

An introduction to the plasma state in nature and in space

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The plasma state of condensed matter is ...

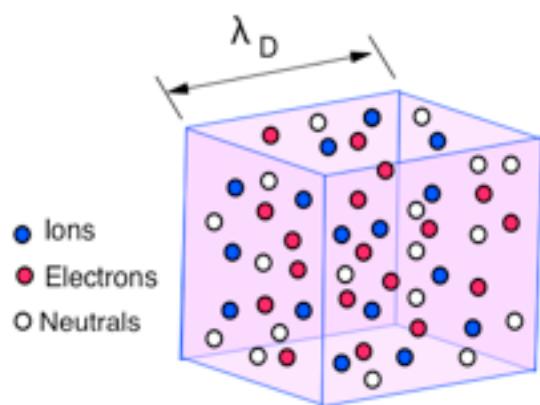
The *classical plasmas* are mixtures of electrons, ions and neutral atoms, resulting from the partial ionization of a neutral gas. The *dusty plasmas* also contain charged solid grains.

They are roughly characterized by the densities n_e , n_i of charged particles, neutral gas atoms n_a and the equilibrium temperature T

The plasma is said *fully ionized* when the density of neutral atoms is n_a negligible and *partially ionized* otherwise.

The electric field, ...

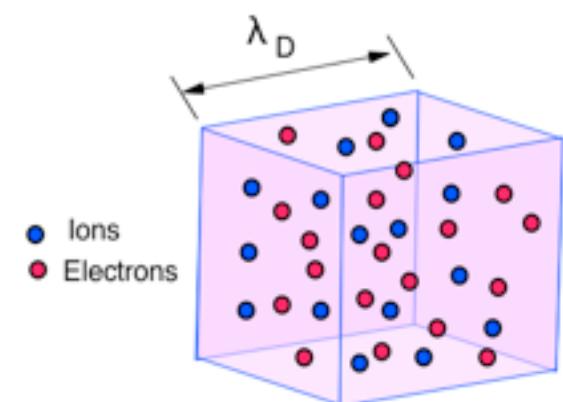
$$\nabla \cdot \mathbf{E} = \frac{e}{\epsilon_o} (Z n_i - n_e)$$



$$n_e \simeq n_i \quad \mathbf{E} \simeq 0$$

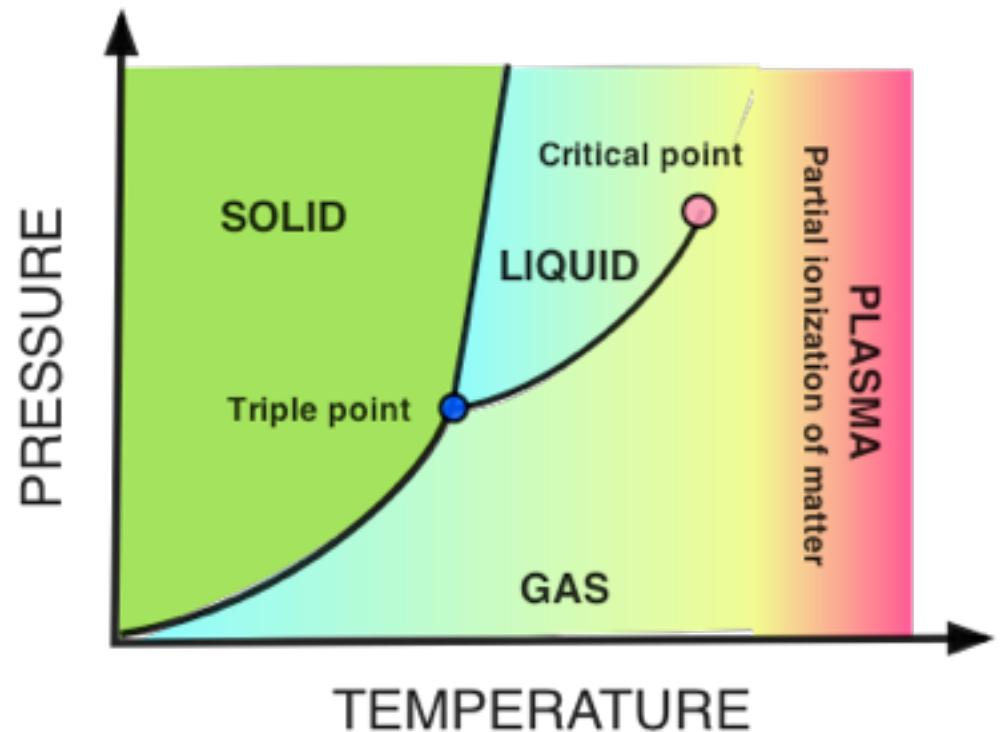
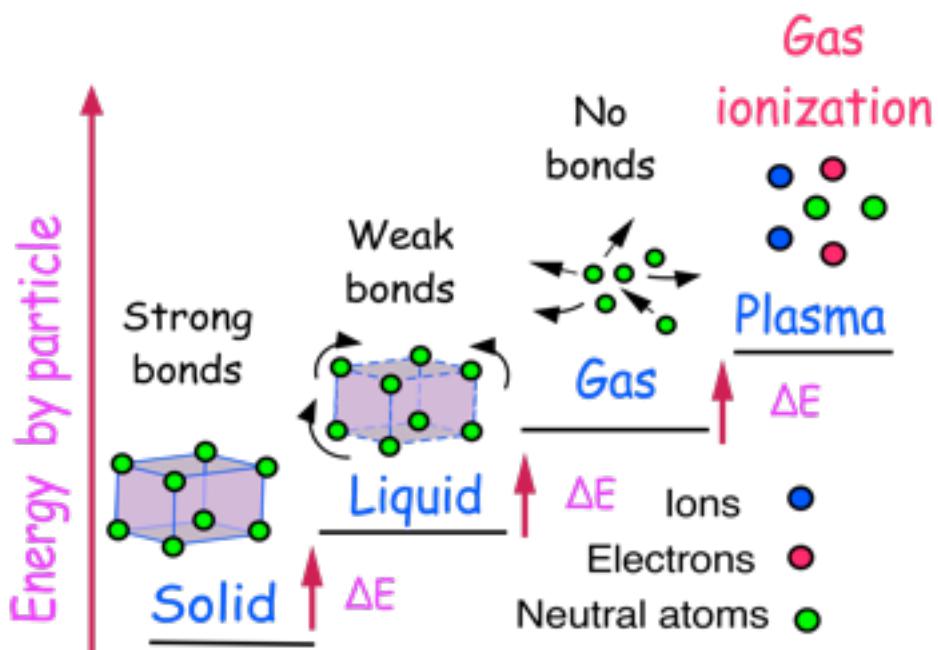
$$L \simeq \lambda_D$$

Quasineutral plasma



Are plasmas a equilibrium state of condensed matter?, ...

