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**Searching  
for  
Magnetic Monopoles**

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*Caltech*

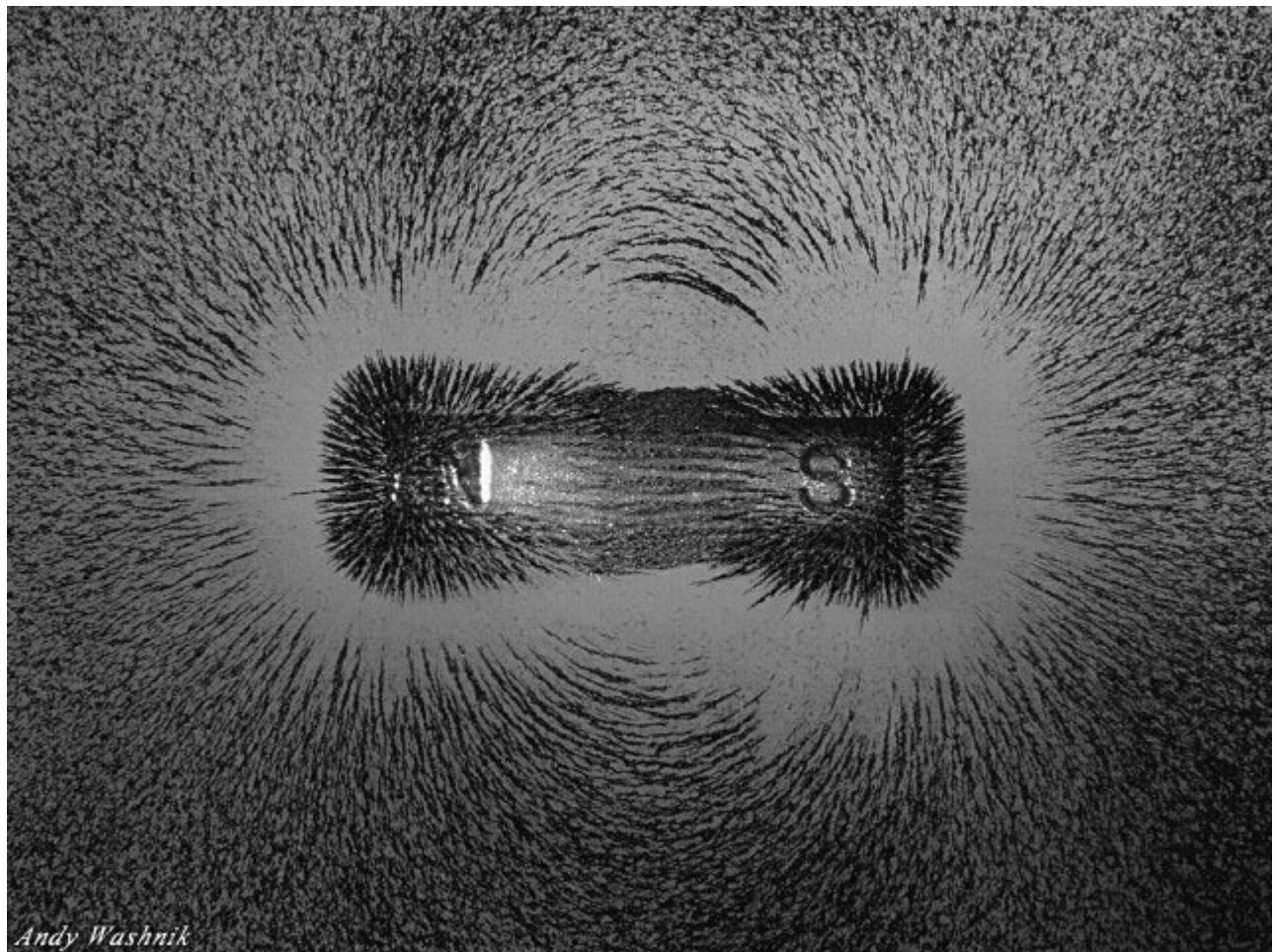
# Magnets in Nature

*ancient history*

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*“... in this stone you should thoroughly comprehend there are two points of which one is called the North, the remaining one the South.”*

