Plasma = a fluid of free charged particles

Maxwell's eqn's:

Gauss's law for electricity	$\epsilon_0 \oint \mathbf{E}\cdot d\mathbf{S} = q$
Gauss's law for magnetism	$\oint \mathbf{B}\cdot d\mathbf{S} = 0$
Ampère's law (as extended by Maxwell)	$\oint \mathbf{B}\cdot d\mathbf{l} = \mu_0\epsilon_0 \frac{d\Phi_E}{dt} + \mu_0 i$
Faraday's law of induction	$\oint \mathbf{E}\cdot d\mathbf{l} = -\frac{d\Phi_B}{dt}$

+ Newton's laws ➡ Magnetohydrodynamics (MHD)

$$\frac{d\rho}{dt} + \rho\nabla\cdot\boldsymbol{V} = 0,$$

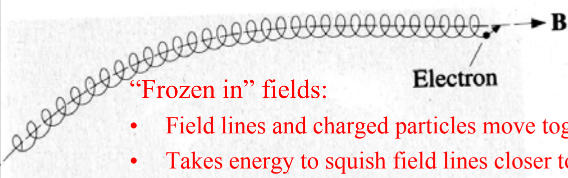
$$\rho\frac{d\boldsymbol{V}}{dt} + \nabla p - \boldsymbol{j}\times\boldsymbol{B} = 0,$$

$$\boldsymbol{E} + \boldsymbol{V}\times\boldsymbol{B} = 0,$$

$$\frac{d}{dt}\left(\frac{p}{\rho^{\Gamma}}\right) = 0,$$

Charged particles in magnetic field feel Lorenz force:

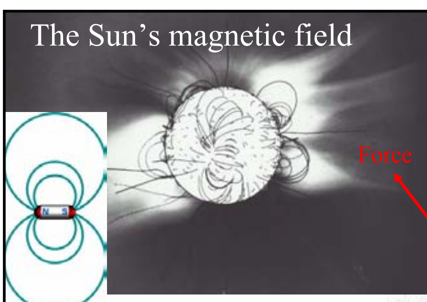
$$\boldsymbol{F} = q\,\boldsymbol{v}\times\boldsymbol{B},$$



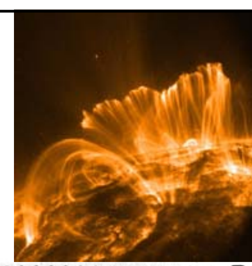
"Frozen in" fields:

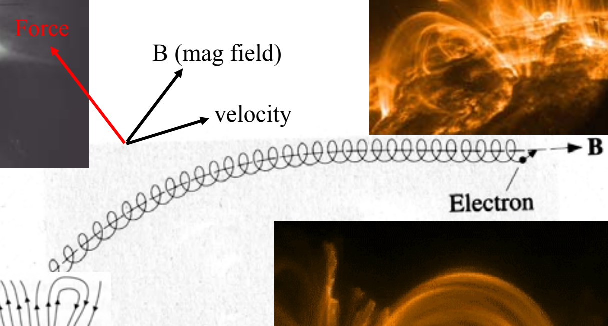
- Field lines and charged particles move together.
- Takes energy to squish field lines closer together
- Takes energy to stretch field lines.

The Sun's magnetic field

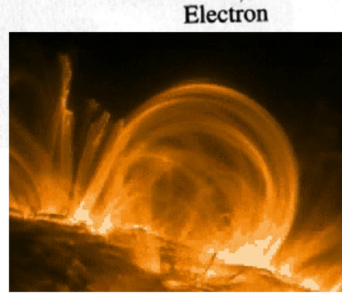


Magnetic Field Lines





X-ray flare movie



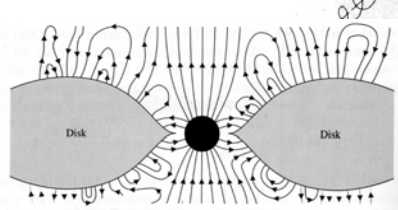
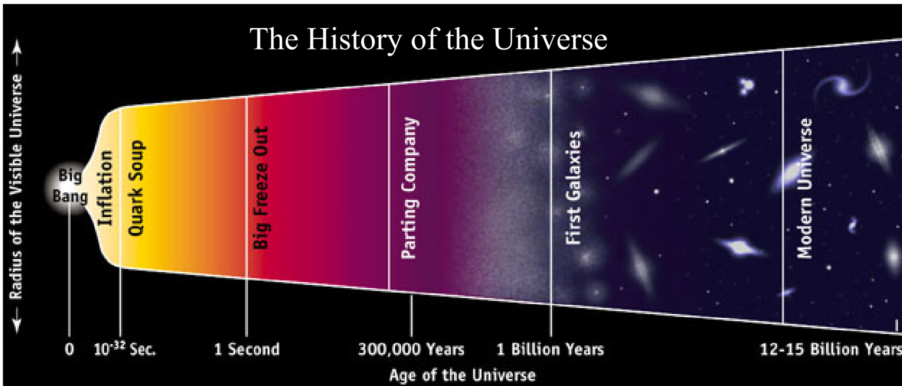


