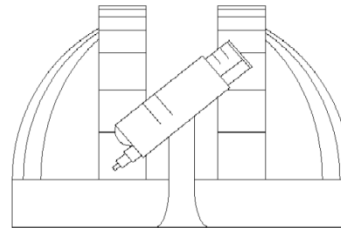


The Universe – a World of Plasma

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Summer University for Plasma Physics and Fusion Research

Greifswald / Germany

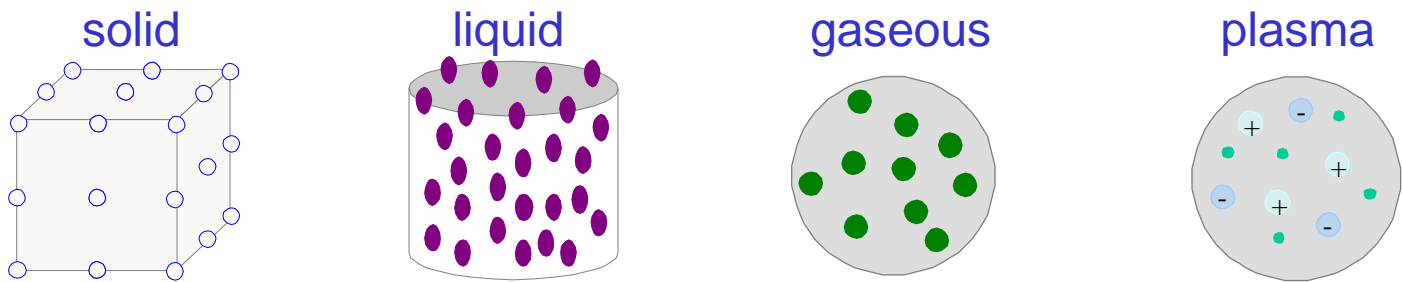
September 19, 2016

contents

- plasma – the fourth state of matter
- gas discharges in laboratory and their applications
- natural plasmas on earth and in the solar system
- sun and stars - compact plasma spheres in the space
- interstellar und intergalactic matter
- summary

plasma – the fourth state of matter

plasma – the fourth state of matter



state of matter	n	energy threshold	energy
solid (crystal)	1	lattice binding energy	0 ... 1 eV
Liquid	2	evaporation energy	0 ... 1 eV
Gas	3	ionization energy	1 ... 100 eV
Plasma	4	nucleon binding energy	10 eV ... 2 MeV
mixture of free nucleons and electrons	5		2 ... 200 MeV

solid → liquid → gas →

typical on earth

????? = **plasma**

typical state of matter in the Universe

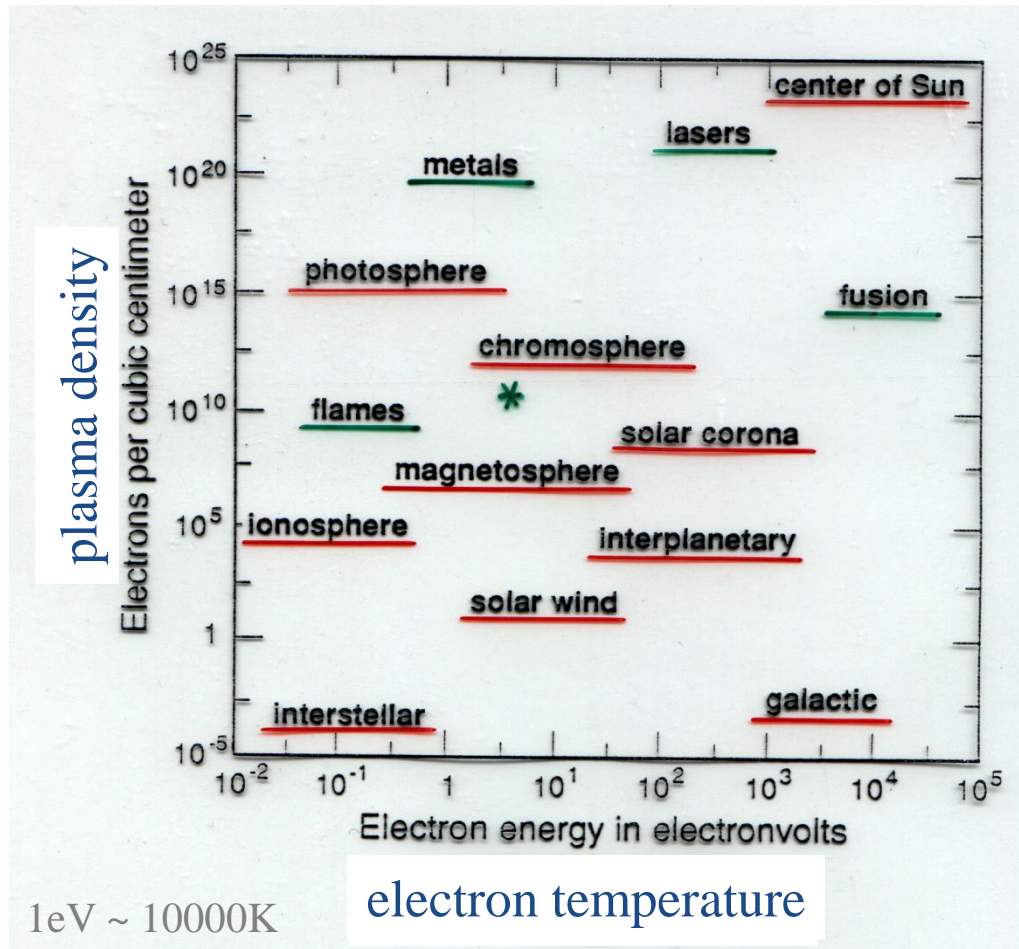
plasma – the fourth state of matter

plasma parameters

- quasi-neutrality
- charge distributions limited to space charges (λ_D)
- ionization degree x
(weakly ionized plasmas : $x \ll 1$,
heavily ionized plasmas : $x \sim 1$)
- plasma density (electron density) n_e
- energy distribution (kT_e), distribution functions (EEDF, IEDF)
- influenced by magnetic fields,
generation of magnetic fields (charge carriers)
- plasma radiation (line, continuum),
light

plasma – the fourth state of matter

typical plasmas



* lab plasma

electron temperature

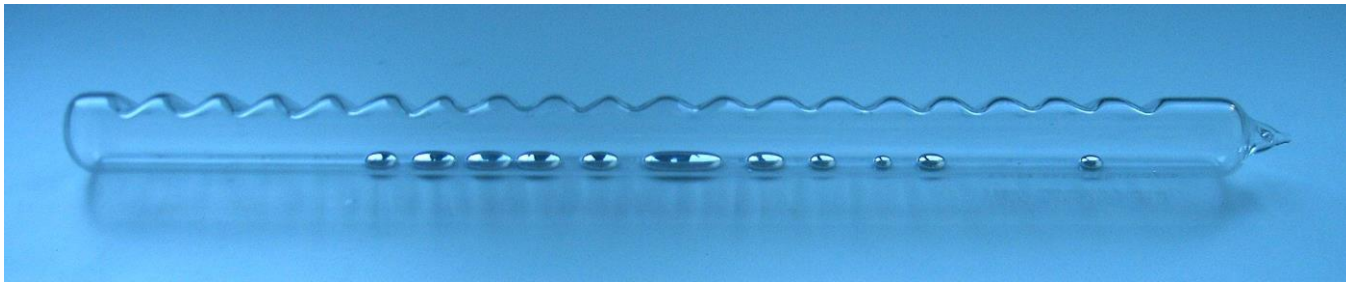
discharge types

- plasmas generated by chemical energy (oxidation)
flames, fire



discharge types

- plasmas generated by mechanical energy (friction)
Hg-droplets, Hg-vapour + Ne



discharge types

- plasmas generated by electric fields
separation of charges, sparks



influence machine (*Elektrisiermaschine*)
by Wilhelm HOLTZ (1865)

Professor in Greifswald 1884-1910

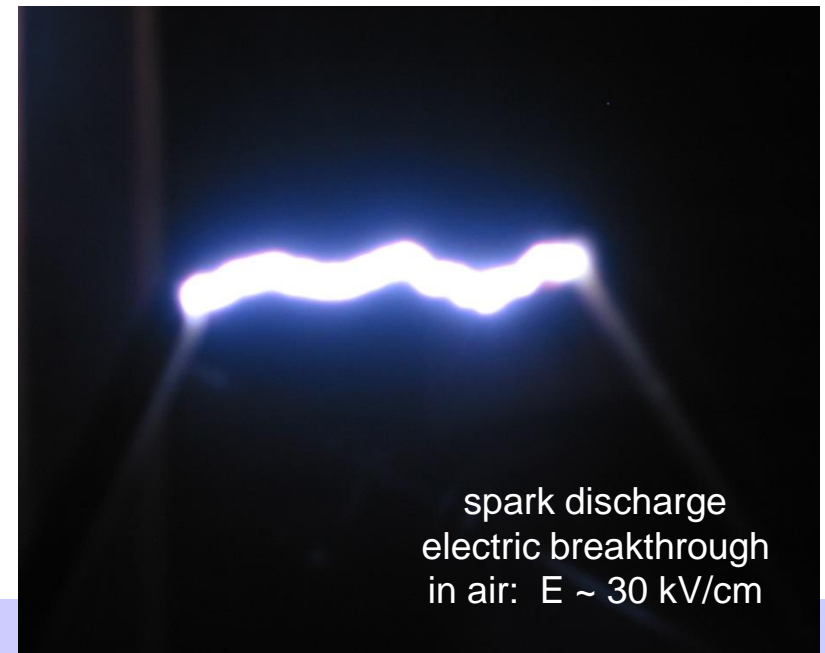
Kleist'sche Flaschen

priest Ewald Jürgen von Kleist, Cammin, 1745

Leidener Flaschen

physicist Pieter van Musschenbroek, 1746

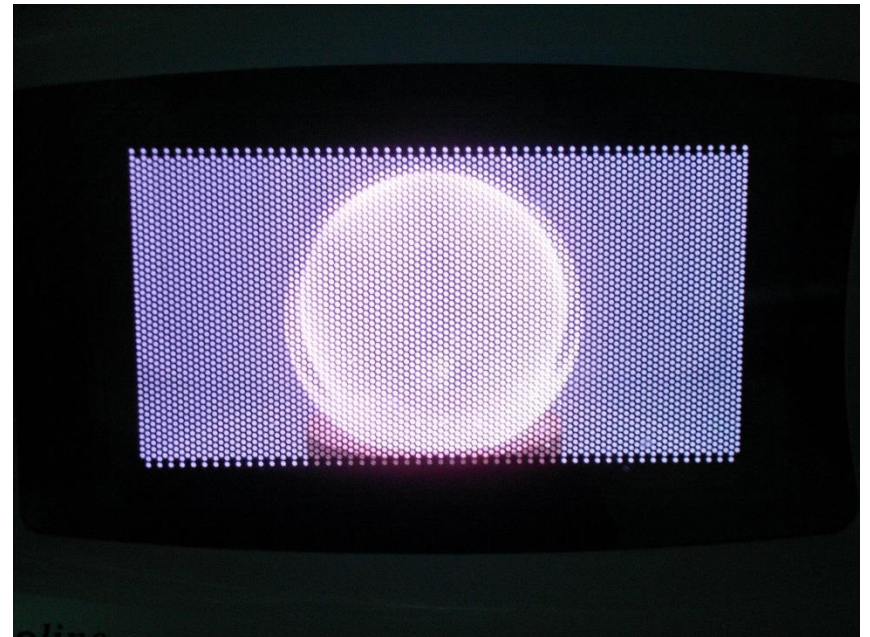
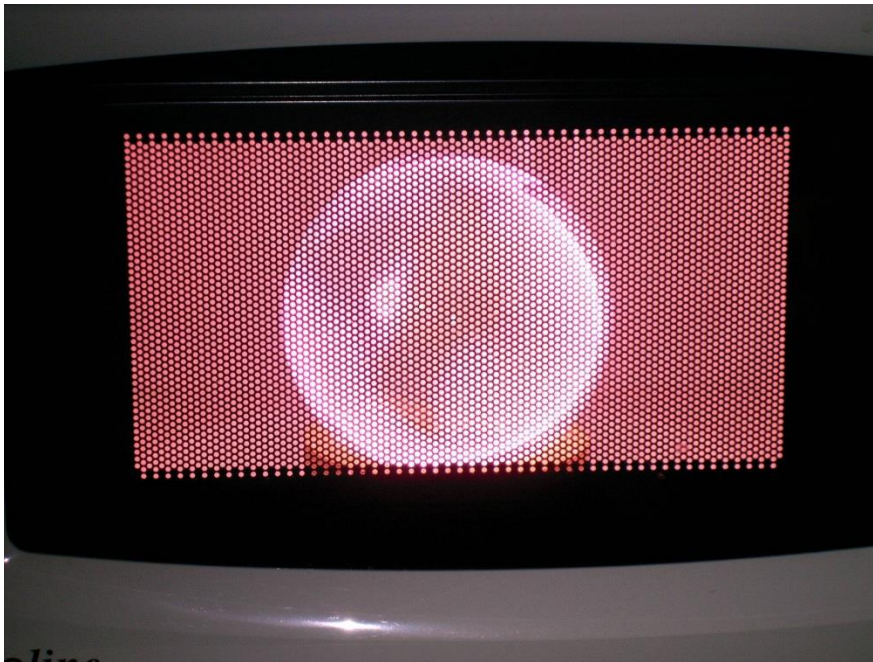
University Leiden



spark discharge
electric breakthrough
in air: $E \sim 30 \text{ kV/cm}$

discharge types

- plasmas generated by electro-magnetic waves
MW glow discharge



plasma physics in the kitchen ...