*--- Petrus Peregrinus (1269 AD)*

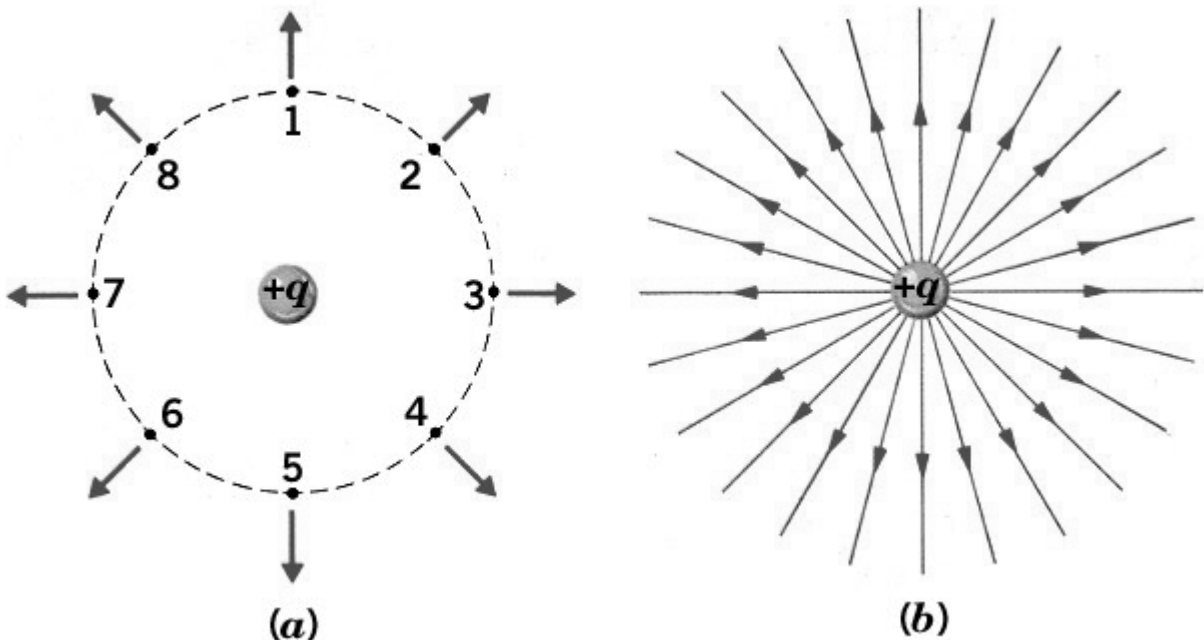


# Magnetic Monopoles

*history*

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**Coulomb**, in 1788, established inverse square force law for both electric charges and magnetic poles



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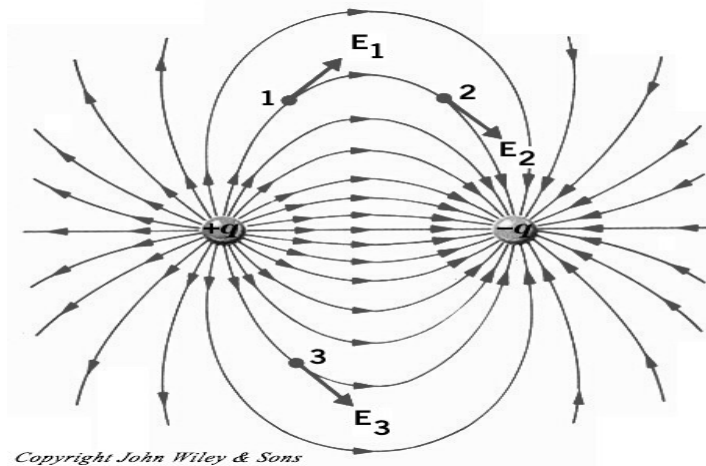
Single Electric Charge

# Magnet Monopoles

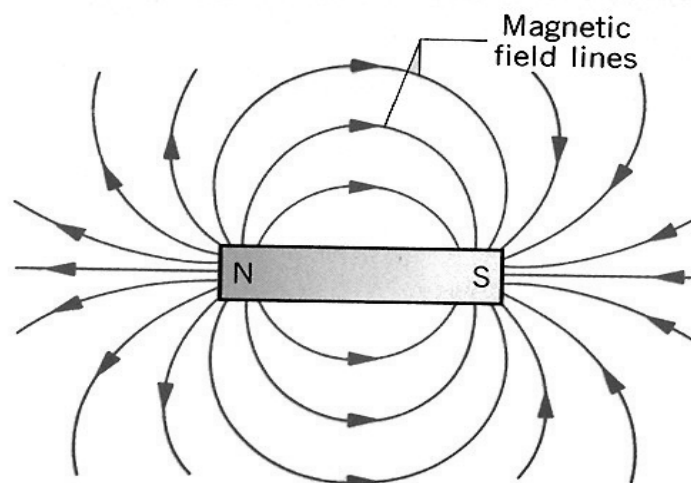
*history*

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- ◆ Ampere for multiple charges -



electric dipole



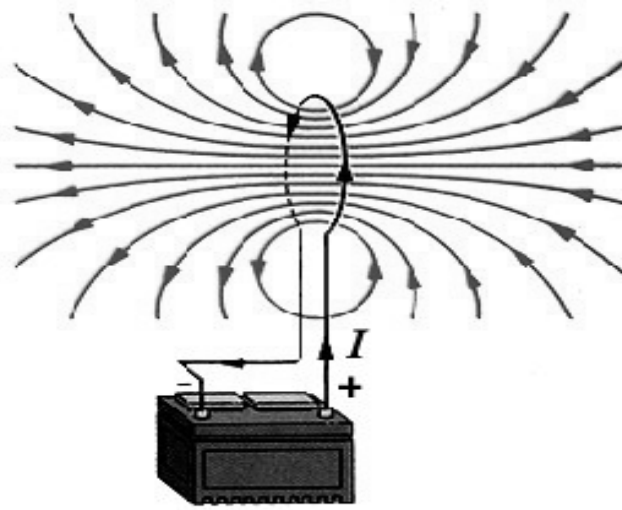
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bar magnet

