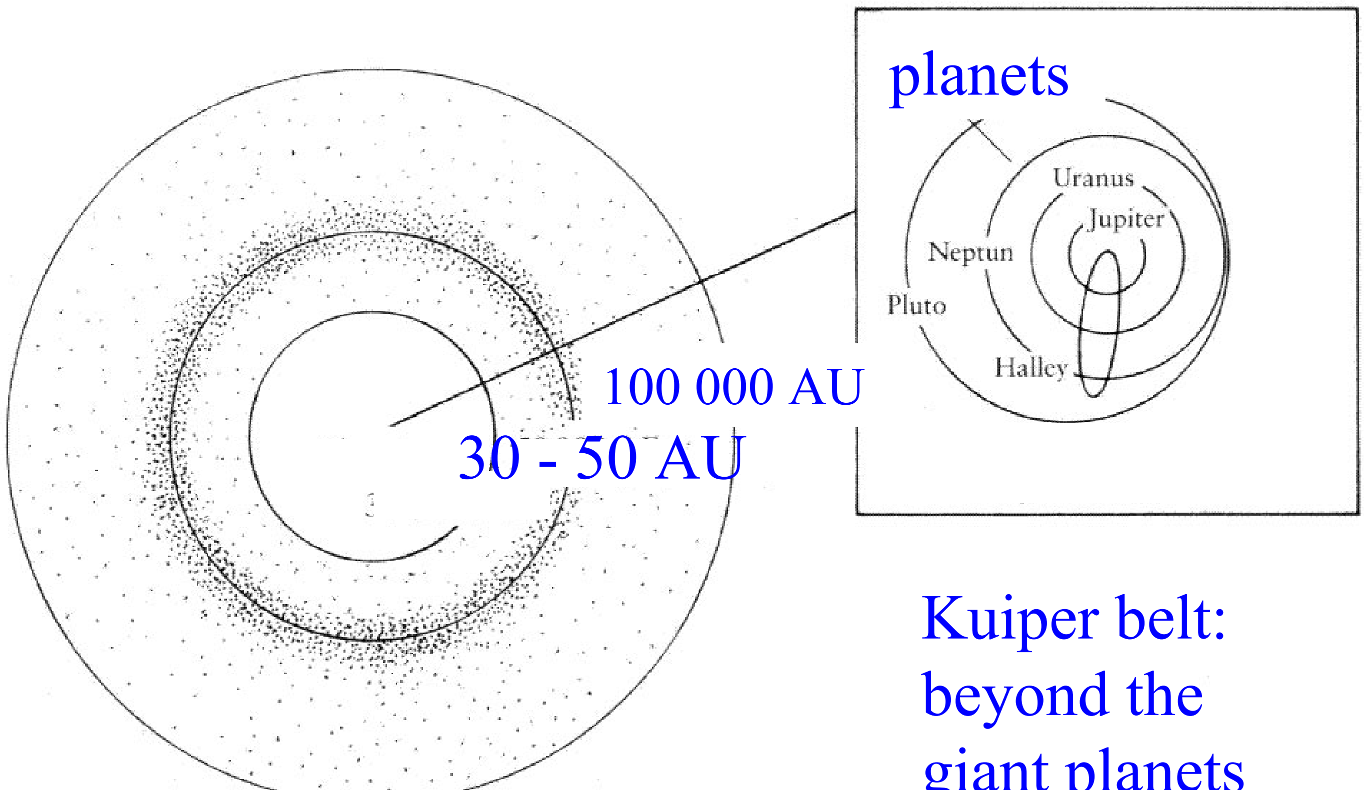
long-period comets
P > 200 yrs

Halley-type comets
20 yrs < P < 200 yrs

short-period comets
P < 20 yrs

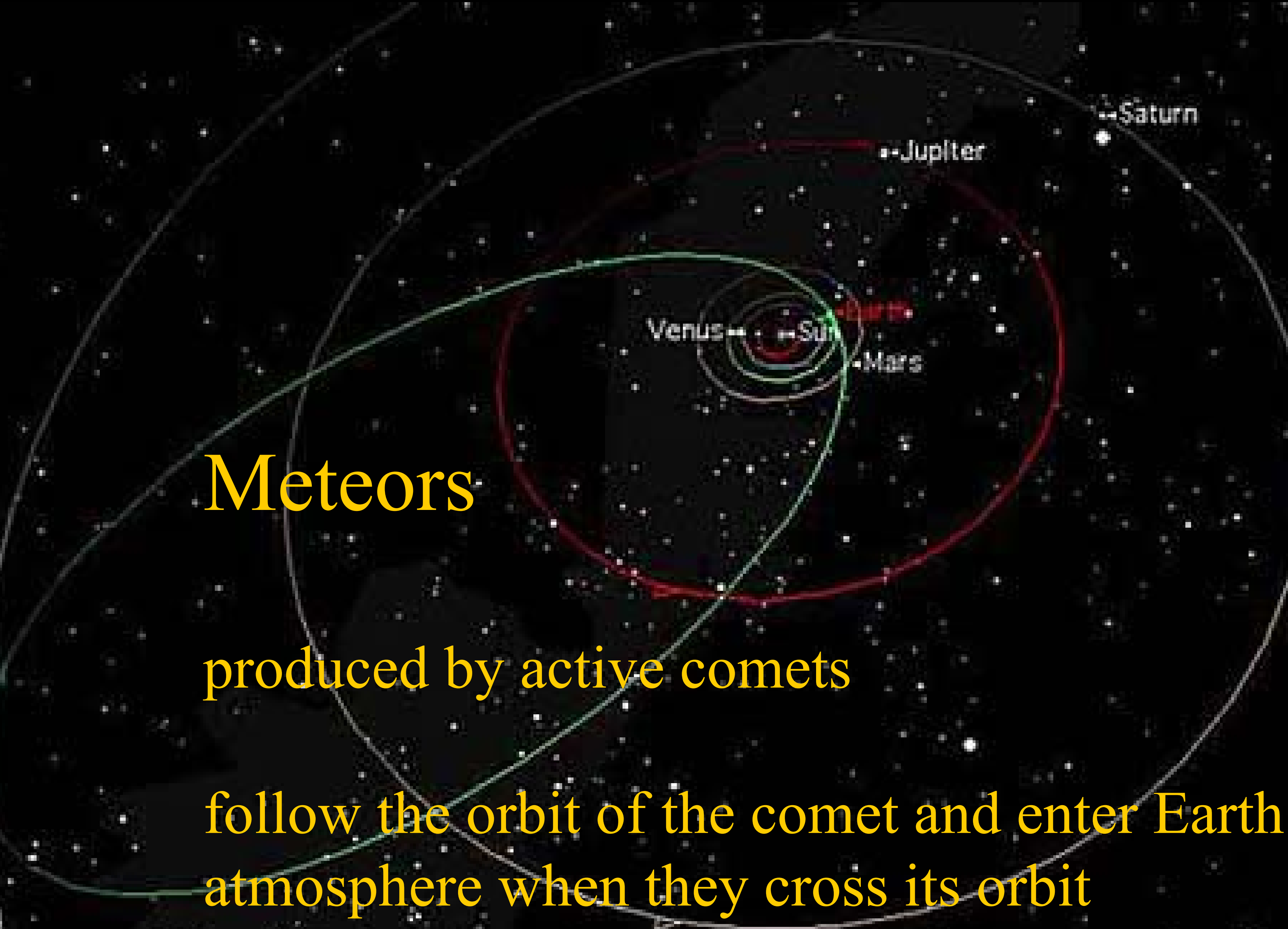
inclinations, i

Two reservoirs of Comets in the solar system - first postulated from the orbits of comets



Oort cloud > 10 000 AU

Kuiper belt:
beyond the
giant planets
About 30 - 50 AU



Meteors

produced by active comets

follow the orbit of the comet and enter Earth atmosphere when they cross its orbit

Size distribution of objects falling onto Earth

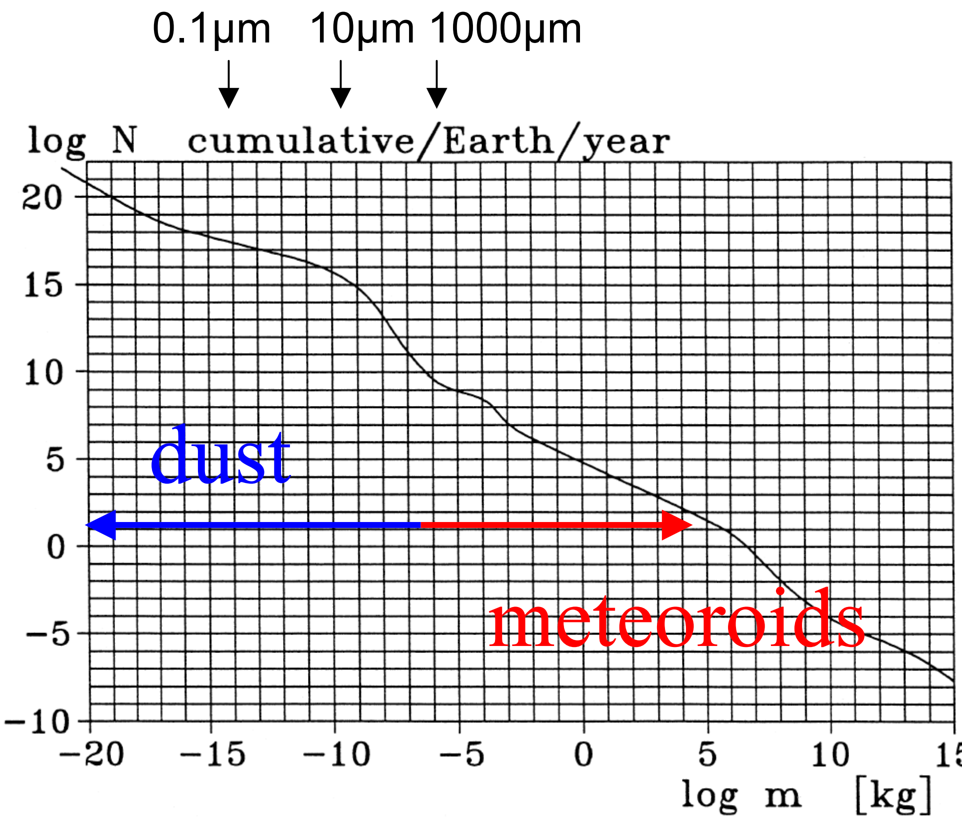


Figure 25. Logarithm (base 10) of the cumulative number, N, of interplanetary bodies with mass equal or greater than m coming to the entire Earth's surface per year is plotted against logarithm of the mass m.

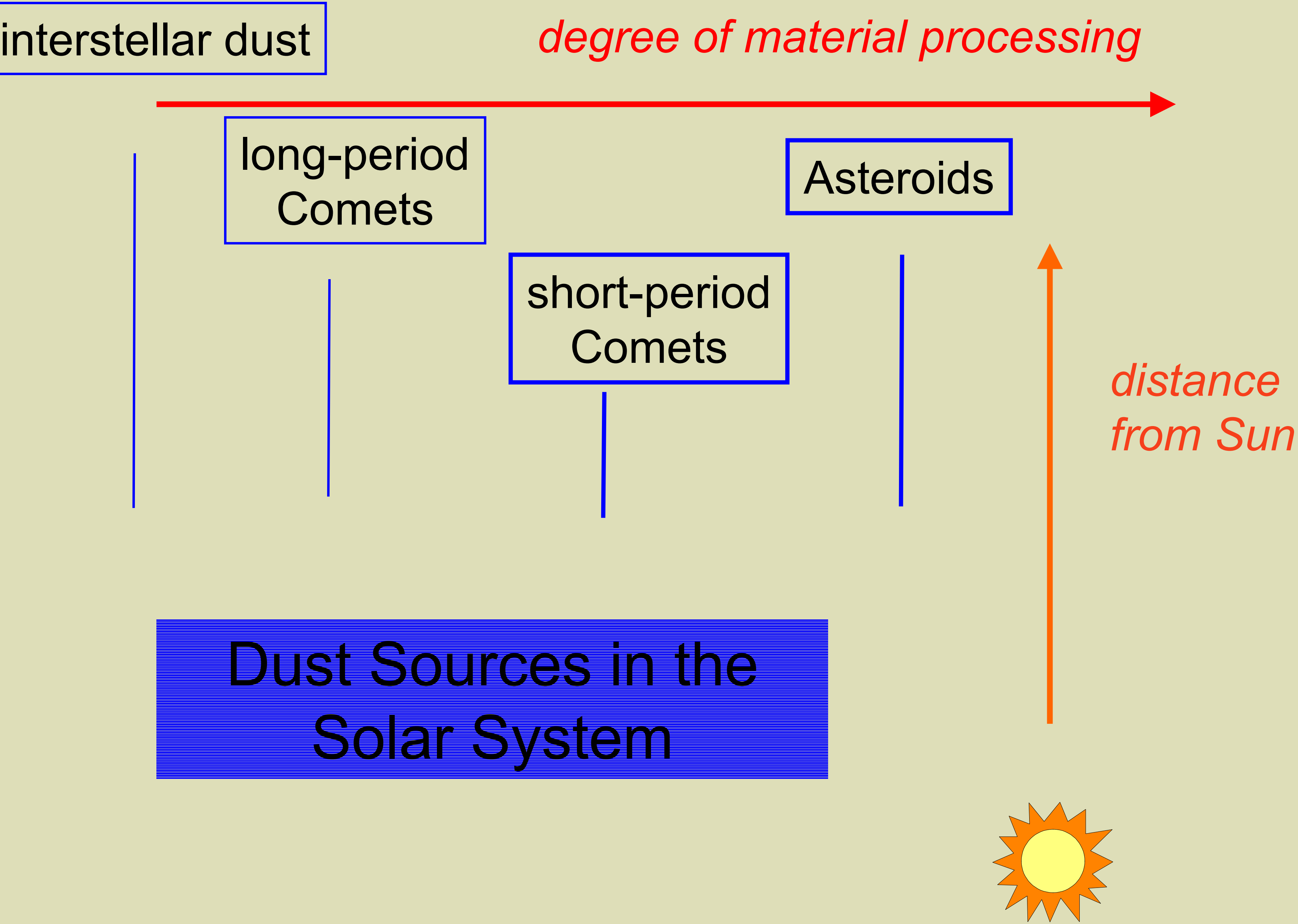
Ceplecha et al. Space Sci. Rev. 1998

Dust Production:

Ejection from comet

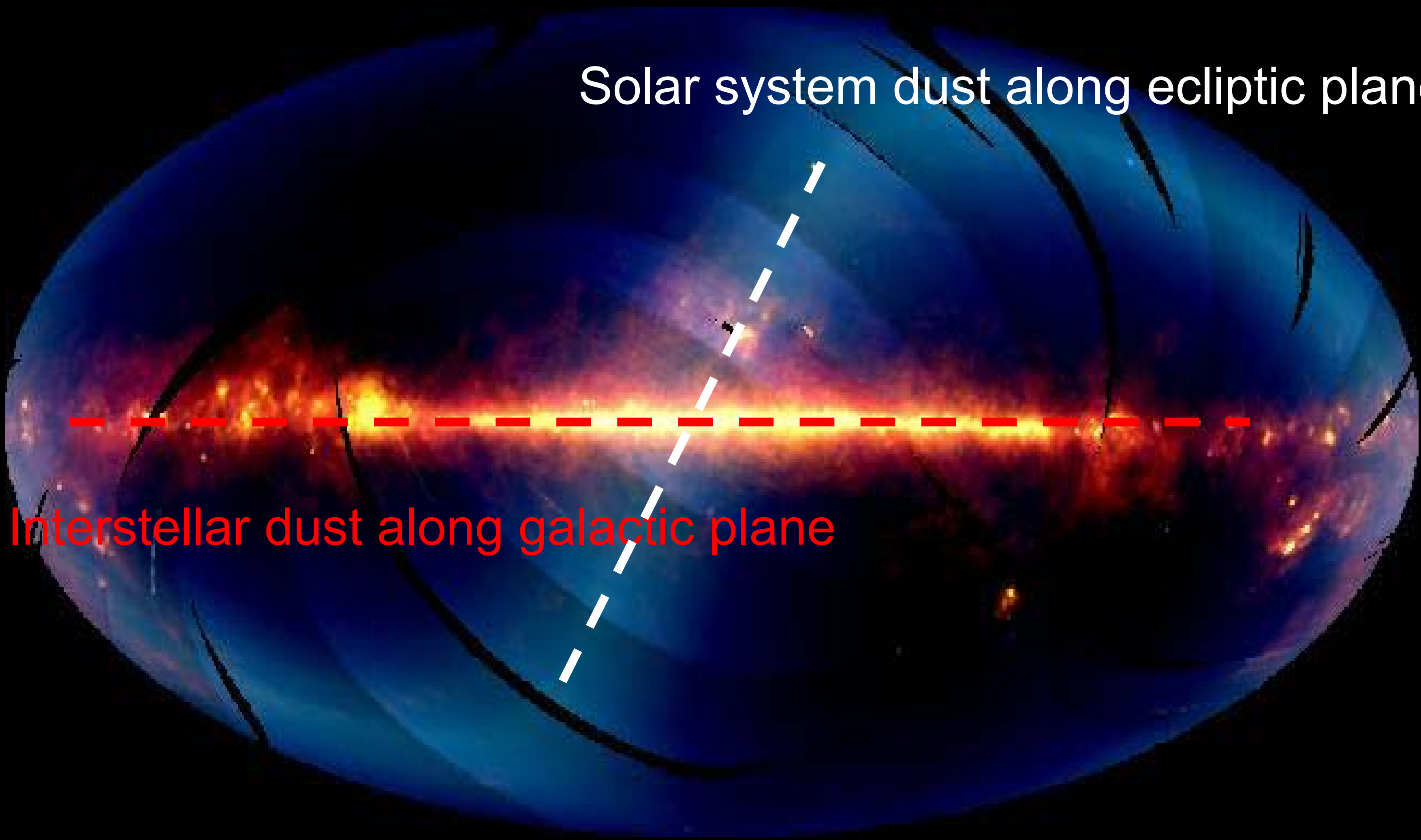
Fragmentation of asteroids & meteroic

Continuous size spectrum!


interstellar dust
degree of material processing
long-period Comets
Asteroids
short-period Comets
distance from Sun
Dust Sources in the Solar System

How do we observe dust ?

