

Dust in the Solar Corona

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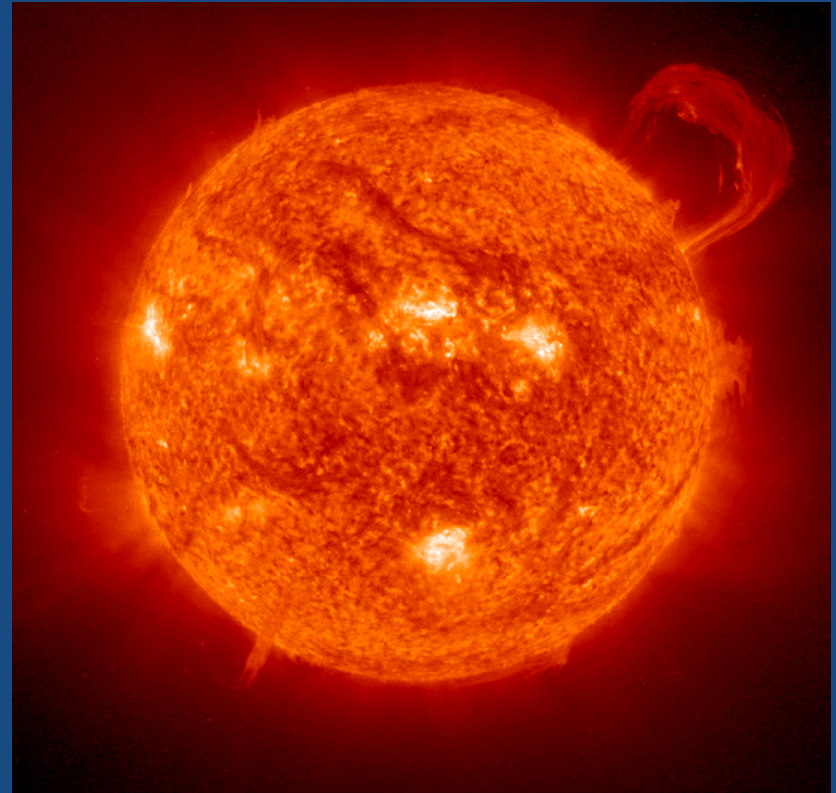


Image credit SOHO

Motivation



Unanswered questions about the Sun:

- coronal heating

- nature of magnetic field

Solar Probe mission to explore such questions, cancelled in 2001.

Plans begun for a new mission with similar objectives.

Approach Sun within 1.3 million miles (3 solar radii).

Spacecraft moving at ~300 km/s at closest approach.

Dust can cause a great deal of damage to an object moving that quickly.

Study dust populations near Sun to better plan mission.

About the Solar Corona

The solar corona is composed of gas, dust, molecules, and magnetic fields that constantly stream off the Sun's surface.



Image Credit Fred Espenak

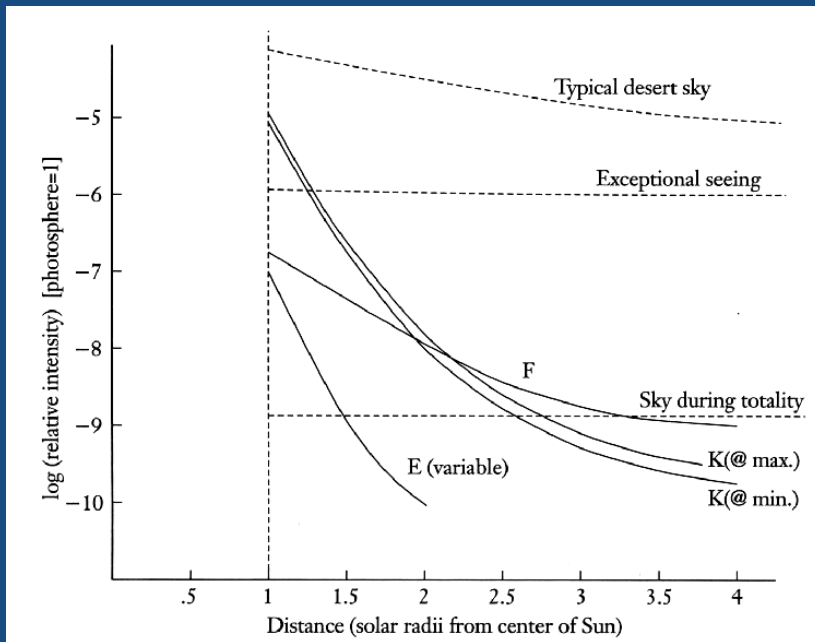


Image credit Golub 2001.