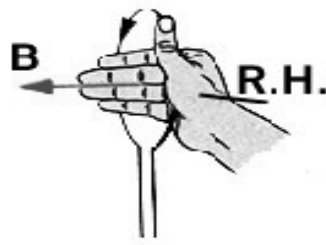
# Magnetic Monopoles

## *history*

- ◆ **Ampere**, in 1820, asserted that all magnetism is due to electric currents [and, responding to criticism of Faraday, invents microscopic currents]



(a)



(b)

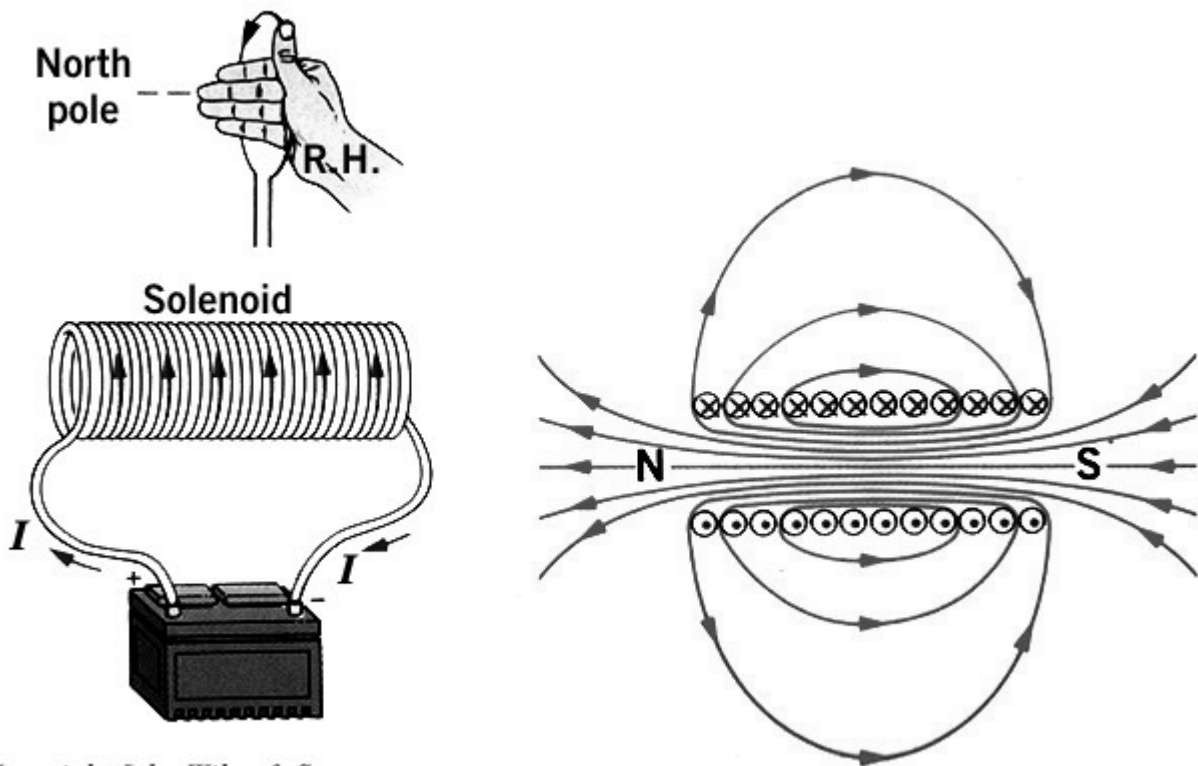
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loop of wire

# Magnetic Monopoles

*history*

- ◆ Ampere postulated magnets as solenoids, following Oersted's



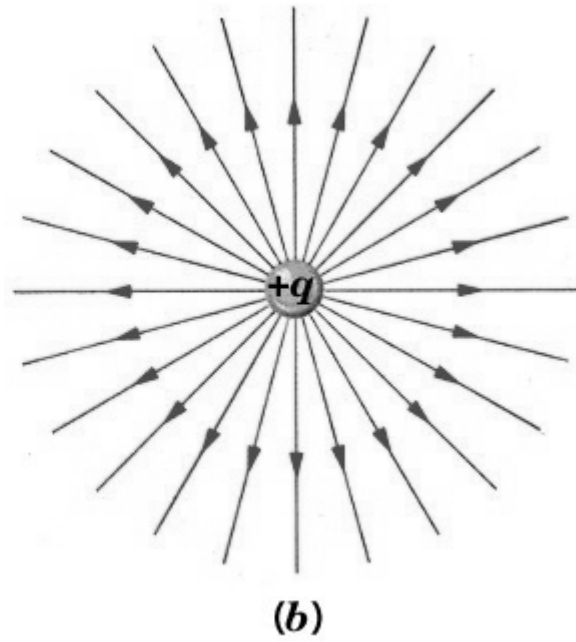
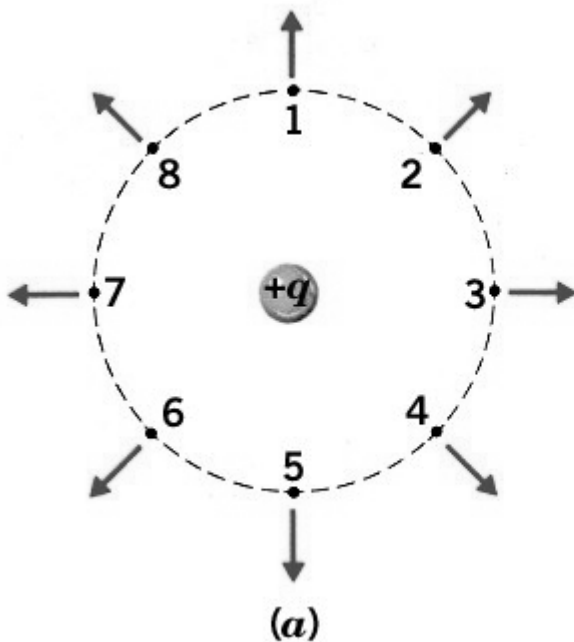
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Solenoid - field like bar magnet

