Introduction to Plasma Physics

PPPL
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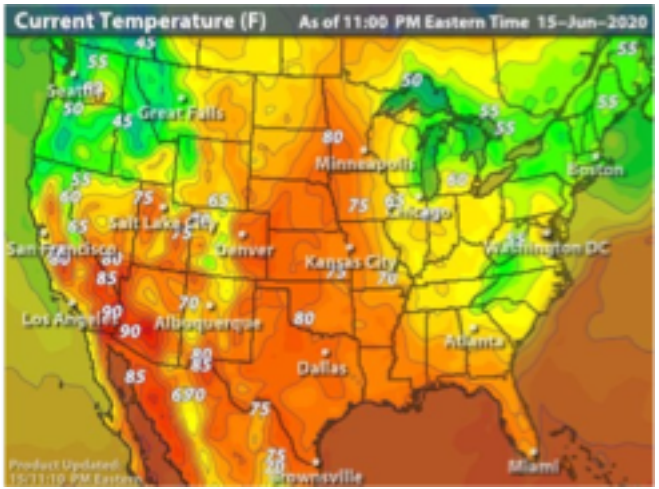
Let's improve our plasma intuition!

- 45 minutes is 9,999.25 hours too few to become an expert in plasma physics
- That's fine! My purpose today is to give you some intuition about the physics that dominates the plasma.
- I want to introduce you to some parameters that you'll hear a lot if you join the field (and during this course): plasma frequency, thermal velocity, Debye length, gyroradius, etc.
- You'll probably not remember the formulas but you'll get an intuition for them and may even rederive them in a "back of the envelope" way.

Super quick math review: fields

- Scalar fields: Every point in space is associated with a given value.

For example: Temperature



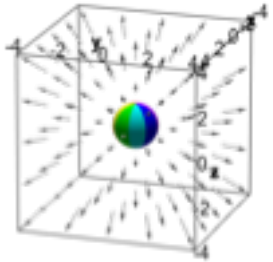
- Vector fields: Every point in space is associated with a given vector.

For example: Wind velocity

Super quick math review: Vector calculus

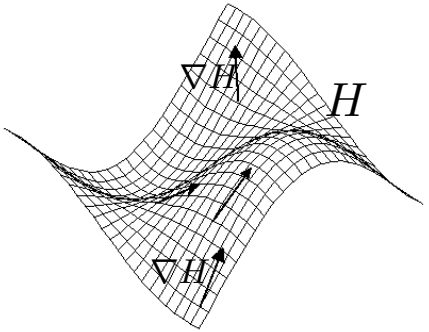
Divergence

$$\nabla \cdot \vec{V} > 0$$



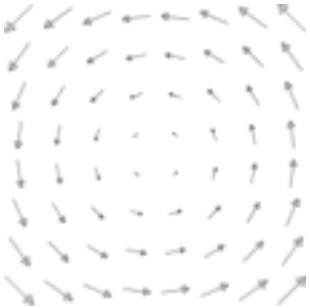
$$\nabla H$$

Gradient



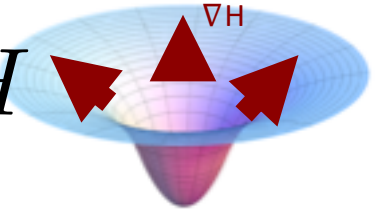
Curl

$$\nabla \times \vec{V} \neq 0$$



H

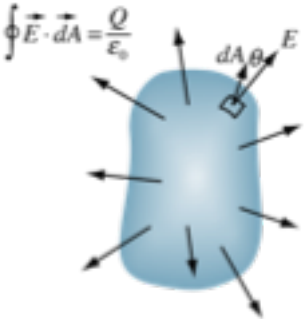
Laplacian



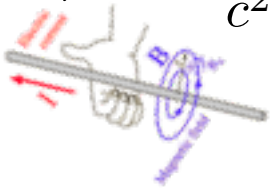
$$\nabla \cdot (\nabla H) = \nabla^2 H > 0$$