The atomic bonds roughly classify the different states of condensed matter *in equilibrium*,



The plasmas are high energy states of matter...

In the **thermodynamic equilibrium** of a gas, the Saha equation predicts the fraction of ionized atoms at a given temperature,

$$\alpha = \frac{n_e n_i}{n_a} \approx 2.4 \times 10^{21} T^{3/2} \exp(-E_I/k_B T)$$

where E_I is the ionization potential of the neutral gas and k_B the Boltzmann constant.

$$T = 300 \text{ K} \quad E_I = 15.8 \quad (\text{Argon}) \quad \alpha \sim 10^{-120}$$

The **ionization remains low except for high temperatures**, or equivalently of non equilibrium states of the gas. Therefore, plasmas require of an **external energy** sources to exist ... however **this situation is frequent in nature**

The plasmas are present in our everyday life...



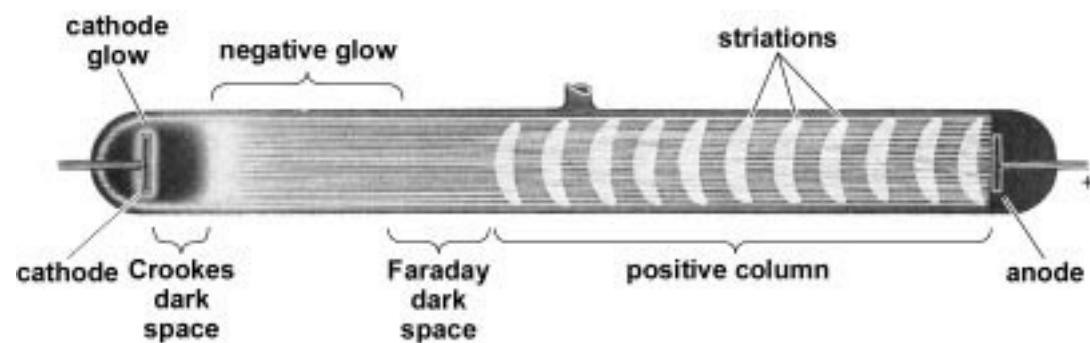
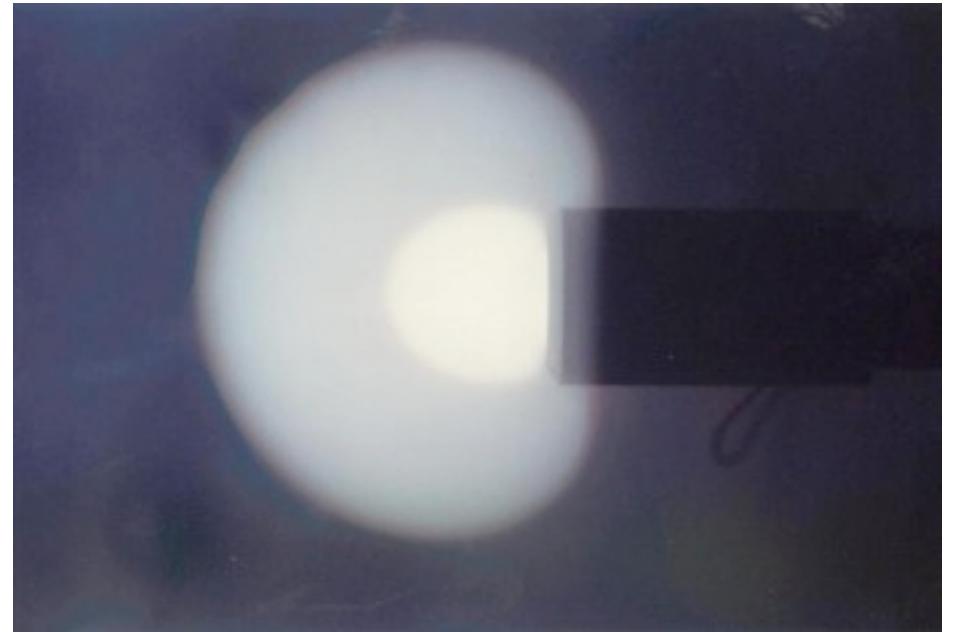
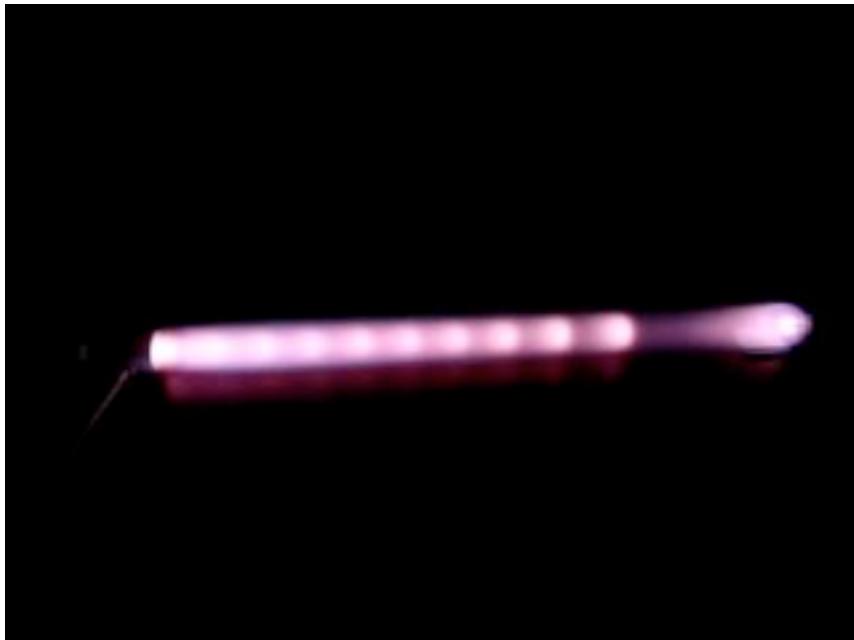
Auroras seen from the
Space Shuttle

