SPACE PHYSICS

Lecture 14

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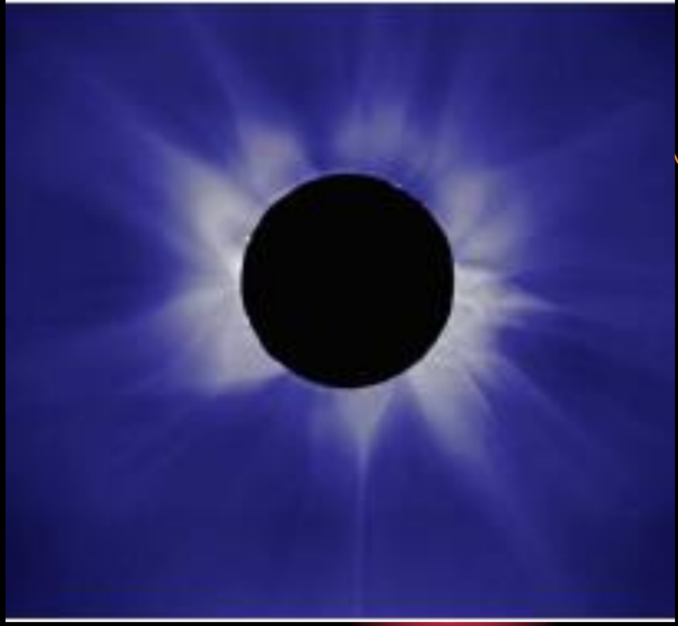
The Interplanetary Environment



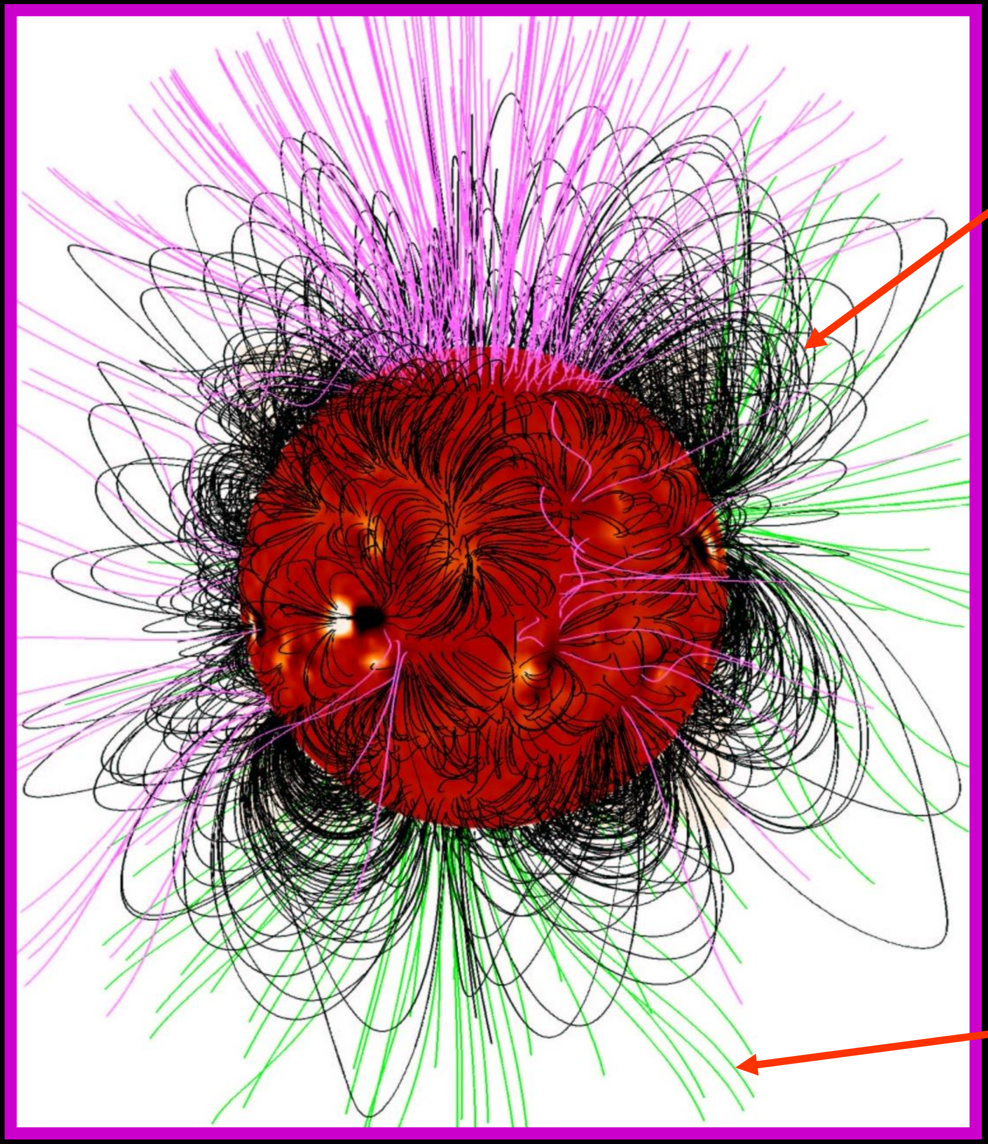
The corona extends as solar wind into the interplanetary medium.