# Magnetic Monopoles

## *history*

- ◆ By this point, the connection between electricity and magnetism is becoming evident, but what is magnetic analog of single electric charge??



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- ◆ are there single magnetic poles?

# Magnetic Monopoles

*modern history*

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- ◆ **Maxwell**, in 1873, makes the connection between electricity and magnetism

$$\nabla \cdot \vec{E} = 4\pi\rho$$

$$\nabla \times \vec{E} = -\frac{1}{c} \frac{\partial \vec{B}}{\partial t} \quad \left( -\frac{4\pi}{c} \dot{j}_m \right)$$

$$\nabla \cdot \vec{B} = 0 \quad (+4\pi\rho_m)$$

$$\nabla \times \vec{B} = \frac{1}{c} \frac{\partial \vec{E}}{\partial t} + \frac{4\pi}{c} \vec{j}$$

**Magnetic  
monopole  
terms**

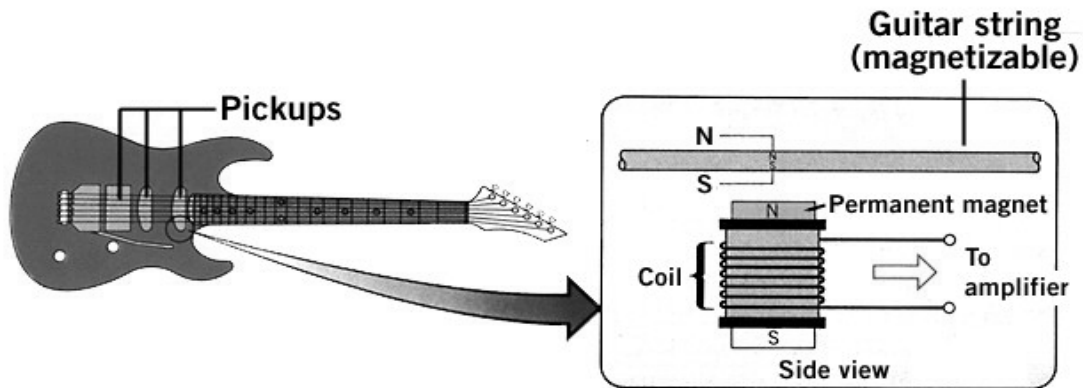
- ◆ introducing magnetic monopole makes equations symmetric