COBE image of the IR sky

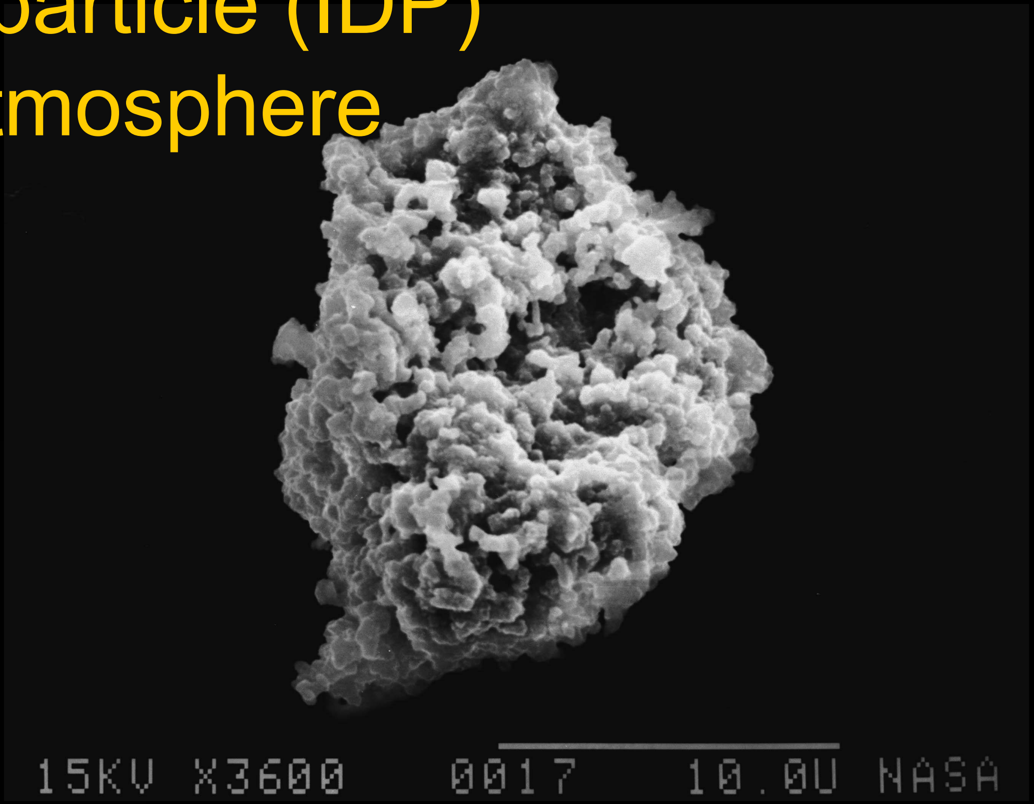


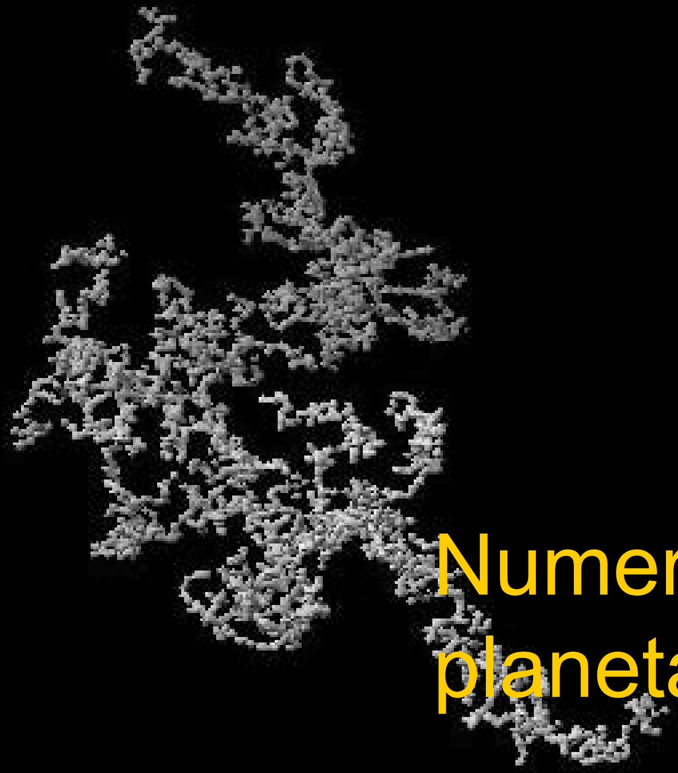
Zodiacal light:

Scattering of sun-light at small dust particles distributed in the solar system and concentrated tc the ecliptic plane

See Prof. Hong's Seminar today

Interplanetary dust particle (IDP) collected in Earth atmosphere





Numerical simulations of inter-planetary dust: aggregate particles

Meteors

brightness seen when particles vaporize in atmosphere

Meteorites

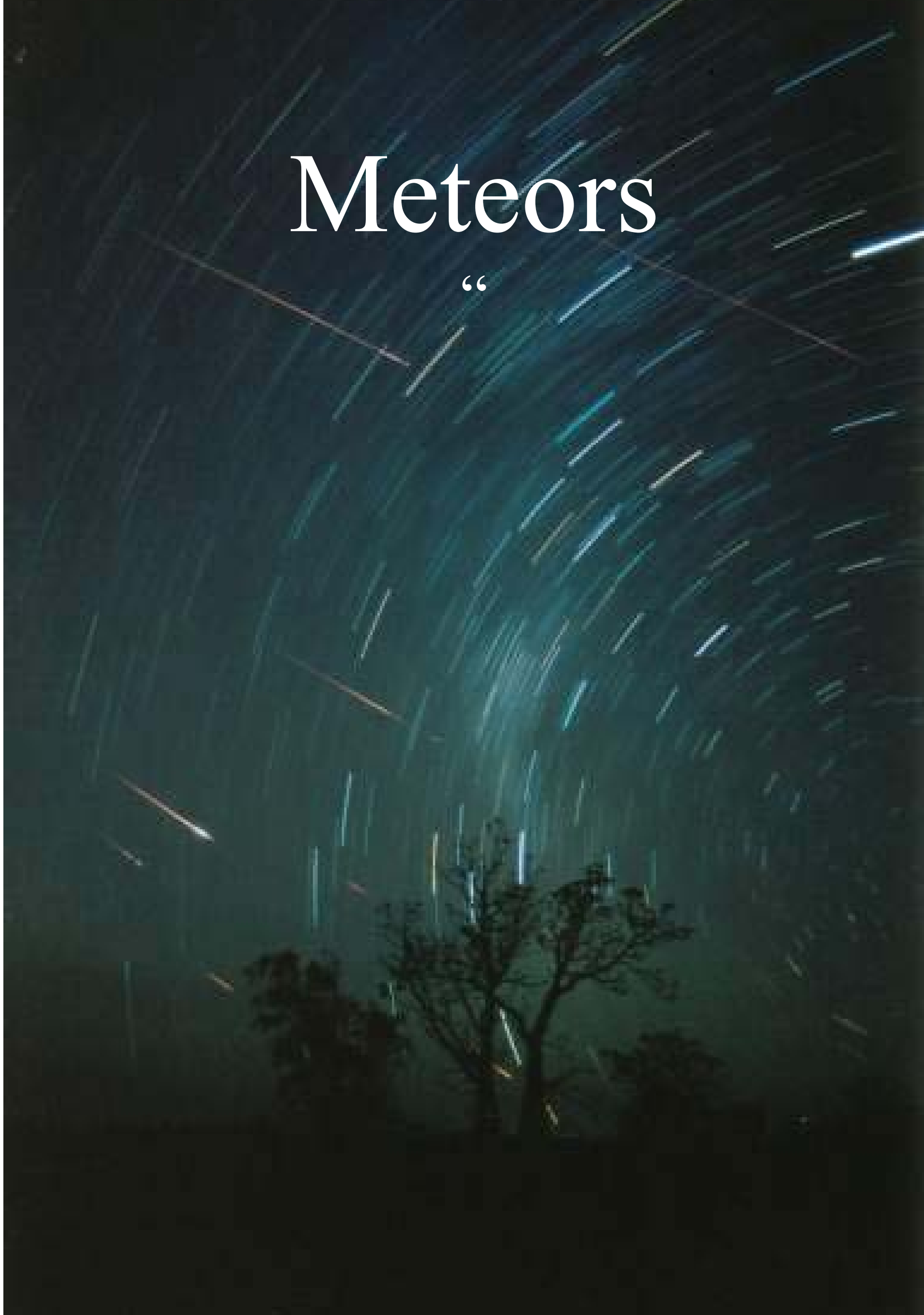
samples collected on the ground

Meteoroides

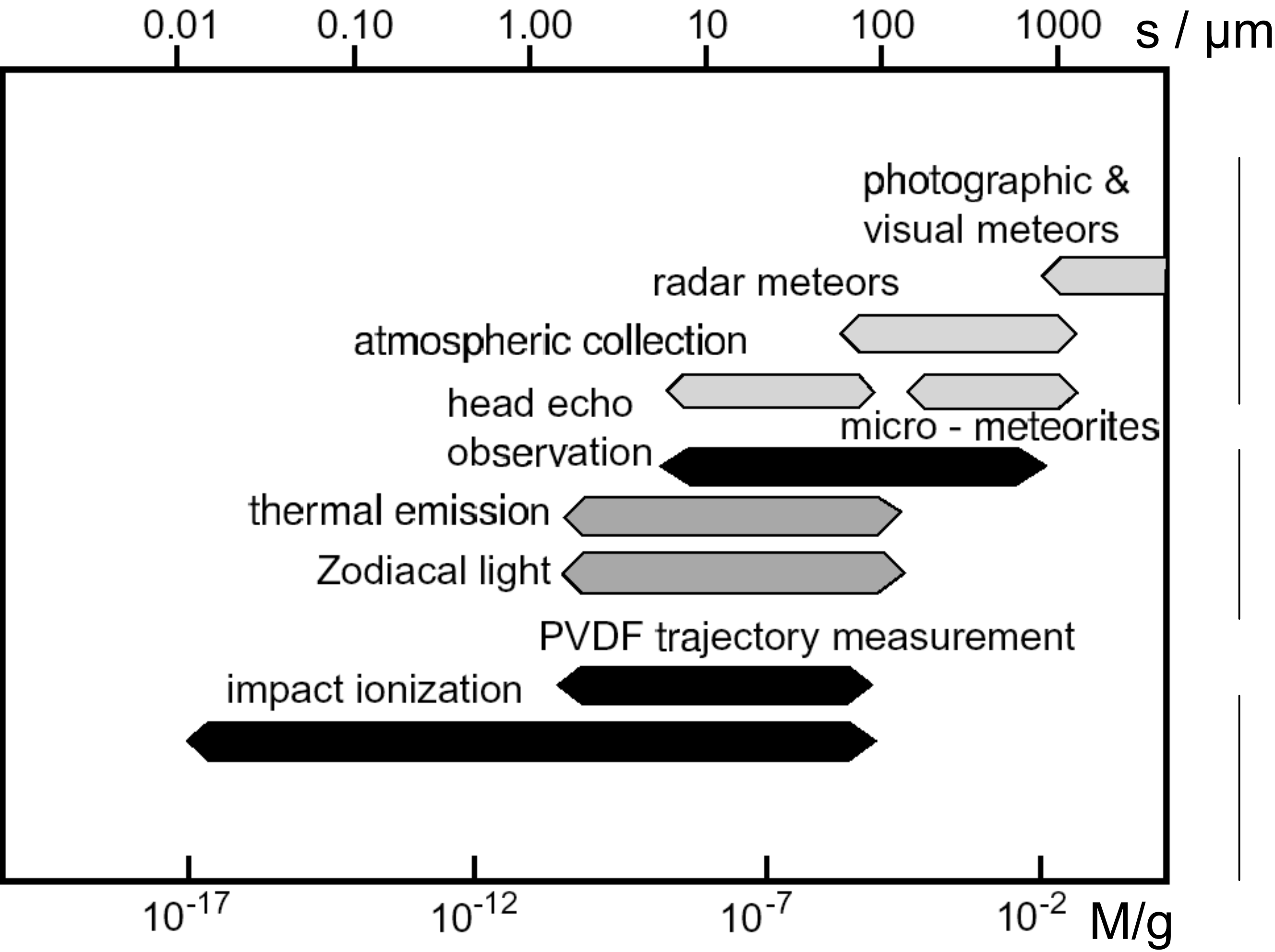
particles in space

Dust

small meteoroids



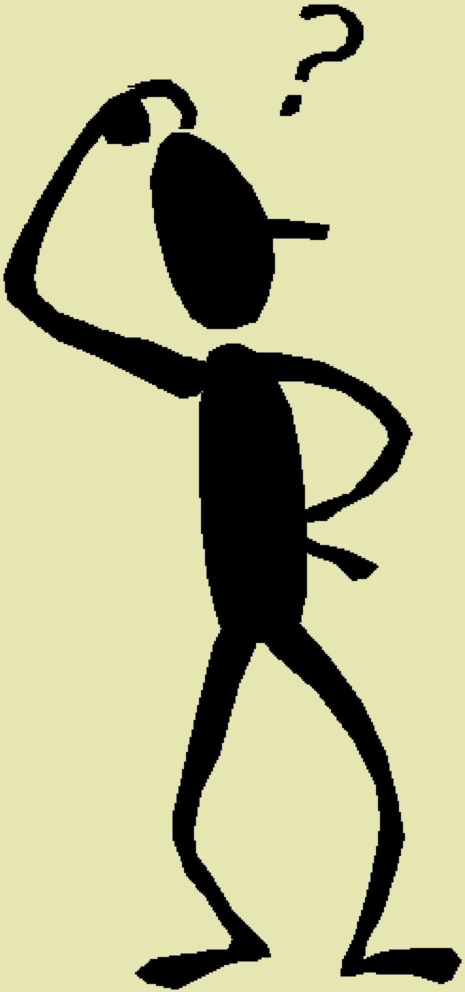
measurement techniques:



detection of near Earth particles

average propertie
& distribution

local detection in
space



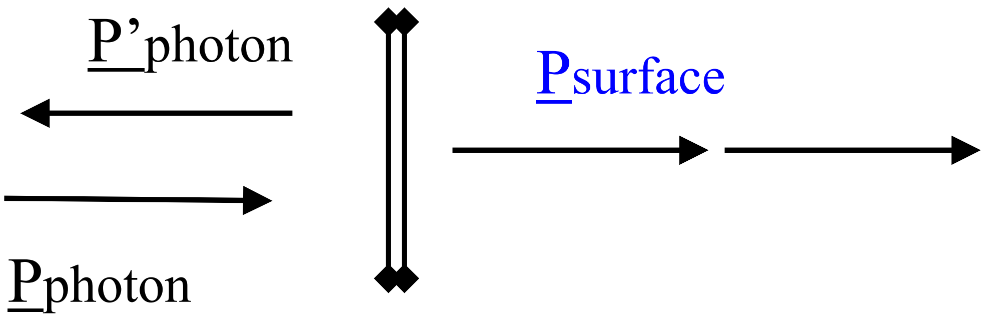
Questions ?

,,,,,,

Dust interactions

Radiation pressure force:

Reflecting surface

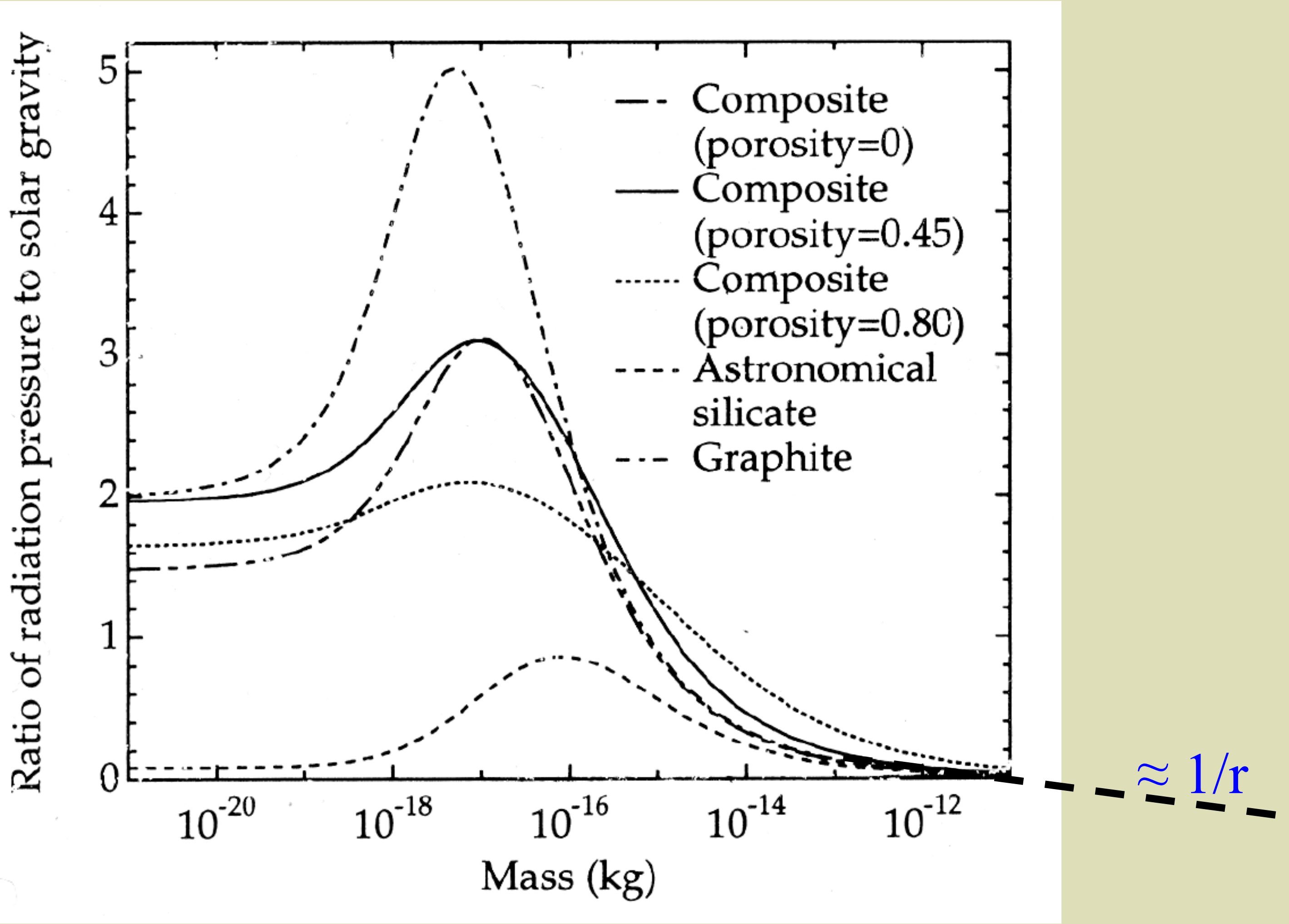


Momentum transfer from solar radiation

approximation: (s particle size, r distance from sun)

F_{rad}	$\approx$	$\pi\, s^2 \bullet 1/r^2$	radiation pressure force
F_{grav}	$\approx$	$\pi\, s^3 \bullet 1/r^2$	gravitational force
ß	$=$	$F_{rad}/F_{gra} \approx 1/s$	ratio independent of r

Consider scattering properties for small grains:

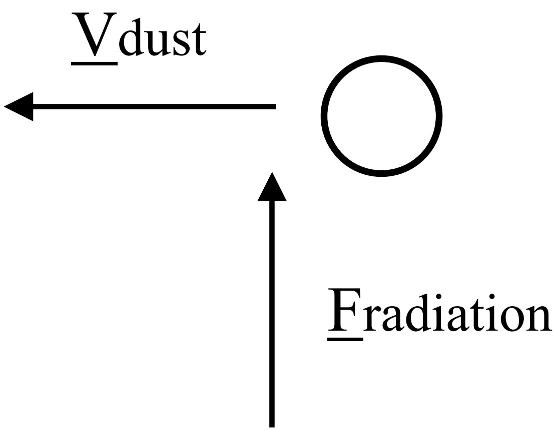


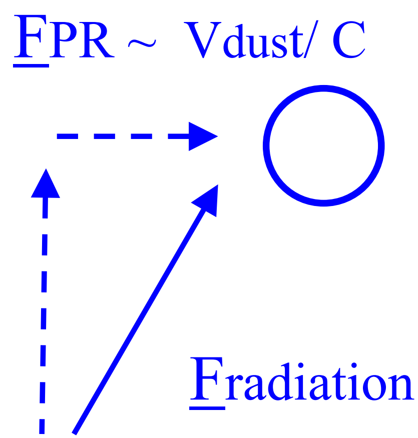
Calculated values $ß = F_{rad}/F_{grav}$ (Mann&Kimura 2000)