The interplanetary medium is structured by the properties of the corona:

Fast solar wind originates in coronal holes

Sometimes the magnetic field lines can break
This releases highly energetic particles from the Sun.

Open and closed magnetic flux



Closed flux: slow solar wind

A small part of the total flux through the solar surface connects as open flux to interplanetary space

Open flux: fast solar wind

Solar Wind

These particles escape through coronal holes and the process is known as solar wind

Extends past Pluto's orbit

Initial velocities of 500 km/s

Speed 250-800 km/s

Temperature:

Protons 2×10^5 K

Electrons 1×10^5 K

Density a few particles/cm^3

The solar wind

A wind of charged particles flows out from the sun through the solar system interplanetary space is called with a plasma

Ionospheres

Ionizing radiation + atmosphere = ionosphere

UV-, gamma, and X-radiation from the sun can ionize particles in a planetary atmosphere

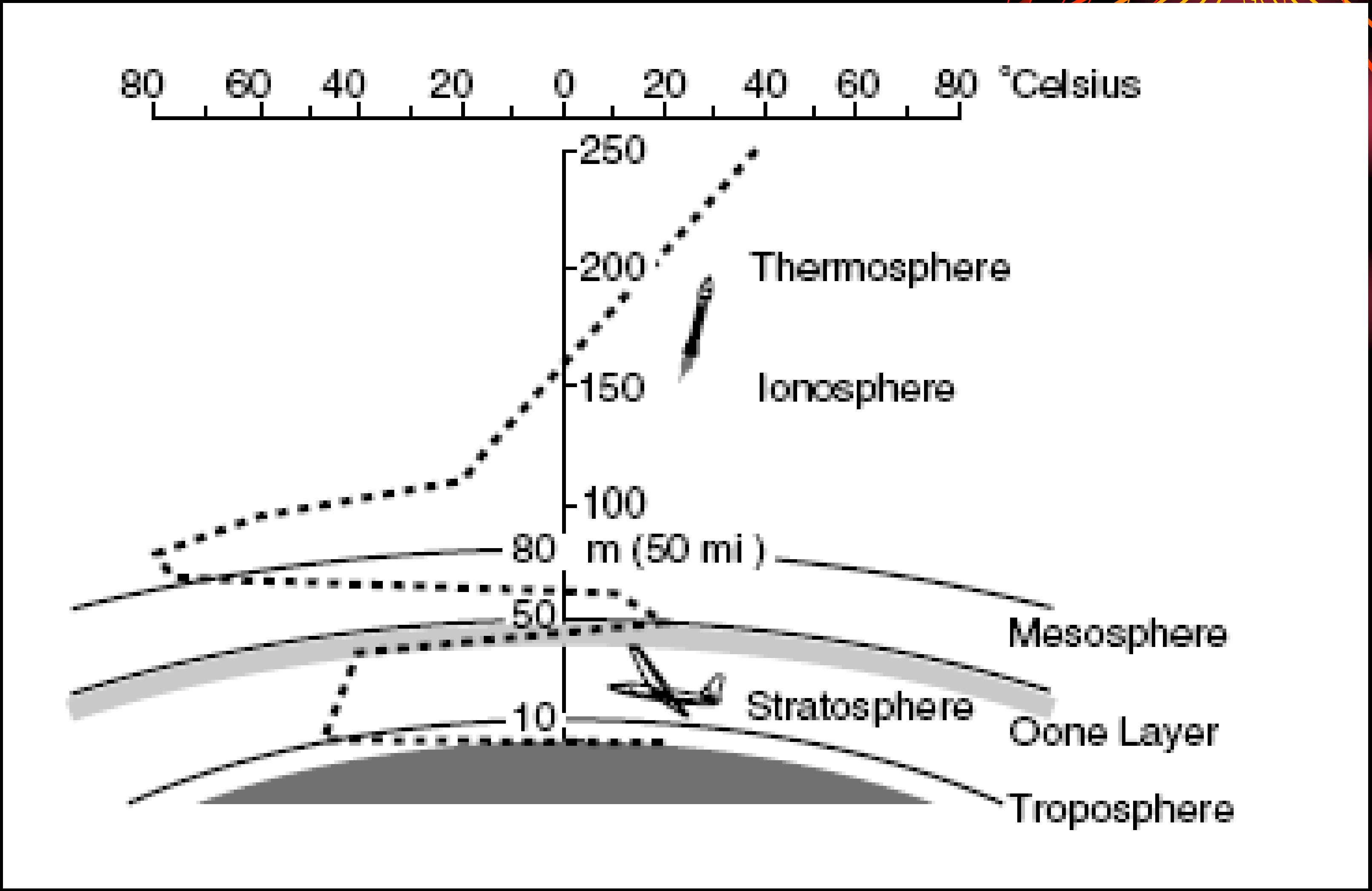
Cosmic radiation can also cause ionization