gas discharges in laboratory and their applications

gas discharges in laboratory



Michael Faraday: Experimental investigations on Electricity
(1838, volume 12 and 13)

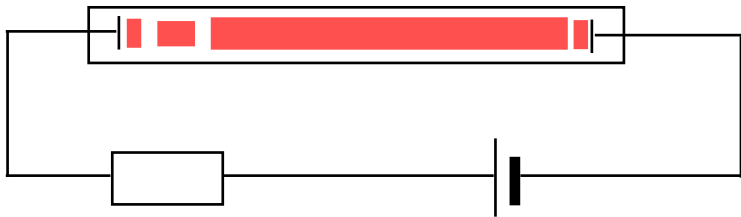
Nr. 1526: **“That form of the gas discharge, which appears as a glow, is very peculiar and beautiful”...**

Nr 1529: **“Dilution of the air enhances wonderfully the glow phenomenon”...**

gas discharges

- plasmas generated by electric fields

glow discharge



arc discharge
corona discharge
barrier discharge



photo: U. Header

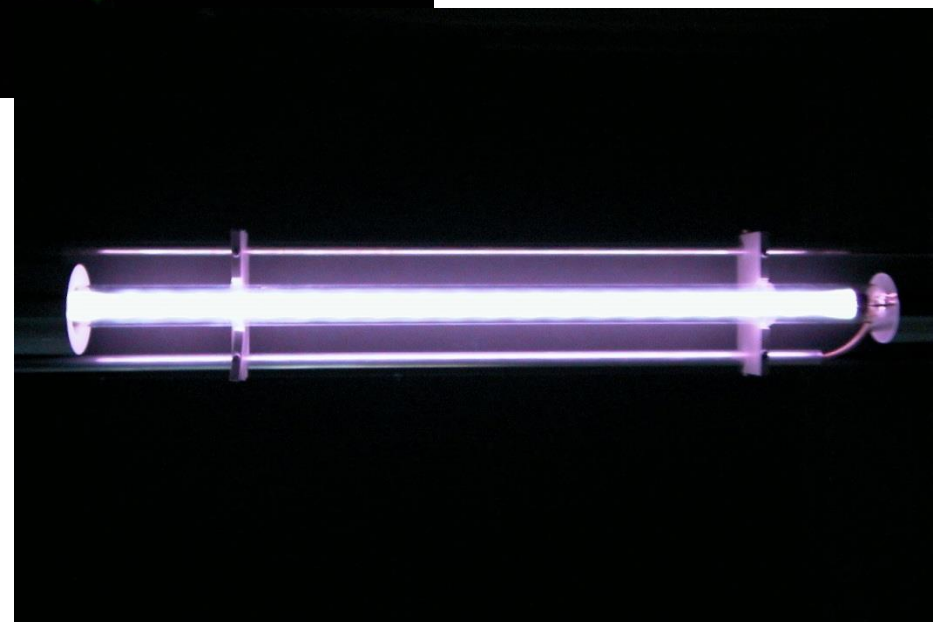
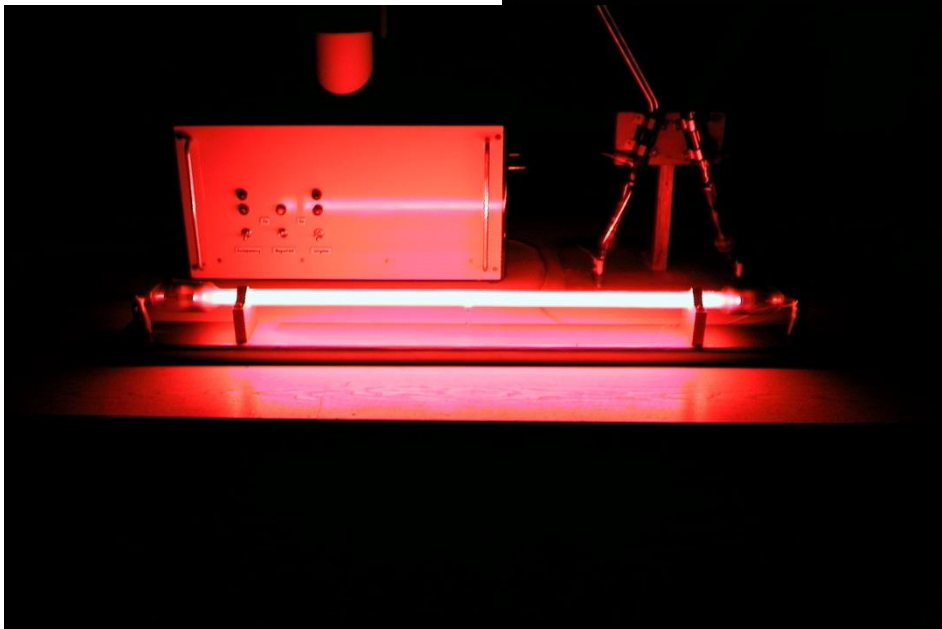
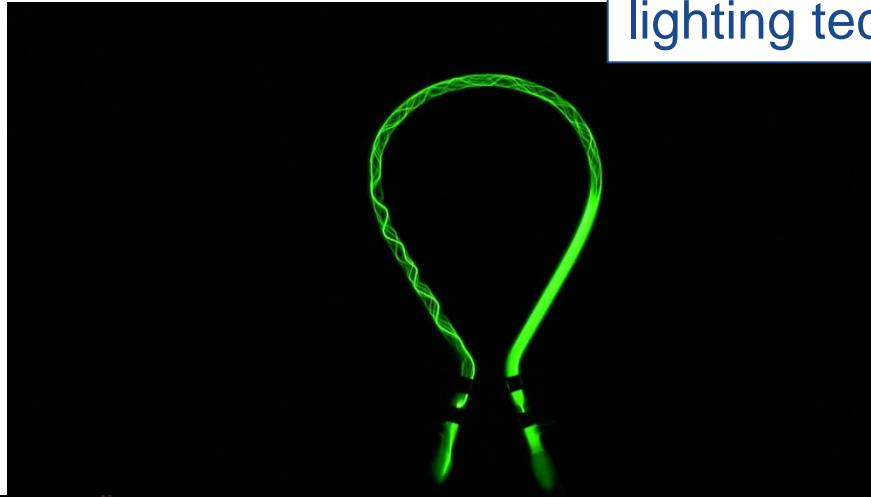
- high temperature plasmas

applications :

- illumination
- energy transformer, **materials**
- surface treatment**
- particle sources
- plasma thrusters, generators

gas discharges

lighting technology, illumination



gas discharges



1850's

Heinrich GEISSLER

Glass blower in Bonn

W.H.Theodor MEYER

Assistant at Phys. Kabinett, Uni Bonn

- **GEISSLER-tubes** in several gases
- first pictures of striations

gas discharges

- each striation corresponds to another excitation made possible by electron acceleration
- spatial structure depends on electrical field pattern
- only operates in a regime with small space charge (very small current)
- in our experiment: space charge and wall effects start having an impact

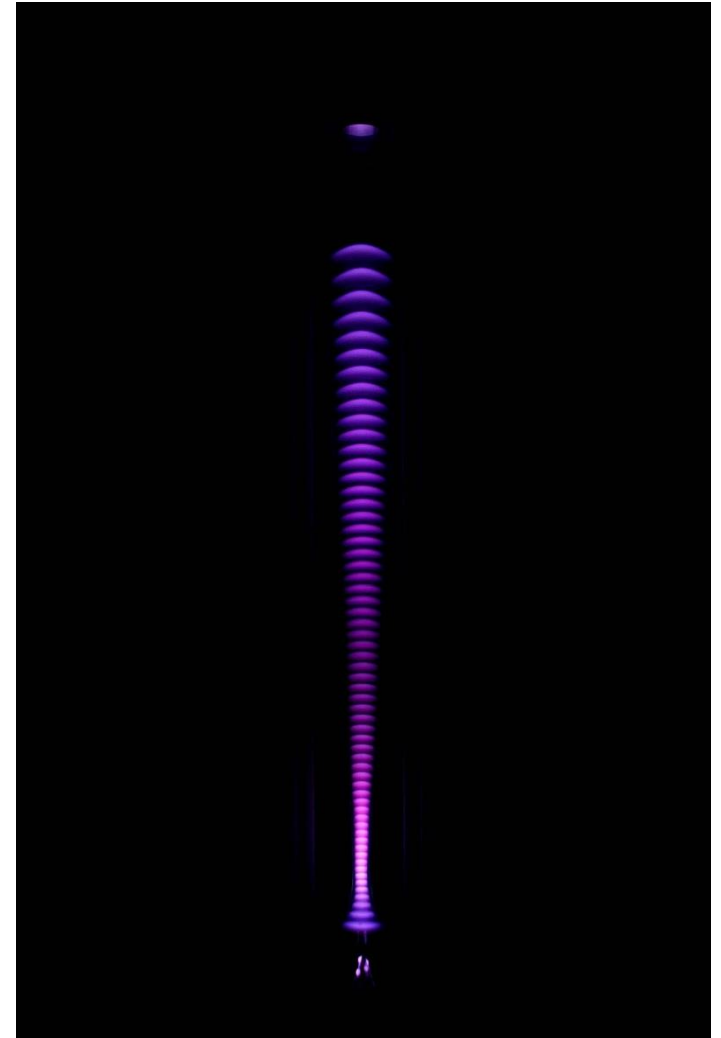


photo: U. Header

gas discharges

standing striations



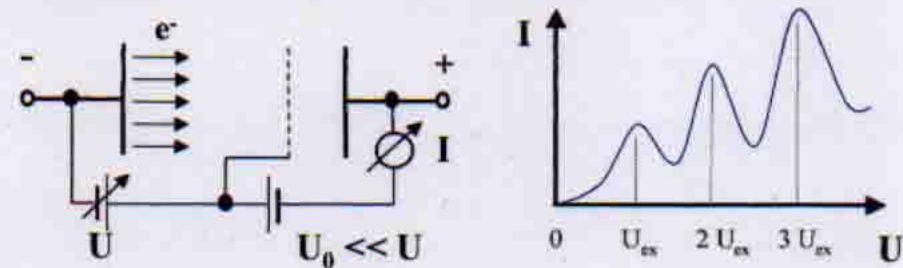
In connection with the conduction of electricity through gases
THE BASIC PHENOMENON OF STRATIFICATION
is some sort of the

FRANCK-HERTZ collision experiment (1914)

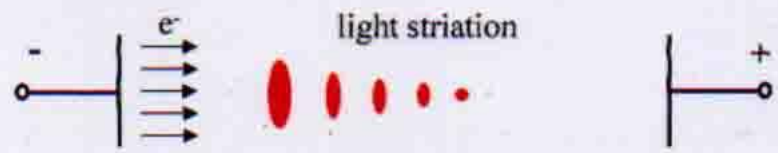
which may be named:

SPATIAL FRANCK-HERTZ EFFECT.