Four Coronal Components:

1. K-corona, scattering off electrons.
2. F-corona, scattering off dust particles.
3. E-corona, emission lines produced by ions in the corona.
4. T-corona, thermal emission of dust particles.

Dust Origins

Interstellar Dust

Origin in other stellar systems

Permeates interstellar medium; just “passing through.”

Often high velocities, hyperbolic orbits

Interplanetary Dust

Origin from comets and asteroids

Asteroid and short-period comets: dust in ecliptic plane

Long-period comets (source in the Oort Cloud) populate all inclinations and thus are the source of most dust outside the ecliptic plane.

Interplanetary Dust composes up to 70% of dust near the Sun.

Dust Dynamics: Overview

In order to best understand where dust exists in the solar system, it is necessary to understand the forces that affect it.

Most straightforward: solar gravity.

Other forces:

- Solar Radiation Pressure

- Poynting-Robertson Drag

- Lorentz Forces

- Sublimation

- Rotational Bursting

Dust Dynamics: Solar Radiation Pressure

Radiation pressure provides a counter to gravity, where the acceleration goes as:

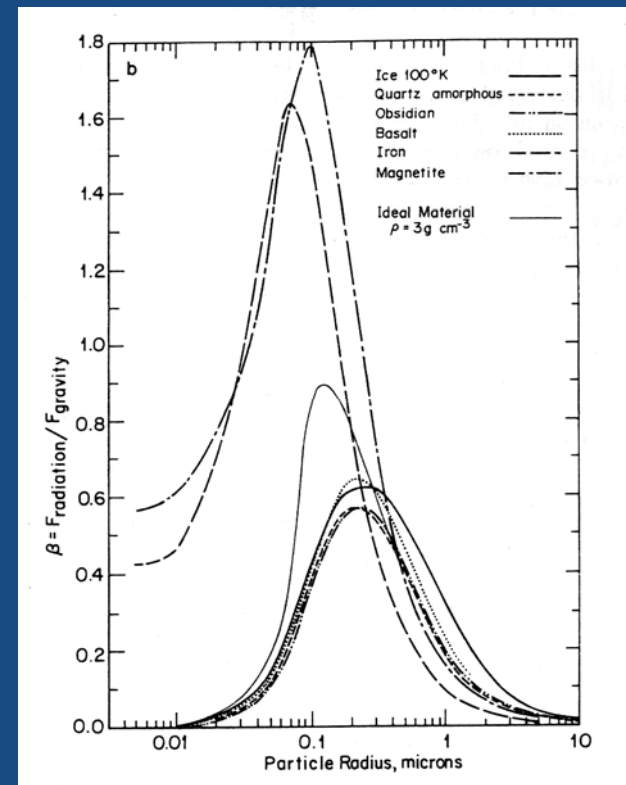
$$\ddot{\mathbf{Y}} = -(1 - \beta) \cdot \frac{GM}{r^2} \cdot \hat{S}$$

β is the ratio of radiation force to gravitational.

Depends on particle radius.

Orbits are unbound for $\beta > 1$.

For most particles ($\beta < 1$), radiation pressure serves to “soften” the effects of gravitation.

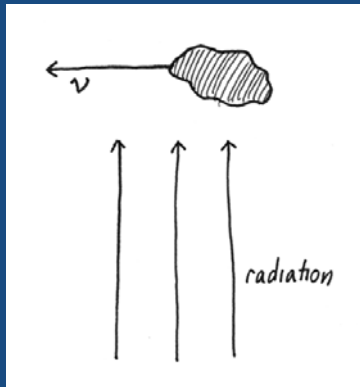


Graph credit Burns 1979.

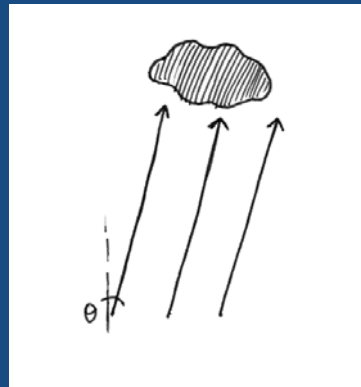
Dust Dynamics: Poynting-Robertson Drag

Solar Radiation also causes Poynting-Robertson drag.