When ionizing the gas, the radiation is stopped by the atmosphere and to not penetrate further down. Therefore, only the upper layer of the atmosphere is ionized → plasma.

This plasma is called the ionosphere.

All planets with atmospheres has an ionosphere: Venus, Earth, Jupiter, Saturn, Uranus, Neptune. In addition, comets evaporates a gas cloud (because of radiation from the sun) which is partly ionized,
causing a cometary ionosphere.

The ionosphere



What is a plasma?

A plasma is a gas of charged particles. As they are charged, electromagnetic fields affect their motion, and therefore the dynamics of the plasma. Also, the charged particles can carry currents creating electromagnetic fields.

Solar system plasmas

The sun

High temperature → **matter is ionized** → **the sun is a plasma**

Magnetospheres

Solar wind + planetary magnetic field = magnetosphere

Thus, all magnetized planets have magnetospheres: Mercury, Earth, Mars, Jupiter, Saturn, Uranus, Neptune

As the particles in the solar wind are charged, their motion is affected by magnetic field from the planets.

Also, the charged particles in the solar wind can carry a current that can change the magnetic fields.

The net result is that the solar wind is deviated by the magnetic field of a planet, and that this magnetic field is connected to a region called the magnetosphere.

The Plasma State

A plasma is an electrically neutral ionized gas.
– The Sun is a plasma
– The space between the Sun and the Earth is "filled" with a plasma.

– The Earth is surrounded by a plasma.

– Over 99% of the Universe is a plasma.

Although a plasma is composed of charged particles – electric and magnetic forces are critical for understanding plasmas.

Space and Astrophysical plasmas

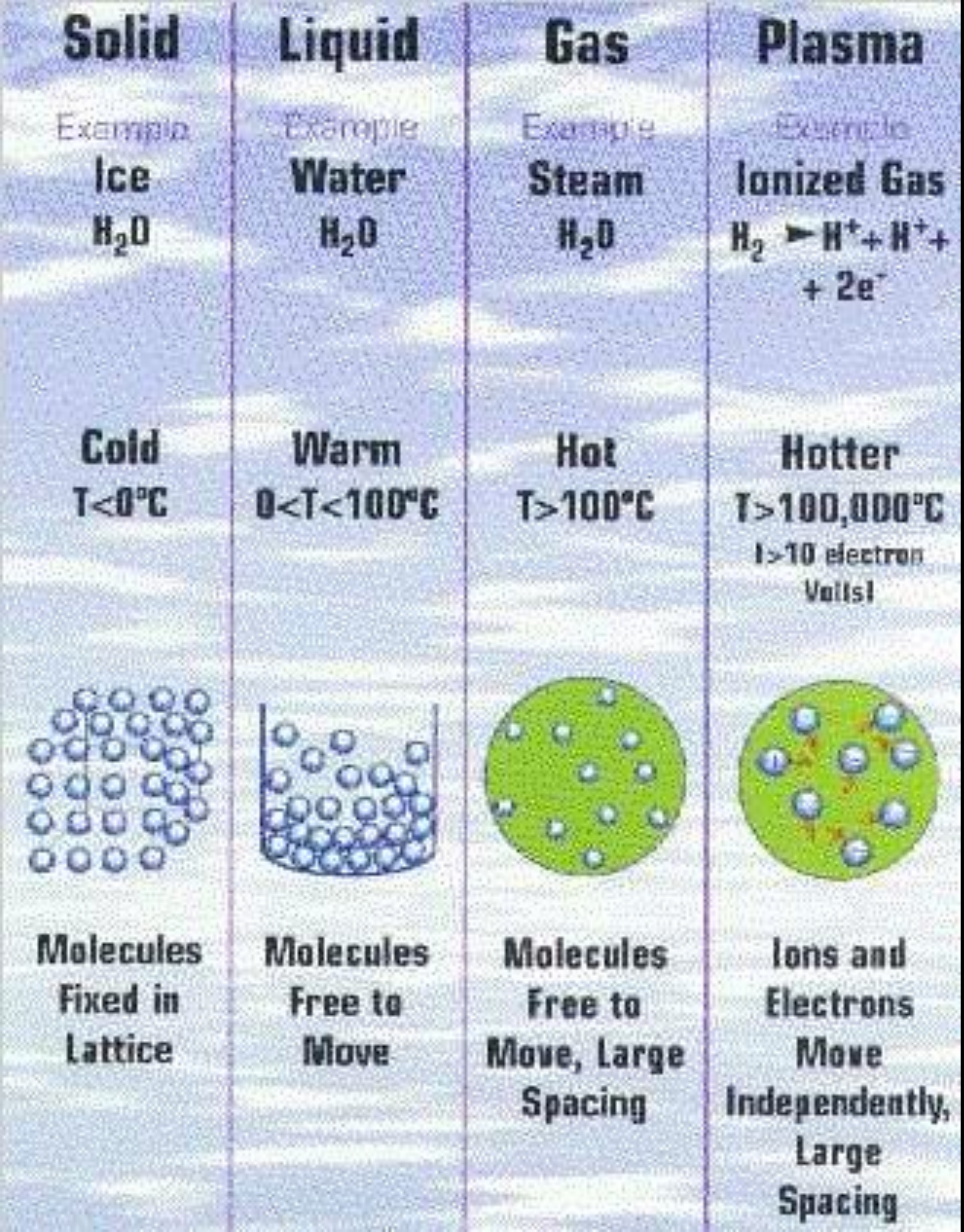
The Sun and other stars
(plasmas heated by nuclear fusion)