The original **FRANCK-HERTZ** experiment shows
*at a fixed place a periodical behaviour of an electron drift
current with increasing electric field strength.*



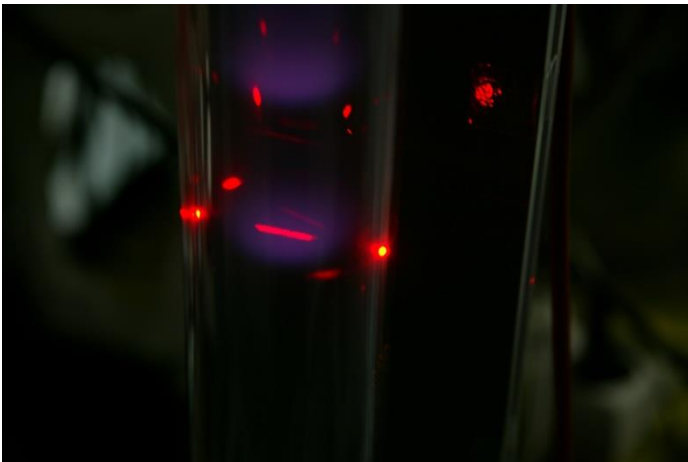
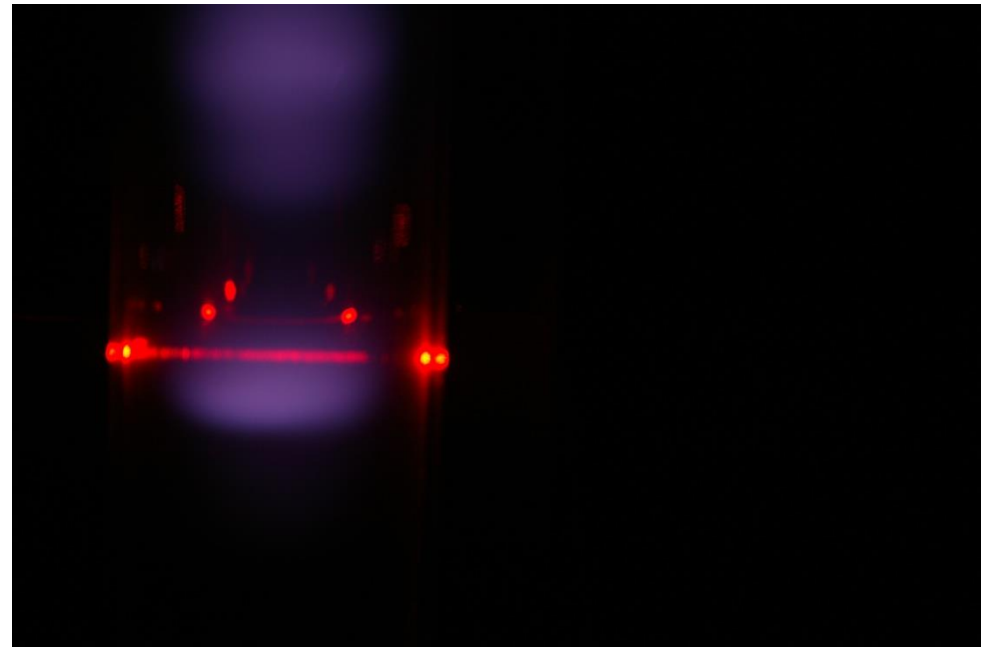
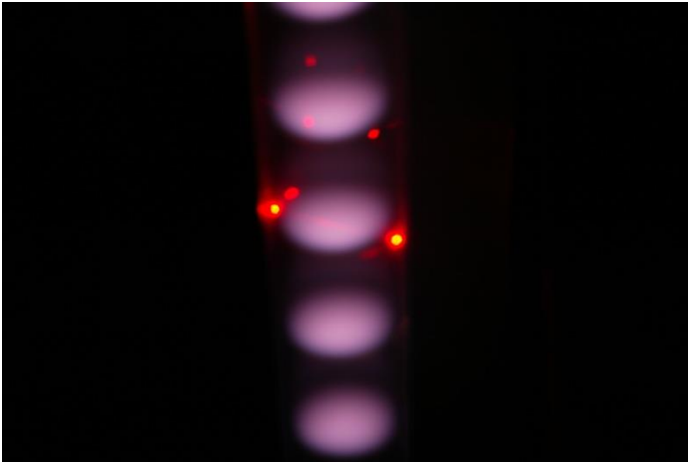
On the other hand the
SPATIAL FRANCK-HERTZ EFFECT shows
*at a constant field strength a periodical behaviour with
increasing space coordinate.*



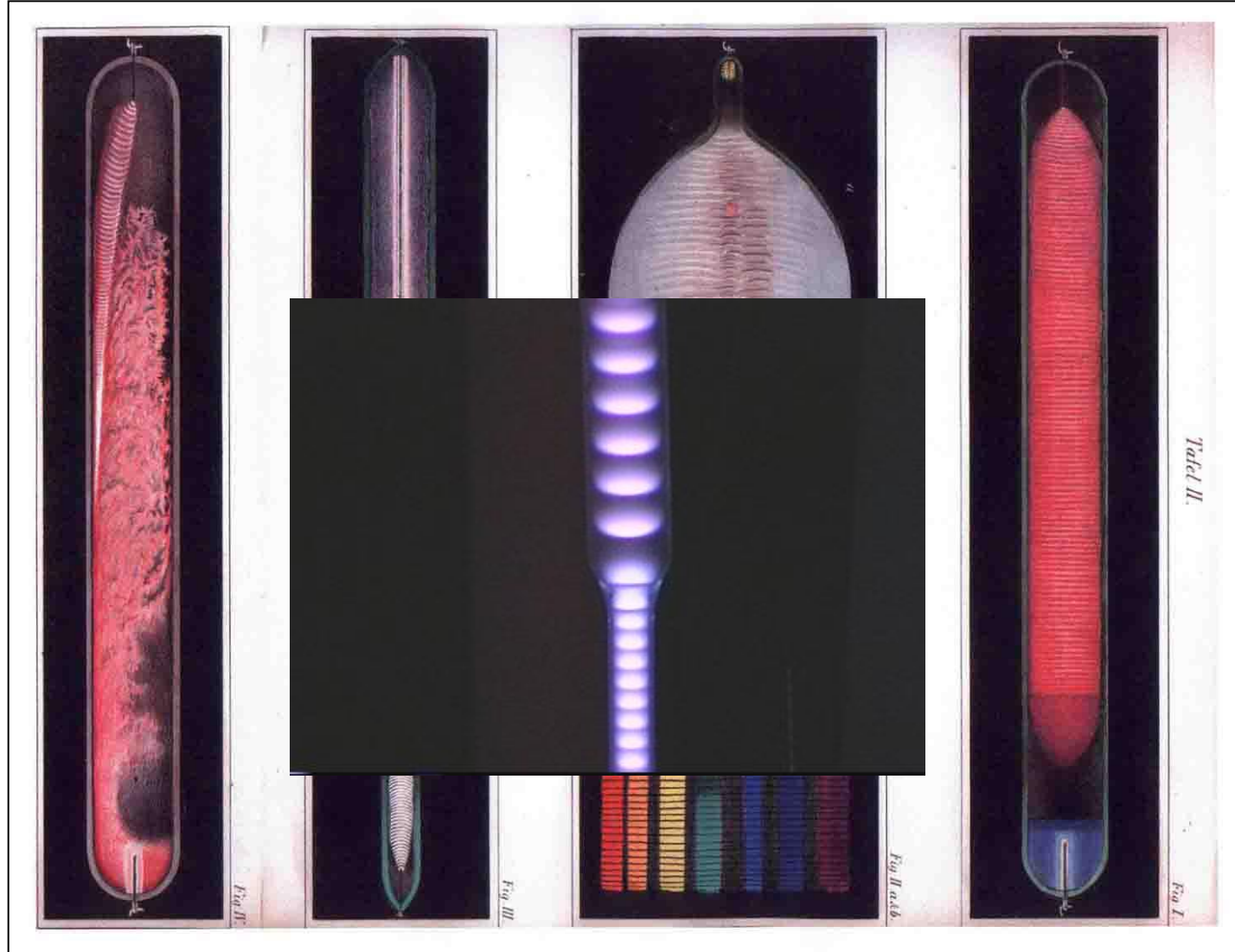
HOLST-OOSTERHUIS discharge: Physica 1(1921)78

gas discharges

dust particles
in a striated discharge



gas discharges



W.H.T. Meyer, Berlin 1858

gas discharges

DC: Cataphoresis / De-mixing

- atoms with the lowest ionization potential (minority species) get ionized first
- they will move to the cathode
- back-diffusion of the gas is slow
- partial pressure gradient builds up: minority gas to cathode, rest to anode
- visible in spectrum

photo: U. Header



gas discharges

plasma – wall – interaction

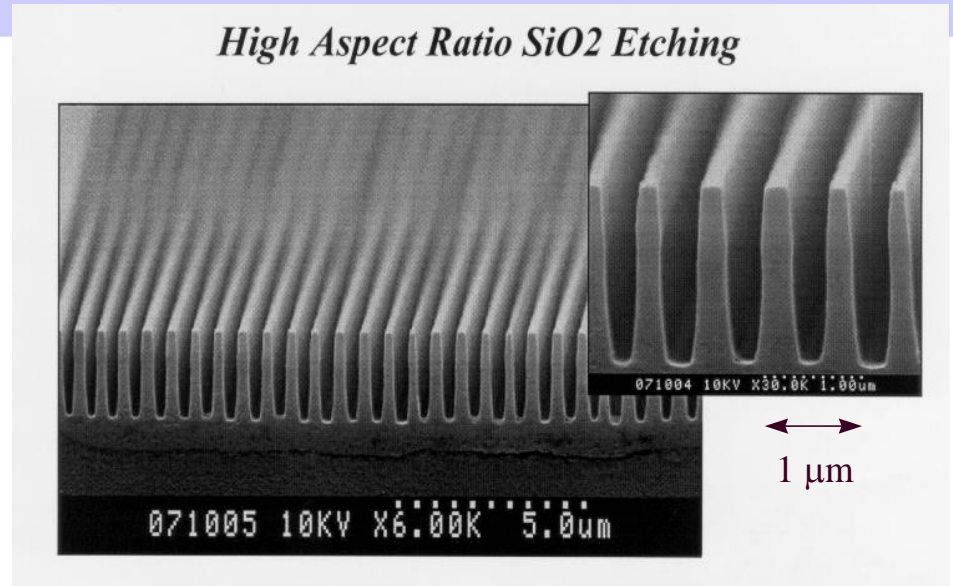
- fusion research
- plasma-processing (LPPP)

(materials, technology, energy sector, optics, sensorics, micro electronics, cryo electronics, opto electronics, biomedical techniques)

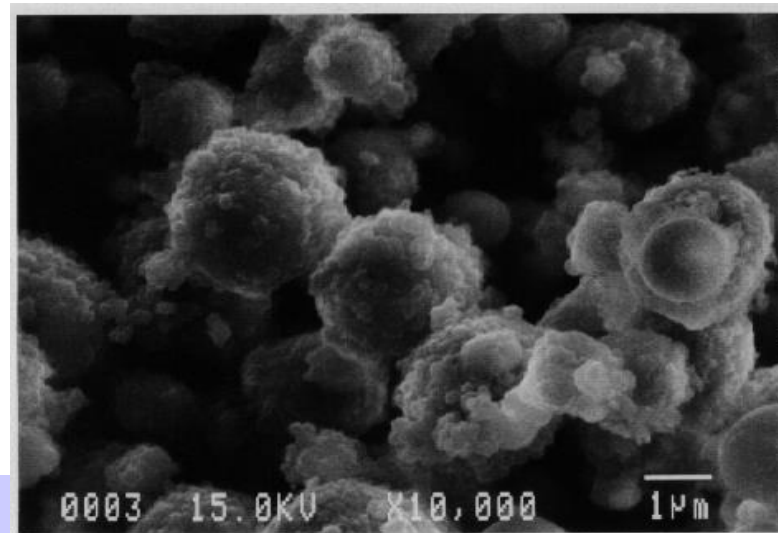
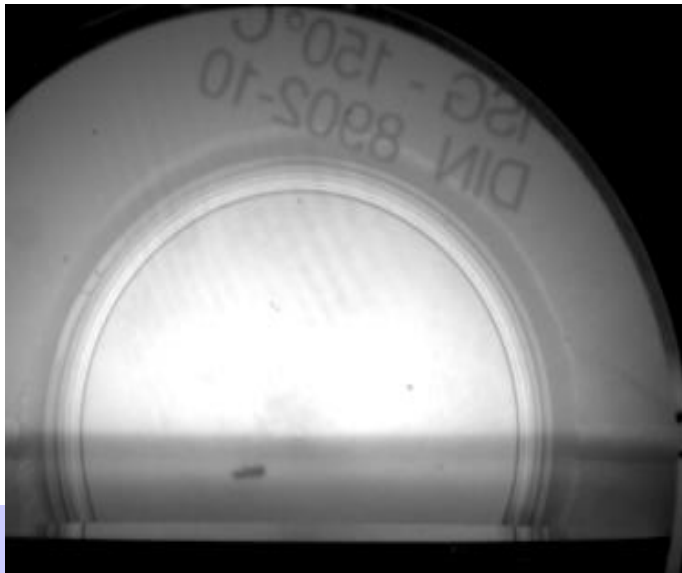
- etching (structuring, cleaning)
- deposition (change of surface properties)
- modification (functionalization)



process plasmas



... etch semiconductors
... coat micro-disperse powder particles



gas discharges

... clean technical surfaces ... etc. ... etc. ... etc. ...



natural plasmas on Earth and in the solar system

natural plasmas on Earth

thunderstorm / lightning



source:

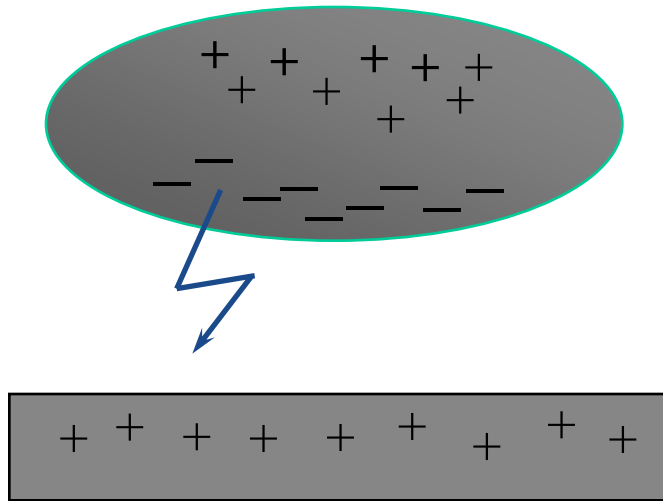
<http://www.meteoros.de/light/blitz.htm>



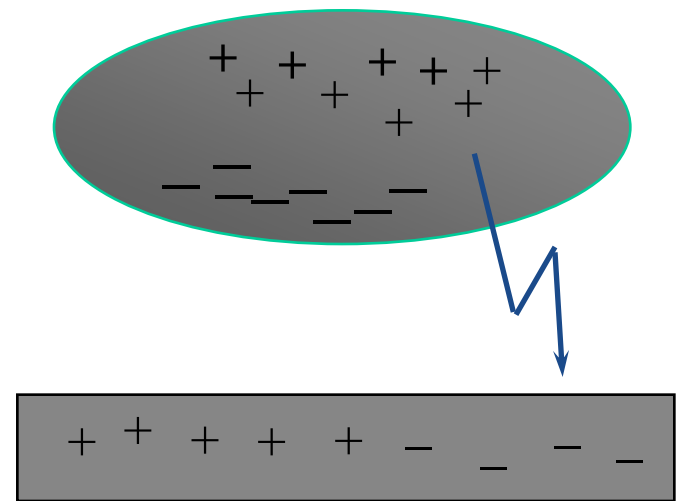
natural plasmas on Earth

- about 10^6 lightning discharges per year in Germany
- generation of large space charge regions due several separation and transport processes of charges in a lightning cloud
mean charge densities : few nC/m³
→ local electric field strength of few MV/m
initiation of a „streamer” discharge
- leading flash ($\sim 10^5$ m/s towards earth)
= thermal ionized plasma core (d \sim 1 cm),
surrounded by a cylindric discharge
(„corona”, d \sim 100 m, charge density ~ 10 μ C/m³)
- from exposed objects starts capturing flash ($\sim 10^7$ m/s) towards the leading flash
„grounding” (main flash as discharge of the cylindric discharge)
→ very bright light, large UV
- current peak with amplitude of 10^4 A for about 100 μ s

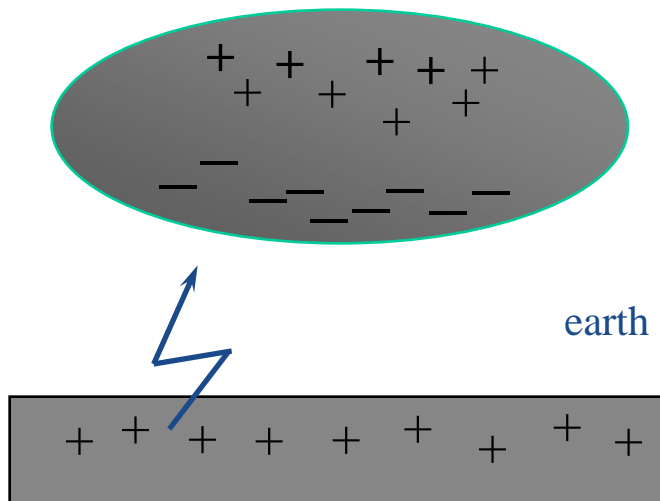
natural plasmas on Earth



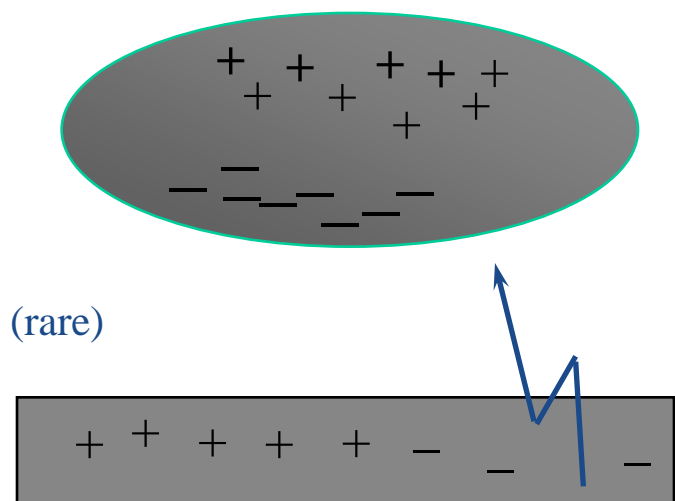
negative cloud - earth - flash (90%)



positive cloud - earth - flash (10%)



earth - cloud - flash (rare)



natural plasmas on Earth



microdischarges of short duration = tiny flashes / lightning

- thin cylindrical weakly ionized plasma columns, $\varnothing \approx 200 \mu\text{m}$
- electron densities: $10^{14} \dots 10^{15} \text{ cm}^{-3}$
- duration: 1 .. 10 ns
- non-equilibrium plasmas ($T_e \gg T_{\text{gas}}$) \Rightarrow well suited for initiation of plasma-chemical reactions

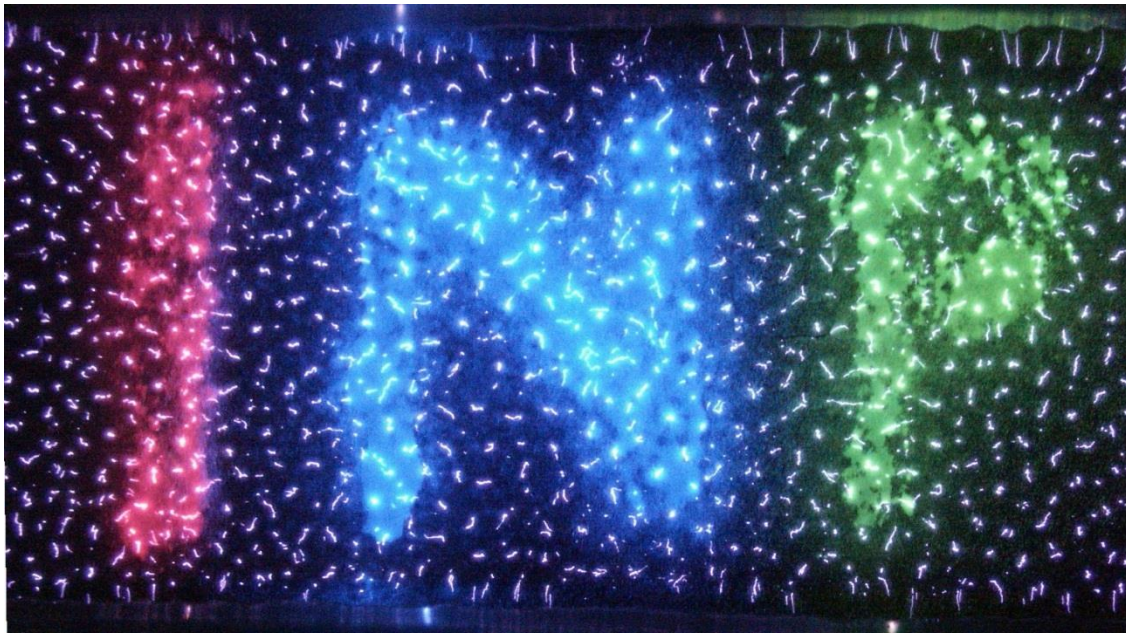
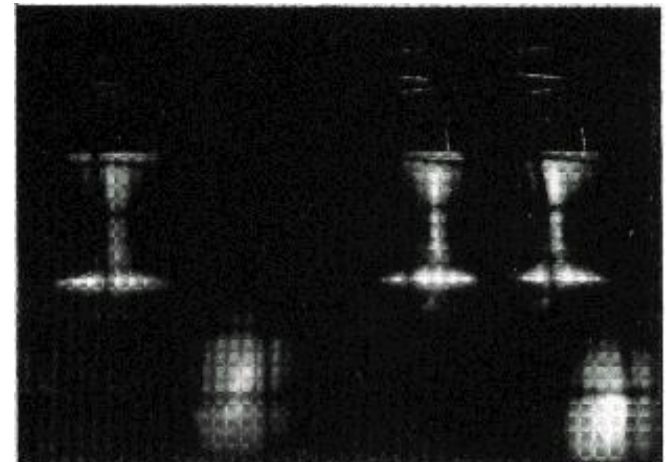


photo: U. Header

Dielectric Barrier Discharge (DBD)



natural plasmas on Earth

polar lights (aurora)



06./07.04.2000, Seebad Heringsdorf

source: L. Stephan (Sternwarte Heringsdorf)

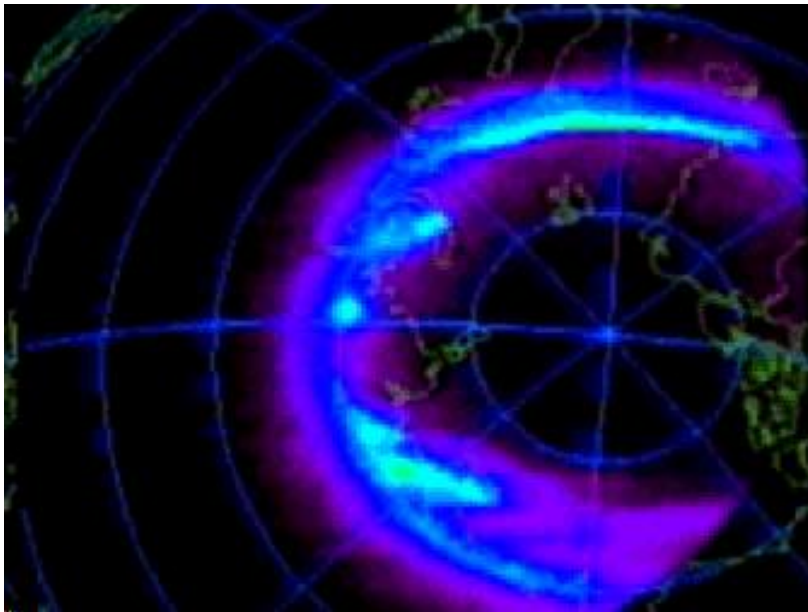


2004, Linköping

source: J. Birch (Linköping University)

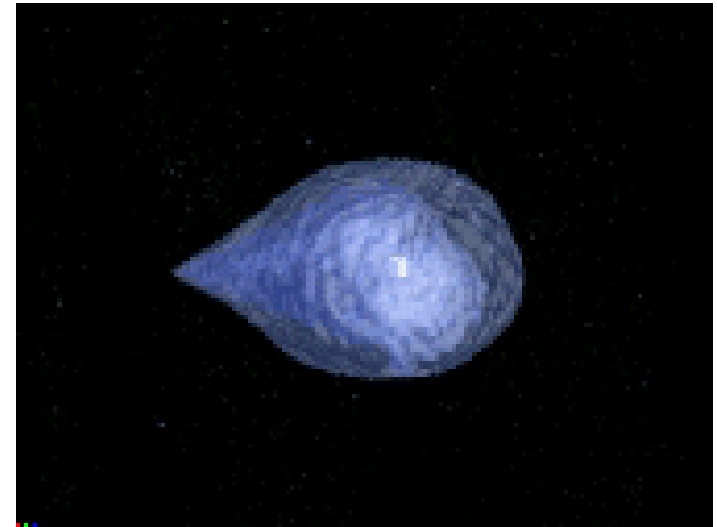
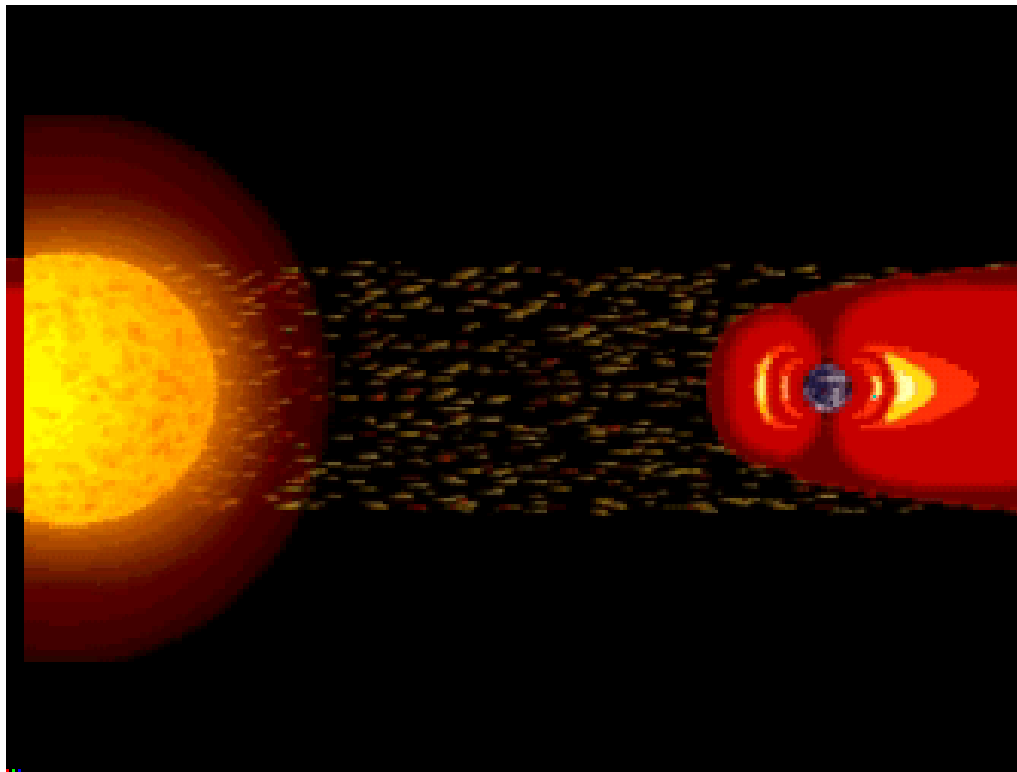
natural plasmas on Earth