NASA

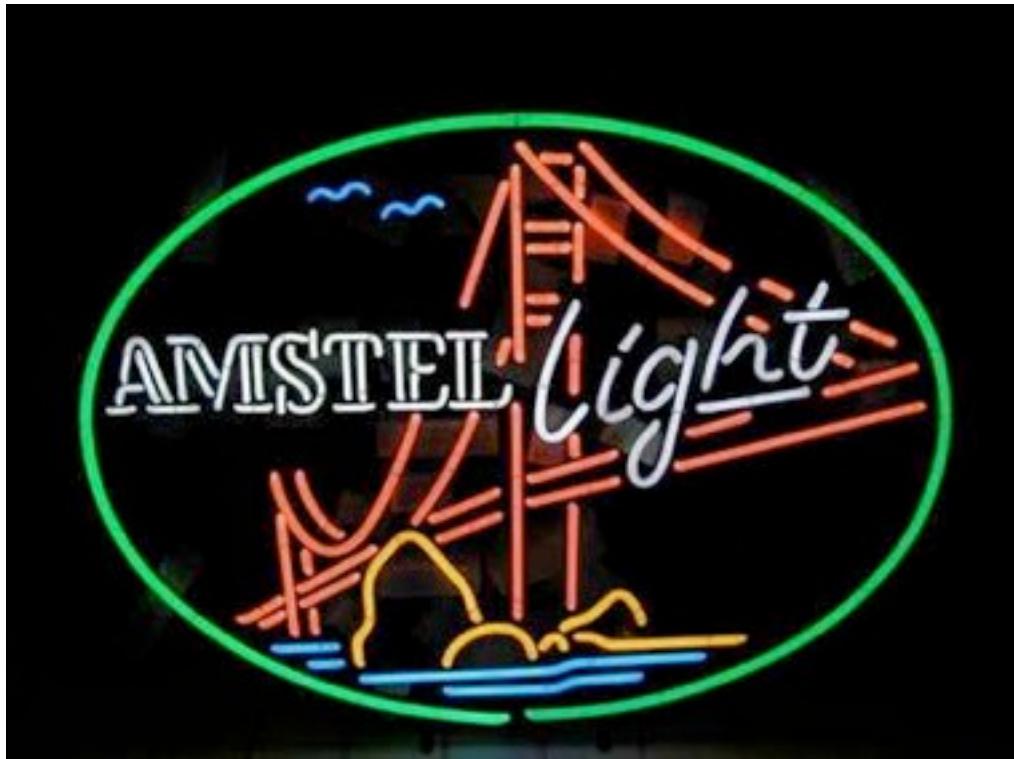


The storms release large amounts of energy that ionize the neutral gases of air. The medium becomes, ...*electrically conductive*...

Laboratory plasmas produced by electric discharges ...



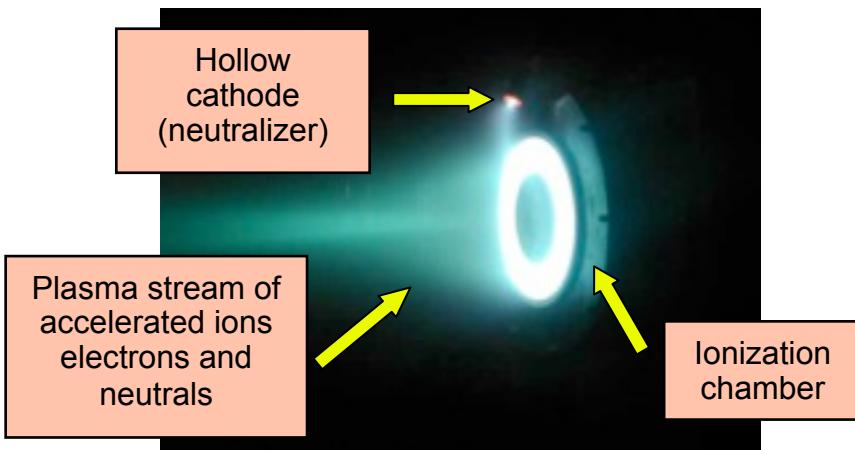
... that give raise to technological breakthroughs ...



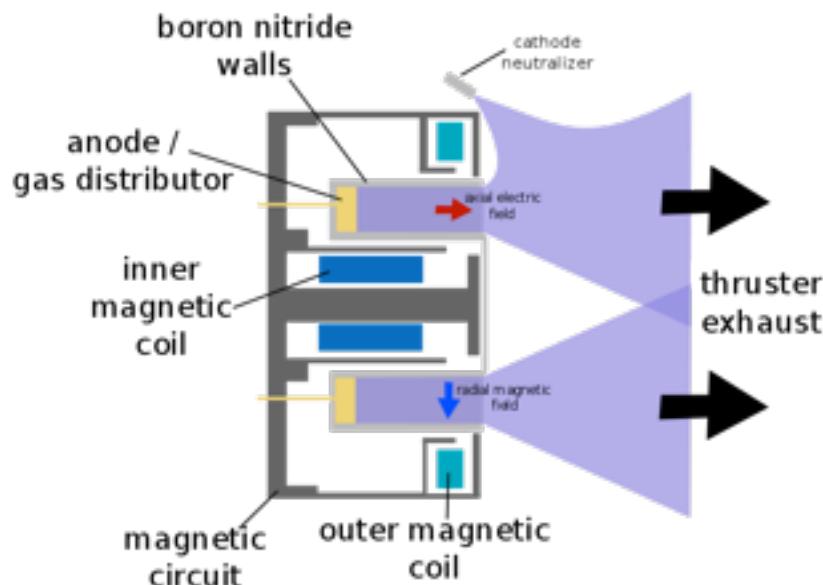
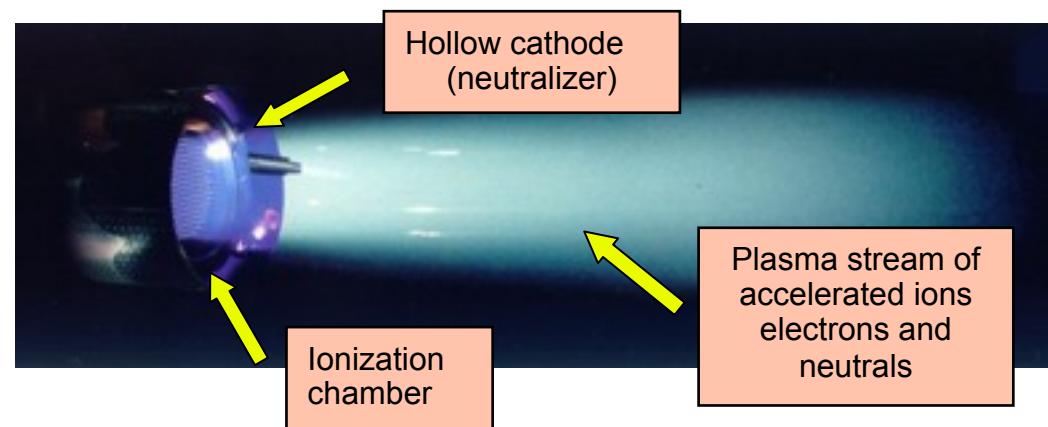
The gas discharge physics is a subject of current research with a huge number of practical applications.

Electric propulsion; different concepts and configurations, ...