Poynting Robertson Effect:

Dust in circular orbit about the sun

Force in frame of moving particle:





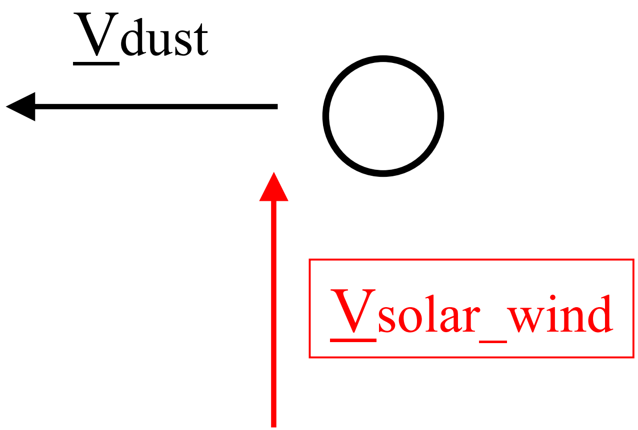
Solar **radiation pressure force** perpendicular to orbital motion

Tangential component of radiation pressure causes loss of orbital energy and angular momentum

Particles drift towards the sun

Plasma / Pseudo Poynting Robertson Effect:

Dust in circular orbit about the sun

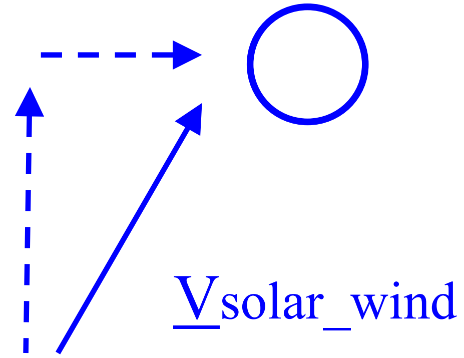


Momentum transfer from impinging solar wind particles

(Recent detailed study for irregular grains by Tetsunori Minato)

Force in frame of moving particle:

FPPR ~ Vdust/ Vsolar_wind



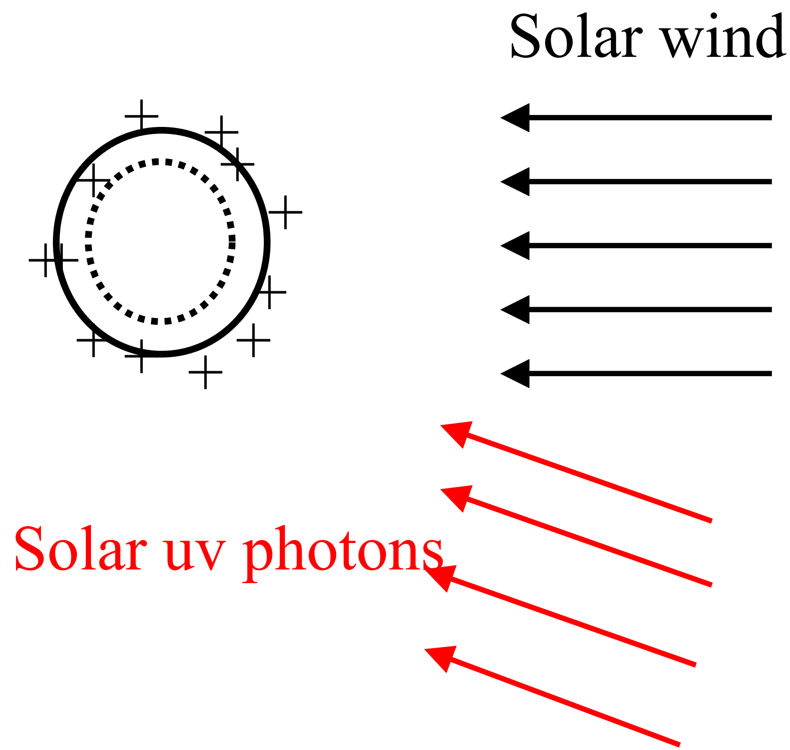
Momentum transfer small compared to radiation pressure but tangential component comparable

Drift towards the sun varies with solar wind conditions

(Fahr et al. 1985, Banaszkiewicz et al. 1993)

Charging of dust particles

Charging by Photo- and electron impact ionization depends on uv flux and parameters of surrounding plasma



Dust in interplanetary medium:

surface potential of ≈ +5volts

equilibrium charge state (≠ magnetospheres)

With Q $\approx \pi s^2$ and M $\approx \pi s^3$

Q/M $\approx$ 1/s --->

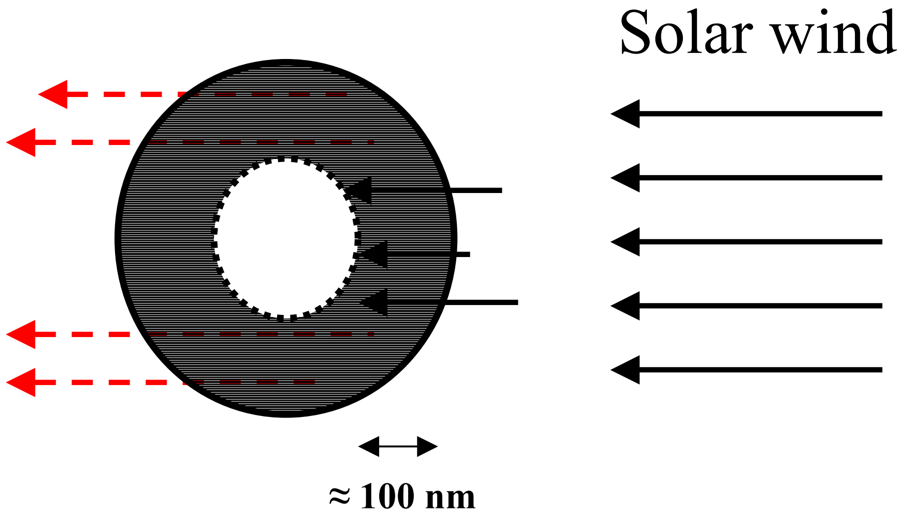
Small grains are deflected by Lorentz force in B-field

Dust interaction with solar wind - Large grains -

Few solar wind particles pass the grains with energy loss

1) **Implantation**

solar wind particles stick in dust surface layer of ≈ 100 nm

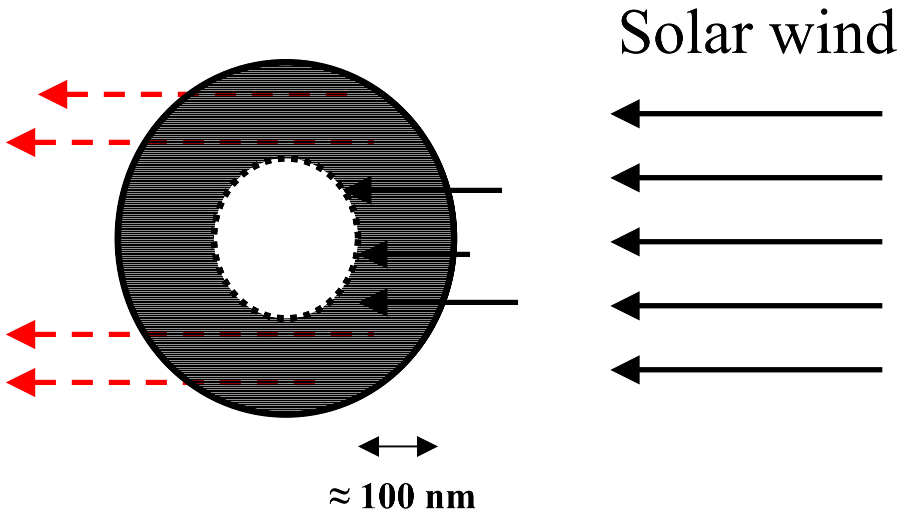


Compare to lunar samples:

Few solar wind particles pass the grains with energy loss

1) <u>Implantation</u>

solar wind particles stick in dust surface layer of ≈ 100 nm



Same process observed in lunar soil:

Study of noble gases in solar wind by heating of lunar samples and analysis of released volatiles

Similar studies were planned for Genesis

Dust interaction with solar wind - Large grains -

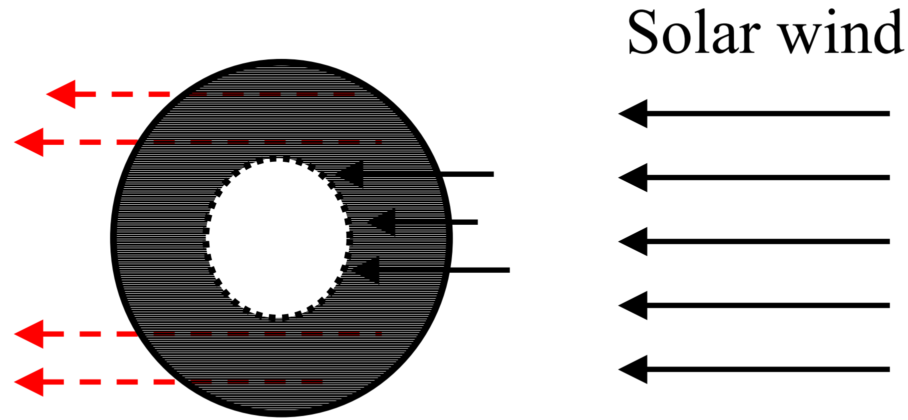
Few solar wind particles pass the
grains with energy loss

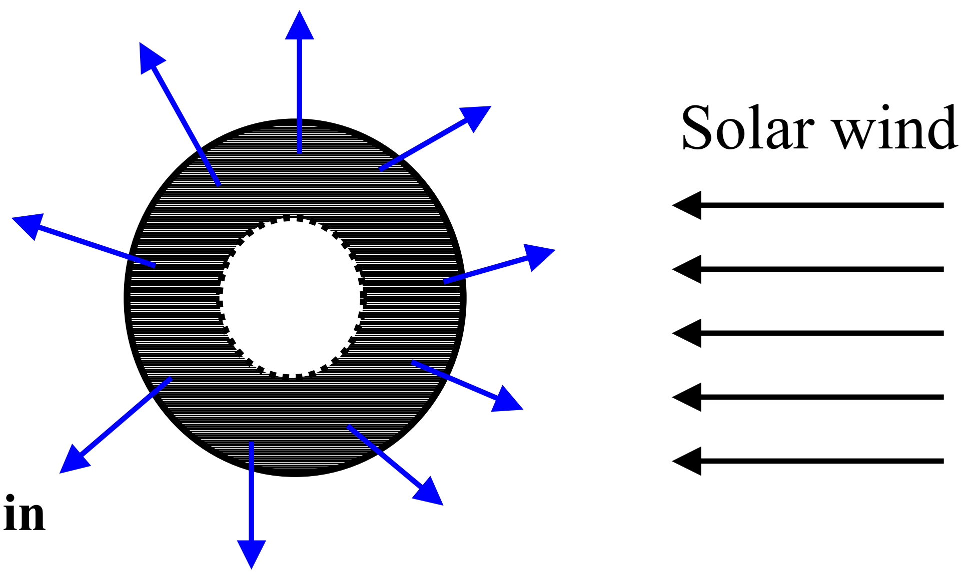
) **Implantation**
wind particles stick in surface
layer of about 100 nm

) **Recombination**
After saturation the further
incoming solar wind particles
recombine with electrons

> production of neutrals*)

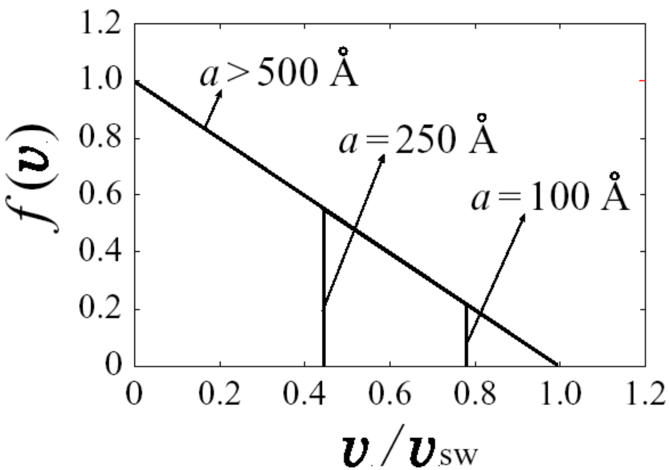
) Discussed to generate pick-up ions in
solar wind (Goeckler&Geiss 2001)



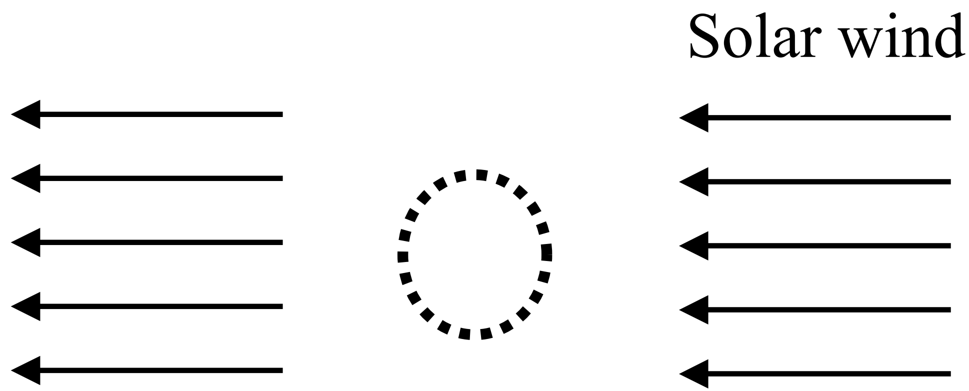


Dust interaction with solar wind- small grains

1) Energy loss



Velocity distribution of protons after passage through grains with size a (Minato et al. A&A Let)



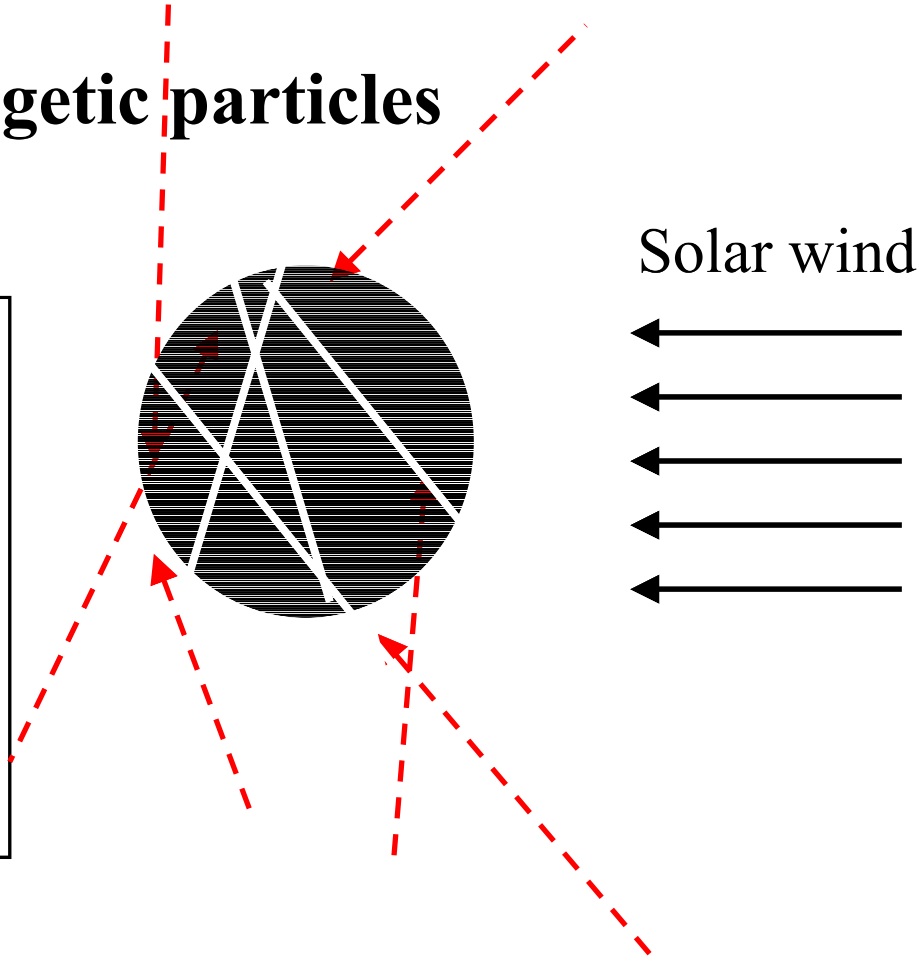
2) Recombination

solar wind particles are neutral or singly charged after passage!

mall grains

roduce Neutrals: $E_{sw} < E_{kin} <$ 0

Dust interaction with energetic particles

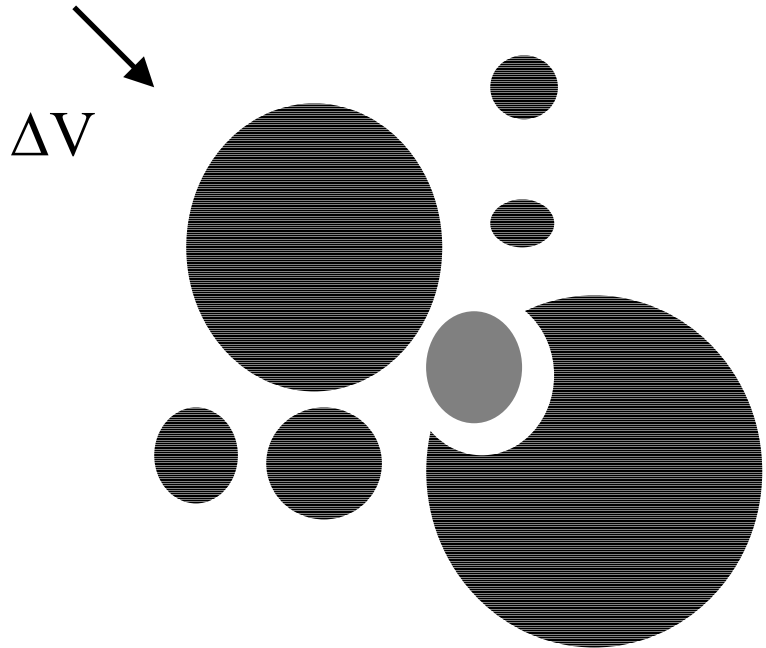


Some solar energetic particles produce “tunnels” when they pass through the dust

Studied for some collected interplanetary dust particles (Bradley 1987)