From point of view of dust particle, incident radiation has a slight angle.



Sun's ref. frame



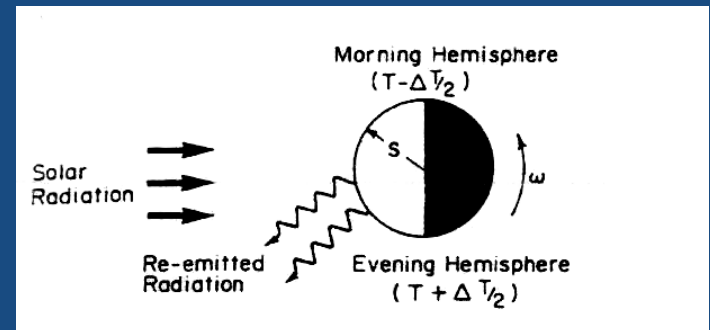
Grain's ref. frame

Small θ -component slows particle down; dissipates energy and angular momentum.

Grain spirals inward slowly.
($\tau \sim 4000$ years from 1 AU.)

Yarkovsky Effect

Affects efficiency of P-R drag for larger objects (1 m - 1 km).

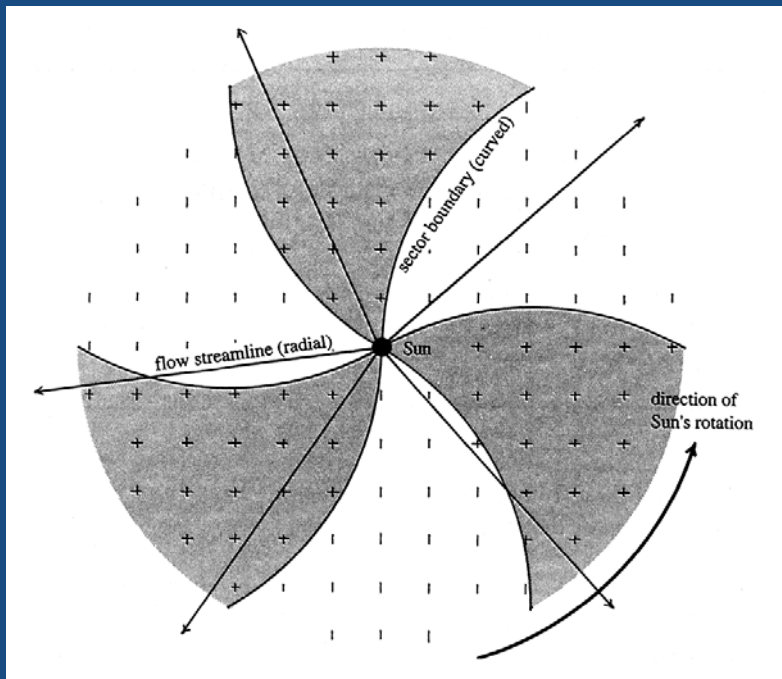


Dust Dynamics: Lorentz Forces

Dust grains in path of solar wind acquire a charge q over time.

Charge comes from interaction with solar plasmas, and from ultraviolet bombardment, which ionizes atoms on the grain's surface.

Charge causes them to interact with the Sun's magnetic field.



$$\mathbf{F} = q\mathbf{v} \times \mathbf{B}$$

Sun's magnetic field has sector structure in the ecliptic plane.

Grain is deflected out of and back into ecliptic as it moves around Sun.

Net result is minimal for larger grains, but small grains may be ejected from the solar system.

Image credit Lewis 1997.

Dust Dynamics: Sublimation

Sublimation provides an inner limit to near-solar dust cloud.

Near the Sun, elements will sublimate, reducing grain radius until it becomes a β -meteoroid and is ejected from the solar system.

Sublimation governs composition of grain particles:

- ice, iron, magnetite, and other heavy elements cannot survive
- most near-solar grains thought to be composed of silicates and carbon, which can survive.

Thought to be a dust-free “sublimation zone” near the Sun, where grains have been entirely obliterated.

Dust Dynamics: Rotational Bursting

Another phenomenon that removes dust from the solar system.