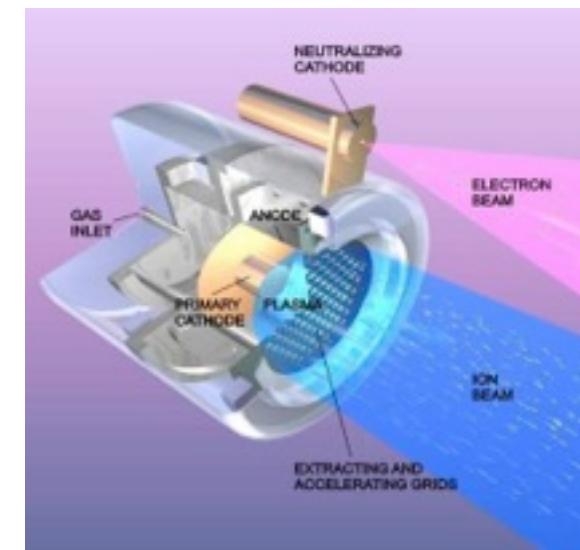
Hall effect thruster



Gridded electrostatic thruster



Ion acceleration by ExB fields



Ion acceleration by a set of metallic grids, essentially static.

Why plasma propulsion in space?, ...

The thrust T is the time derivative of momentum

$$T = \frac{d}{dt} (M_s(t) V_{ex})$$

Total mass of the
spacecraft

$$M_s(t) = m_p(t) + m_d$$

Decreasing
propellant mass

Exhaust velocity of
the propellant

Payload mass
(dry mass)

The objective is to increment $\Delta V = V_f - V_i$ the velocity of the payload mass m_d by using the decreasing propellant mass $m_p(t)$ expelled with a constant exhaust velocity V_{ex}

$$\begin{aligned} M_{si} &= m_{pi} + m_d \\ M_{sf} &= m_d \end{aligned}$$

$$\Delta V = V_f - V_i = \int_{V_i}^{V_f} dV = -V_{ex} \int_{m_{pi}+m_d}^{m_d} \frac{dM_s}{M_s}$$

$$\Delta V = V_x \ln \left(\frac{m_d + m_{pi}}{m_d} \right)$$

$$\frac{m_{pi}}{m_d} = e^{\Delta V / V_{ex}} - 1$$

The mass of propellant required to increment ΔV the rocket speed exponentially decreases when V_{ex} grows

The specific impulse

Introducing I_{sp} in seconds as, $I_{sp} = \frac{V_{ex}}{g_o}$ $\Delta V = I_{sp} g_o \ln \left(\frac{m_d + m_{pi}}{m_d} \right)$

Using the previous equation we obtain two equivalent definitions for I_{sp}

$$T = V_{ex} \dot{m}_p = I_{sp} g_o \dot{m}_p \quad I_{sp} = \frac{\dot{m}_p V_{ex}}{\dot{m}_p g_o} \quad I_{sp} = \frac{T}{\dot{m}_p g_o}$$

The specific impulse allows to compare the efficiency of the different propulsion systems

Electric charge acceleration is an attractive idea because ions accelerated up to $E_b = 1 \text{ eV}$ (voltage drop of 1 volt) reach velocities in the order of $V_{ex} \approx 10^5 \text{ m/s}$, much higher than conventional chemical thrusters.

System	$V_{ex} (\text{m/s})$	$I_{sp} = V_{ex}/g_o (\text{s})$
SSME (Space shuttle)	4.400 (hot gases)	450
Gridded ion thruster	30.000 (ions)	3.000
Hall Ion thruster	10.000-30.000 (ions)	1.000-3.000

And how much thrust we obtain? ...

The values of thrust are in mN in this table

$$T = \sqrt{\frac{2 M_i}{e}} I_{ion} \sqrt{V_{acc}}$$

Xenon	Acceleration voltage (V_{acc})					
	I_{ion} (mA)	1	10	100	1.000	1500
1	0,00165	0,0052	0,00165	0,052	0,064	0,165
5	0,00825	0,0261	0,0825	0,261	0,32	0,825
10	0,0165	0,0522	0,165	0,522	0,64	1,65
50	0,0825	0,2609	0,825	2,61	3,2	8,25
500	0,165	0,523	1,65	5,22	6,39	16,5
100	0,825	2,609	8,25	26,1	31,95	82,5
1000	1,65	5,22	16,5	52,18	63,9	165
1500	2,48	7,83	24,75	78,27	9,586	247,5

The electric propulsion, ...

Advantages

- Powered by solar panels.
- Propelled by chemically inert gases (xenon) of easy long term stowage.
- High efficiency: large values of the specific impulse allows long term missions.

Drawbacks

- Only operate on the outer space.
- Low levels of thrust, in the order of 1-100 mN (space manoeuvres take long!)
- Require of neutral gas mass flow rates in the order of tens of sccm (standard cubic centimeters by minute).
- The large electric power (typically few kW) required limits the use of these systems to heavy satellites with large solar panels (up to 30 kW).

Plasma propulsion foreseen future ..

Space waste and orbiting debris is one of the main concerns of space industry. In a nearby future legislations will bind satellite builders to provide the orbiters with the means to abandon the orbit after the mission.

The plasma propulsion offers considerable advantages for applications as in orbit station keeping, long-term geostationary satellites and deep space missions or planetary probes.

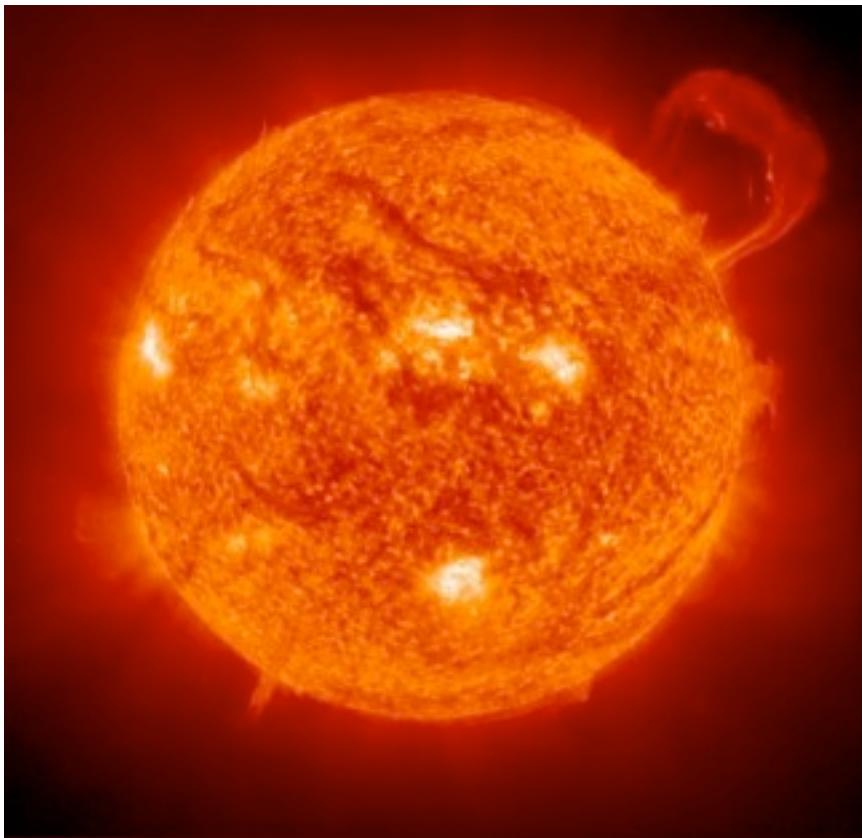
Recent reviews and ideas from plasma physics;