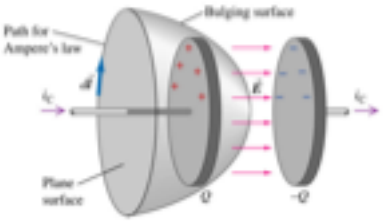
Gospel according to Maxwell

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

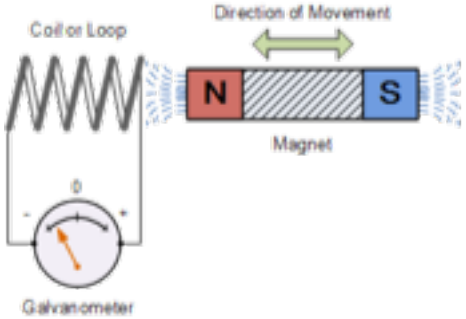


$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2} \frac{d\vec{E}}{dt}$$

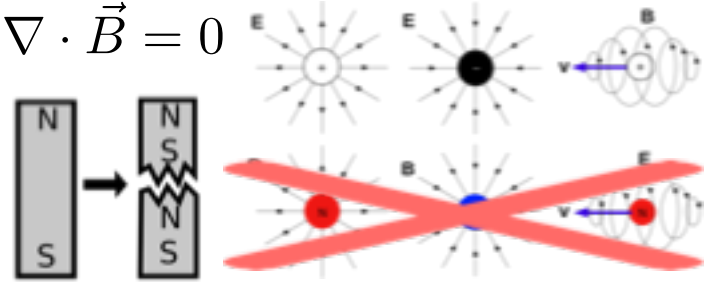




$$\nabla \times \vec{E} = -\frac{d\vec{B}}{dt}$$



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



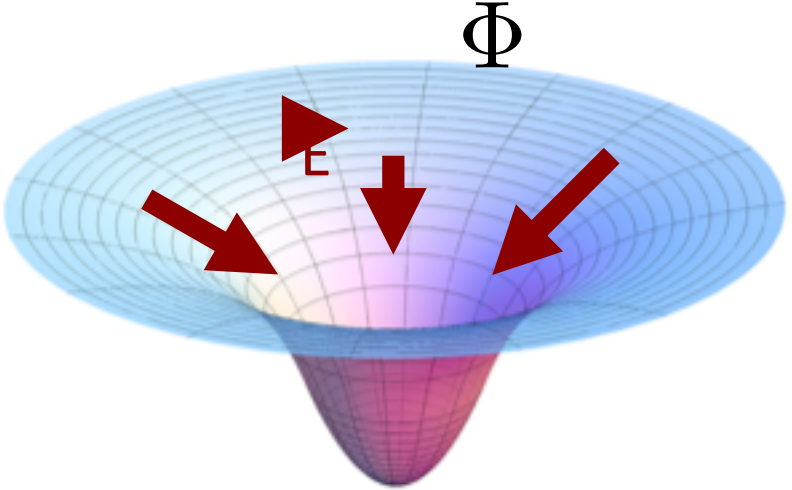
Electric potential and Poisson's equation

$$\vec{E} = -\nabla\Phi$$

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot (-\nabla\Phi) = \frac{\rho}{\epsilon_0}$$

$$\nabla^2\Phi = -\frac{\rho}{\epsilon_0}$$



Potential energy of a charge in an electric potential = $q\Phi$

Before I start, some further reading

- Introduction to Plasma Physics, Francis F. Chen, 1974
- Introduction to Plasma Physics, R.J. Goldston, P.H. Rutherford
- Plasma Physics Notes, Richard Fitzpatrick

From this lecture:

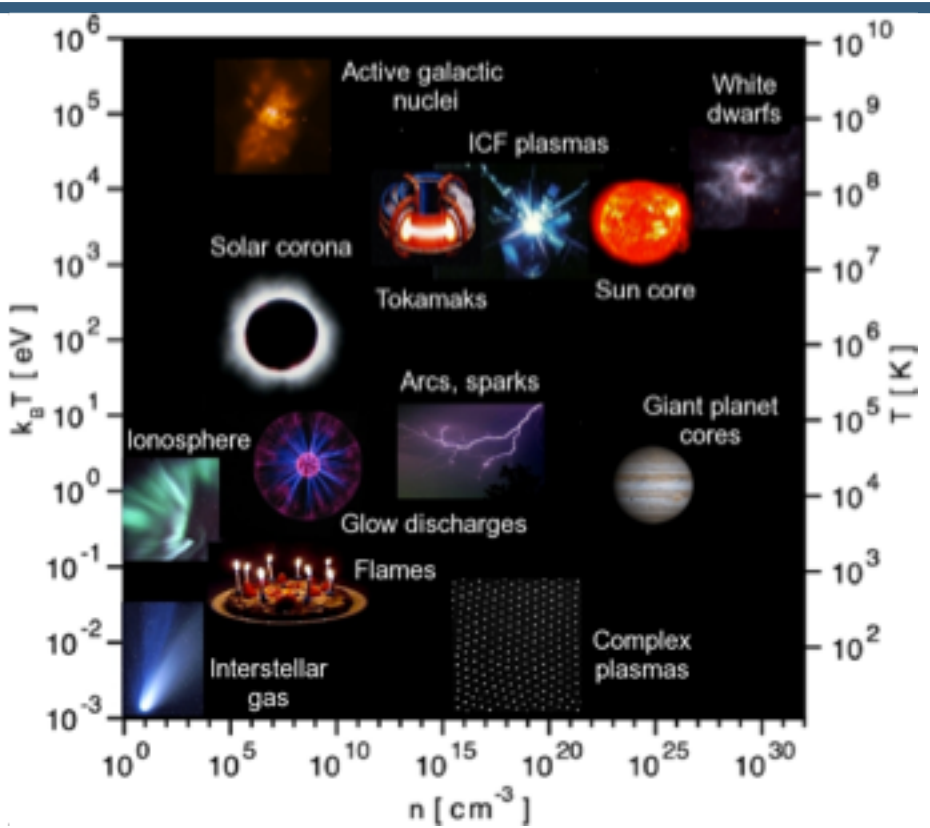
- Feynman lectures
- Introduction to Electrodynamics, David Griffiths, 1981

Poll

Plasma is a rich and varied field of study

- **Plasma is the 4th state of matter:** It is qualitatively different than gas due to its collective behavior, particularly its interactions with E&M fields.

- **Plasmas cover a wide range of densities and temperatures** This makes the field rich in scope



Saha's equation tells you the degree of ionization

Ionization energy

$$\frac{n_i}{n_n} \approx 2.4 \times 10^{21} \frac{T^{3/2}}{n_i} e^{-U_i/k_B T}$$

Degree of ionization

For nitrogen at standard temperature and pressure (STP):

$$\frac{n_i}{n_n} \approx 10^{-122}$$

At STP, most of what's around us is neutral

Comparison between electric/gravitational forces

The electric and gravitational forces exerted on m_1 by m_2 are:

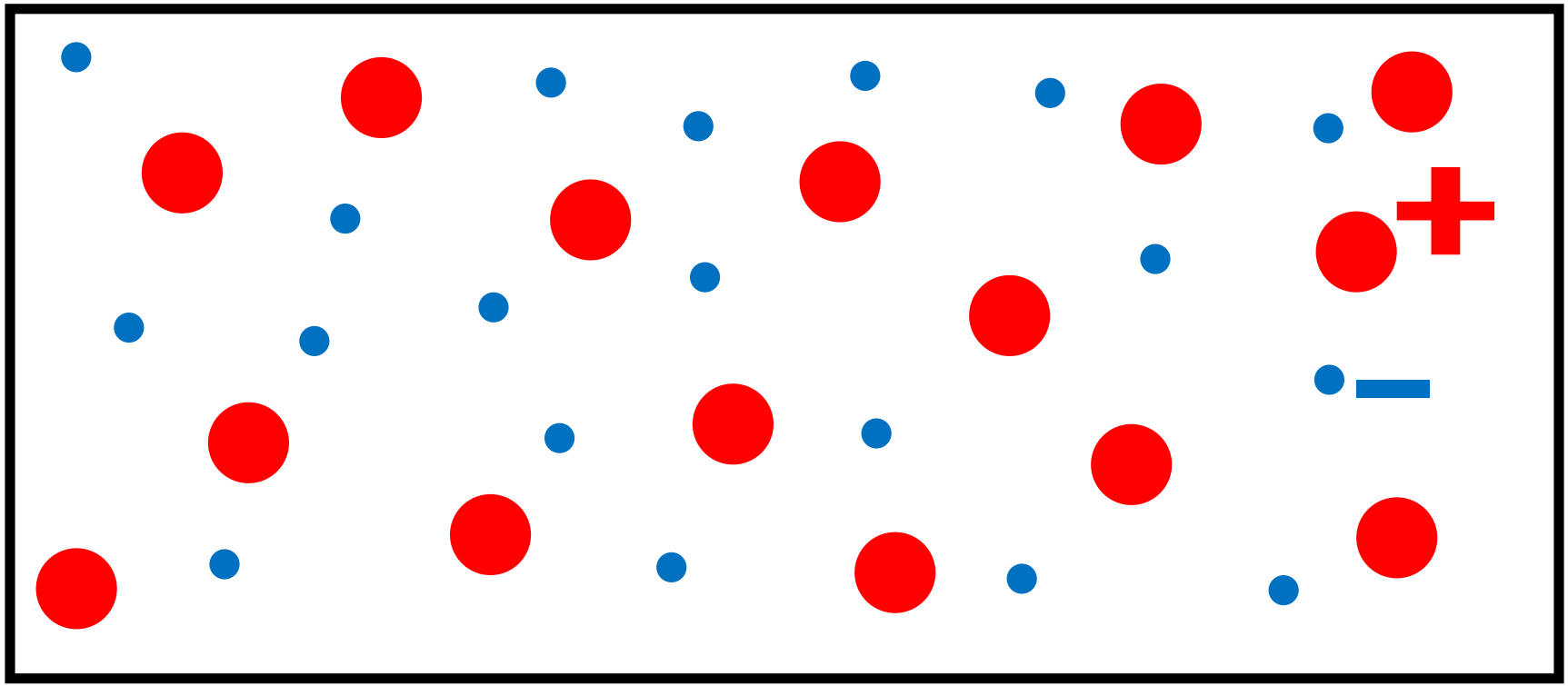
$$m_1\vec{a} = \Sigma\vec{F} = \vec{F}_G + \vec{F}_E = \left[-\frac{Gm_1m_2}{r_{1,2}^2} + \frac{q_1q_2}{4\pi\epsilon_0 r_{1,2}^2}\right]\hat{r}$$

Assuming one is an ionized deuterium atom and the other is an electron:

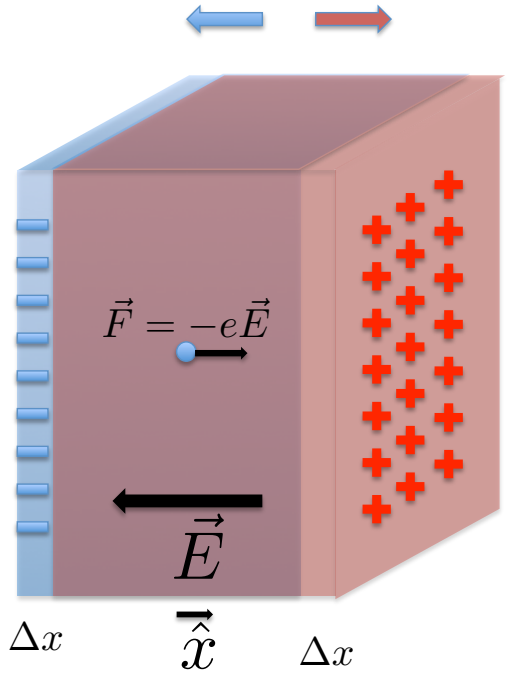
$$\frac{F_E}{F_G} = 1.1 \times 10^{39}$$

Gravity is irrelevant for lab plasmas (but not for astrophysical ones)

Even though it's (partially/fully) ionized, plasma equilibrium is quasi-neutral

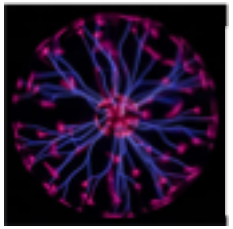


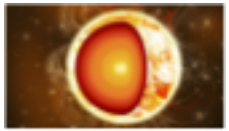
We start with a thought experiment where we disturb this quasi-neutrality

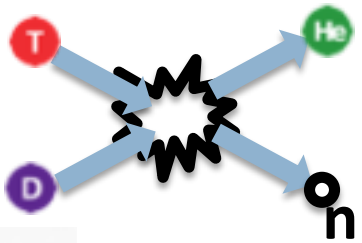


An aside on temperatures

1ev = 10,000K (11,600, but whatever)







~1eV

13.6eV

~1keV

~10keV

~10MeV