The solar wind

The interplanetary medium (space between planets)

The interstellar medium (space between star systems)

The Intergalactic medium (space between galaxies)



A plasma is a mixed gas or fluid of neutral and charged particles. Partially or fully ionized space plasmas have usually the same total number of positive (ions) and negative (electrons) charges and therefore behave quasineutral.

Interactions in plasmas

In a gas of neutral particles (henceforth called a neutral gas.), the particles interact with each other only through collisions.

In a plasma, the particles interact with each other at all times through the electromagnetic forces.

Thus, the dynamics of a plasma is inherently more complicated than that of a neutral gas.

Many people consider solid, liquid, gas and plasma to be the only four phases of matter. This is not true, as there exist many others, but they are generally more exotic with names like hadron gas or Bose-Einstein Condensate.

Temperatures

The kinetic energy of a plasma particle is considerably higher than its potential, where charged particles travel at high speeds.

If the potential were greater than the kinetic, then the plasma state would be destroyed as the ions and electrons would want to clump together into bound states atoms. This is why plasmas typically arise at very high temperatures.

Temperature controls the degree of plasma ionization. In particular, plasma ionization is determined by the "electron temperature" relative to the ionization energy, (and more weakly by the density), in a relationship called the Saha equation.

A plasma is sometimes referred to as being "hot" if it is nearly fully ionized, or "cold" if only a small fraction, (for example 1%), of the gas molecules are ionized, but other definitions of the terms "hot plasma" and "cold plasma" are common. Even in a "cold" plasma, the electron temperature is still typically several thousand degrees Celsius. Plasmas utilized in "plasma technology" ("technological plasmas") are usually cold in this sense.

Degree of ionization

For plasma to exist, ionization is necessary. The term "plasma density" by itself usually refers to the "electron density", that is, the number of free electrons per unit volume.

The degree of ionization of a plasma is the proportion of atoms which have lost (or gained) electrons, and is controlled mostly by the temperature. Even a partially ionized gas in which as little as 1% of the particles are ionized can have the characteristics of a plasma (i.e., response to magnetic fields and high electrical conductivity).

Plasmas

Existence of plasma

In a gas in thermal equlibrium at temperature T, the number of neutral molecules n_n and free electrons n_e are related by the Saha equation

$$\frac{n_{\mathrm{e}}}{n_{\mathrm{n}}} = \left(\frac{2\pi K T}{h^2}\right)^{3/4} \frac{1}{\sqrt{n_{\mathrm{n}}}} \exp\left(-\frac{V_{\mathrm{i}}}{KT}\right)$$

Where K and h are Boltzmann's and Planck's constants, and V_i is the ionization energy for the neutral particles. For ordinary air at room temperature, one gets a ridiculously small number, $n_e/n_n \sim 10^{120}$. For the gas to become a plasma, n_e/n_n must obviously reach much higher values. Looking at the Saha equation, we can identify three possibilities:

- High temperature ($KT \sim Vi$). This gives high kinetic energy to the particles, so that molecules may be ionized in collissions.

- Low density. This makes the probability of recombination low: once an atom is ionized, it is hard to nd an electron to recombine with in such a way that both energy and momentum are conserved in the recombination.