C. Charles. Plasmas for spacecraft propulsion. J. Phys. D: Applied Physics. **42** 163001 (2009)

E. Ahedo. Plasmas for space propulsion. Plasma Phys. Control. Fusion 53 (12) 124037 (18 pp.) (2011)

R.H. Frisbee. Advanced space propulsion for the 21st century. J. Prop. Power. **19** (6) pp. 1129-1154 (2003)

Plasmas are everywhere present in space, ...



The Sun ejects large amounts of charged particles in the form of *solar flares*, charged particles following the local magnetic field lines. Note that we deal with false colors, we only see the radiation from the H_{α} line of hydrogen spectra.

The lengths scale involved in solar flares are huge ...



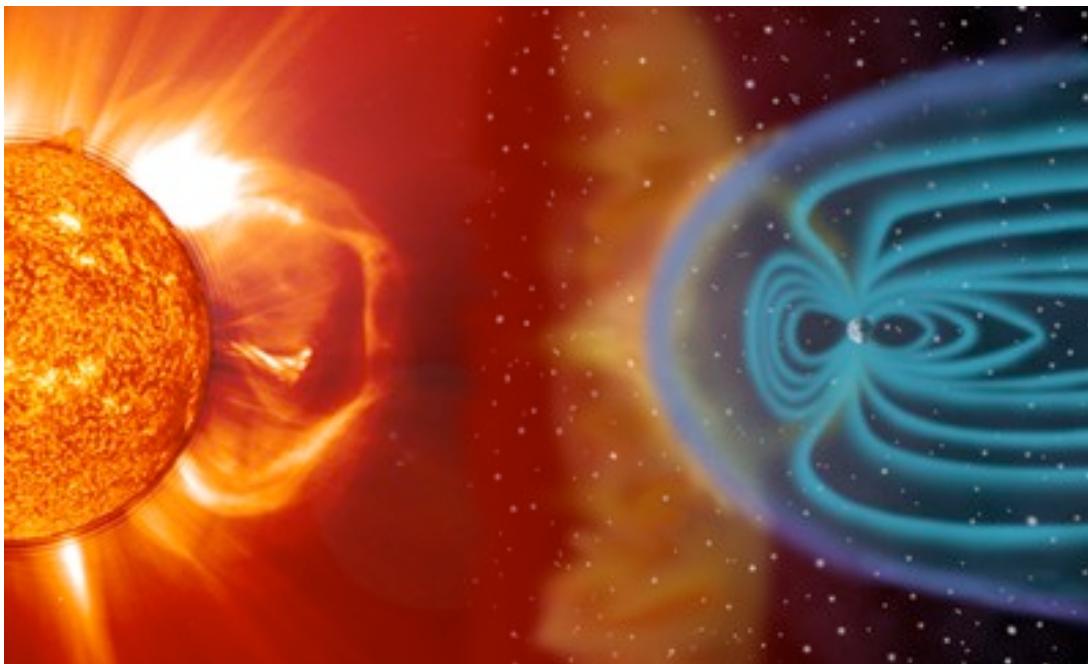
We can see these solar flares in action by courtesy of NASA, note that the time scale is not realistic,

The plasma structures in the sun chromosphere ...



These impressive images evidence the complex structure of the **sun chromosphere**, (we only see the H_α line of hydrogen spectra) where the transport of charged particles involves to **plasma waves and instabilities**.

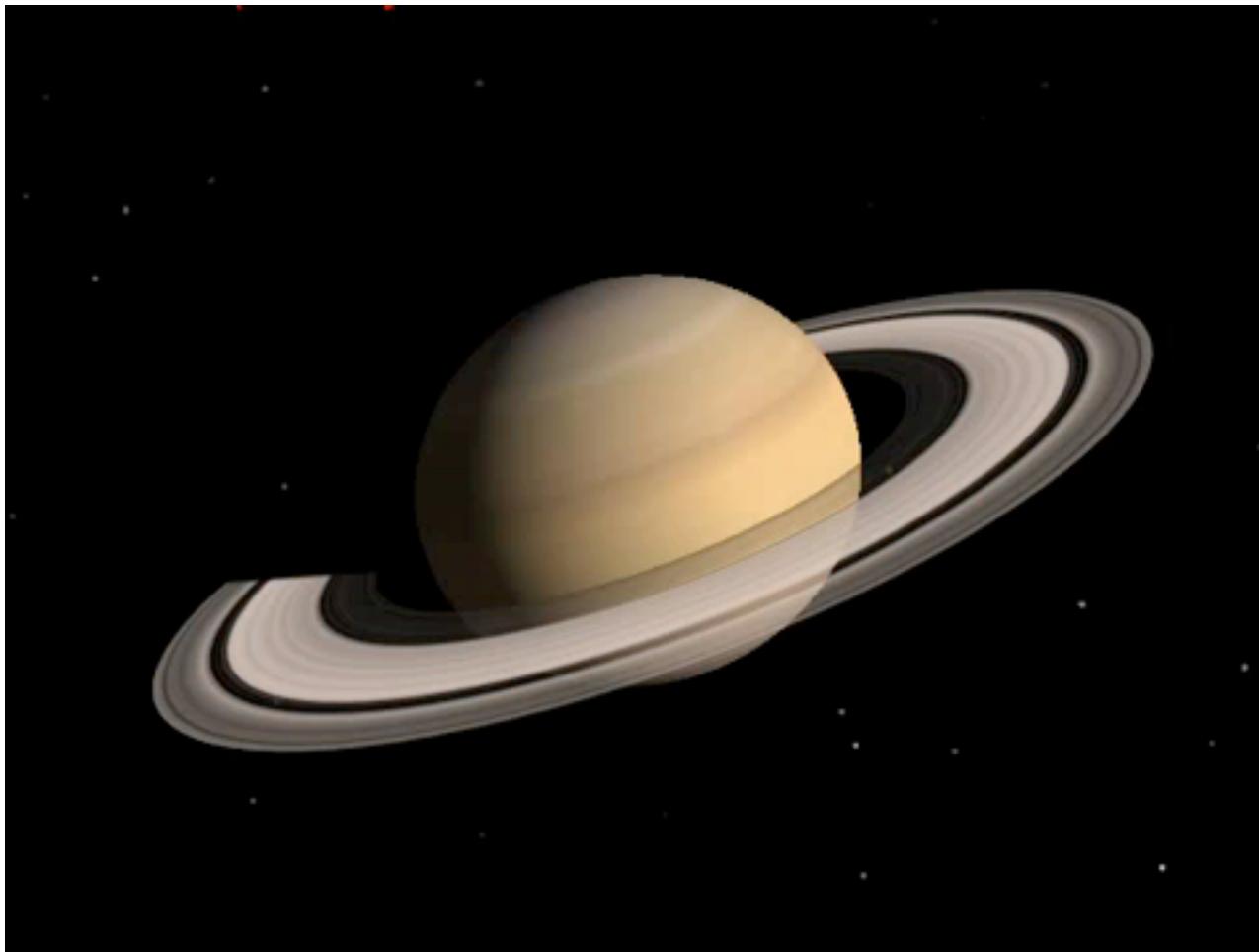
The plasma structures in the sun chromosphere ...