# Maxwell's equations

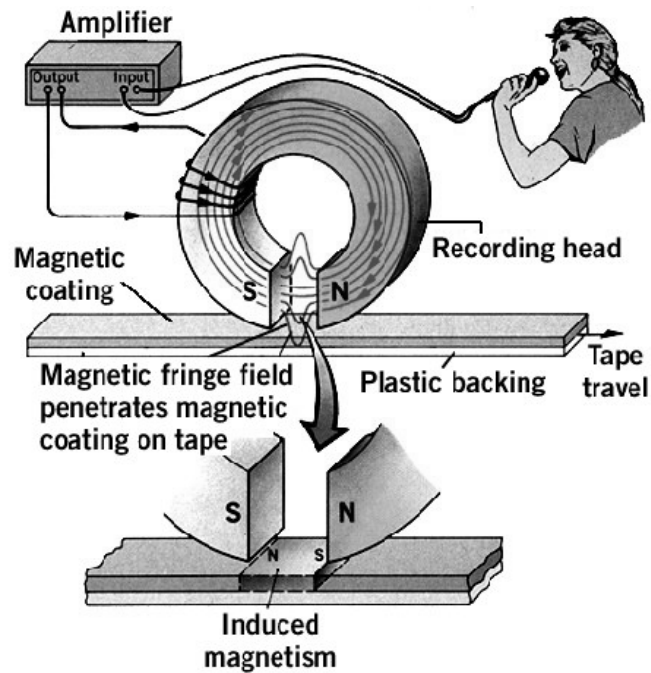
## *consequences*

### ◆ making music electronically



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### ◆ recording music

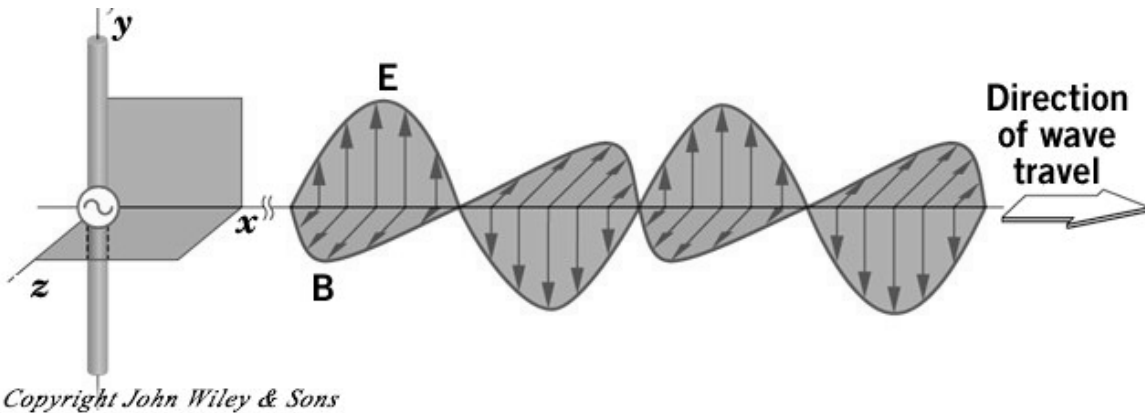


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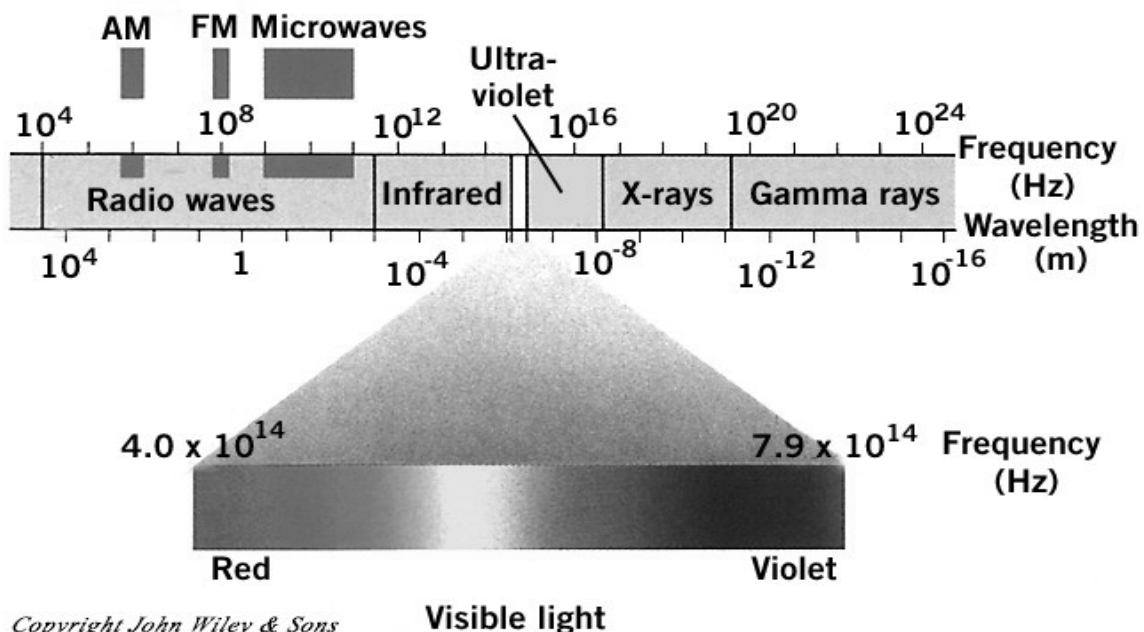
# Maxwell Equations

## *electromagnetic waves*

### ◆ electromagnetic waves



### ◆ spectrum of em waves



# Magnetic Monopoles

## *quantization of charge*

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- ◆ Electric charge always comes in discrete values a multiple of the charge of the electron

$$Q = n \times q_e = n \times 1.6 \cdot 10^{-19} \text{ coulombs}$$

- ◆ **Dirac**, in 1931, made connection of isolated poles and quantization of electric charge

$$\frac{eg}{\hbar c} = N/2$$

- ◆ The first strong **scientific** motivation for magnetic monopoles.
  - It inspired a large variety of imaginative experiments.