- electrons (mainly from solar wind) come along the earth magnetic field into **polar zones** ($65^\circ \dots 75^\circ$)
excitation by collisions of atomic N, O (etc.) in high atmospheric regions ($h > 100 \text{ km}$)
light phenomena (de-excitation, recombination)
- ionosphere : $p \sim 10^{-4} \text{ Pa}$, $T_g \sim T_e \sim 10^3 \text{ K}$, $n_e \sim 10^6 \text{ cm}^{-3}$, $x \sim 10^{-4}$



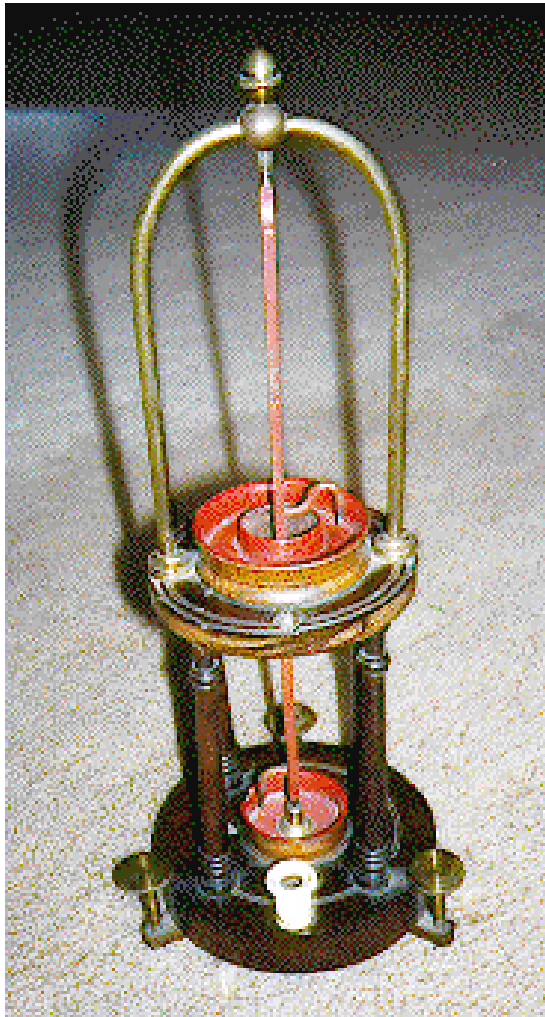
natural plasmas on Earth

polar lights and solar wind



interaction
with magnetosphere of earth

natural plasmas on Earth



Faraday Philosophical Motor (~ 1830)

(Quelle: John Williams Collection)

<http://w1tp.com/impersci.htm>

plasmas in magnetic fields



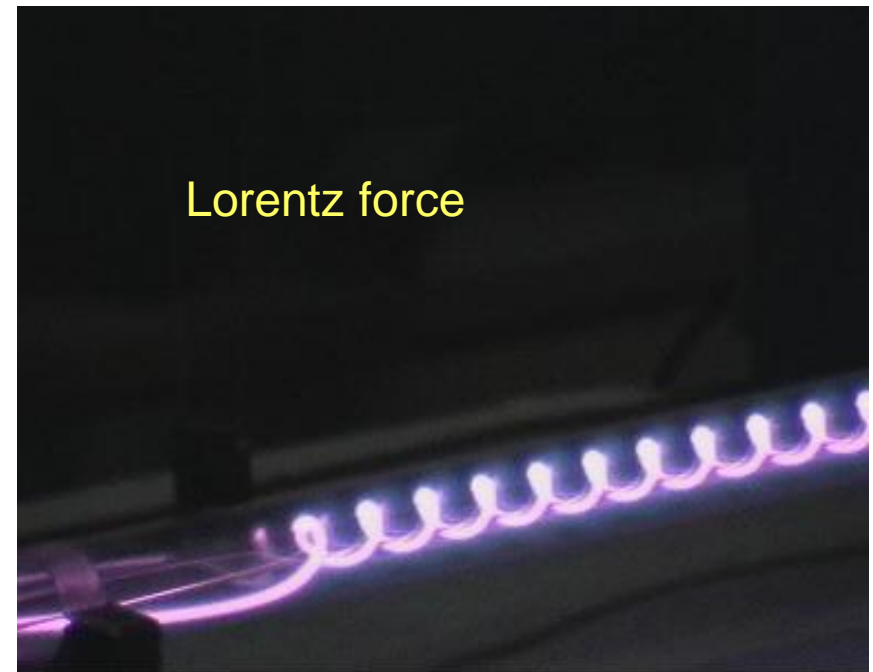
Foto:
U. Header

Kewitz, T., Kersten, H.,
"Phänomene in Gasentladungen",
Galvanotechnik **103**(2012), 1080-1088.

natural plasmas on Earth

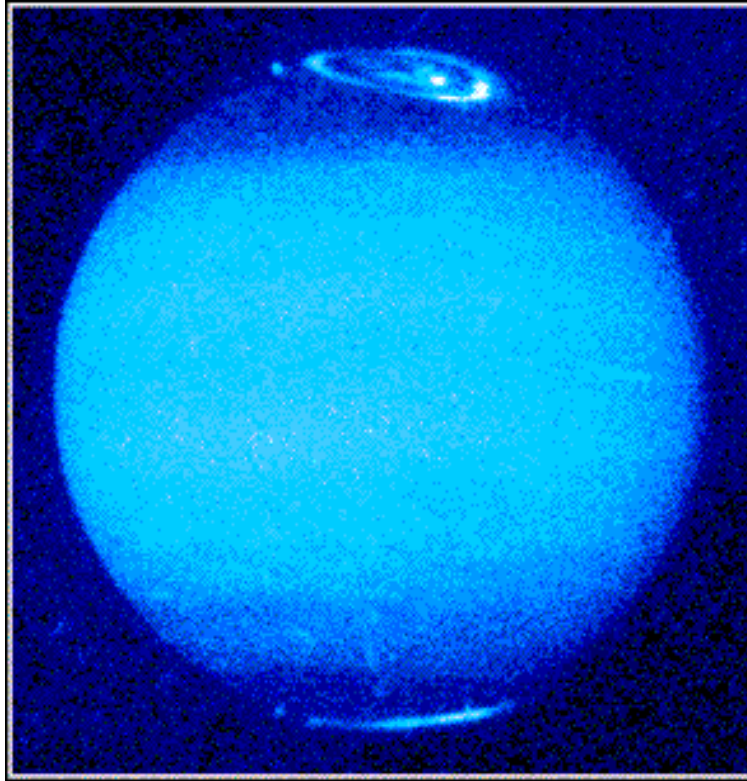
- magnetic field starts the spiral, but is only needed for starting
- then the structure propagates from cathode to anode
- at anode: rotation starts, but the screwing wave does not propagate.
- the screw is attached to the inner tube. If it also touches the outer tube, it does not propagate anymore