- Non-equilibrium. In this case, the Saha equation is no longer valid. For space plasmas, collision mean free paths are usually long and collision frequencies low. This means that it takes a very long time for the plasma to come into equilibrium, and many interesting things may happen before the plasma comes to equilibrium.

The Motion of Charged Particles

Particle description of plasmas

Equation of motion

$$m\frac{d\vec{v}}{dt} = q\vec{E} + q\vec{v} \times \vec{B} + \vec{F}_g$$

Thus, if the electromagnetic (EM) fields E and B are given, we can, at least in principle, get the particle motion v(t) and position r(t) by integration. To calculate the EM fields E(r; t) and B(r; t), we have Maxwell's equations:

Poisson’s Equation

$$\nabla \cdot \mathbf{E} = \rho / \epsilon_0$$

E is the electric field
ρ is the charge density
ε_0 is the electric permittvity of free space (8.85×10^{-12} Farad/m)

Gauss’ Law (absence of magnetic monopoles)

$$\nabla \cdot \mathbf{B} = 0$$

Faraday’s Law

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

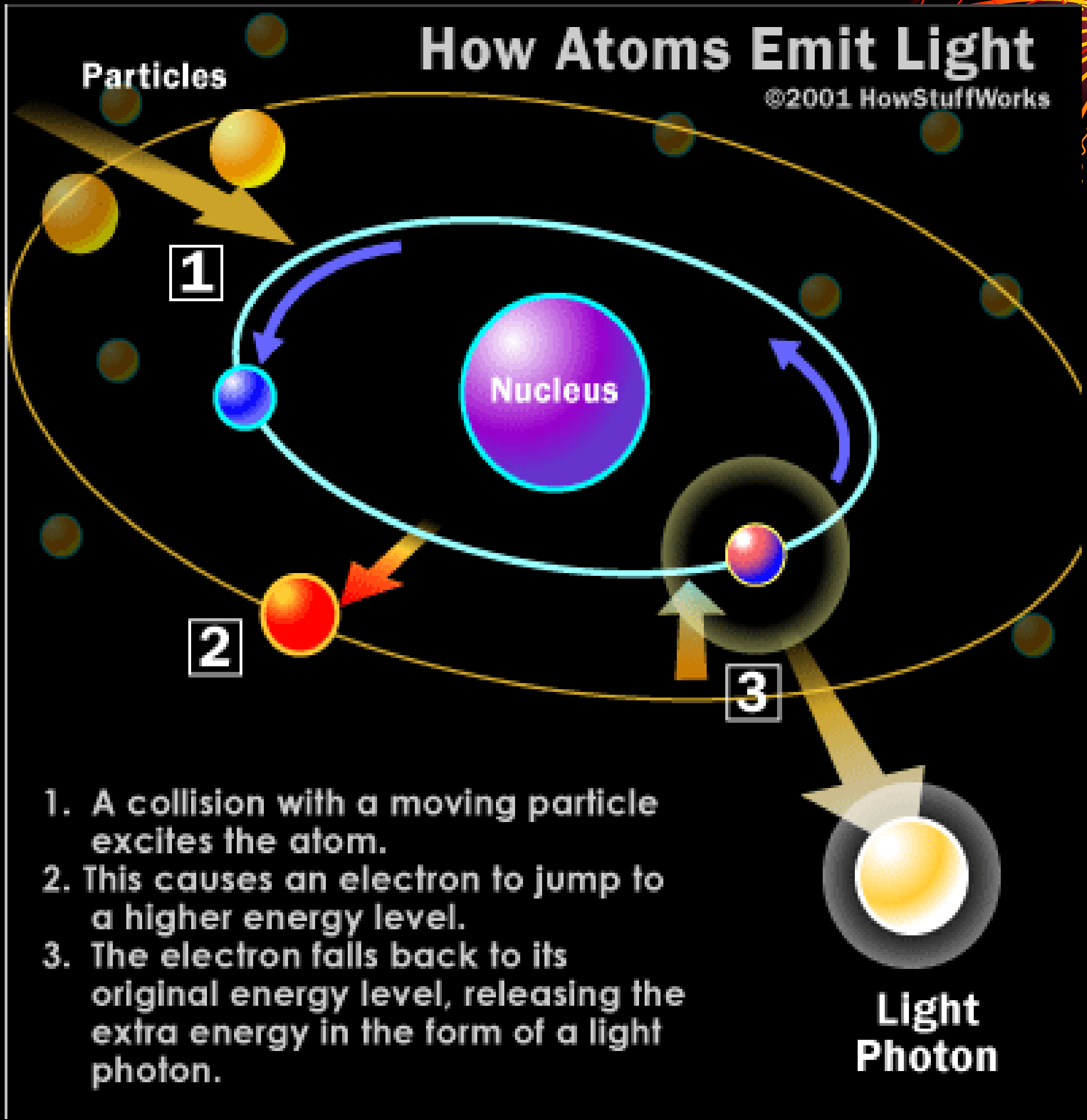
Ampere’s Law

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

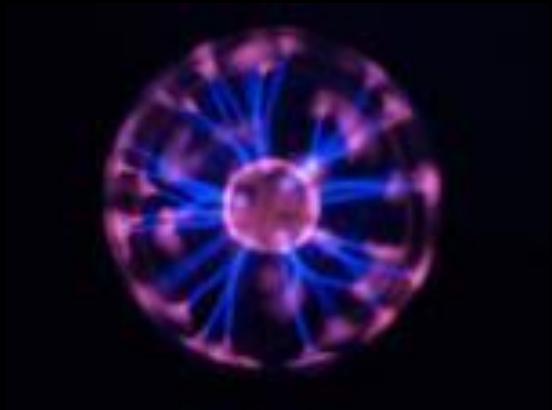
Terrestrial plasmas

The polar aurora

Lightning is an example of plasma present at Earth's surface. Typically, lightning discharges 30,000 amperes at up to 100 million volts, and emits light, radio waves, X-rays and even gamma rays. Plasma temperatures in lightning can approach ~28,000 kelvin and electron densities may exceed 1024 m^{-3}.


How Atoms Emit Light
©2001 HowStuffWorks
Particles
1
Nucleus
2
3