This solar stream of energetic particles **reach the Earth in minutes and penetrates the geomagnetic field** at the poles, forming the **aurora** at high latitudes

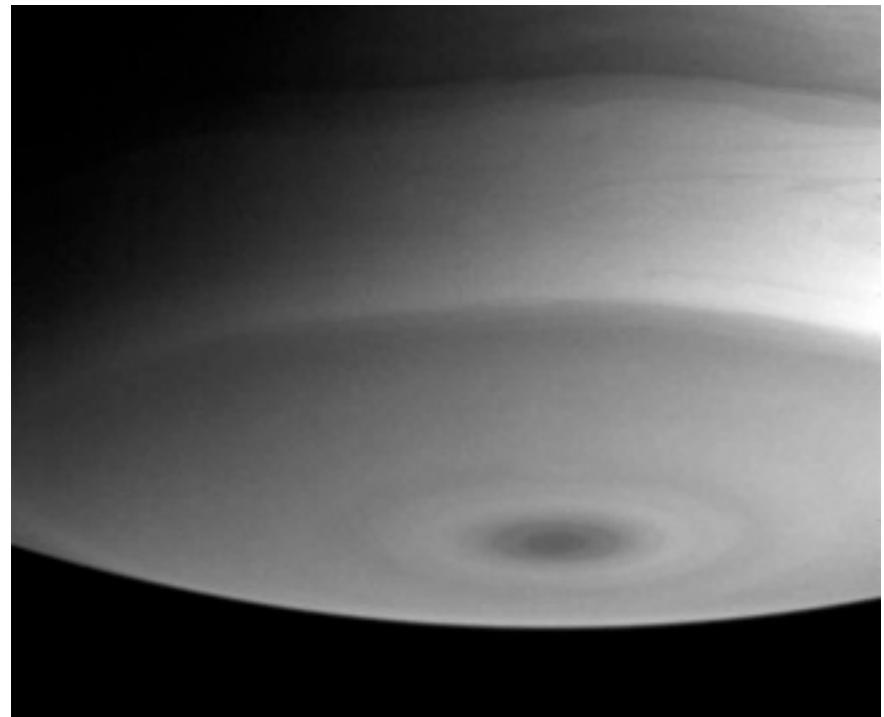
The particles moves along the magnetic field lines and **impact ionization** and excitation generates new particles and visible light

The plasmas are everywhere present in solar system ...



The impressive images from *Saturn* taken by Cassini show the planet shadow over the rings that are a *dusty plasma*.

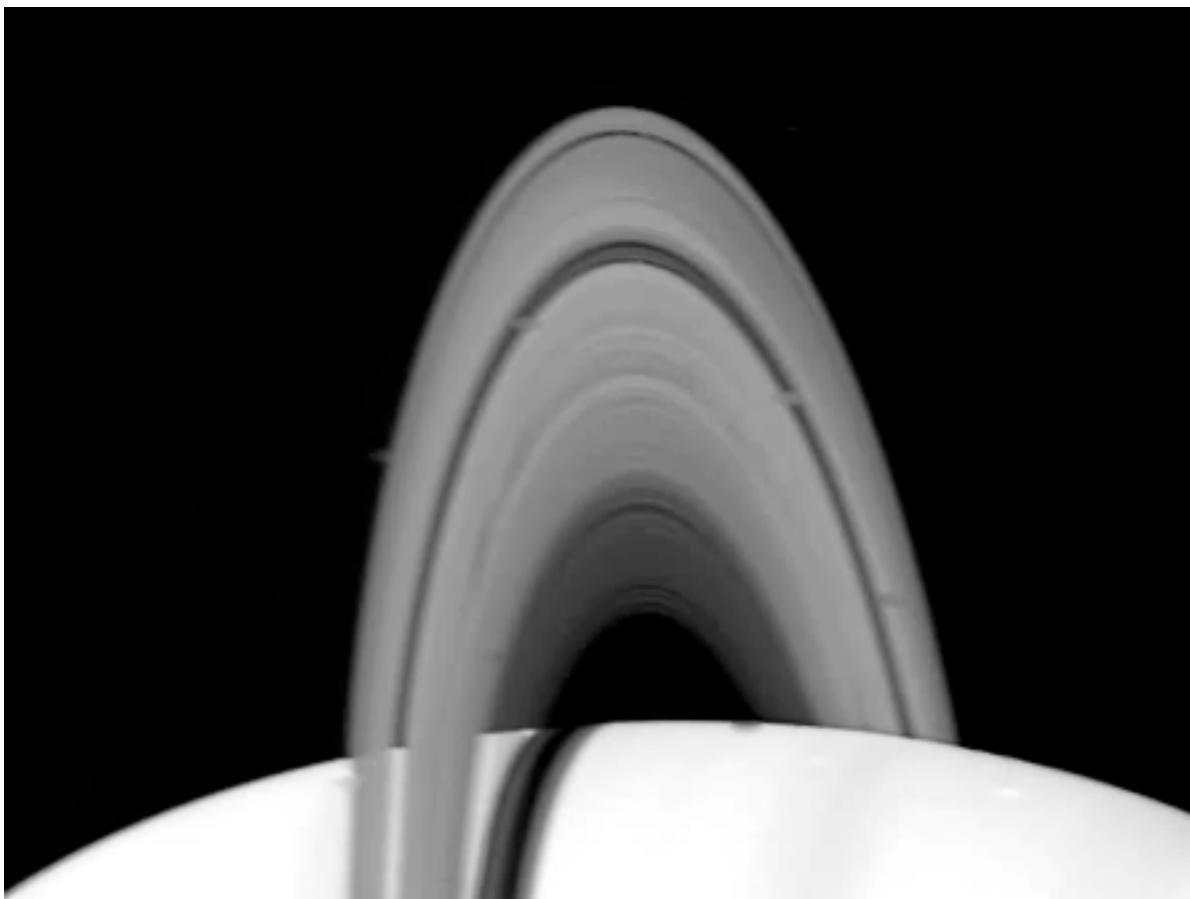
The filtered light reveals the plasma activity, ...