screwing discharge

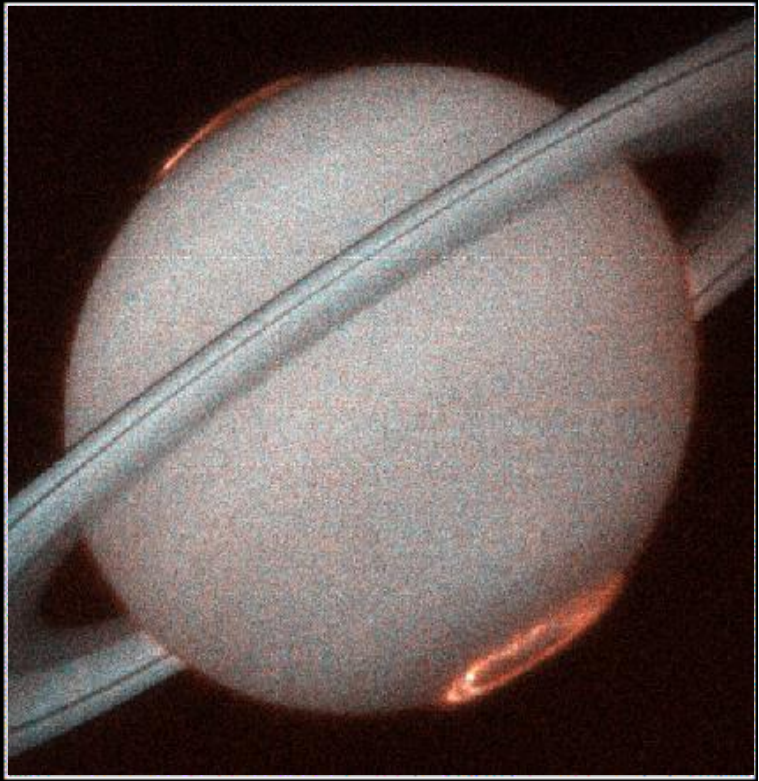


natural plasmas in the solar system

auroral lights at giant planets



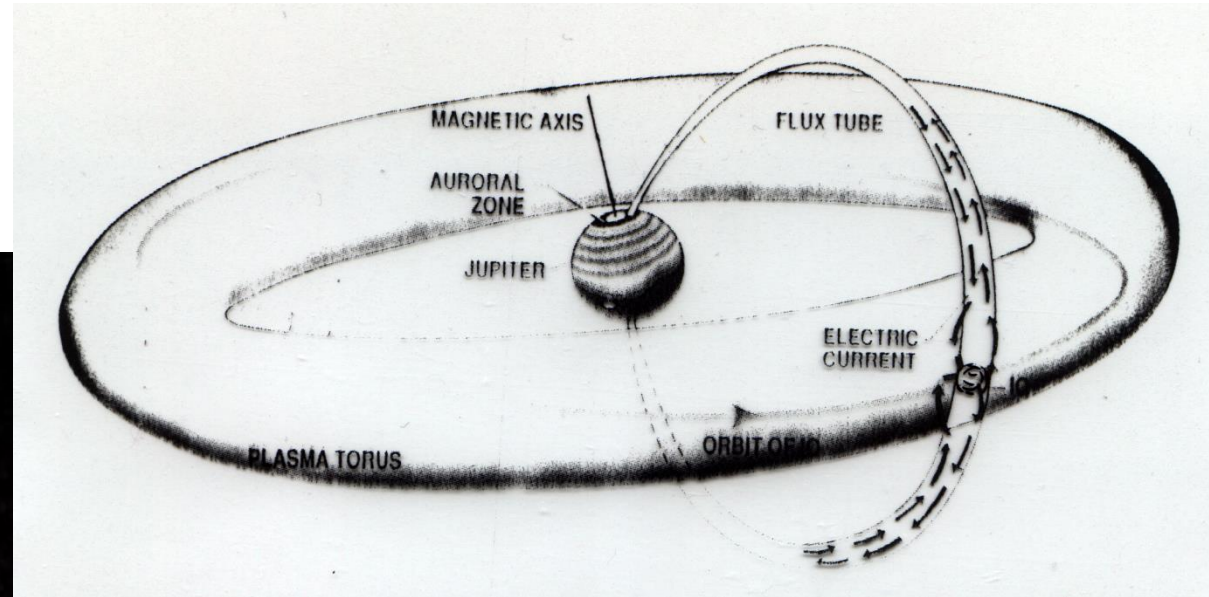
Jupiter



Saturn

natural plasmas in the solar system

plasma-torus surrounding Jupiter



strong interaction with jovian moons
and space crafts at jupiter



natural plasmas in the solar system

solar wind :
plasma of the interplanetary space

= continuous, in radial direction flowing **particle flux** from sun

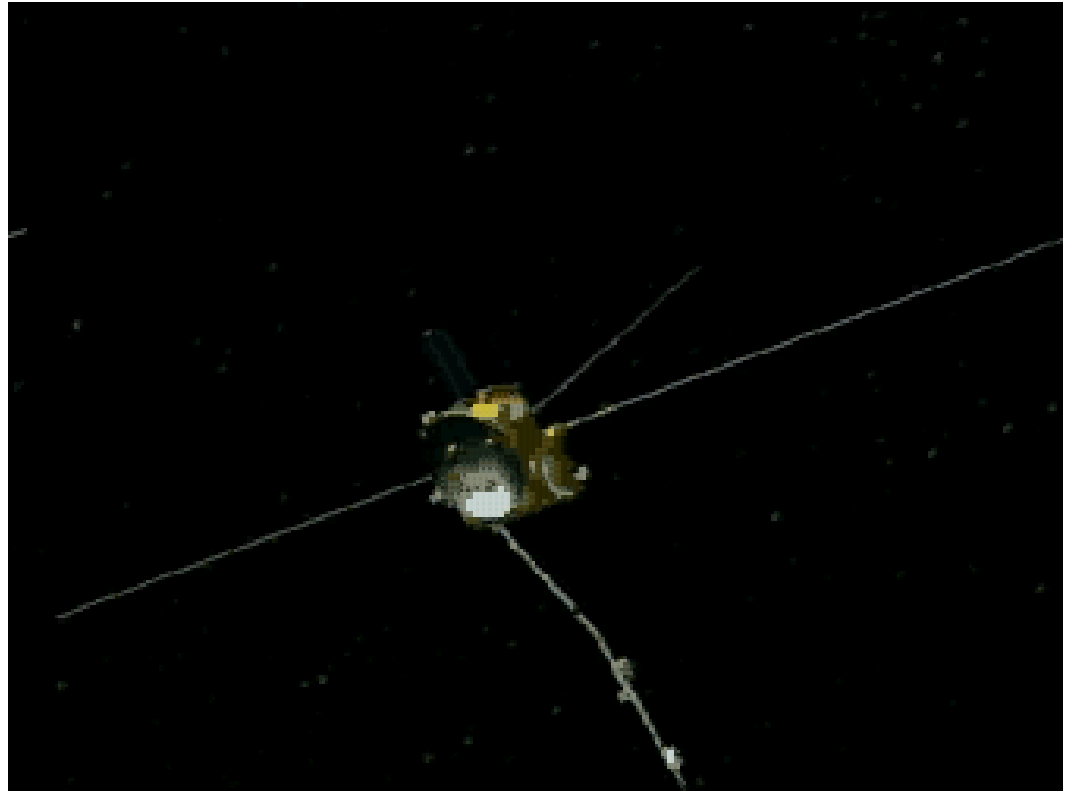
- solar wind (**electrons, protons, ions**) is essentially driven by the dynamics of sun's corona
- strong **variation** ($300 \dots 700 \text{ km/s}$ at earth),
(depends on sun activity)
- $n_e \sim 10^7 \text{ cm}^{-3}$, $T \sim 10^5 \text{ K}$, magnetic field $\sim 5 \cdot 10^{-9} \text{ T}$
→ **conductivity of the plasma**, interplanetary magnetic field („Ballerina-model”)

solar wind

Figure 1 is a polar plot showing the speed of the solar wind in km s^{-1} as a function of solar longitude. The plot is centered on the Sun, with a color scale from 100 to 1000 km s^{-1} . The plot shows the solar wind speed as a function of solar longitude, with data from Ulysses/SWOOPS (red lines) and Ulysses/MAG (blue lines) overlaid on the background. The plot shows the solar wind speed as a function of solar longitude, with data from Ulysses/SWOOPS (red lines) and Ulysses/MAG (blue lines) overlaid on the background.

natural plasmas in the solar system

observation of solar wind



e.g Ulysses, Soho etc.

natural plasmas in the solar system

cometary tails



Sun and stars – compact plasma spheres in space



Sun and stars

plasma sphere „Sun“

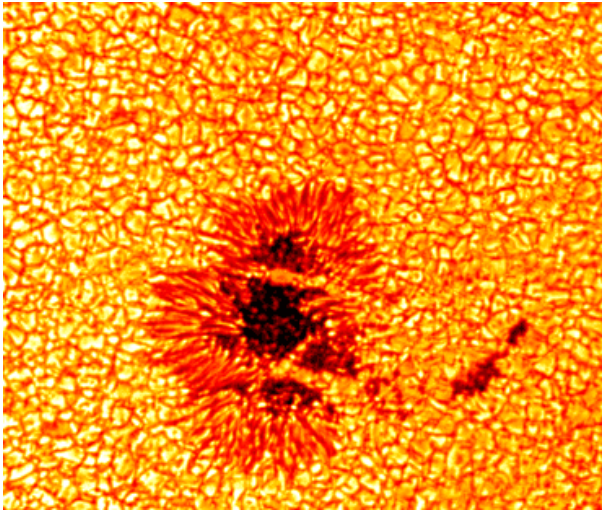
= „classic“ cosmic plasma system :

- plasma of „atmosphere“ : photosphere, chromosphere (radiation, emission, absorption)
- hot, but thin plasma of sun's corona, which is immediately connected to the solar wind
- dense, thermal, and completely ionized plasma in the interior of the sun (fusion, radiation transport, convection)

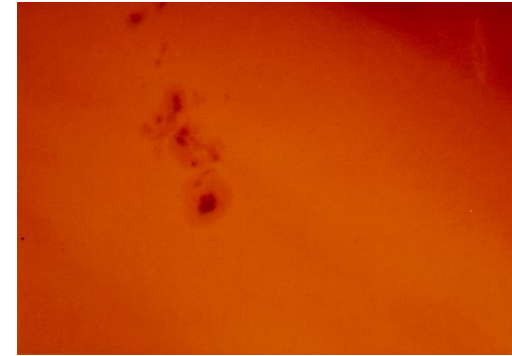


Sun and stars

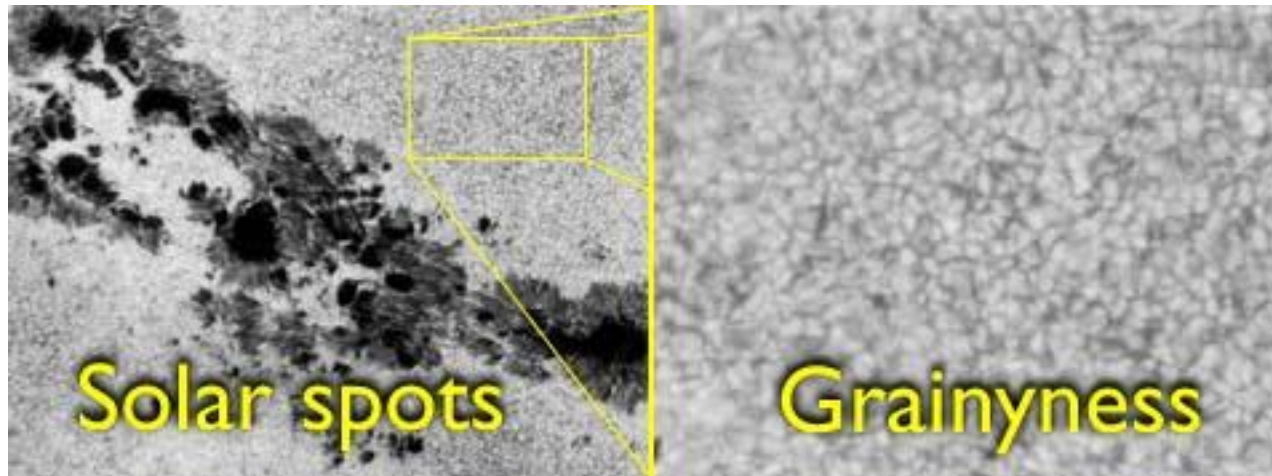
photosphere



sun spots,
connection to local magnetic fields



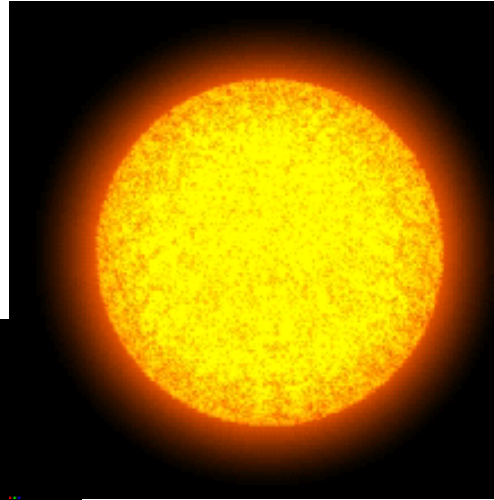
granulation (grainyness) by convection
in the deeper layers of the photosphere



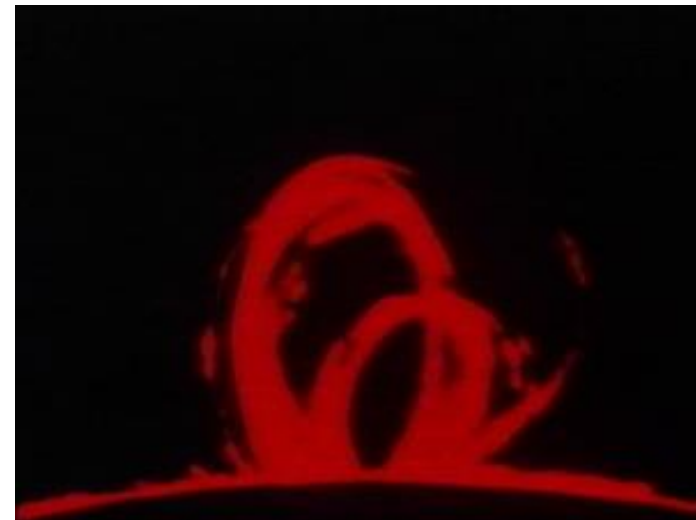
Sun and stars

chromosphere

= transition layer between
photosphere and corona



prominences
= giant clouds of matter
in chromosphere
and corona

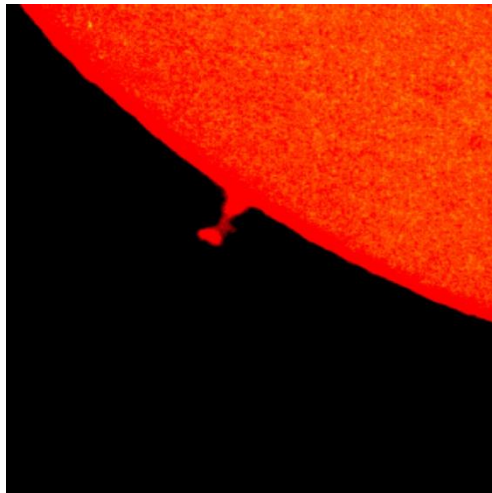


Sun and stars

prominences



areal type

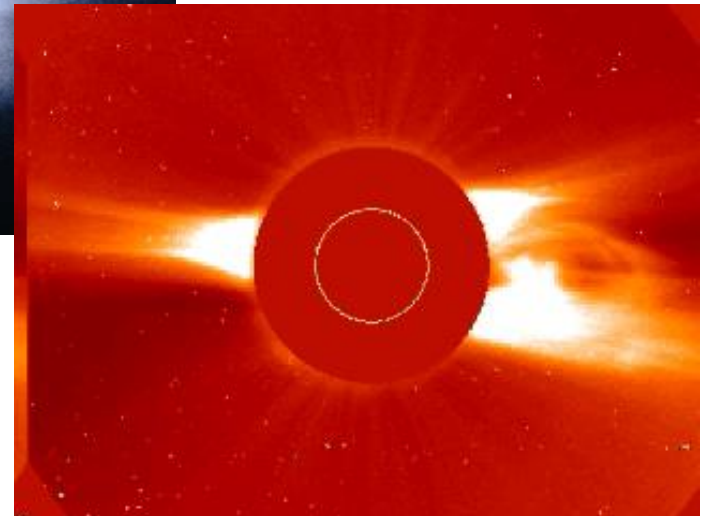
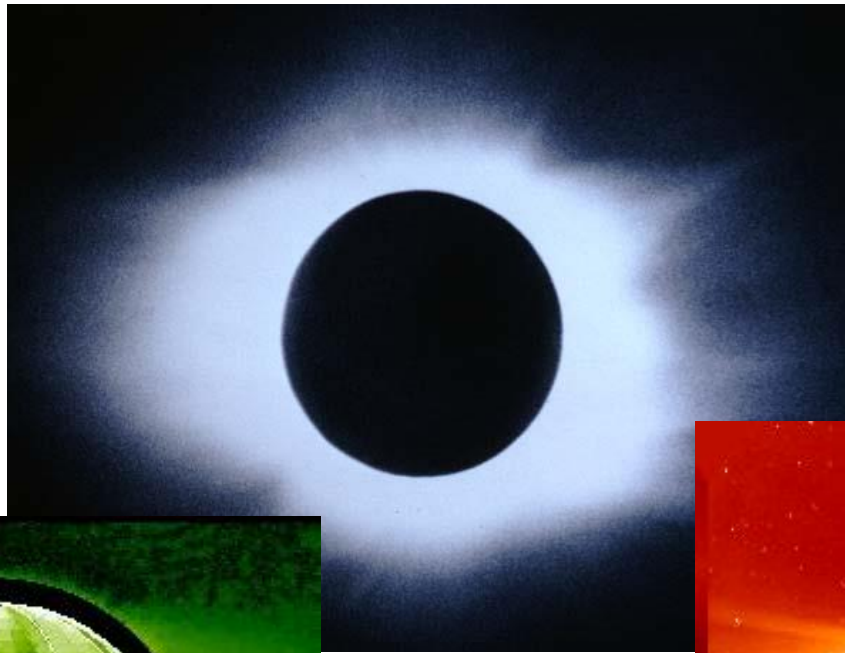