Sputtering of dust material also process of dust destruction (important for dust evolution in the interstellar medium (ISM

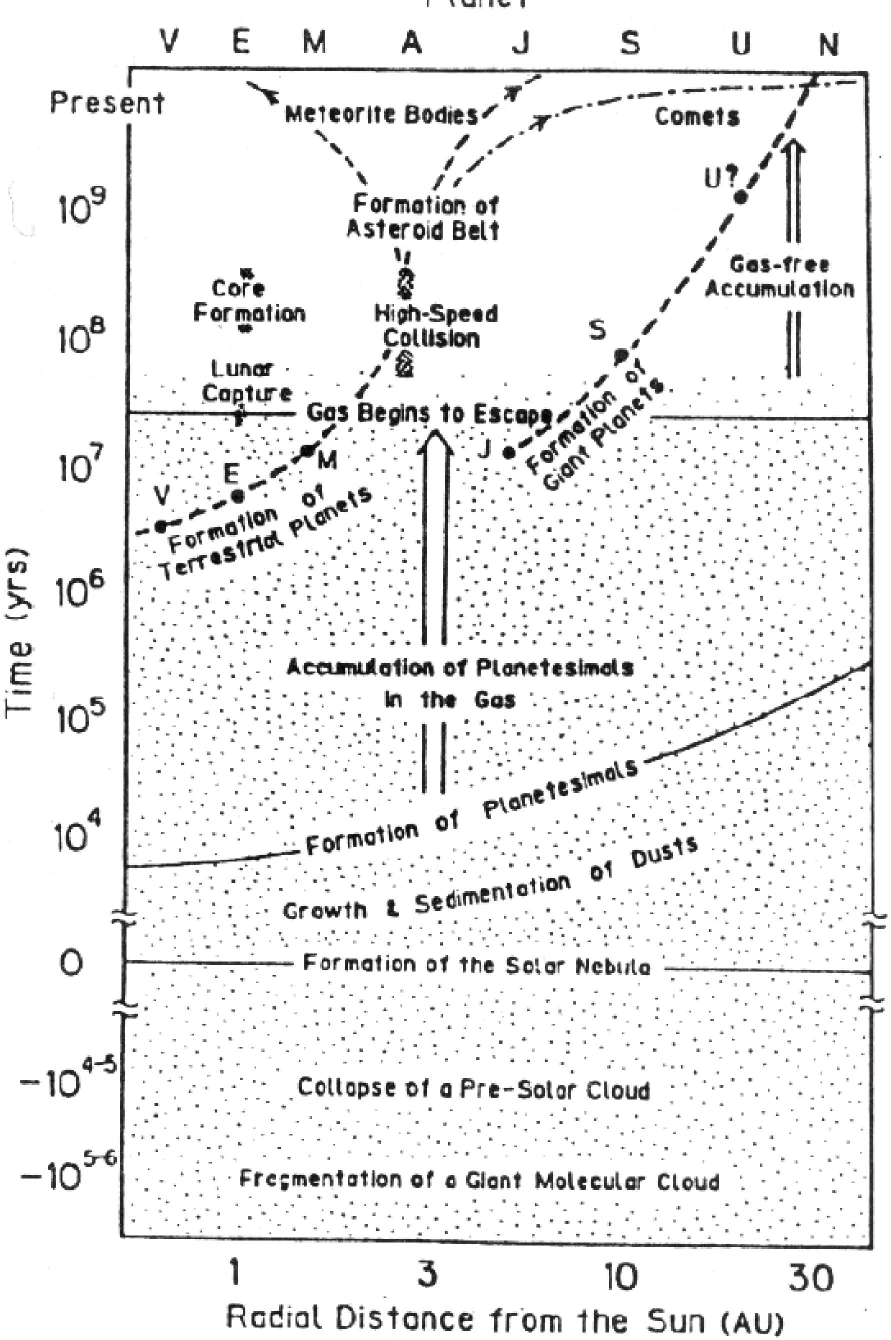
Mutual collisions:



Particles in Keplerian orbits have relative velocities of a fraction (like 1/10) of the orbital speed

With ΔV of the order of km/s collisions in the solar system are catastrophic !

Destruction of large dust particles and formation of smaller fragment particles



By the way:

this is different from solar system formation: small relative velocities

The presence of planetesimals (and of planets in particular) causes gravity perturbations and therefore high relative velocities and catastrophic collisions

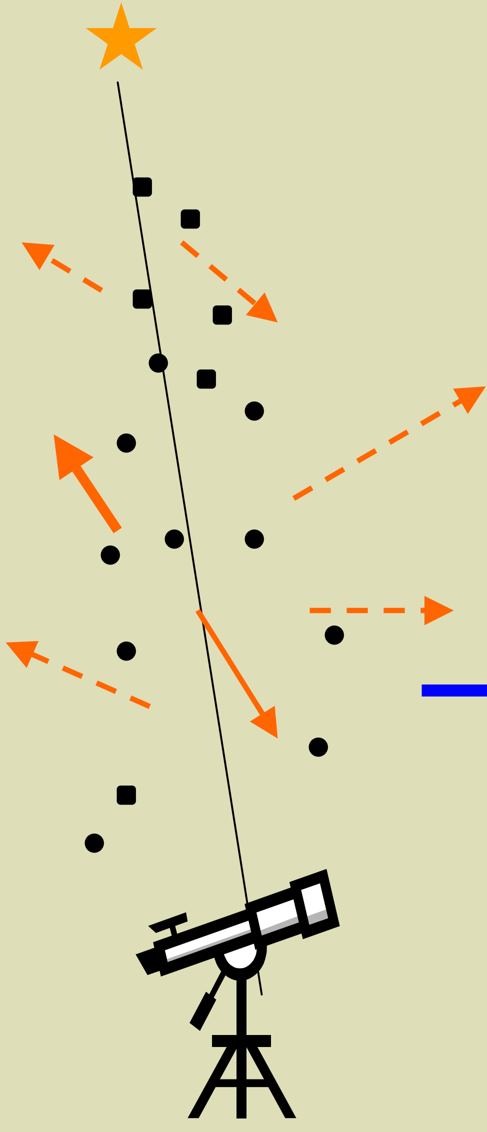
(see Protostars and planets IV and L. Schutltz, Einführung in die Plnetologie)

Dust in the solar system:

follows the collisional evolution of small solar system bodies and also shows their material composition

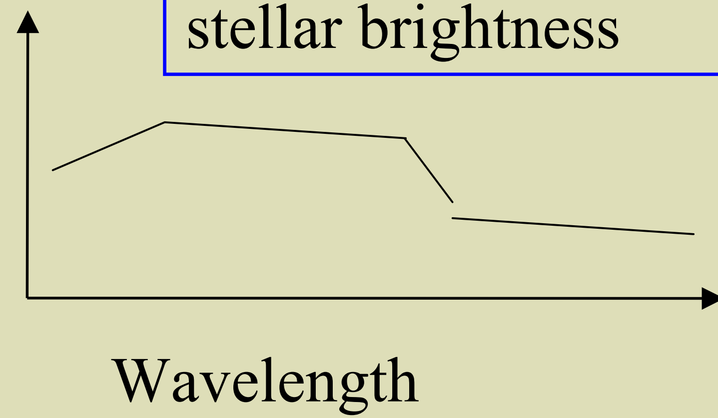
cometary dust may contain pristine material and may show similarities to the interstellar dust out of which the solar system was formed

Astronomical Observations of Dust in the Insterstellar Medium (ISM):



Extinction

dust reduces observed stellar brightness



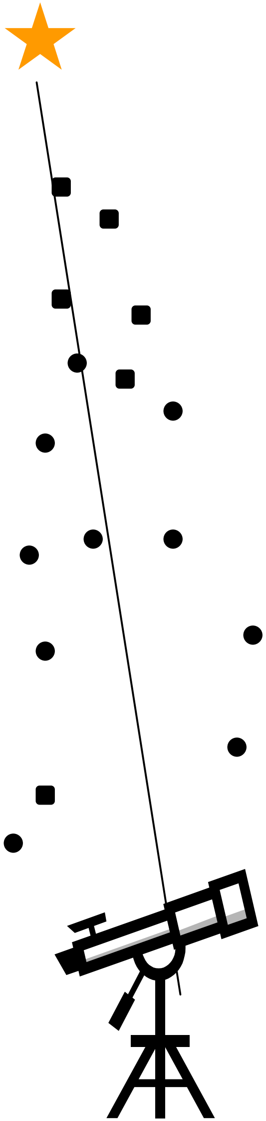
Derive density & size distributio and some material composition

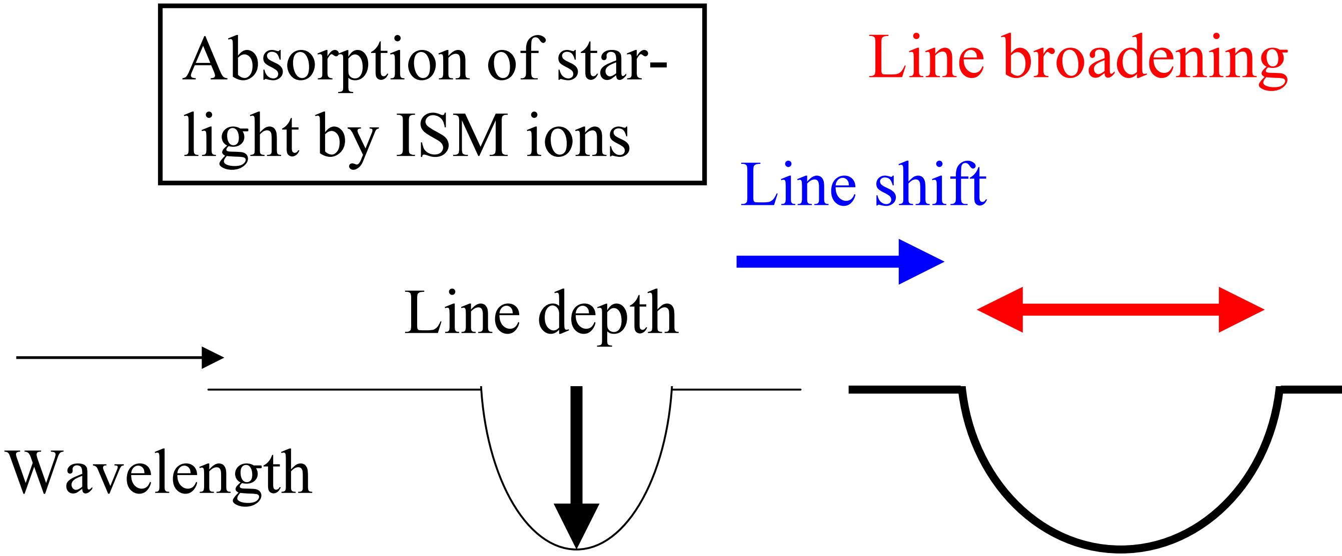
Other observations:

Polarization

IR & mm emission

Observation of interstellar medium (ISM) gas:

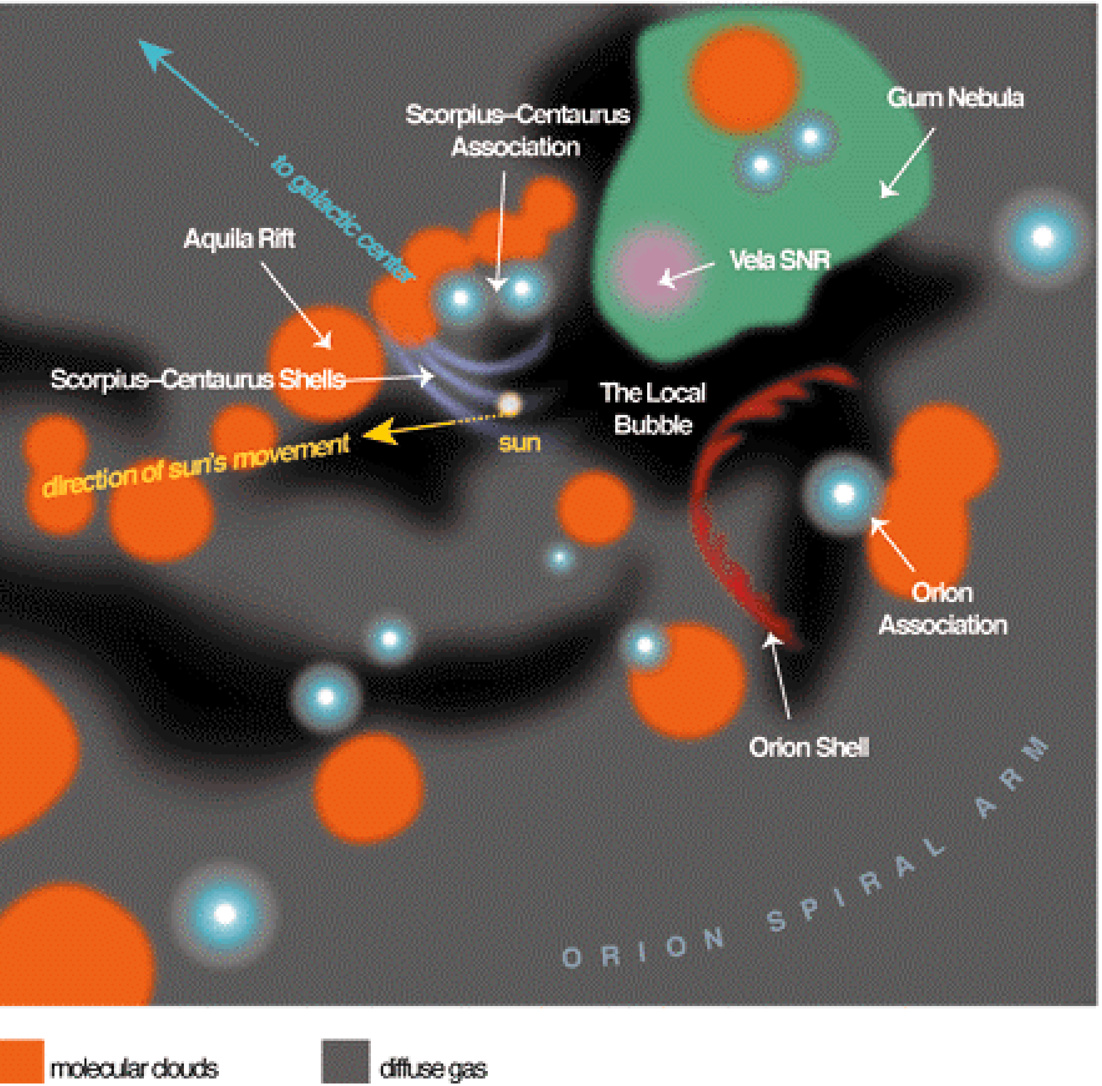




Derive <u>column density</u>, <u>bulk velocity</u> and <u>thermal velocity</u> of certain species

(cf.Linsky et al. 1993, Lallement 1998)

Interstellar medium around the Sun



Components of the interstellar medium:

hot very low density material *(**black**)*

T = 10^6 K, n < 10^{-3} cm^{-3}

warm, partly ionized material *(**violet**)*

T = 10^4 K, n ~ 0.3 cm^{-3}

cold, dense molecular clouds *(**orang**)*

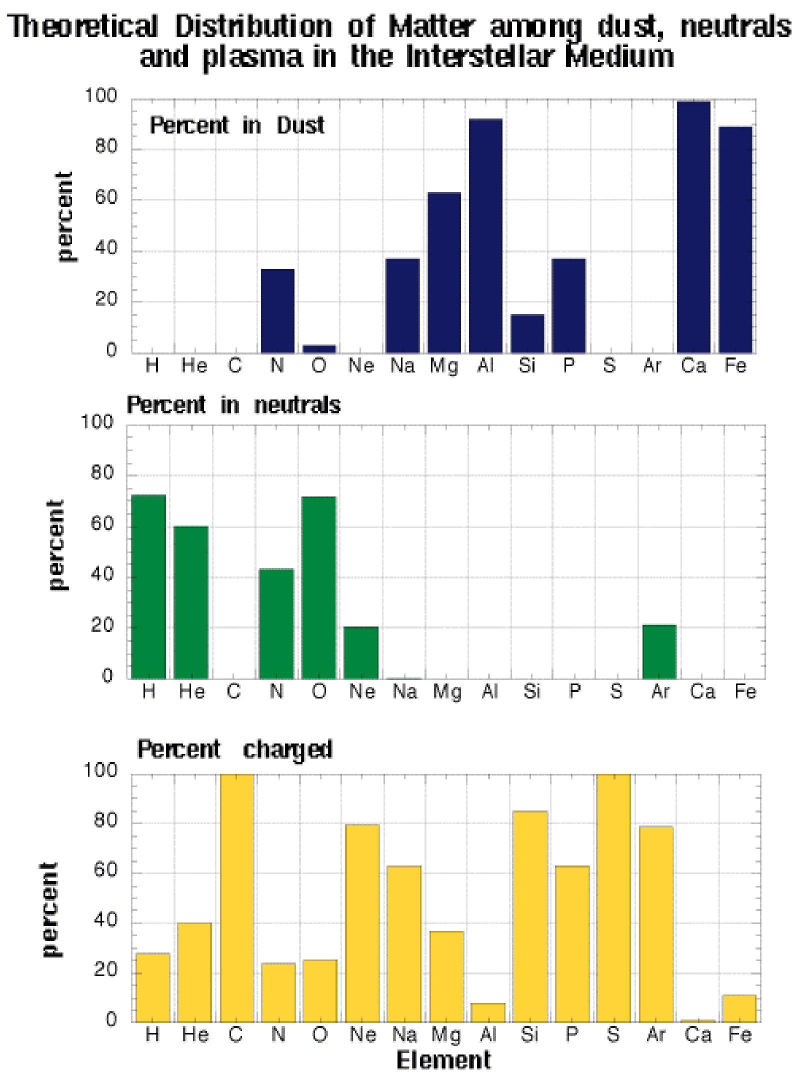
T < 100 K, n > 10^3 cm^{-3}

ionized hydrogen *(**green**)*

the map shows a region of ~ 1500 Ly, 10^9 AU

(Figure: P. Frisch, in: American Scientist 2000)

Distribution of chemical elements in the interstellar medium (mainly known from theory)