1. A collision with a moving particle excites the atom.
2. This causes an electron to jump to a higher energy level.
3. The electron falls back to its original energy level, releasing the extra energy in the form of a light photon.
Light Photon

در زندگی روزمره نیز با چند نمونه محدود از پلاسما مواجه میشویم



گازهای داخل یک لامپ فلورسان یا لامپ نئون

تابش ملایم شفق قطبی

جرقه رعد و برق

Since plasmas are very good conductors, electric potentials play an important role. The potential as it exists on average in the space between charged particles, independent of the question of how it can be measured, is called the "plasma potential", or the "space potential". If an electrode is inserted into a plasma, its potential will generally lie considerably below the plasma potential due to what is termed a Debye sheath. The good electrical conductivity of plasmas causes their electric fields to be very small. This results in the important concept of "quasineutrality", which says the density of negative charges is approximately equal to the density of positive charges over large volumes of the plasma ($n_e = \langle Z \rangle n_i$), but on the scale of the Debye length there can be charge imbalance. In the special case that *double layers* are formed, the charge separation can extend some tens of Debye lengths.

- **Comparison of plasma and gas phases**

Plasma is often called the *fourth state of matter*. It is distinct from other lower-energy states of matter; most commonly solid, liquid, and gas.

Although it is closely related to the gas phase in that it also has no definite form or volume, it differs in a number of ways, including the following:

Plasma properties and parameters

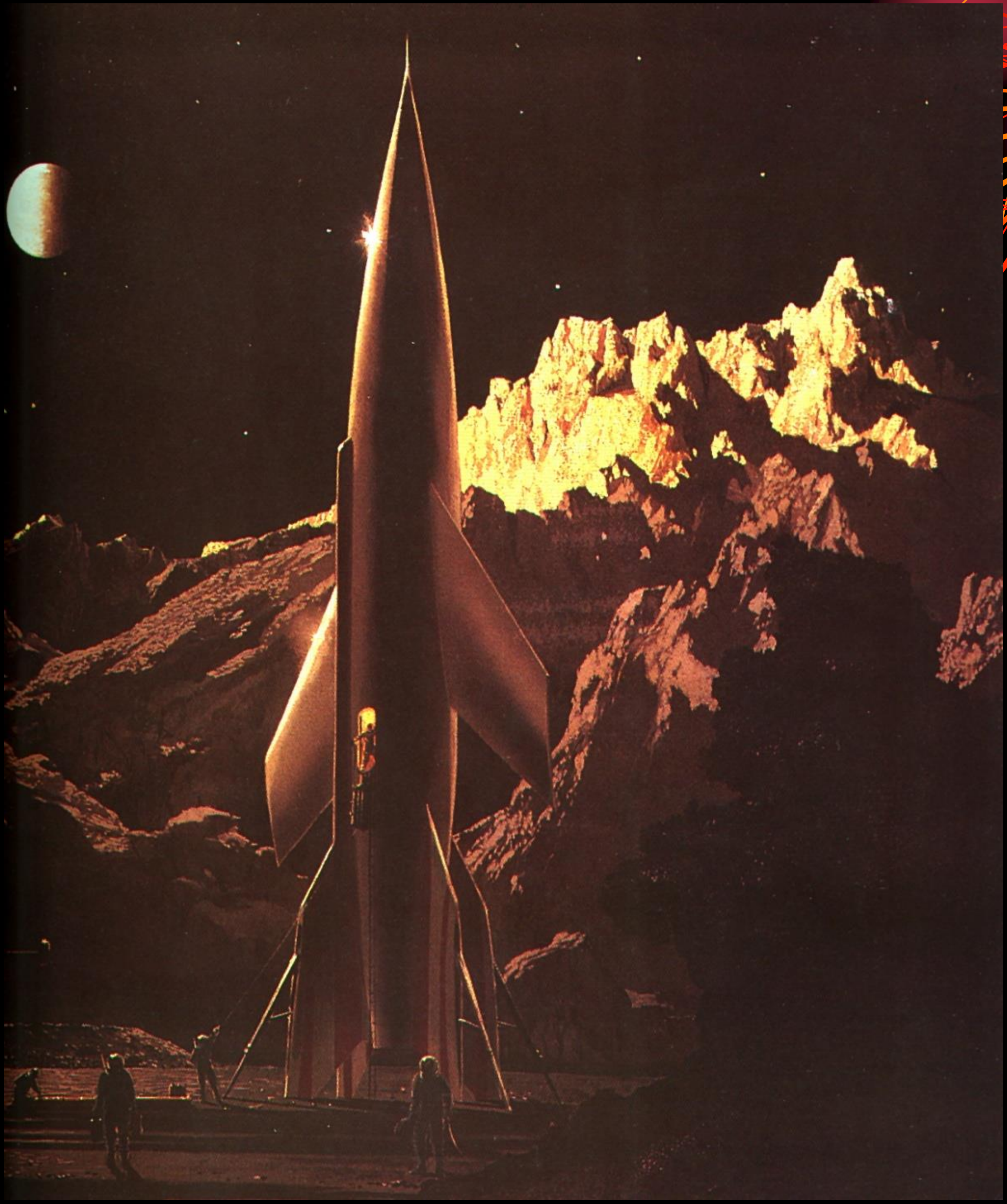
Definition of a plasma

Plasma is loosely described as an electrically neutral medium of positive and negative particles (i.e. the overall charge of a plasma is roughly zero). It is important to note that although they are unbound, these particles are not ‘free’. When the charges move they generate electrical currents with magnetic fields, and as a result, they are affected by each other’s fields. This governs their collective behavior with many degrees of freedom. A definition can have three criteria:

1) **The plasma approximation**: Charged particles must be close enough together that each particle influences many nearby charged particles, rather than just interacting with the closest particle (these collective effects are a distinguishing feature of a plasma). The plasma approximation is valid when the number of charge carriers within the sphere of influence (called the *Debye sphere* whose radius is the Debye screening length) of a particular particle are higher than unity to provide collective behavior of the charged particles. The average number of particles in the Debye sphere is given by the plasma paramete, "Λ" (the Greek letter Lambda).

- **2) Bulk interactions**: The Debye screening length (defined above) is short compared to the physical size of the plasma. This criterion means that interactions in the bulk of the plasma are more important than those at its edges, where boundary effects may take place. When this criterion is satisfied, the plasma is quasi neutral.

3) **Plasma frequency**: The electron plasma frequency (measuring plasma oscillations of the electrons) is large compared to the electron-neutral collision frequency (measuring frequency of collisions between electrons and neutral particles). When this condition is valid, electrostatic interactions dominate over the processes of ordinary gas kinetics.



Plasma dynamics is governed by the interaction of the charged particles with the self-generated (by their motions through their charge and current densities) electromagnetic fields. These internal fields feed back onto the particles and make plasma physics difficult.

more than 99% of all know matter in the universe is in the plasma state.

Plasma Frequency: Typical oscillations in a plasma are electron plasma oscillations