# Dirac Monopoles

## *accelerator searches*

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**Fermilab  
proton-antiproton  
collider**

- ◆ direct detection:  
(immediately after production in high-energy collisions)
  - thin plastic sheets surround interaction regions.
- ◆ indirect searches:  
(where monopoles are searched for a long time after their production)
  - dump beam into ferromagnetic materials. Later put in 200 Kgauss pulsed magnetic field to ‘pull monopoles out’

# Dirac Monopoles

*more experiments*

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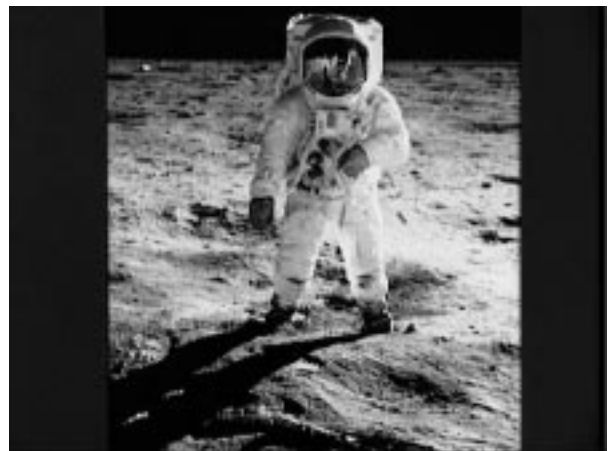
## ◆ Cosmic Rays

- Price reported event from 18 m<sup>2</sup> plastic detector in 1975. Later excluded by Alvarez. Then they published an upper limit.



## ◆ Moon Rocks

- One of the first scientific experiments with moon rocks was to search for a concentration of magnetic monopoles by Alvarez.



# Magnetic Monopoles

## *Grand Unified Theories*

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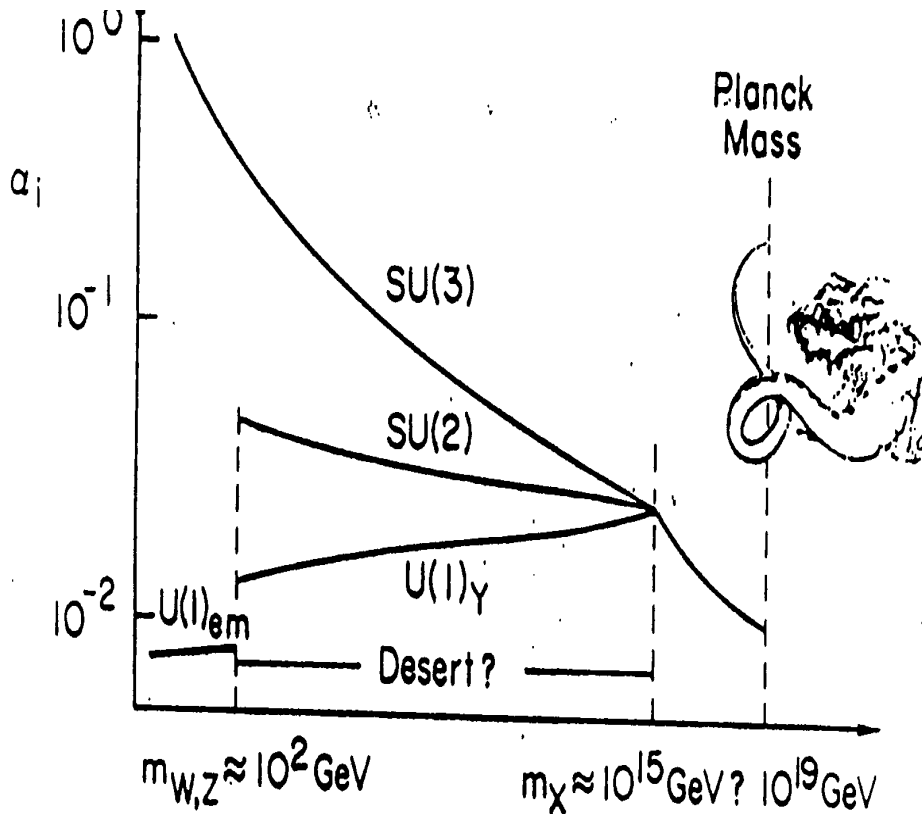
- ◆ **'t Hooft and Polyakov (1974)** discovered that monopoles are fundamental solutions to non-Abelian gauge theories
  - may be primordial monopoles present in the Universe

$$m_M = \frac{4\pi}{g} \frac{E_X}{\alpha_{GUT}} \approx 0.01 \times 10^{16} \text{ GeV}$$

- GUT monopoles are superheavy, and therefore, not producible from particle accelerators
- Search for GUT monopoles as rare non relativistic particles in the cosmic rays