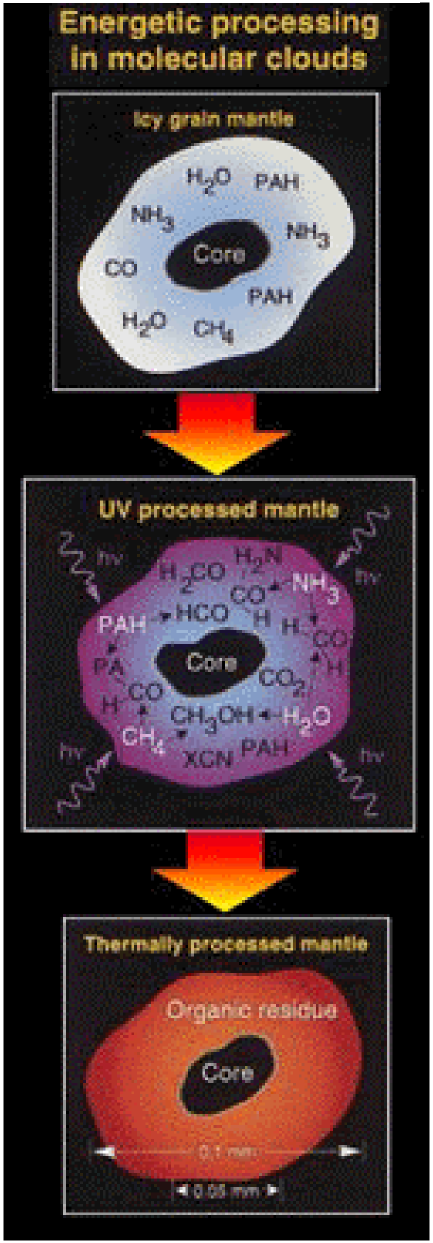
Dust

Neutral Gas

Ions

From NASA – Intersetllar Probe Webpag

< 0.1µm



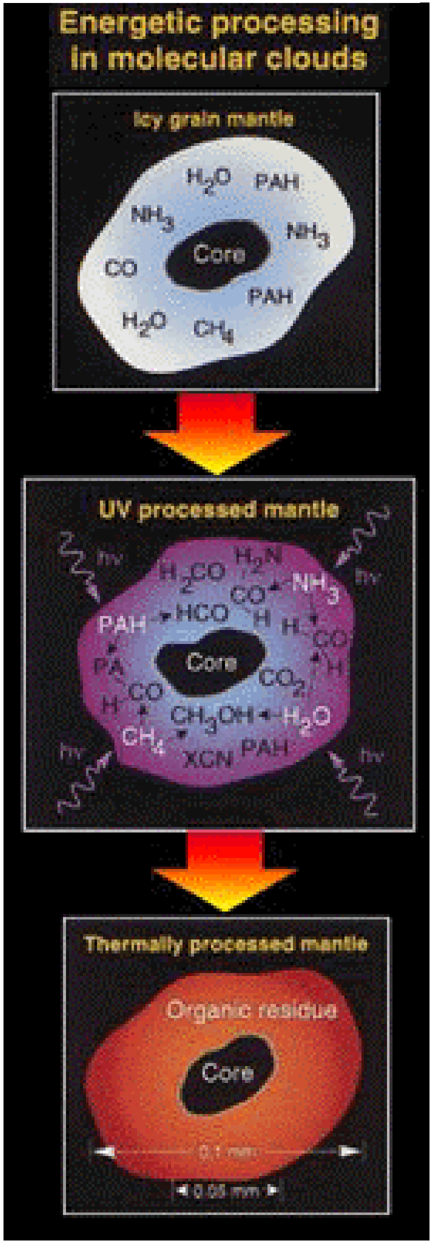
Picture of dust evolution in the interstellar medium *(cf. Greenberg &Li 1996)*

- Condensation of small grains in late stellar atmospheres
- formation of icy mantles in cool inter-stellar medium regions
- formation of organic refractory mantles under uv radiation

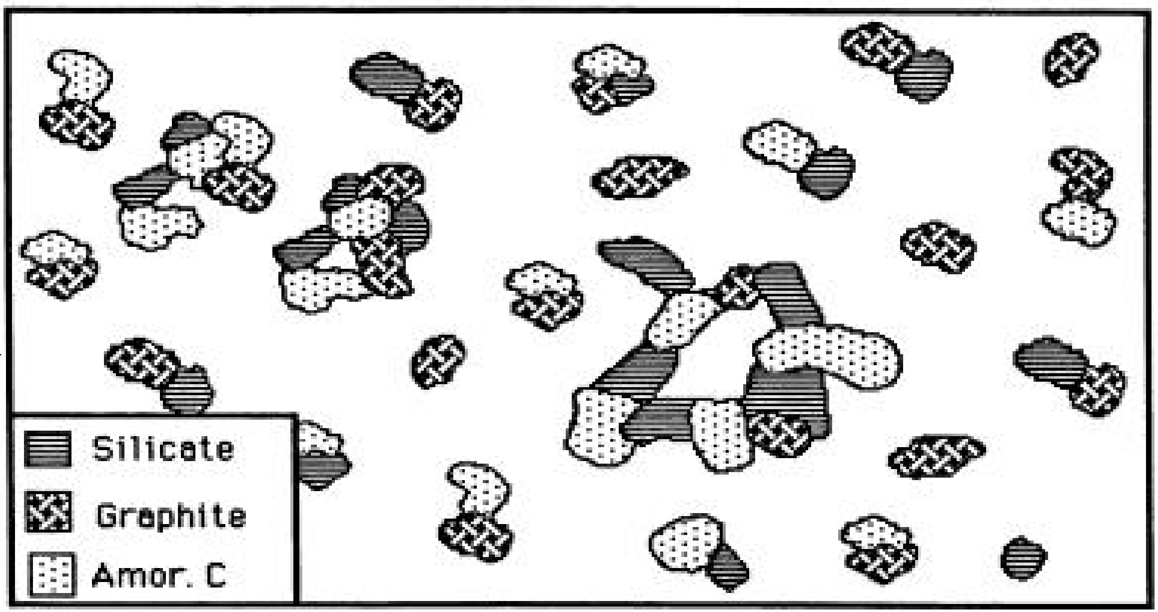
From NASA – Intersetllar Probe Webpag

< 0.1μm

Picture of dust evolution in the interstellar medium *(cf. Greenberg &Li 1996)*

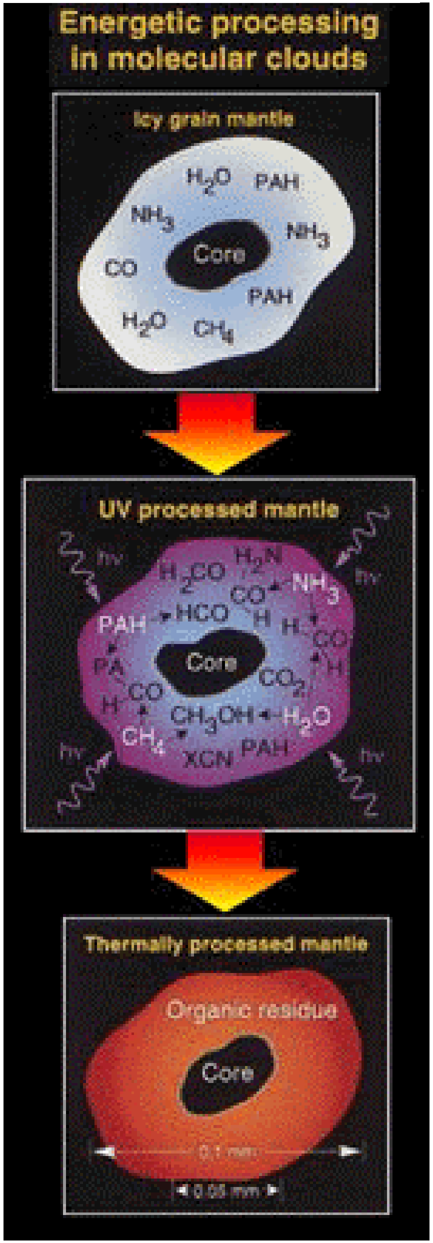


collision fragmentation and sputtering destroy large particles again



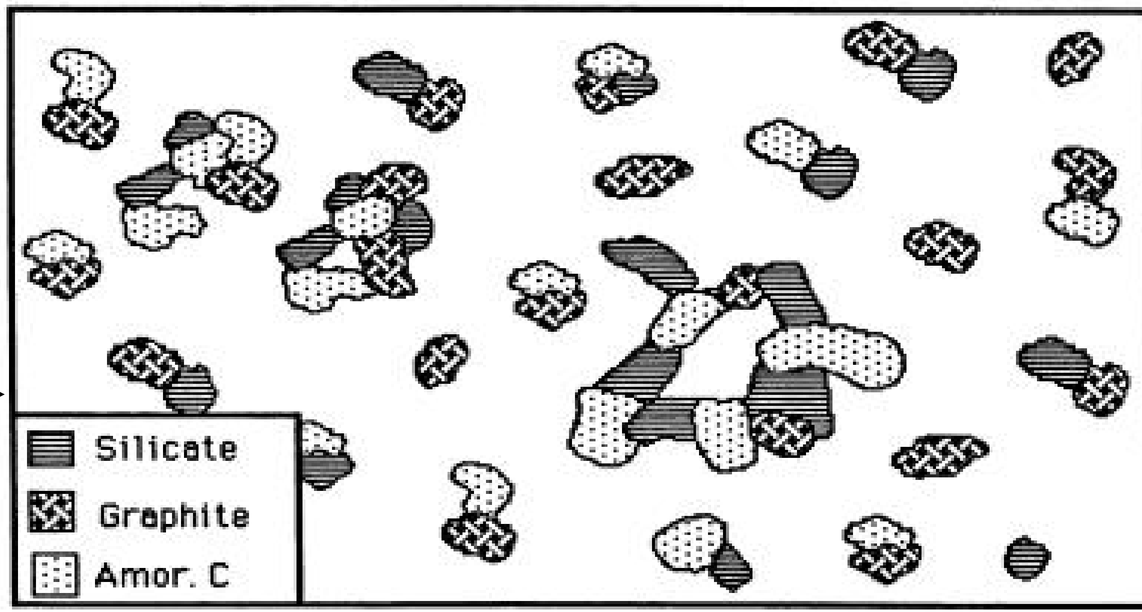
(cf. Whiffet, 1984, Mathis, 1996)

< 0.1μm



Picture of dust evolution in the interstellar medium *(cf. Greenberg &Li 1996)*

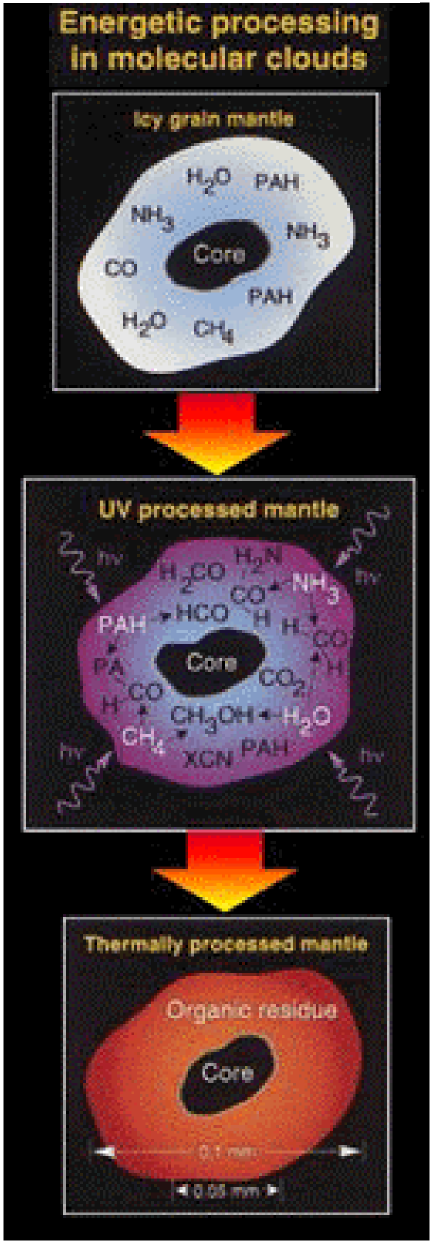
collision fragmentation and sputtering destroy large particles again



(cf. Whiffet, 1984, Mathis, 1996)

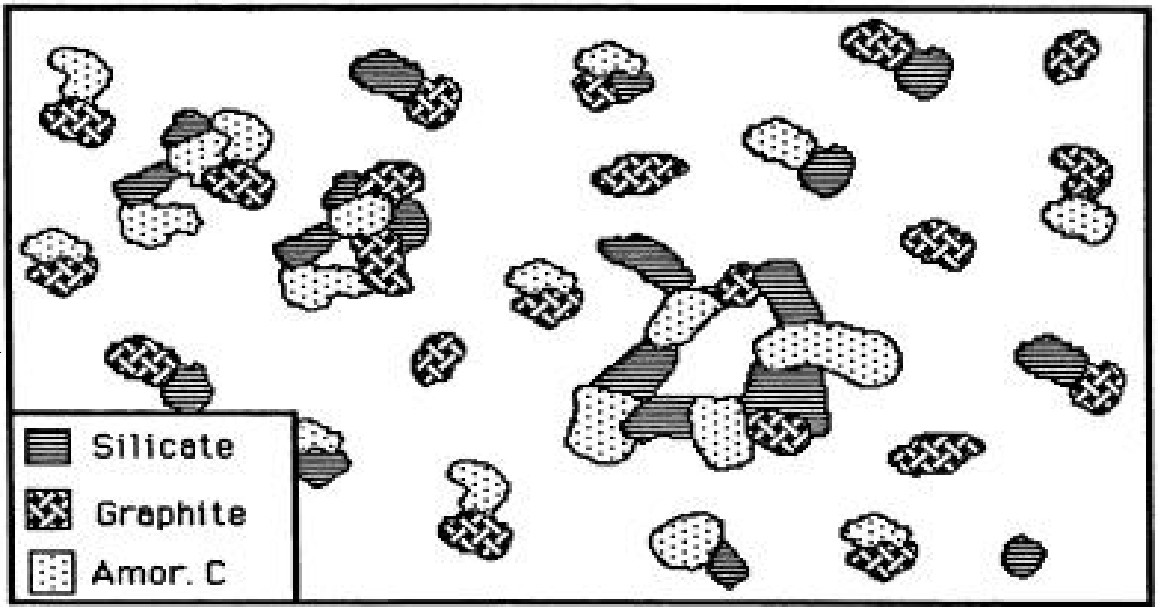
< 0.1μm

Picture of dust evolution in the interstellar medium *(cf. Greenberg &Li 1996)*

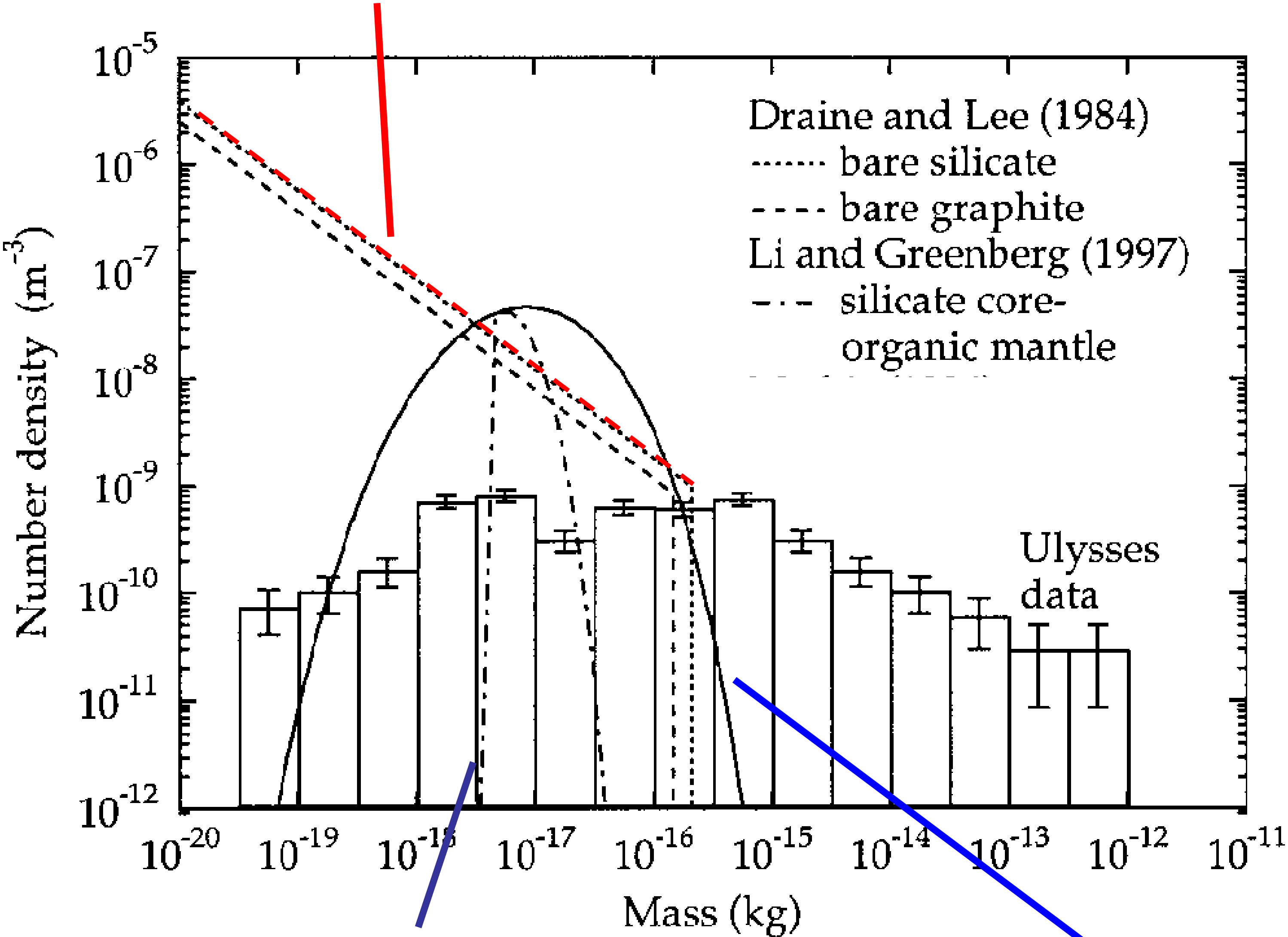


Size distribution of dust depends on physical evolution of interstellar medium (gas)