These impressive images shows the light emission caused electron impact collisions between neutrals and electrons at the poles

The structure of the rings is an example of a *dusty plasma*.

The spokes at the saturnian rings, ...



These waves along the saturnian rings were observed in 1980 by the Voyager

These radial spokes are waves located between 1.52-1.72 R_s

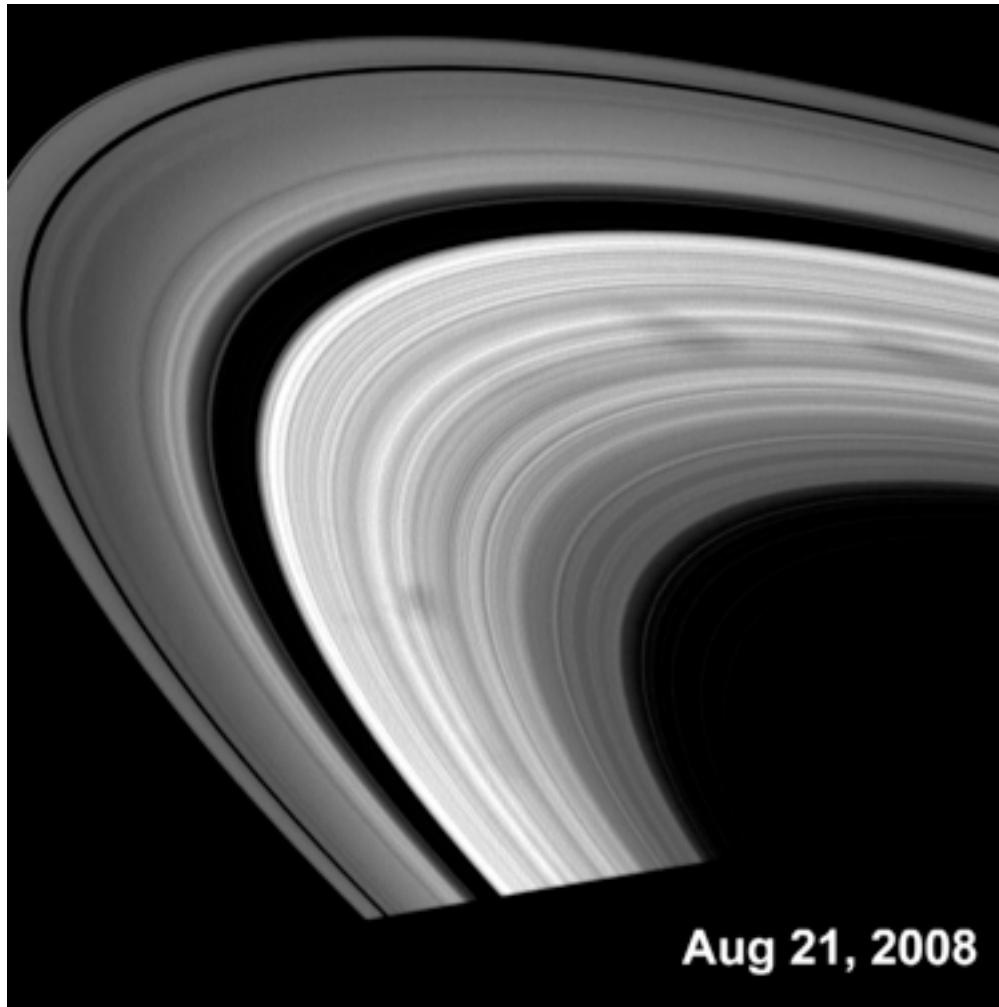
The solid particle densities in these rings are about,

$$n_g \approx 1 \text{ cm}^{-3}$$

The spokes are waves in a dusty plasma, ...