Grains are not idealized spheres, no many times we approximate them as such.

Grains are irregularly shaped.

Reflectivity and irregular heating can push on grains, causing them to rotate faster until particle bursts.

Effects of rotational bursting increase as grain nears the Sun.

Provides another mechanism of dust removal for nearest grains.

Occurs on shorter timescales than P-R drag.

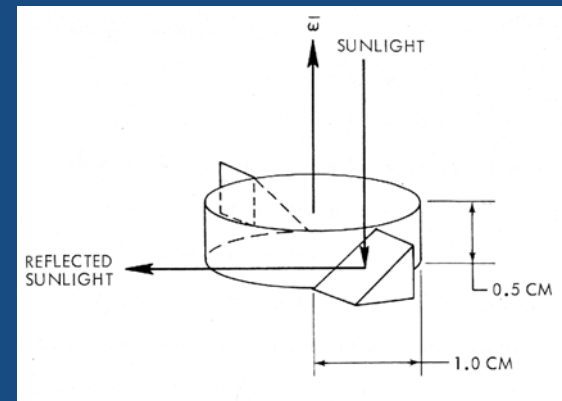


Image credit Paddack 1973

Dust Grain Characteristics

Composition

Sublimation and blackbody observations tell us that grains are most likely made of silicates and small amounts of carbon.

Grains are probably highly porous. See image.

Sizes

Grain sizes near Sun between $0.01 \mu\text{m}$ and $100 \mu\text{m}$ in diameter. Smaller particles subject to ejection, larger particles not as effected by P-R drag. Mass $m \sim 10^{-11} \text{ kg}$.

Temperatures

Grains absorb energy from sunlight, loose energy through re-radiation and sublimation. Temperature observed to be $\sim 2100 \text{ K}$.

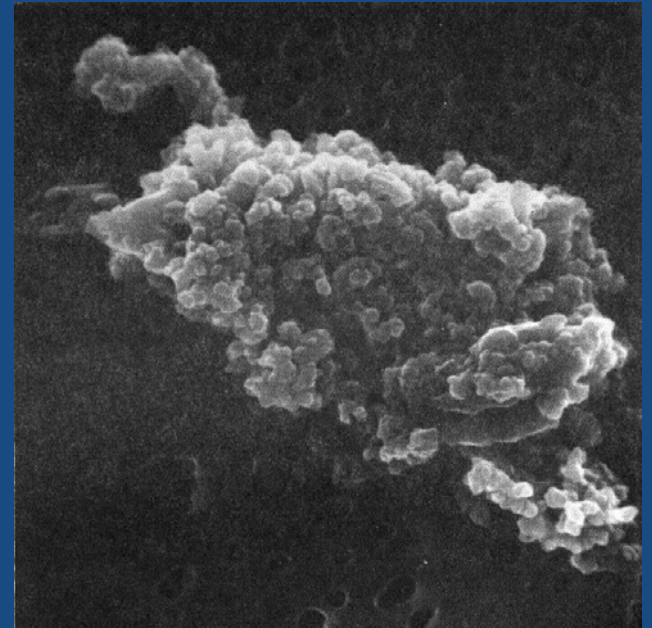


Image credit Brownlee 1963.

Location: Observations

Dust best observed by measuring brightness of F-corona.

F-corona can be difficult to separate from K-corona, line-of-sight problems when interpreting data.

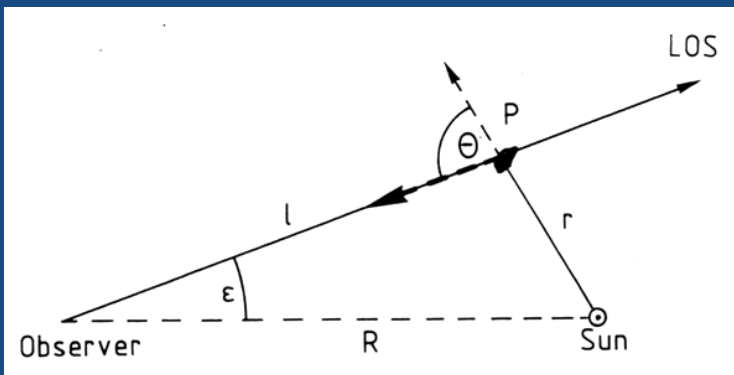


Image credit Mann 1992.