rod type

Sun and stars

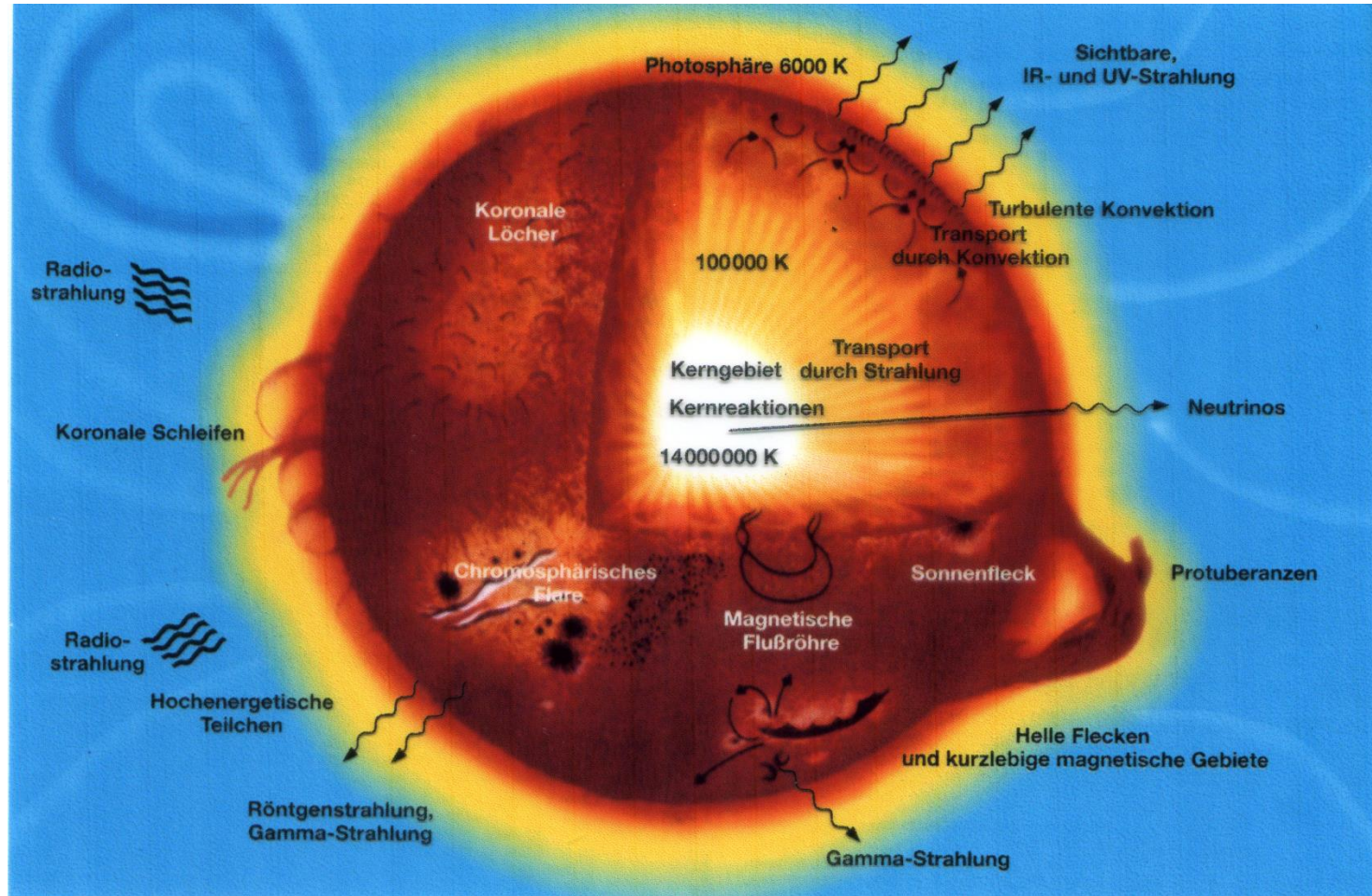
= outer atmosphere („gleaming ring“)

Sun's corona



Sun and stars

The Sun as a star



source: High Energy Astrophysics Science Archive Research Center, NASA Goddard Space Flight Center, (J. Lochner, M. Gibb, P. Newman)

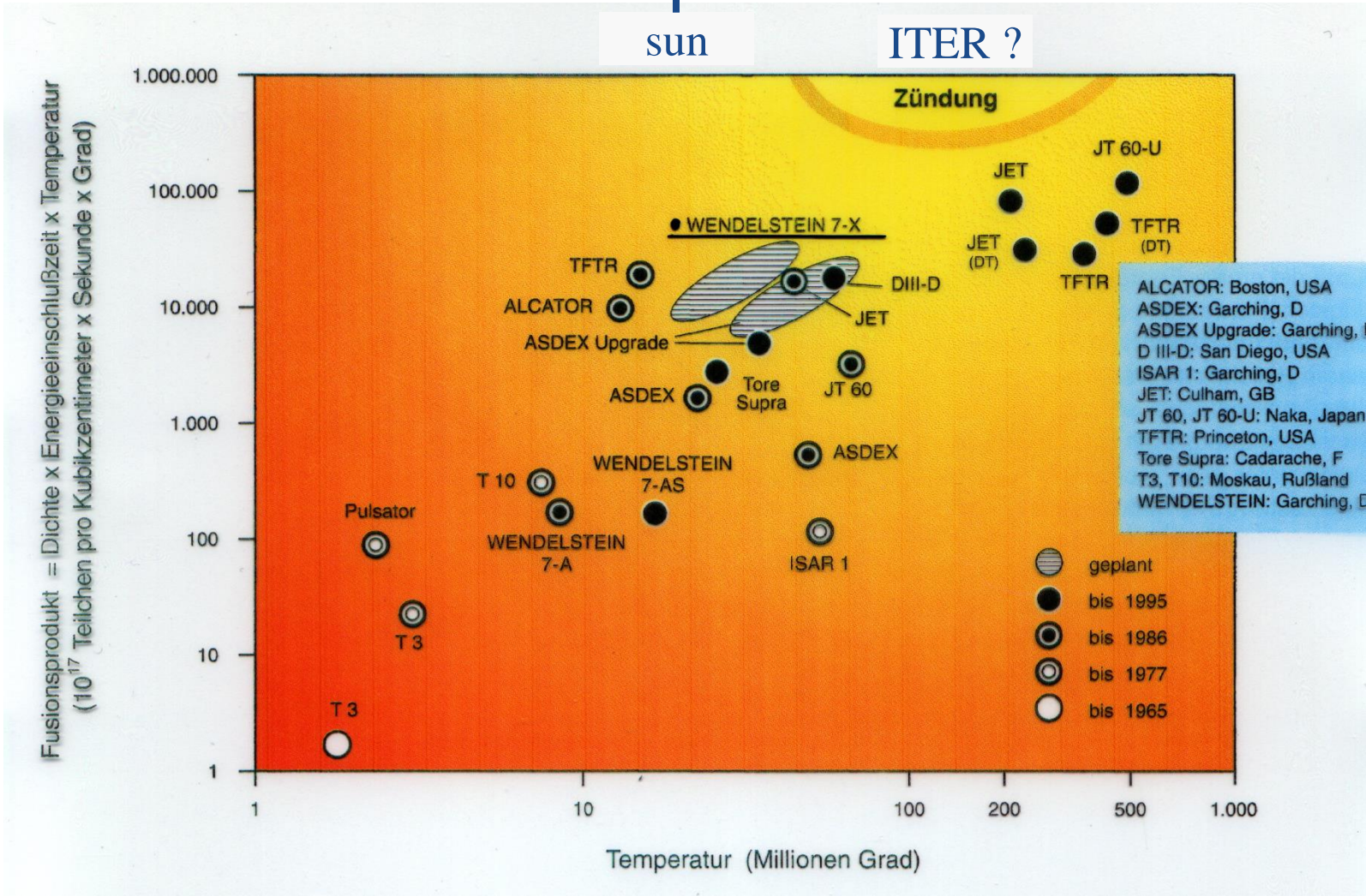
Sun and stars

fusion plasmas



sun

ITER ?



Sun and stars

stars: compact plasma spheres in space



↔ **see Sun !!!**

- stars in different phases of their development :
ZAMS, main sequence, giant stage, white dwarf

↔ **different plasma phases**
(density, temperature, energy conversion)

interstellar and intergalactic matter

interstellar matter

planetary nebulae

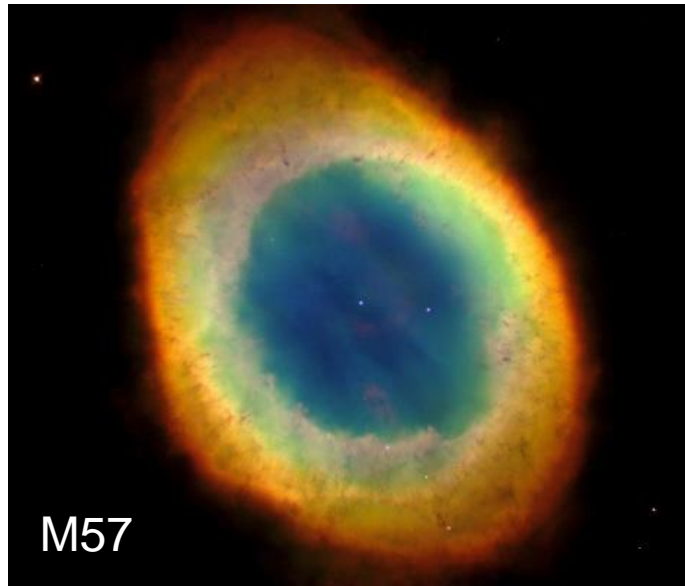
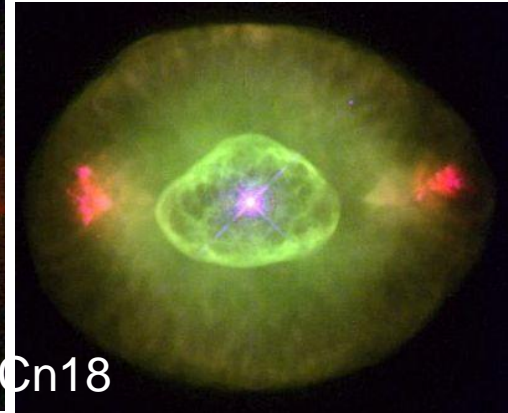
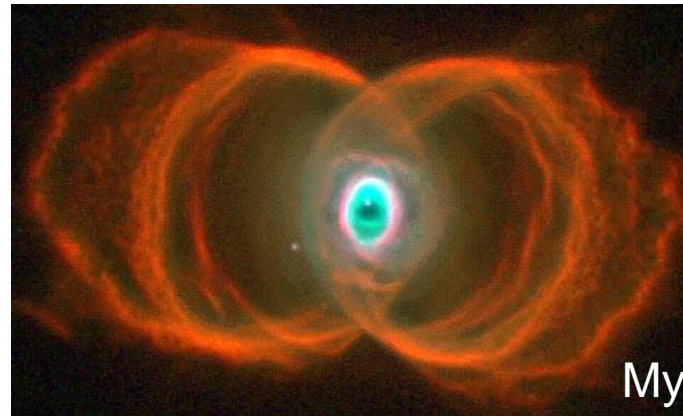
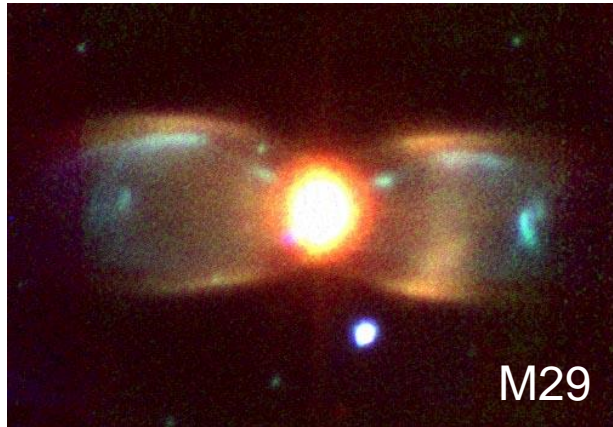
... are remnants of exploding sun-like stars
which „feed“ (similar to SNR) the interstellar medium