# Grand Unification

*energy scale*

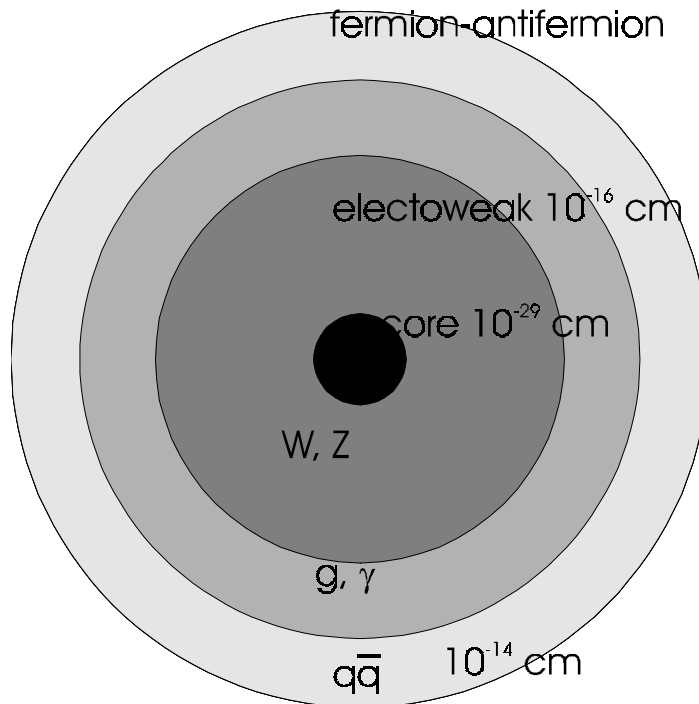


- ◆  $SU(3)$ ,  $SU(2)$ ,  $U(1)$  couplings  
'converge' at energy scale  $\sim 10^{15}$  GeV
  - not quite (e.g. needs supersymmetry or ??)
- ◆ Unification scale appears to be well below Planck mass, where quantum gravity effects  $\sim O(1)$

# GUT Monopole

## Structure

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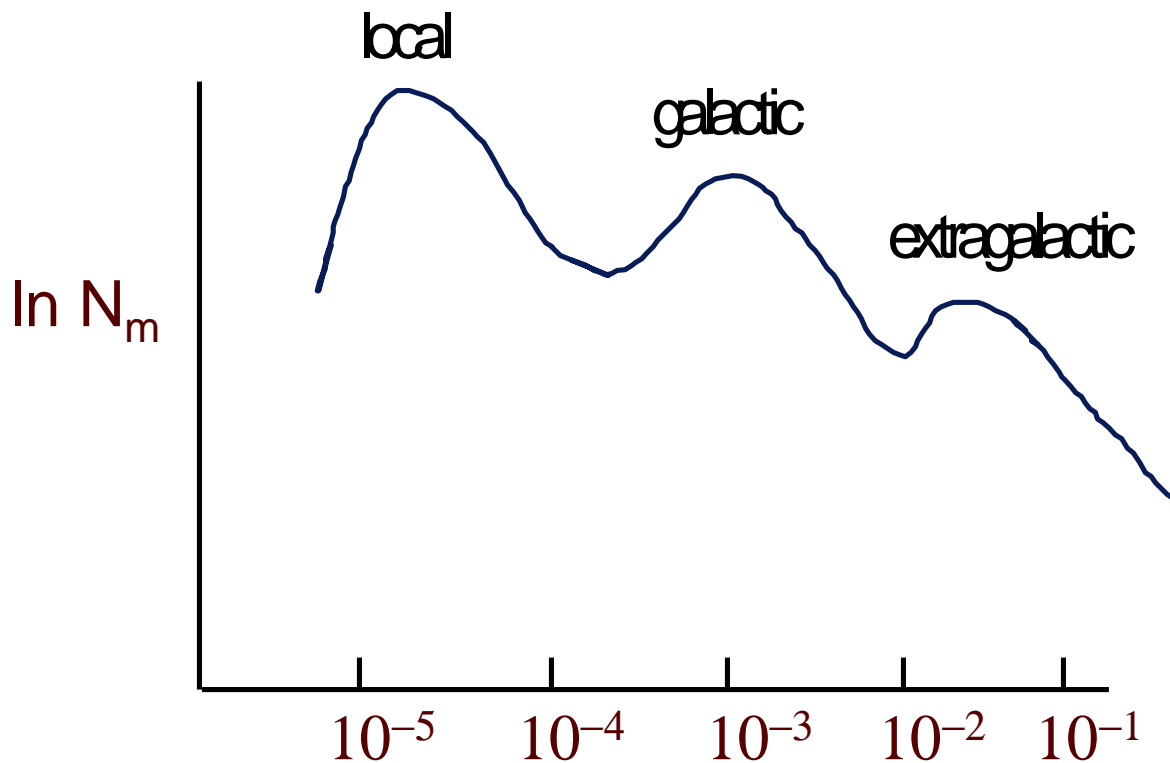


- ◆ grand unification core
  - virtual X-bosons ( $10^{-29}$  cm)
- ◆ electroweak unification
  - virtual W, Z,  $\gamma$ , g ( $10^{-16}$  cm)
- ◆ confinement region
  - g,  $\gamma$  ( $10^{-13}$  cm)
- ◆ condensate
  - fermion-antifermion pairs ( $r \sim m_f^{-1}$ )



# GUT Monopoles

*flux vs  $\beta$*



## ◆ escape velocity $\beta$

- earth :  $\beta = 3.7 \cdot 10^{-5}$
- solar system :  $\beta = 10^{-4}$
- galaxy :  $\beta = 10^{-3}$
- cluster of galaxies :  $\beta = 3 \cdot 10^{-3}$

# Monopole Abundance

*early universe*

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- ◆ GUTS + standard cosmology leads to *glut* of monopoles

- for a monopole mass  $\sim 10^{16}$  GeV

$$\rho_M \geq 5 \times 10^{-18} \text{ gm} / \text{cm}^3$$

- taking Hubble constant  $\sim (10^{10} \text{ yr})^{-1}$

$$\rho_c = \frac{3H^2}{8\pi G} \approx 8 \times 10^{-29} \text{ gm} / \text{cm}^3$$

**E**

$$\Omega \equiv \frac{\rho}{\rho_c} \geq 3 \times 10^{11} \quad \text{and} \quad t_0 \leq 30,000 \text{ yrs}$$

- ◆ The Monopole Problem !!!!!!