> 0.1μm



Conventional extinction models

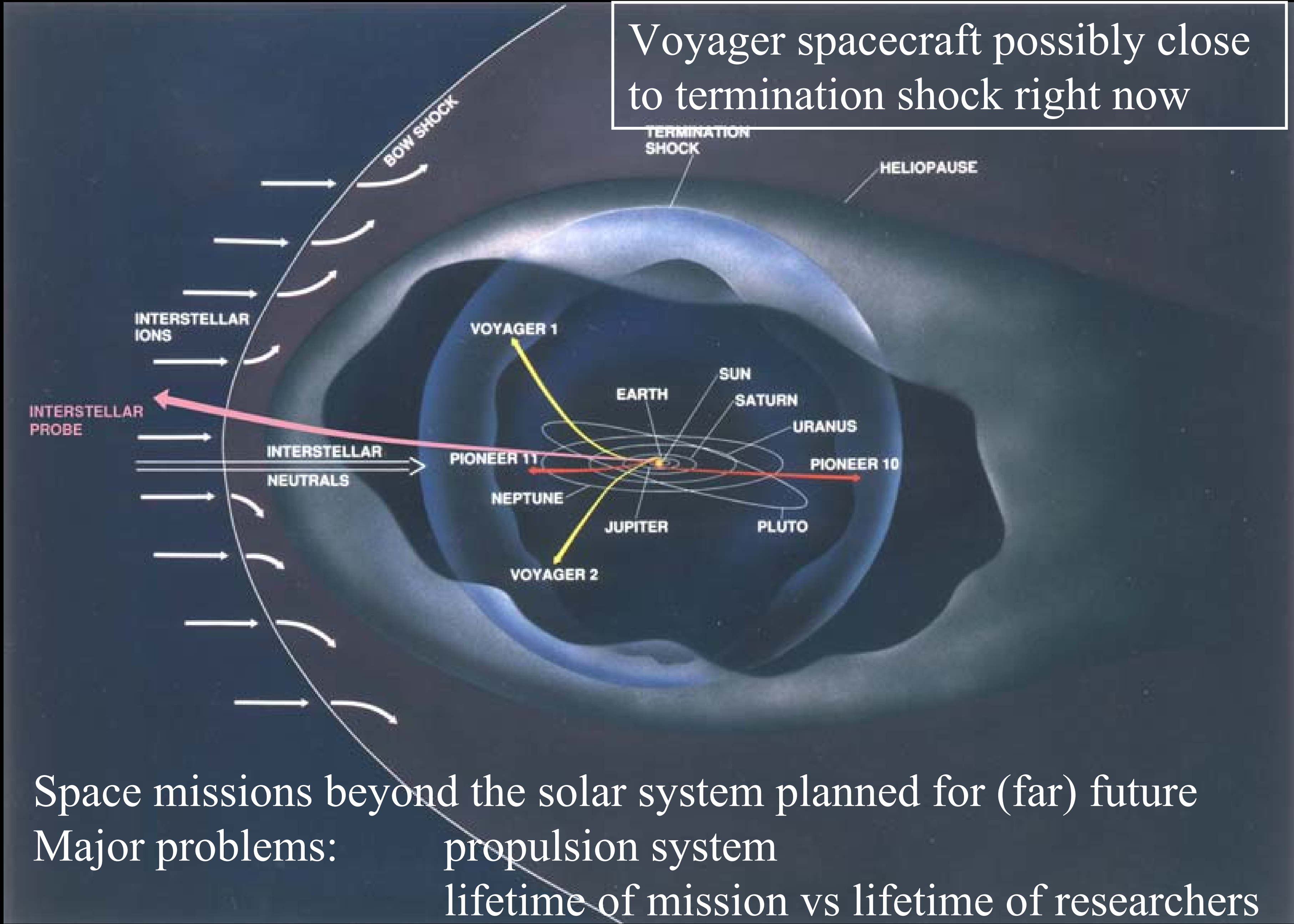


Core mantle particles

Mann & Kimura 2001)

Large composite grain

Voyager spacecraft possibly close to termination shock right now



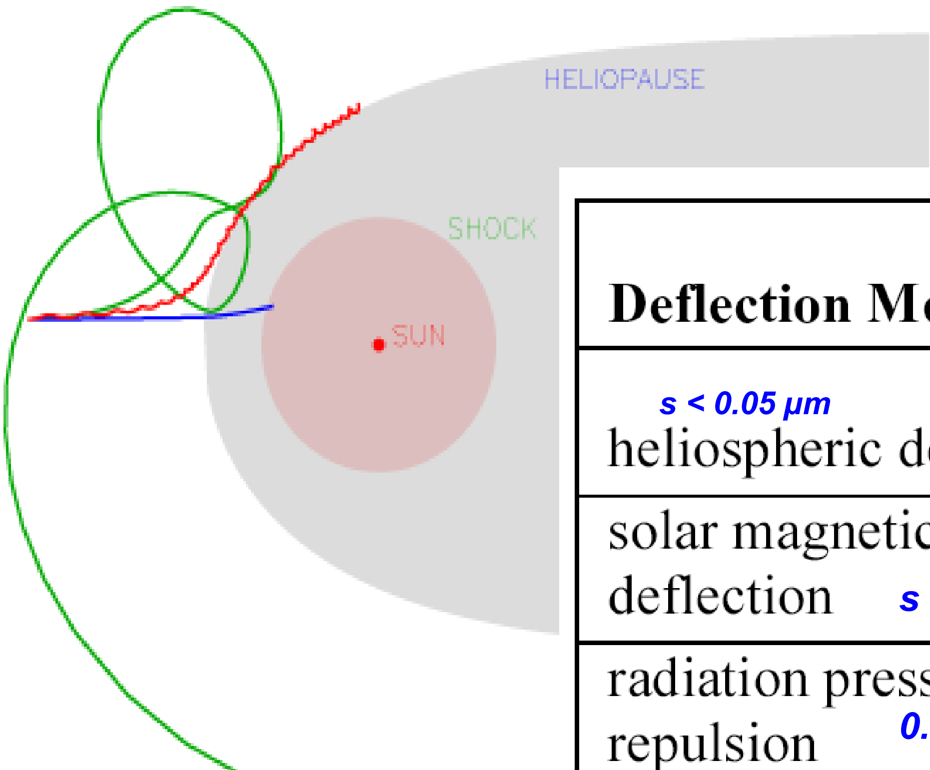
Space missions beyond the solar system planned for (far) future

Major problems: propulsion system

lifetime of mission vs lifetime of researchers

From NASA - Intersetllar Probe Webpag

Deflection of Interstellar Dust

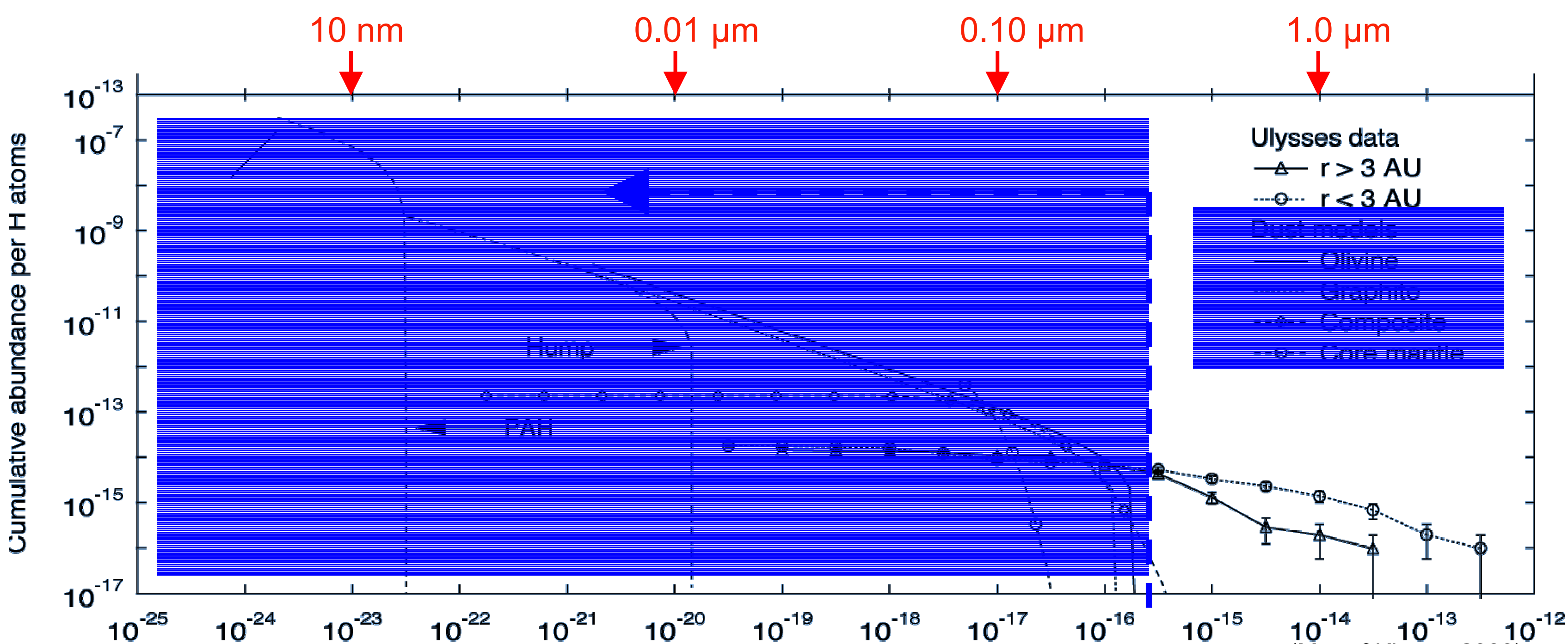


Deflection Mechanism	Mass Interval
s < 0.05 µm heliospheric deflection	$m < 10^{-18}$ kg
solar magnetic field deflection *s < 0.10 µm*	$m < 10^{-17}$ kg
radiation pressure repulsion *0.10 µm - 0.50 µm*	10^{-17}kg $< m < 10^{-15}$kg
> 0.50 µm gravitational focusing	$m > 10^{-15}$ kg

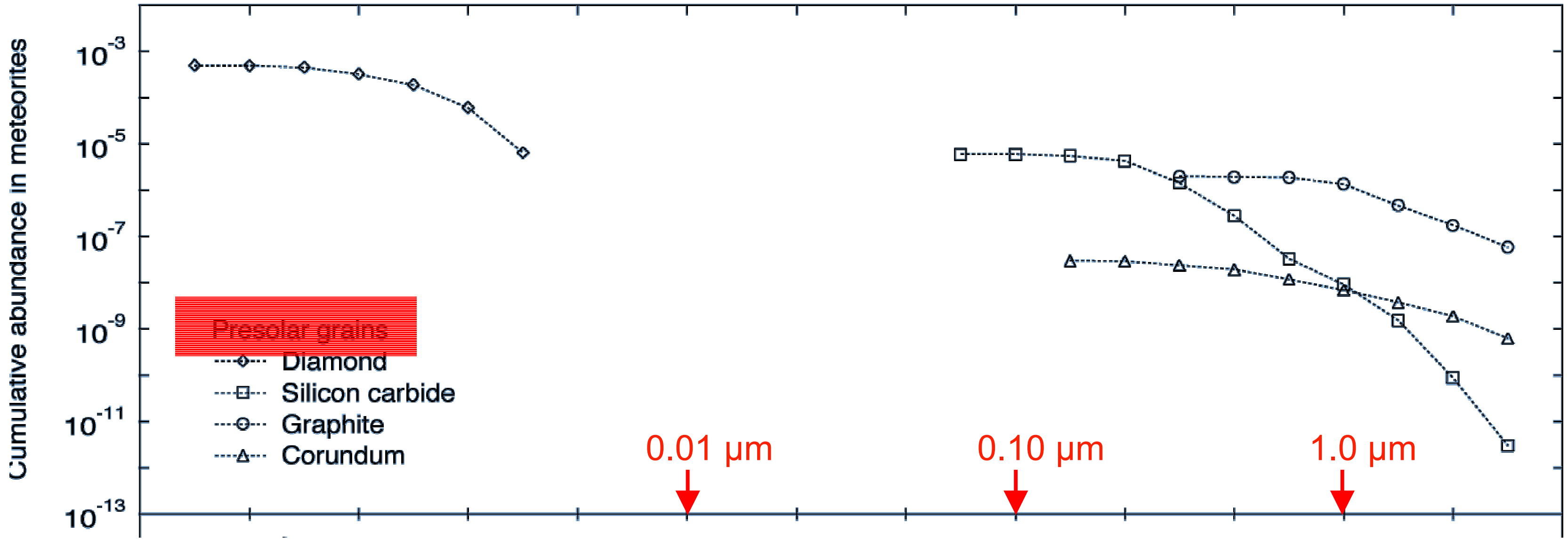
(Czechowski & Mann 2003, Mann&Kimura 2000)

Astronomical Observations:

describe particles < 1 µm
over a large spatial region



Interstellar grains separated from meteoroids:



(Mann&Kimura 2000)

But

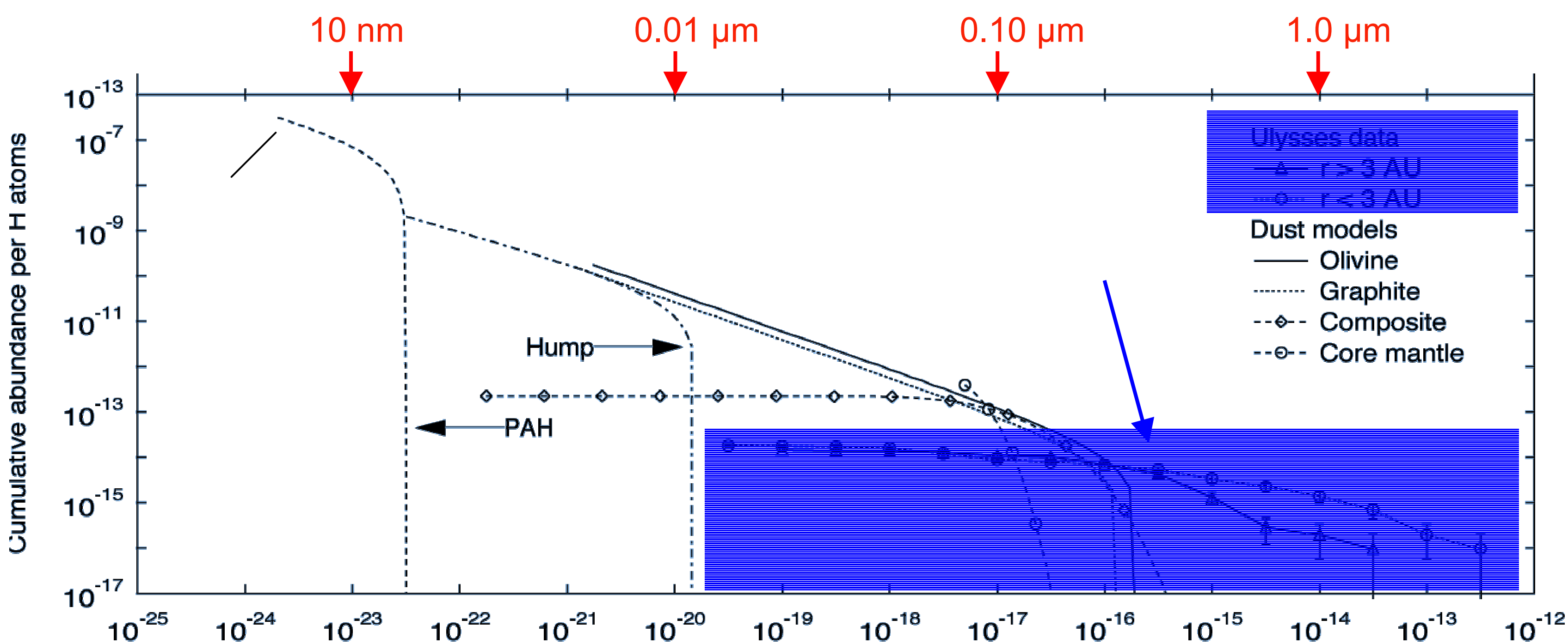
Chemical extraction method only works for certain materials

Most solid particles don't survive solar nebula conditions under which the planetary system is formed

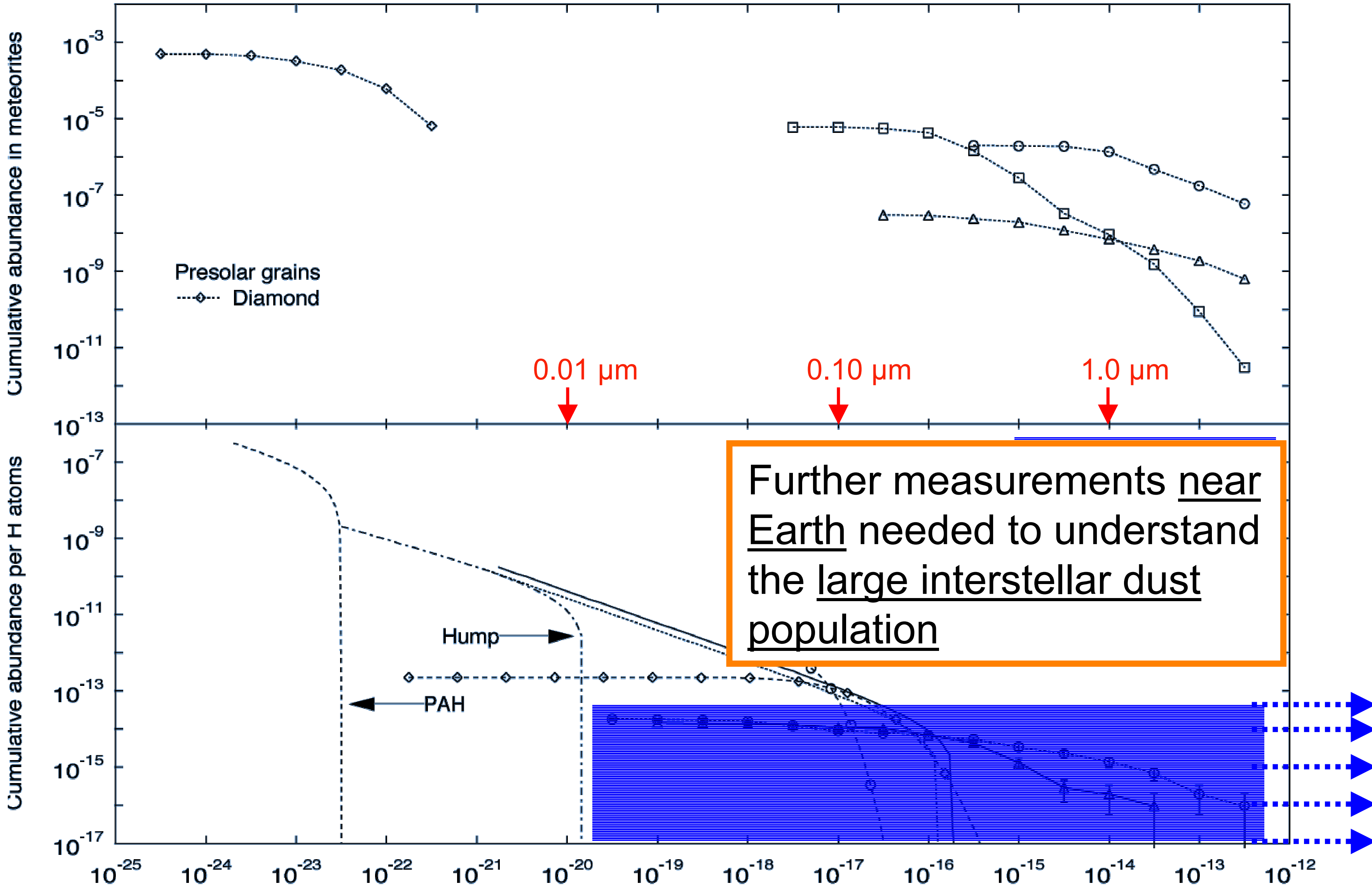
In - situ Measurements from spacecraft:

(Grün et al. 1994, 1998, Krüger et al. 2001)

- large size end of the spectrum
- biased by dust dynamics
- local interstellar cloud dust



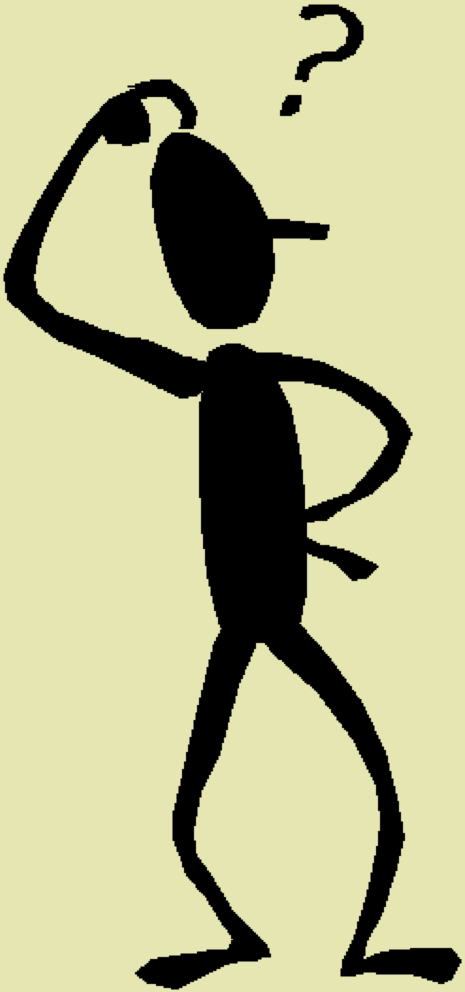
Pre-solar grains and in-situ measurements exceed models for interstellar dust:



Interstellar Meteors ?

observations (Baggaley) still subject to debate among observers

Need methods with reliable velocity measurements for instance with headecho observations (Pellinnen-Wannberg 2002, Janches et al.2003)



Questions ?