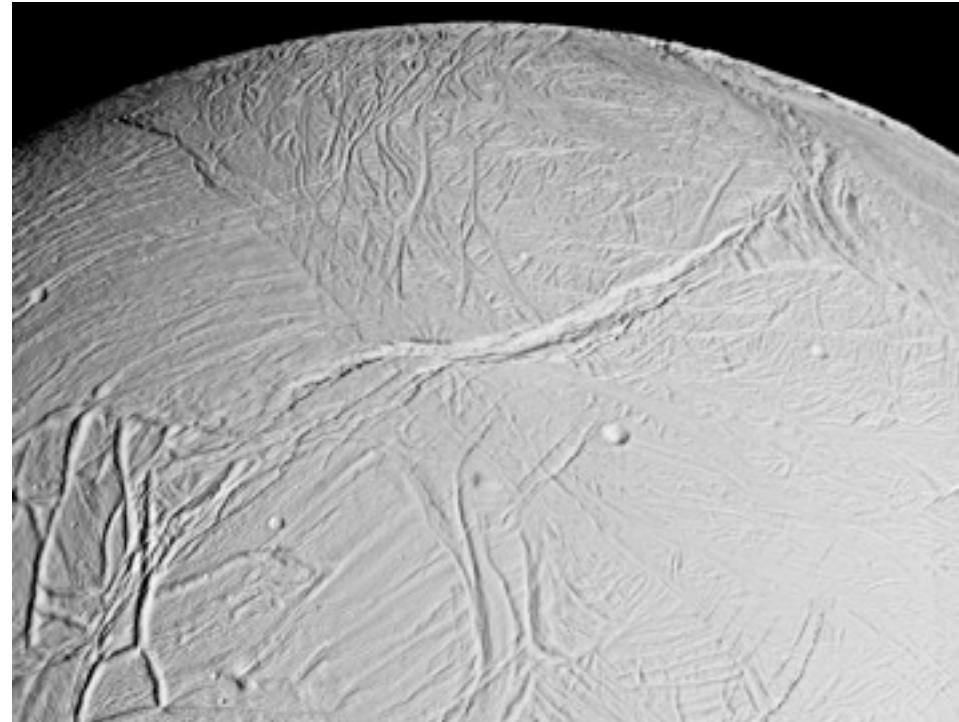
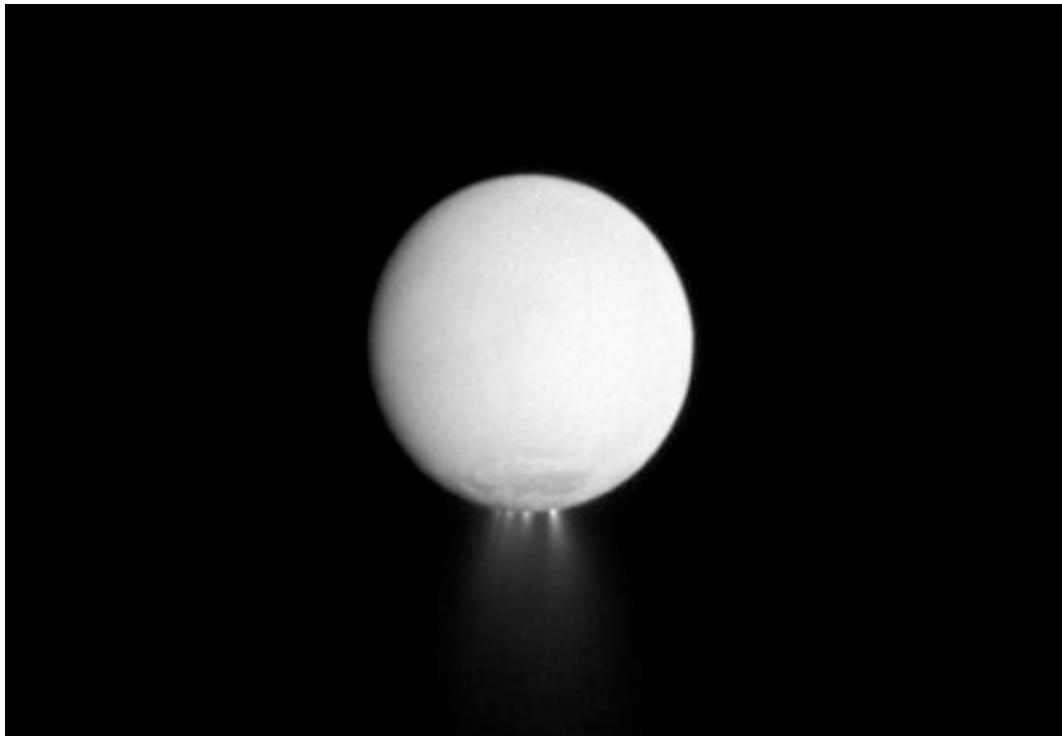
These spokes are *waves in the dusty plasma* of the rings and the fluctuations of n_g produce the dispersion of light.

The spokes are waves in a dusty plasma, ...



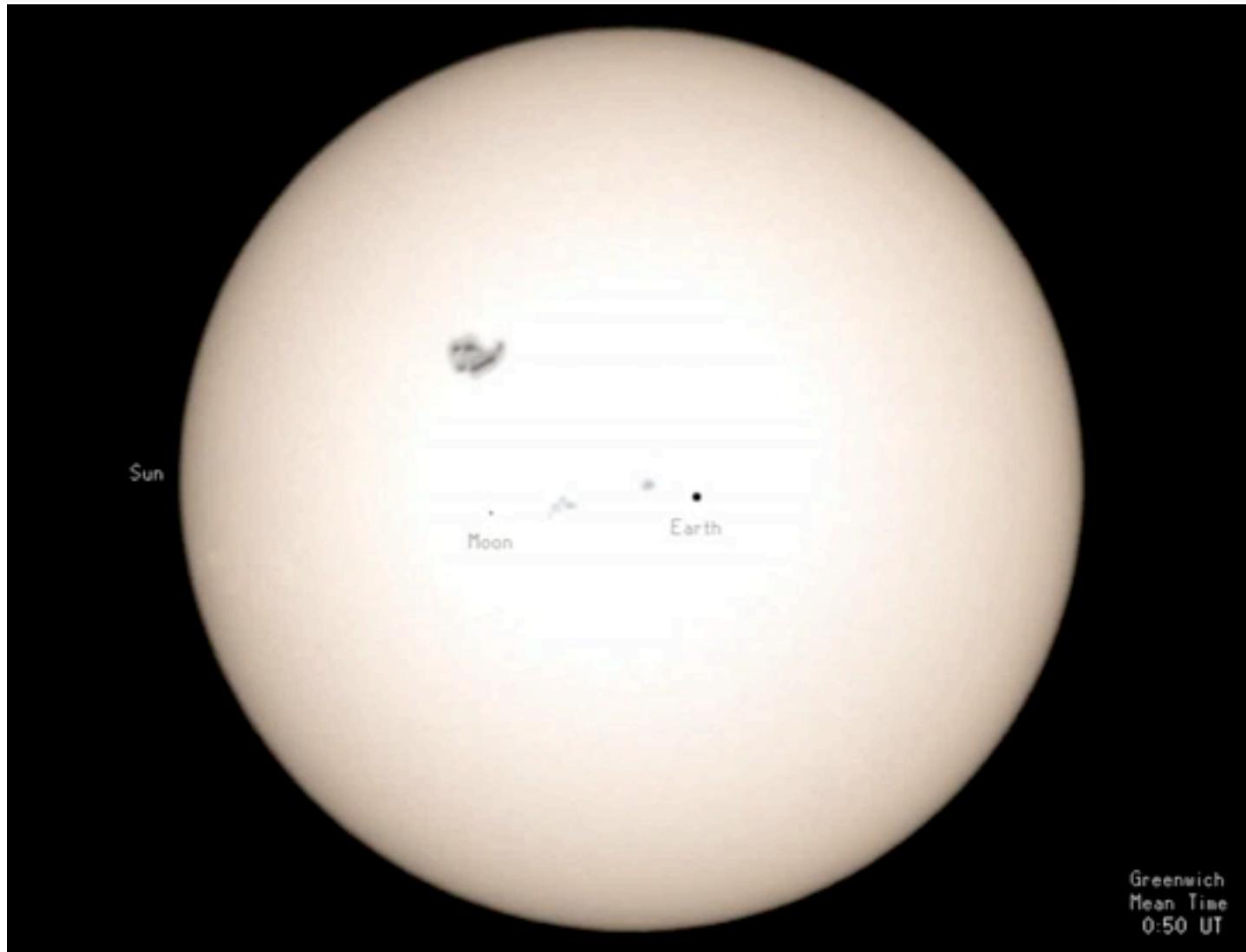
These spokes are *waves in the dusty plasma* of the rings and the fluctuations of n_g produce the dispersion of light.

The intriguing moon of Encelado, ...



This satellite seems to feed the saturnian rings with material from below its iced surface, but ...how?... Is this situation stable?

Have you ever been in Titan?, ...



This is not a computer simulation!

Unfortunately, the physical description of plasmas is hard as we will see in the next lecture, ...