Helix-nebula (NGC 7293)

interstellar matter

planetary nebulae



ring nebula

interstellar matter

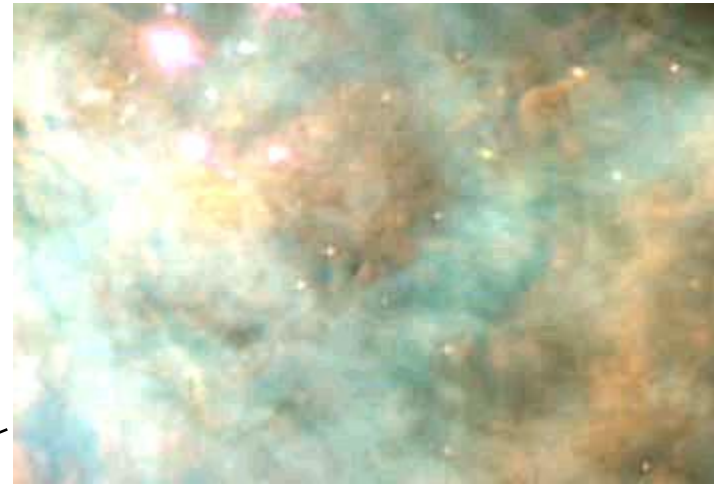
- = very thin plasma, which fills the **interstellar space** : $\sim 10\%$ of $m_{Galaxis}$?
(inhomogeneous and anisotrop)
- components: **gas / plasma** (10^{-24} g/cm^3) and **dust** (10^{-26} g/cm^3) $\sim 99:1$
 - chemical composition similar to stellar atmospheres (H_2 , H, He, molecules)
 - concentration in galactic plane \longrightarrow **formation of stars**
 - dust ($20 \dots 50 \text{ K}$) has an essential meaning for the formation of stars :
cooling, catalyst
 - HI-regions (21cm-line)
 - HII-regions ($\sim 10\%$) \longrightarrow luminous gas nebula
 - H_2 - and molecular clouds (~ 100 molecules)
 - **emission and absorption** (electromagnetic spectrum)

interstellar matter

interstellar clouds



... are regions of star formation,
like Orion nebula M42

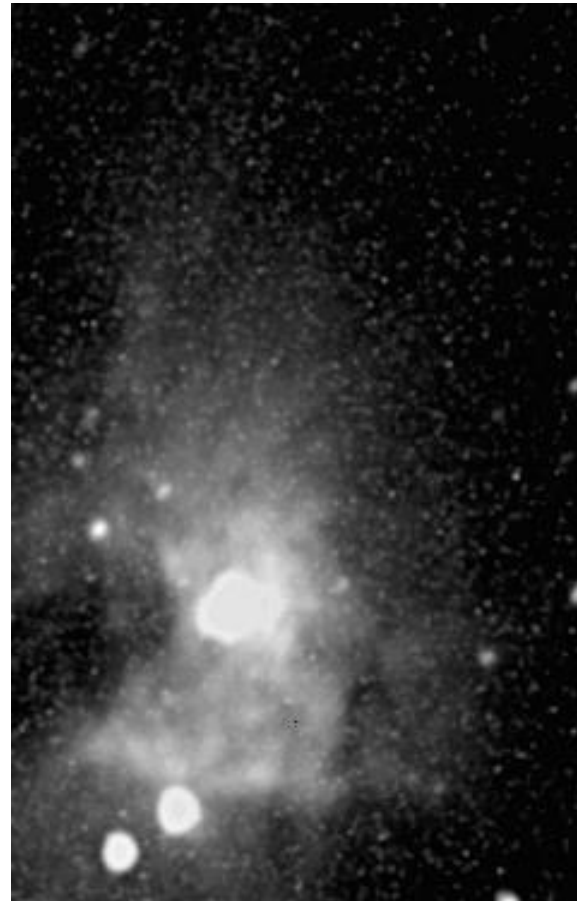


interstellar matter

interstellar clouds

Orion-nebula
M 42

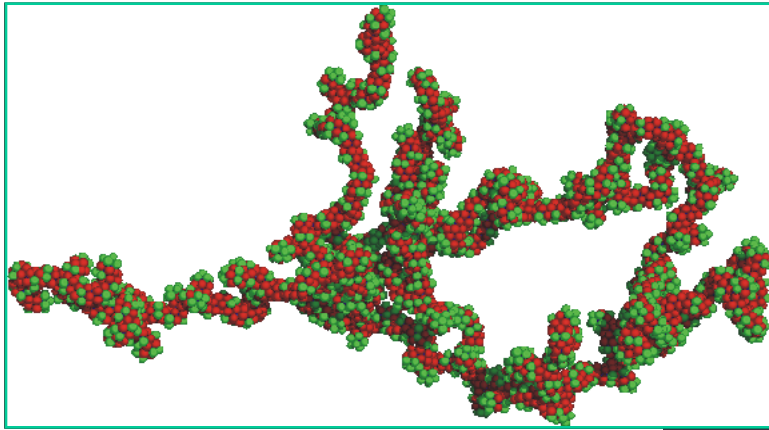
HST



..... observed in

Observatory Greifswald

interstellar matter



dust in interstellar clouds

particle growth :
molecules, clusters, particles,
solids in pre-stellar nebulae

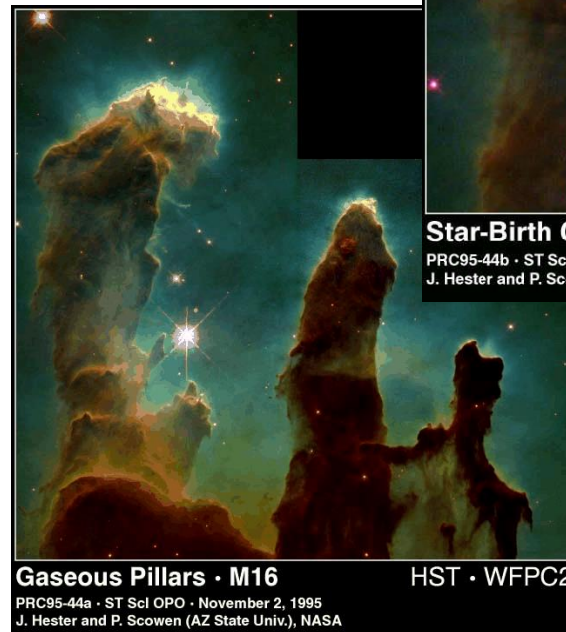


interstellar matter

interstellar clouds



eagle-nebula



interstellar matter

HI-, HII-regions, molecular clouds



Northern America nebula (NGC7000)

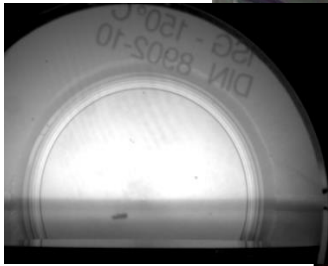
HII-emission and
dark clouds in Orion



© Royal Observatory, Edinburgh / Anglo-Australian Observatory

summary

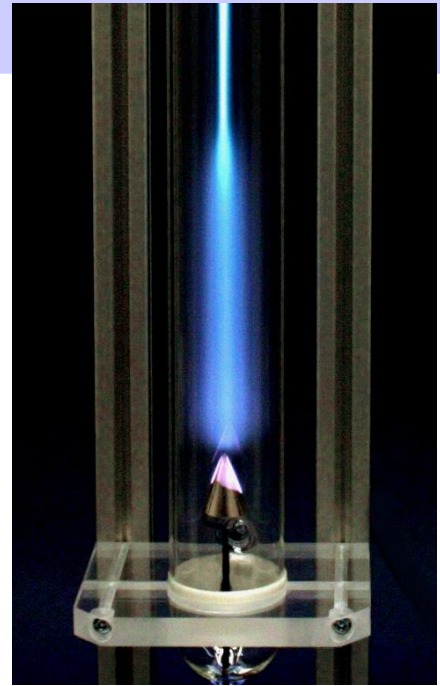
	l_c meters	B tesla	ρ_m kg/m ³
<i>Laboratory experiments</i>			
Mercury	0.1	1	10 ⁴
Sodium	0.1	1	10 ³
Hydrogen	0.1	1	10 ⁻⁷
<i>Cosmic plasmas</i>			
Earth's interior	10 ⁶	10 ⁻³ (?)	10 ⁴
Sunspots	10 ⁷	0.2	10 ⁻¹
Solar granulation	10 ⁶	10 ⁻²	10 ⁻⁴
Magnetic variable stars	10 ¹⁰	1	10 ³ (?)
Interstellar space	10 ²⁰	10 ⁻⁹ (?)	10 ⁻²¹ (?)
Interplanetary space	10 ¹¹	10 ⁻⁸	10 ⁻²⁰
Solar corona	10 ⁹	10 ⁻⁴ (?)	10 ⁻¹⁵ (?)
Dark clouds	10 ¹¹	10 ⁻¹⁰	10 ⁻¹⁷



summary

Bright or dim discharge ?

photo: U. Header

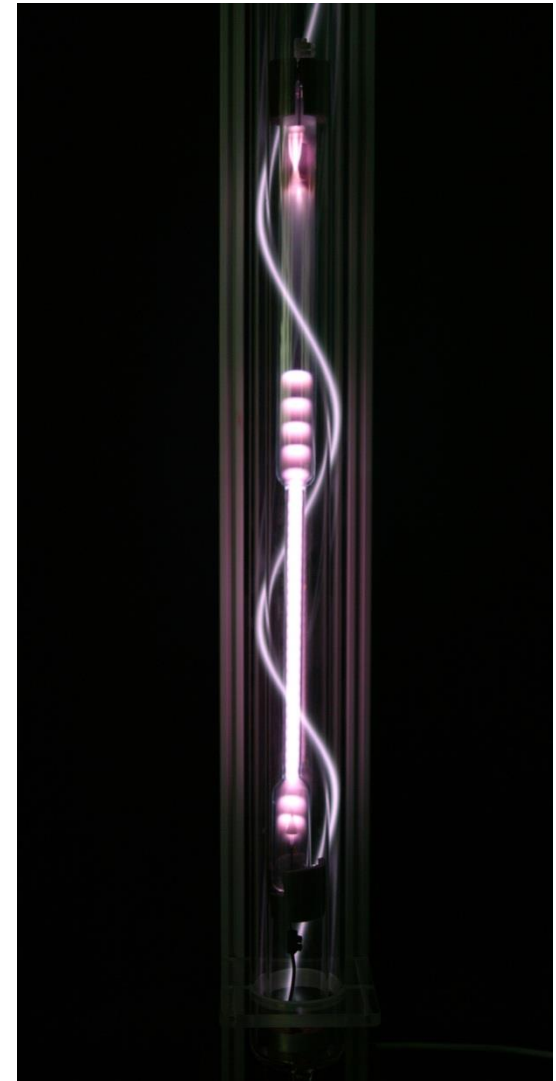
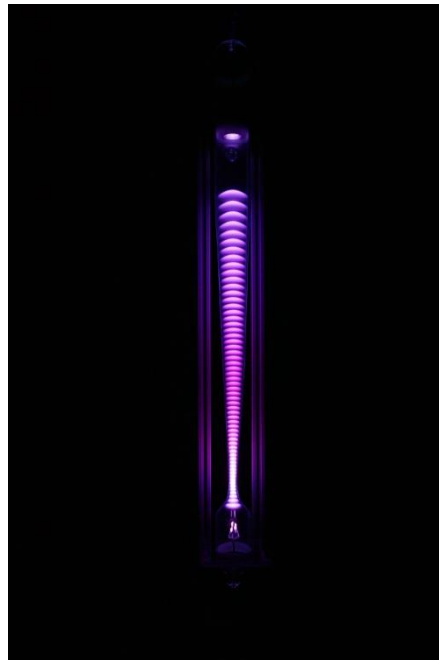


- on axis: electron and gas temperature high, gas density low, E/p high
- this effect is self-enhancing: plasma contracts itself
- at low current: strong depopulation of EEDF tail over exc. Energy due to inelastic collisions
- over a certain boundary: more and more elastic e-e collisions cause Maxwellization, population of the EEDF tail and a jump-wise increase in ionization
- this then causes a jump-wise contraction

summary



photos: U. Header



standing striations
moving striations
spiral discharges

summary

Plasma exists in all of its modifications – from dense, thermal **fusion plasmas in the interior of the stars** to the strongly anisothermal, **weak plasma of the interstellar space**.

The „existence” of cosmic plasmas is based on the interaction between **the matter (mainly gas) with radiation fields**.

The plasma as „fourth state of matter” is the most **dominant existence of matter** in the Universe.