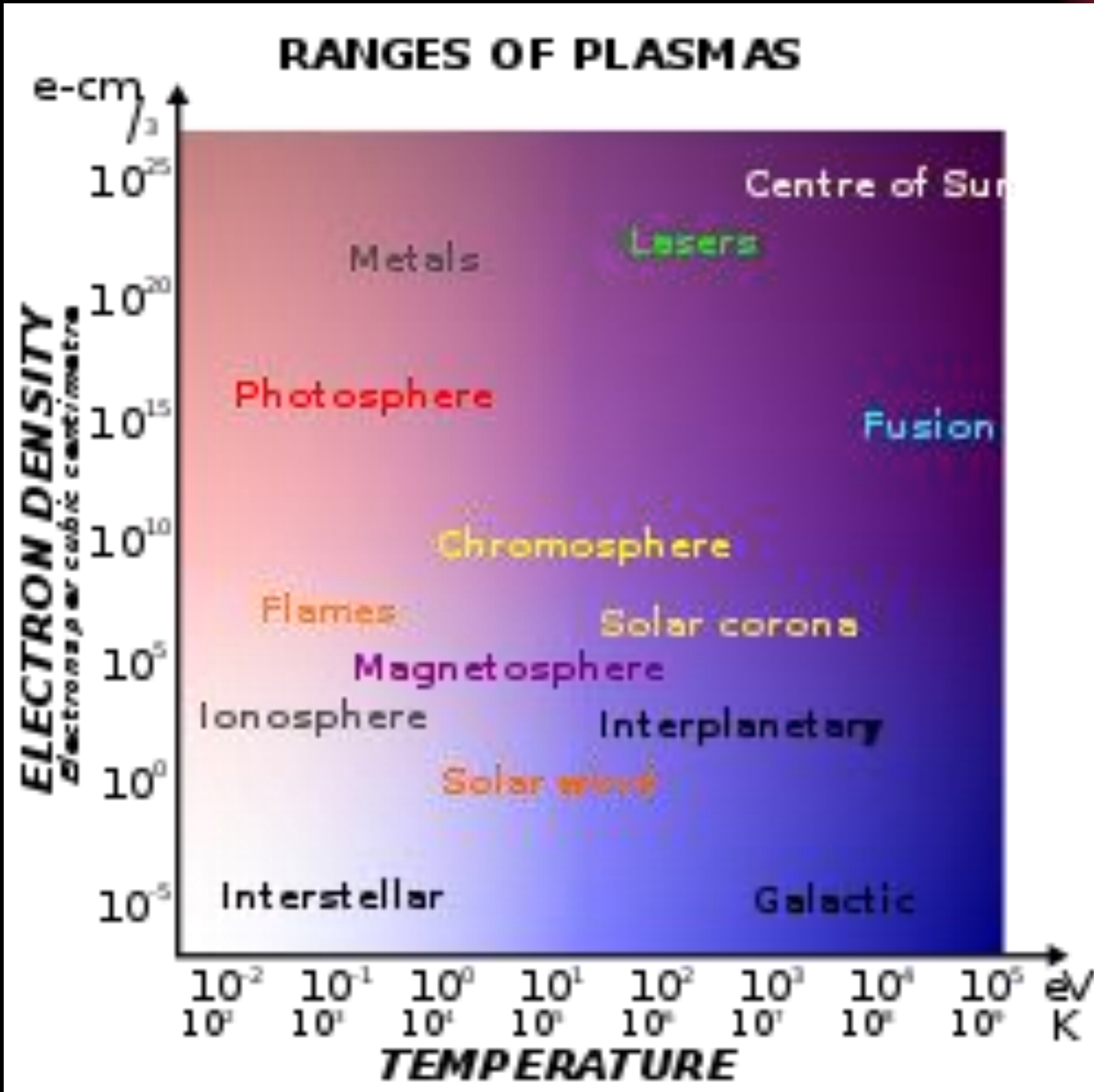
- The degree of ionization, α is defined as $\alpha = n_i/(n_i + n_a)$ where n_i is the number density of ions and n_a is the number density of neutral atoms. The *electron density* is related to this by the average charge state $\langle Z \rangle$ of the ions through $n_e = \langle Z \rangle n_i$ where n_e is the number density of electrons

- Plasma temperature is commonly measured in kelvins or electronvolts and is an informal measure of the thermal kinetic energy per particle. In most cases the electrons are close enough to thermal equilibrium that their temperature is relatively well-defined, even when there is a significant deviation from a Maxwellian energy distribution function, for example, due to UV radiation, energetic particles, or strong electric fields. Because of the large difference in mass, the electrons come to thermodynamic equilibrium amongst themselves much faster than they come into equilibrium with the ions or neutral atoms. For this reason, the "ion temperature" may be very different from (usually lower than) the "electron temperature". This is especially common in weakly ionized technological plasmas, where the ions are often near the ambient temperature.

- Based on the relative temperatures of the electrons, ions and neutrals, plasmas are classified as "thermal" or "non-thermal". Thermal plasmas have electrons and the heavy particles at the same temperature, i.e., they are in thermal equilibrium with each other. Non-thermal plasmas on the other hand have the ions and neutrals at a much lower temperature, (normally room temperature), whereas electrons are much "hotter".

Ranges of plasma parameters

Plasma parameters can take on values varying by many orders of magnitude, but the properties of plasmas with apparently disparate parameters may be very similar (see plasma scaling). The following chart considers only conventional atomic plasmas and not exotic phenomena like quark gluon plasmas:



Range of plasmas. Density increases upwards, temperature increases towards the right. The free electrons in a metal may be considered an electron plasma