Figure 26.24 An accretion disk and its magnetic field orbiting a rotating black hole.

http://farside.ph.utexas.edu/teaching/plasma/lectures/node60.html



Planck time | Nucleosynthesis of H, He, Li | Galaxy Formation | Now

Inflation

Decoupling of CMB

Hot → Cool

High density → Low density

Interactions

Four forces in Nature

1 Gravity

Newton

3 Weak Interaction

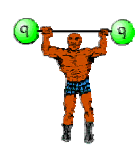
Beta (radioactive) decay
Muon decay

Time scales: $10^{-12} \sim 10^{3}$ sec

2 Electromagnetism

Faraday

4 Strong Interaction



Hold nuclei together
Particle collision

Time scales: 10^{-23} sec

(These slides compliments of Prof. Yuan)

Leptons

- Don't feel the strong force
- Integer or Zero charge
- Flavours:

e^-	"electron" (0.511 MeV)	(1897)	In atoms
μ^-	"Muon" (206 m_e)	(1937)	First seen in Cosmic Ray
τ^-	"Tau" (17 m_μ)	(1975)	Seen at SLAC (Stanford Linear Accelerator Center)
ν_e	"electron neutrino" Pauli's explanation of Beta Decay (1930)	(1956)	
ν_μ	"Muon neutrino"	(1962)	
ν_τ	"Tau neutrino"	(2000)	

Mass

$\nu_e < 3 \text{ eV}$

$\nu_\mu < 0.19 \text{ MeV}$

$\nu_\tau < 18.2 \text{ MeV}$

Quarks

- Feel the strong force
- Fractionally charged

$$Q = \begin{Bmatrix} 2/3 \\ -1/3 \end{Bmatrix} \times \text{ Proton charge}$$

- Constituents of neutron (udd) and proton (uud)

$\begin{pmatrix} u \\ d \end{pmatrix}$ "up" "down"

- Flavors:

u	"up"
d	"down"
s	"strange"
c	"charmed"
b	"bottom"
t	"top"

Baryon
A strongly interacting particle that is composed of quarks and has a spin that is an integer multiple of $\hbar$ (e.g., a quark, neutron, or proton).

The Standard Model of Particle Physics

- Matter fields (make up all visible matter in the universe)
  - Fermions (Spin 1/2)

Lepton (No Strong Interaction)

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$$e_R^- \quad \mu_R^- \quad \tau_R^-$$

Quarks (q)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \; u_R \; u_R \quad c_R \; c_R \; c_R \quad t_R \; t_R \; t_R$$

$$d_R \; d_R \; d_R \quad s_R \; s_R \; s_R \quad b_R \; b_R \; b_R$$

3 families

  - Scalar (Spin 0)

Higgs Boson (Not yet found!)

(From Higgs Mechanism —— Spontaneous Symmetry Breaking)

The Standard Model of Particle Physics

- Interactions (mediated by interchanging Gauge Bosons, spin-1 force carrier)

1) Electromagnetic Interaction (QED)

Photon (massless)

2) Strong Interaction (QCD)

Gluon (massless) (1979)

3) Weak Interaction

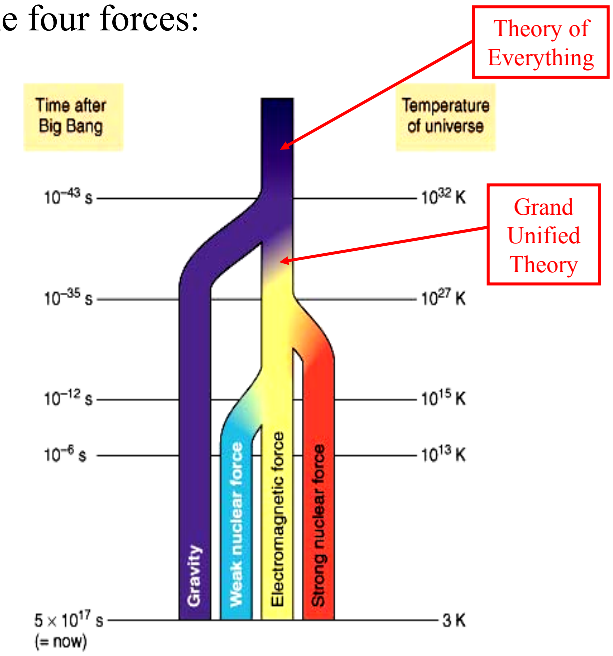
W^+, W^- and Z Gauge Bosons (1983)

(massive $M_W = 80.4$ GeV, $M_Z = 91.187$ GeV   1 GeV $= 10^9$ eV)

In SM, the Mass of W-boson, either $W^\pm$ or Z, arises from the Higgs Mechanism

(Without it, Gauge Bosons have to be massless from gauge principle.)

“Freezing out” of the four forces:



- Massless gauge bosons.
- Many additional massive particles (dark matter candidates)

- Quarks
- Massive gauge bosons
- Leptons
- Gluons
- Photons