Additional Slides

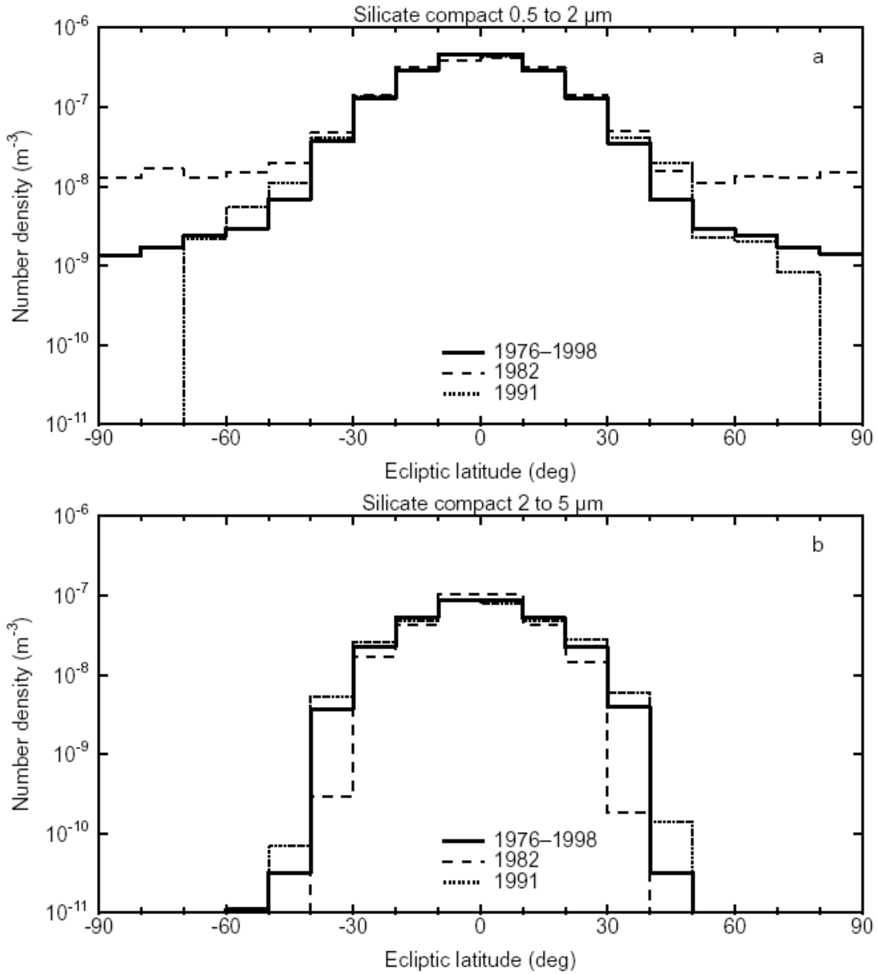


Figure 11. The variation of dust number density with latitude due to Lorentz force perturbations for compact silicate particles with an initial distribution ±30°. The solid line denotes an average profile for the entire solar cycle, the dashed line shows the profile for a strong magnetic field in 1982 and the dotted line the profile for a weak magnetic field in 1991. The upper figure shows particles with sizes 0.5–2 μm. The lower figure shows number densities for particles with sizes 2–5 μm (Mann, Krivov, and Kimura, 2000).

The deflection of particles by Lorentz force near the sun: initial distribution +/- 30 degree from the ecliptic

(Mann et al. 2004, Space Sci. Rev.)

Gravitational force F_{grav} and radiation pressure force F_{rad}

The major forces acting on a dust particle with the mass m in a distance r from the star are the gravitational force F_{grav} and the radiation pressure force $F_{pr.}$ Both forces are proportional to $1/r^2$ and it is useful to calculate their ratio: as

$$\beta = \frac{F_{rp}}{F_{grav}} \tag{2}$$

$$\beta = \frac{\pi \cdot R_{star}^2}{\gamma \cdot M_{star} \cdot c} \frac{G}{m} \int_0^\infty B(\lambda, T) Q_{pr}(s, \lambda) d\lambda \tag{3}$$

where G is the effective geometric cross section, B the Planck function, R_{star} the radius of the star, c the velocity of light, Q_{pr} is the efficiency factor for radiation pressure, γ is the gravitational constant and s the particle size [12]. This equation is valid for particles at distance r >> $R_{star.}$

(Köhler and Mann 2003)

From Czeplecha et al.Space Sci. Rev.

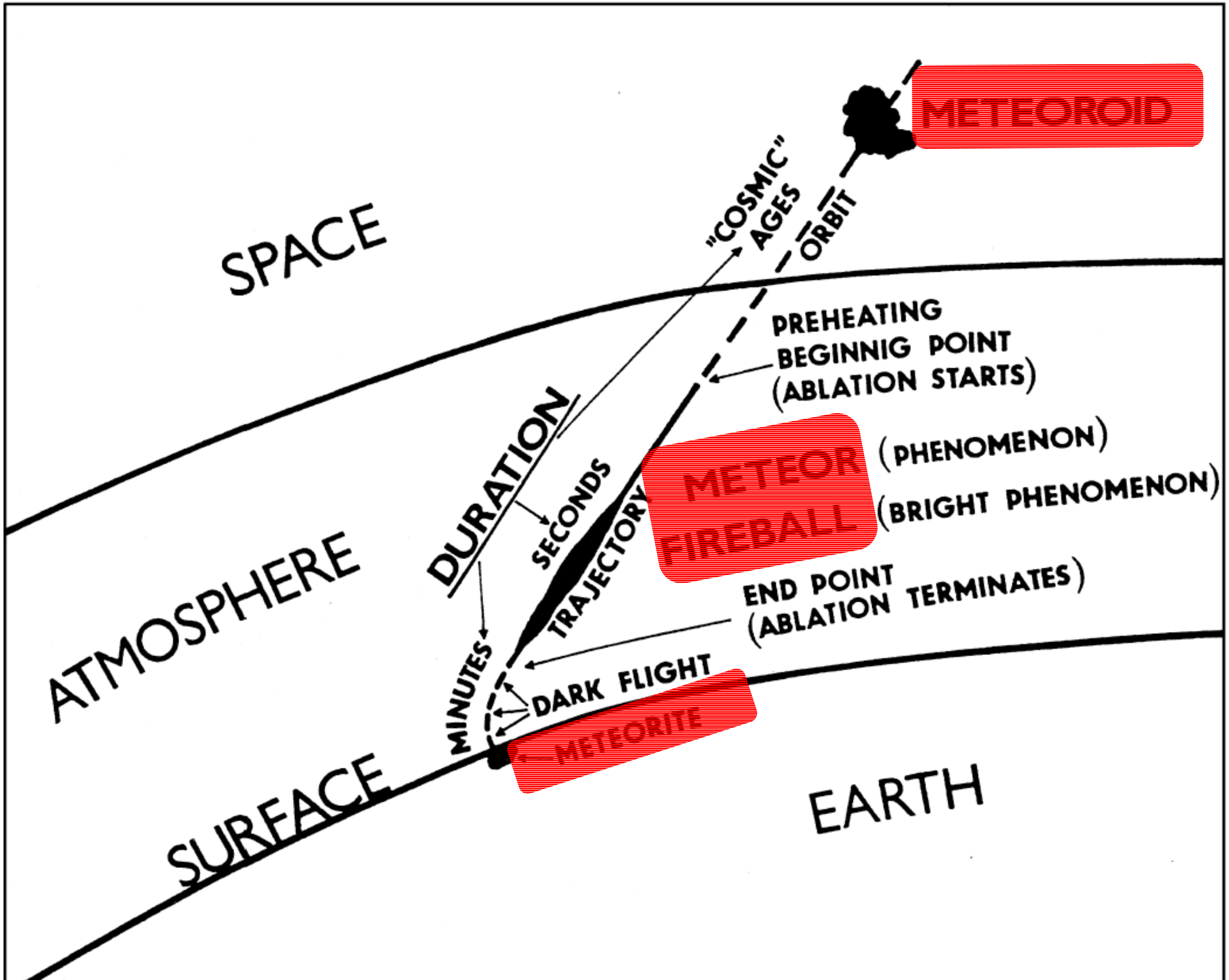
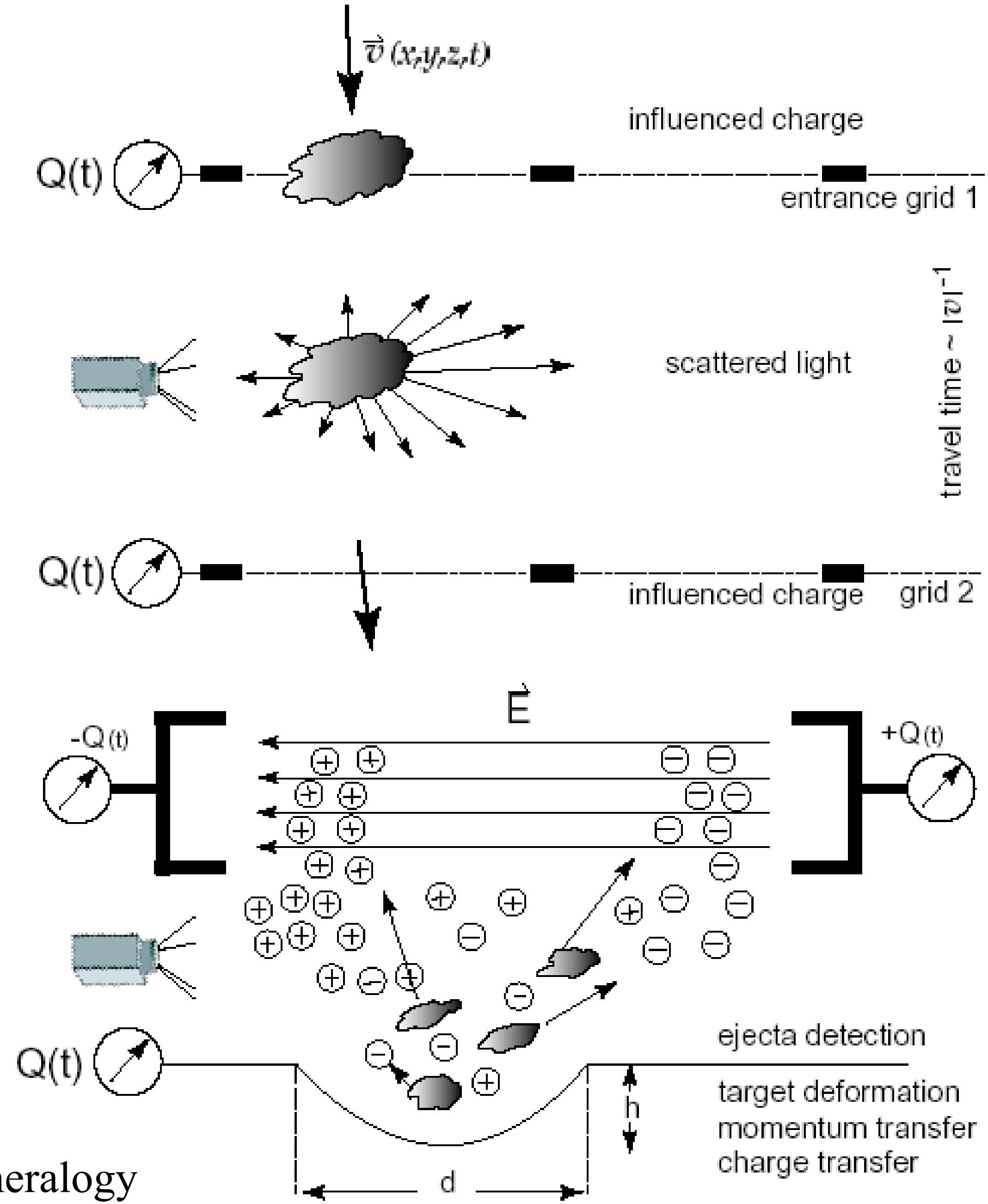


Figure 2. Basic terminology for meteors.

DUST MEASUREMENTS IN SPACE

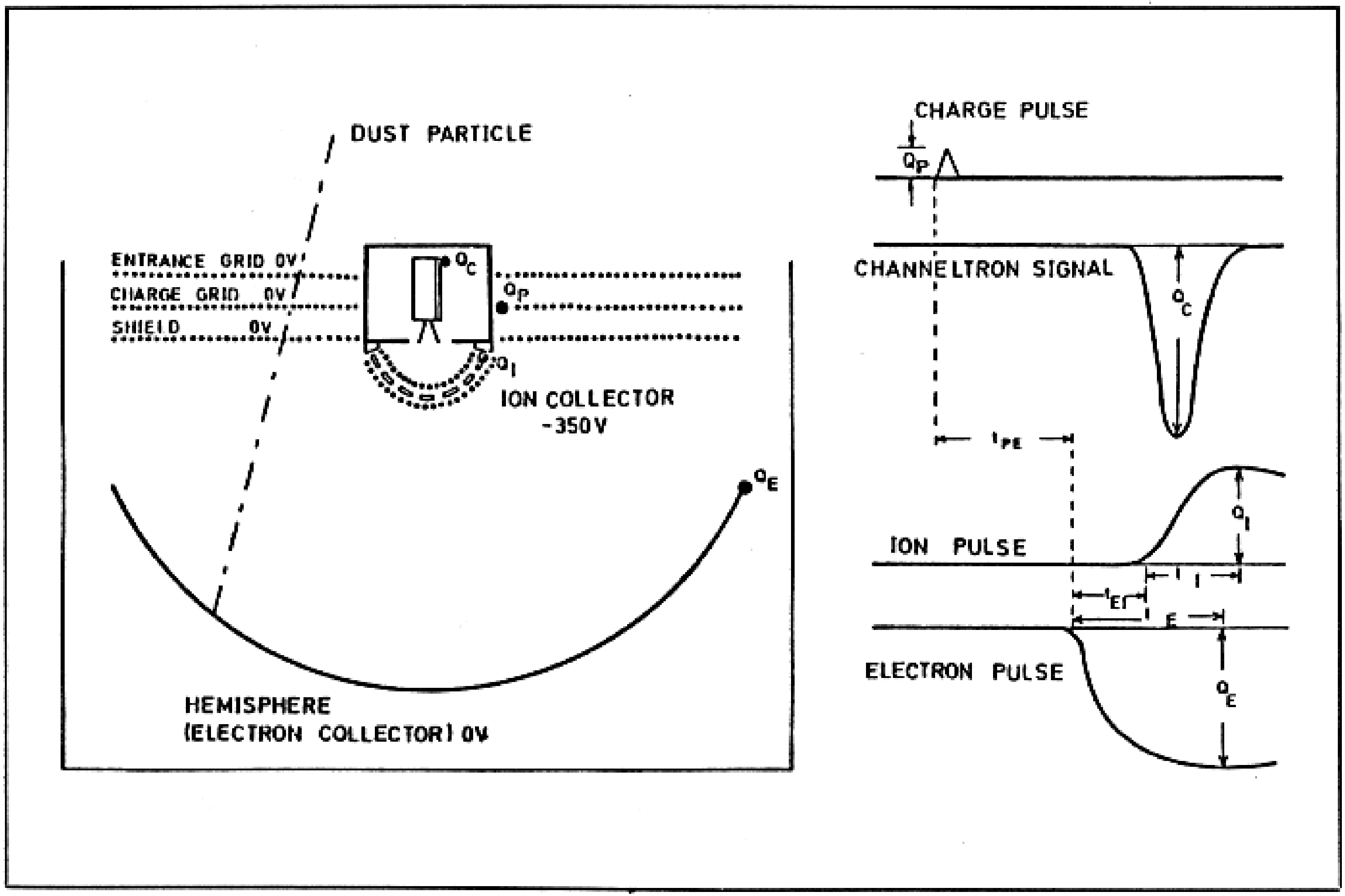
see
ESA and NASA Webpages
http://www.mpi-hd.mpg.de/dustgroup/
http://ifp.uni-muenster.de/

DUST DETECTION:
IMPACT IONIZATION:



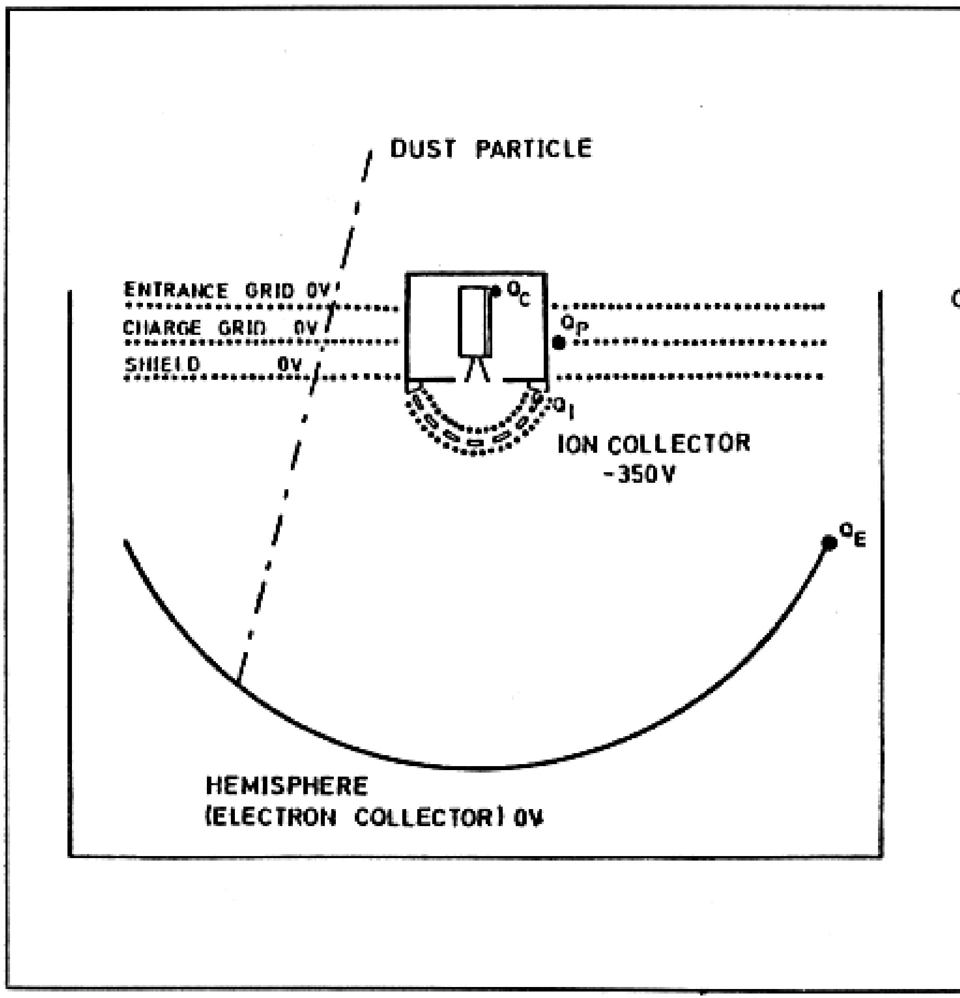
Mann & Jessberger in: Astromineralogy

Ulysses DUST DETECTOR



(Grün et al., Planet. Space Sci. 1992)