# Monopole Abundance

## *inflationary scenario*

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### ◆ idea

- defer the phase transition to much later, after extreme supercooling
  - » solves monopole problem
  - » also, resolves horizon and flatness problems
- In the simplest version, the number of monopoles is very small
  - » however, not SU(5) and the calculated flux depends critically on several parameters (mass of GUT monopole, temperature to which the universe reheats, etc)

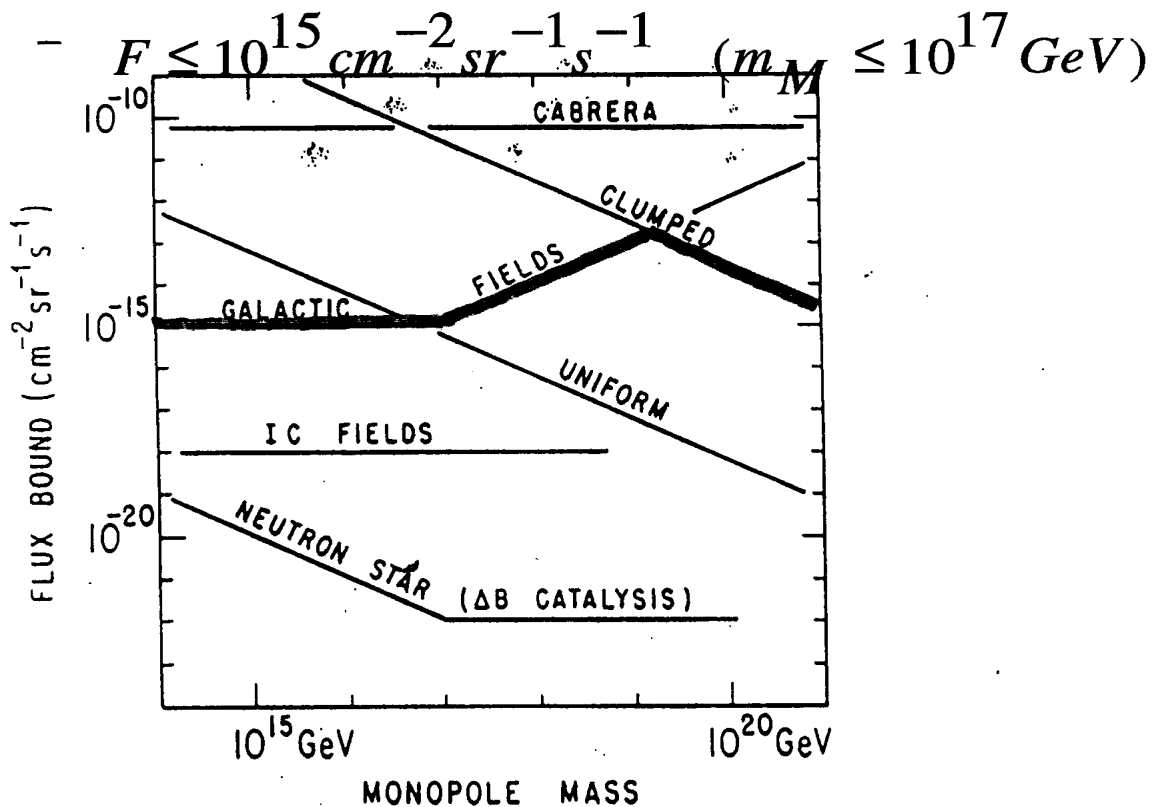
### ◆ conclusion

- no guidance from cosmology about monopole flux -- could be a glut or a famine

# Monopole Flux

## *astrophysical bounds*

- ◆ mass density of the universe
  - uniformly distribution ( $n_M < 2 \cdot 10^{-21} \text{ cm}^{-3}$ )
  - clumped distribution ( $n_M < 10^{-16} \text{ cm}^{-3}$ )
- ◆ galactic magnetic field
  - $B \sim 3 \cdot 10^{-6}$  gauss
  - Parker limit - too many monopoles would 'short' out this field



# Magnetic Monopoles

## *conclusions*

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### ◆ Theory/Motivation

- Charge Quantization has been primary motivation for magnetic monopole (Dirac)
- Grand Unification - ‘superheavy’ monopoles are intrinsic to theory
- Could be contributor to dark matter of the Universe

### ◆ Experiment

- **NO** evidence for Dirac Monopoles from accelerator searches, etc
- **NO** evidence for Grand Unified Monopoles at level of Astrophysics bounds ( $\sim 10^{-15} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ )
- Present searches (eg. MACRO) will probe factor of 10-20 below bound