Solar Dust Ring?

F-corona enhancement at $4 R_{\odot}$ observed during 1966 solar eclipse.

Not observed during 1991 eclipse.

Either a transient feature, or never there to begin with.

Inner solar system number distribution $n(r) \sim r^{-1.3}$, but changes near Sun.

1991 eclipse observations indicate even distribution between 2 and $9 R_{\odot}$.

Dust-free zone must therefore exist inside 2 to $3 R_{\odot}$.

Location: Models

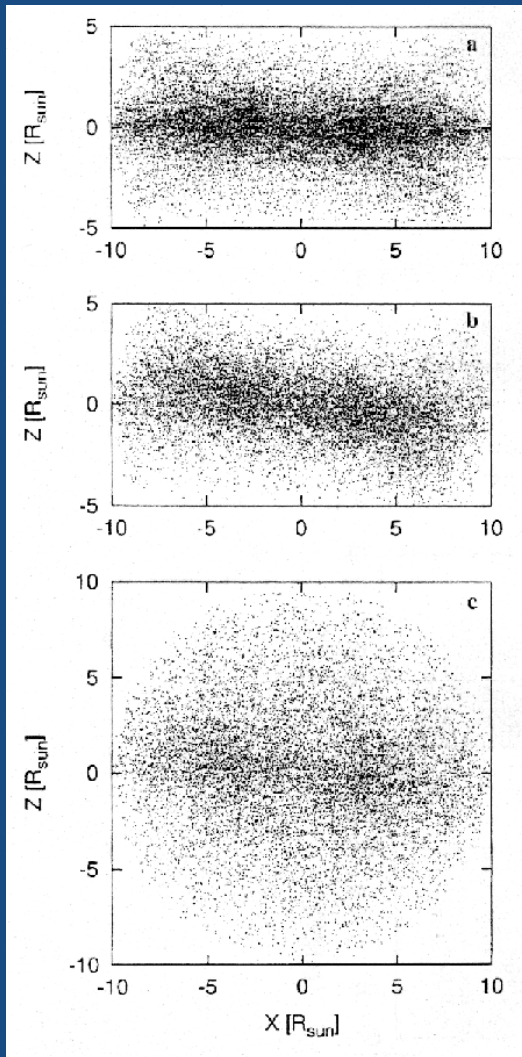


Image credit Mann *et al.* 2000

Most elaborate modeling to date by Mann *et al.*
at the *Max-Planck-Institut für Astronomie*.

Dust models begin with more well known
distribution at 1 AU.

Track dust's evolution through solar system.

Accounting for solar gravity, radiation pressure,
P-R effect, Lorentz forces, and sublimation.

At left, simulation results for grain sizes 3 μm ,
0.5 μm , and 0.1 μm .

Found number density to be $\sim 10^{-8} \text{ m}^{-3}$.

Implications for Spacecraft

An object in an elliptical orbit will follow velocity relation

$$v = \sqrt{G \cdot M \cdot \left(\frac{2}{r} - \frac{1}{a} \right)}$$

Which becomes, at perihelion,

$$v = \sqrt{G \cdot M \cdot \frac{(1+e)}{p}}$$

Thus, at closet approach, spacecraft will be moving at ~300 km/s.

A dust grain in a circular orbit will move at ~200 km/s in the same direction.

Velocity of impact ~100 km/s.

For a mass of 10^{-11} kg, each impact will have ~0.01 J of energy.

Satellite in orbit with $p = 4 R$ and $e = 0.75$ has an orbital period of 7.4 days.

With a dust flux of $4 \times 10^{-3} \text{ m}^{-2} \text{ s}^{-1}$, a 1 m^2 satellite could encounter as many as 2500 impacts over one orbit, thus absorbing up to 25 J with each orbit.

Summary

Potential for damage to spacecraft by dust grains near the Sun is not insignificant.

Perhaps more importantly, the dust near the Sun is not well understood.

Many forces conspire to move dust around the solar system: solar radiation, magnetic effects, Poynting-Robertson drag, sublimation, and rotational bursting.

Dust is subject to forces that do not affect larger bodies like the Earth; provide a way to study these subtler forces.

Perhaps new solar mission should also include a dust detector to better understand the population of dust near our Sun.

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