DUST DETECTOR: Ulysses



(Grün et al., Planet. Space Sci. 1992)

DUST DETECTRO ABOARD CASSINI (Srama et al. 2001)

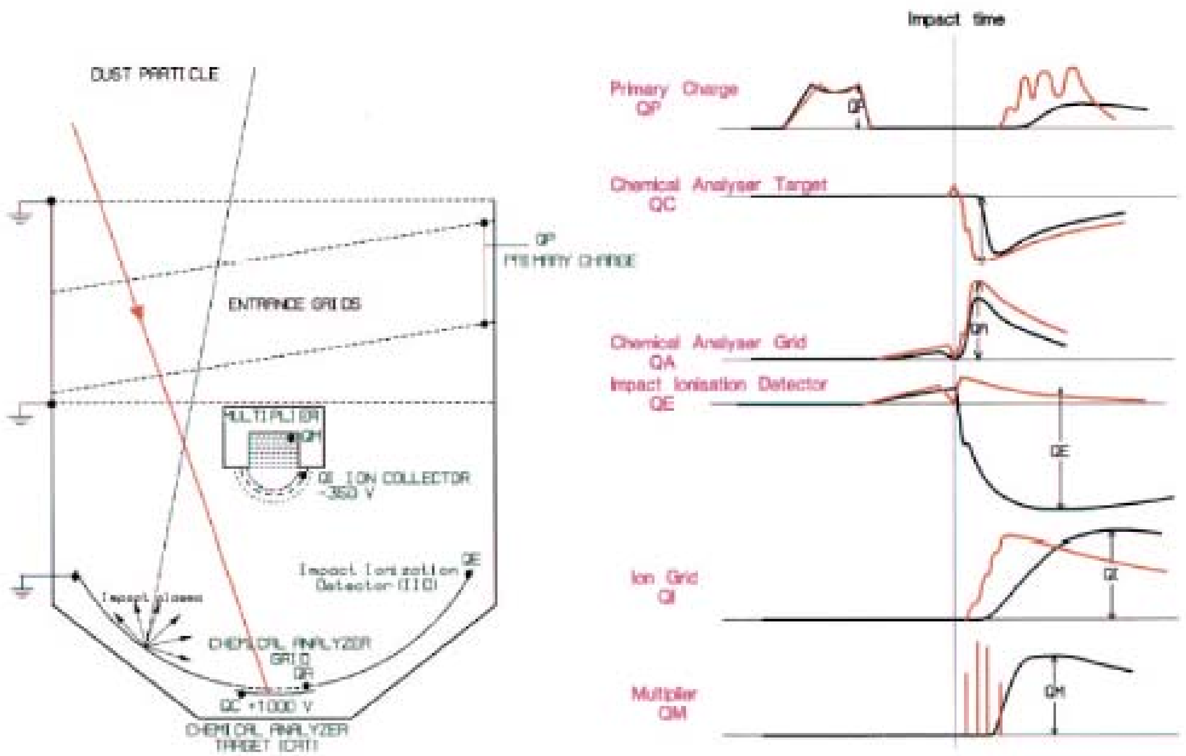


Fig. 3. The impact ionization dust analyzer aboard Cassini (Srama and Grün 1997). The left hand side of the figure show the schematics of the detector, the right hand side shows the different channels of measured signals: The particle velocity is estimated through the sequence of charges that are induced in a system of tilted entrance grids (denoted as primary charge QP on the right hand side of the figure) before they impact onto the target plate. The produced ions and electrons are detected at the target plate (QE, QA, QC) and in the ion collector (QI). Ions that are produced are accelerated due to the applied voltage and measured as a function of their flight time at a multichannelplate (QM).

TIME OF FLIGHT SPECTRUM OF IMPACT IONIZATION PRODUCED IONS ABOARD CASSINI

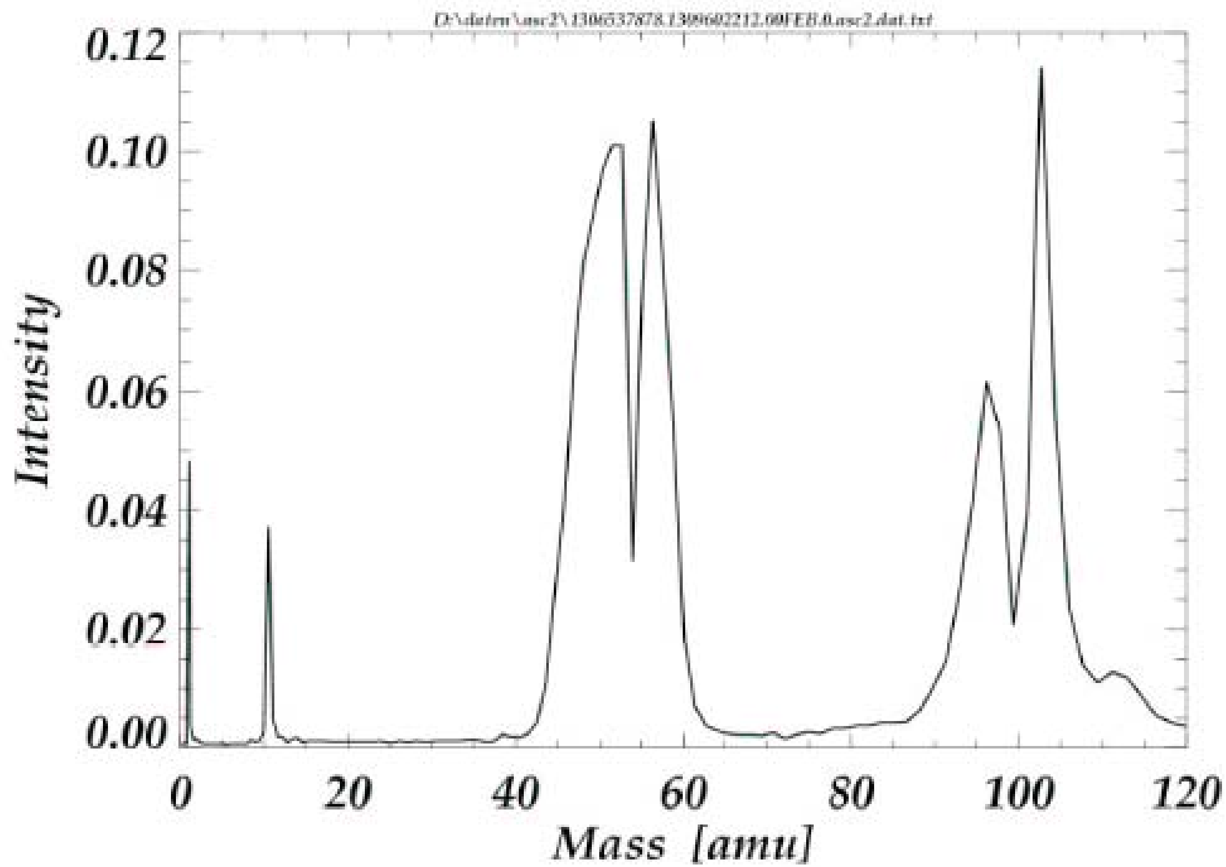


Fig. 4. The first mass spectrum of time-of-flight ion measurements with the Cassini dust analyzer corresponding to channel QM in figure 3.

PI: E. GRUEN from Mann & Jessberger in: Astromineralogy

RESULT FROM GIOTTO MISSION:
ELEMENT ABUNDANCE OF COMETARY DUST

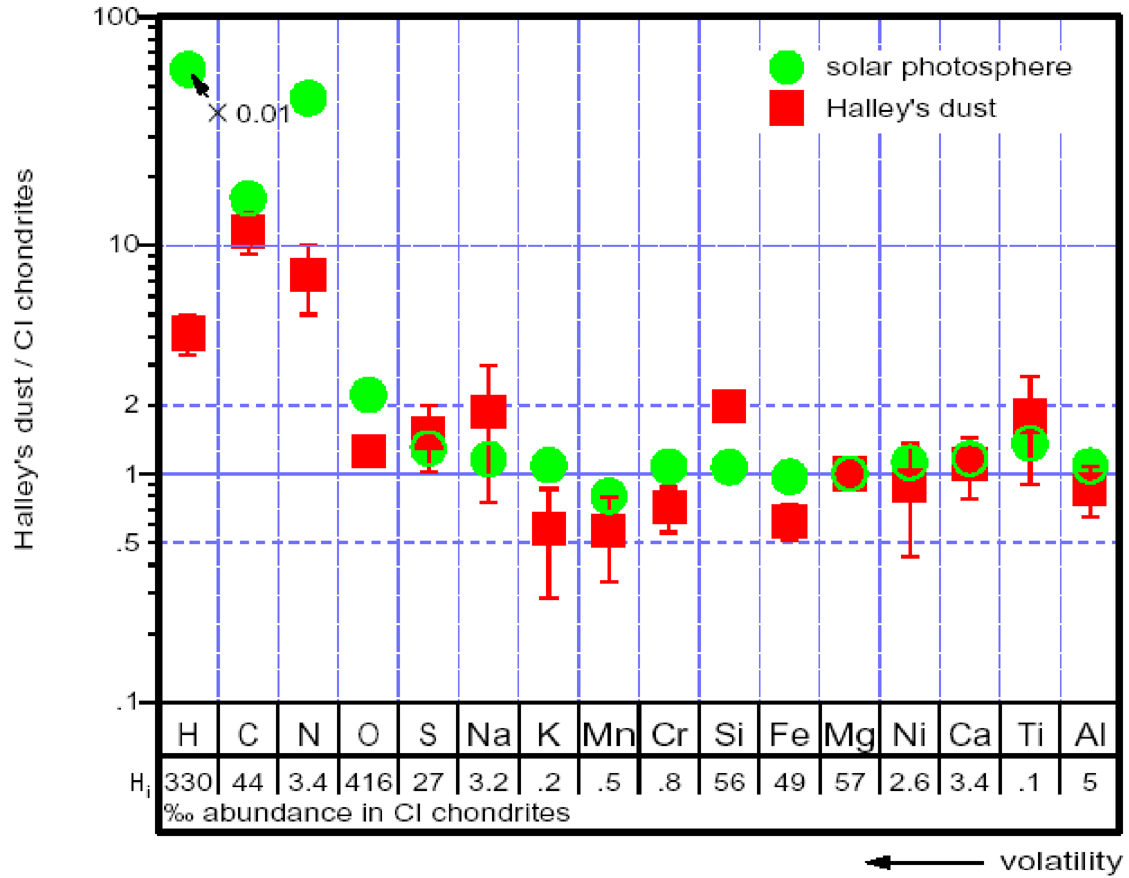
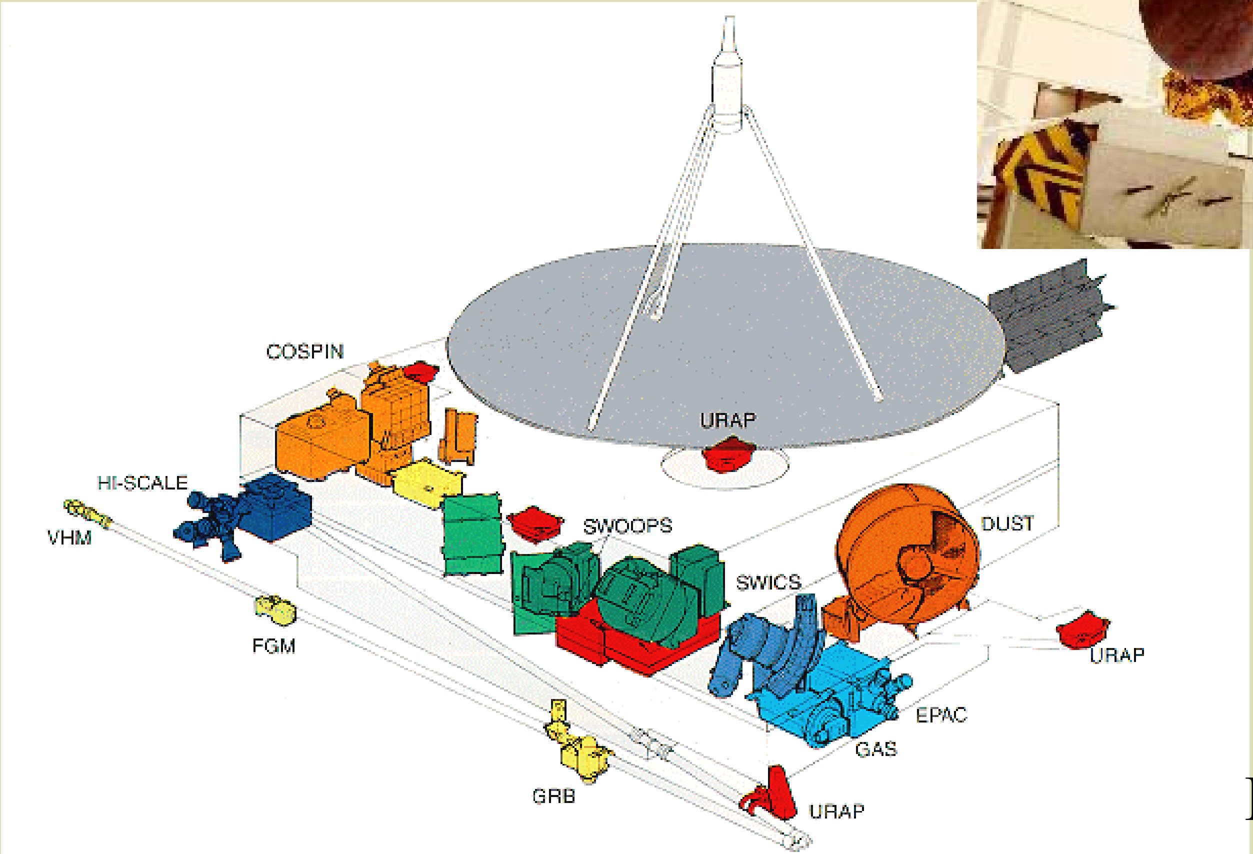


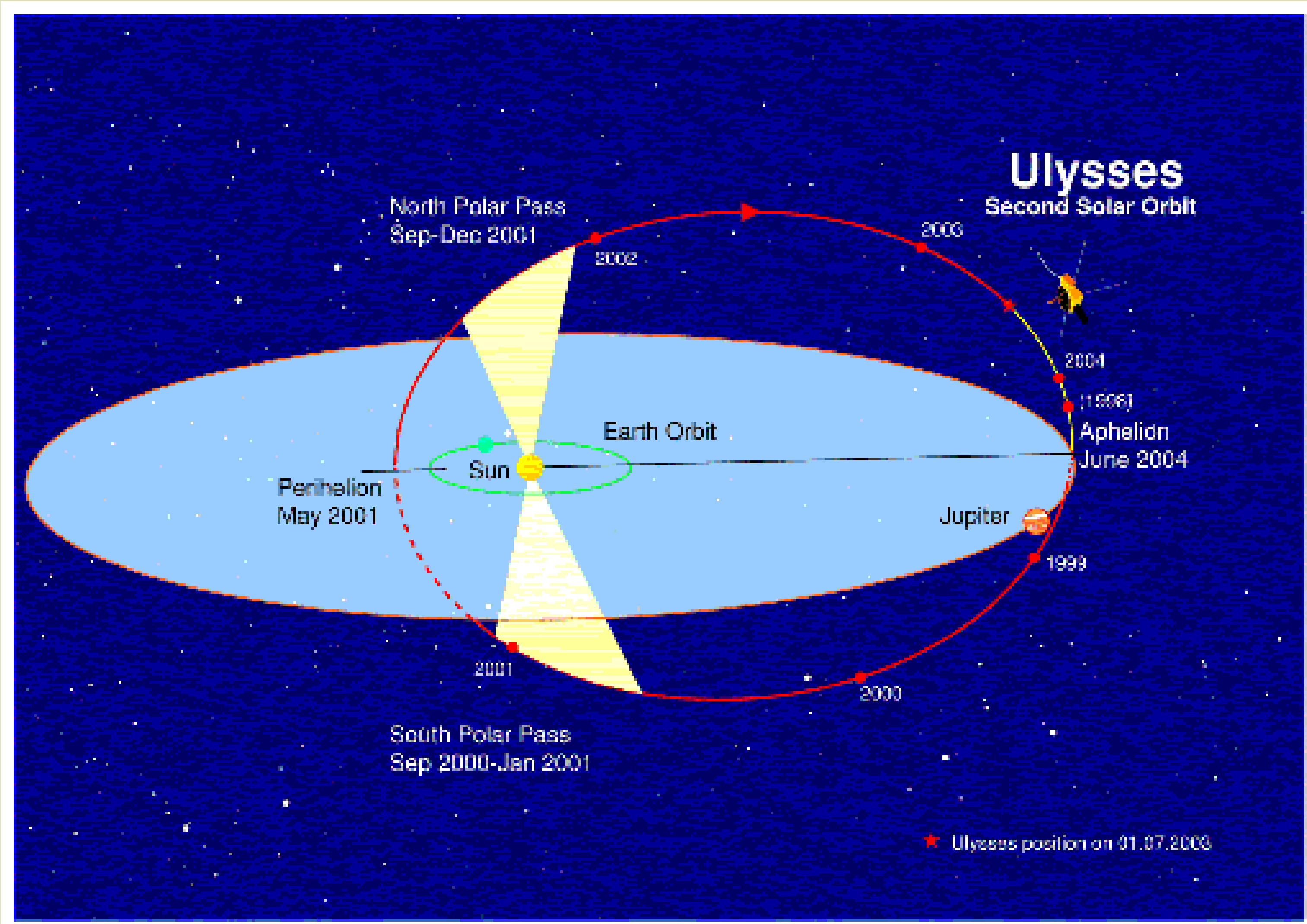
Fig. 5. Mg≡1 normalized element abundances in the dust of comet Halley and the solar photoshere, both relative to the abundances in CI-condrites. The elements are ordered according to their volatility and recent abundance values were used as explained in the text. The solar hydrogen abundance is multiplied by 0.01. Because of the lack of calibration, Halley's dust data are believed to be certain within a factor two.

Mann & Jessberger in: Astromineralogy

ULYSSES SPACECRAFT



ESA Ulysses Webpag



ESA Ulysses Webpag