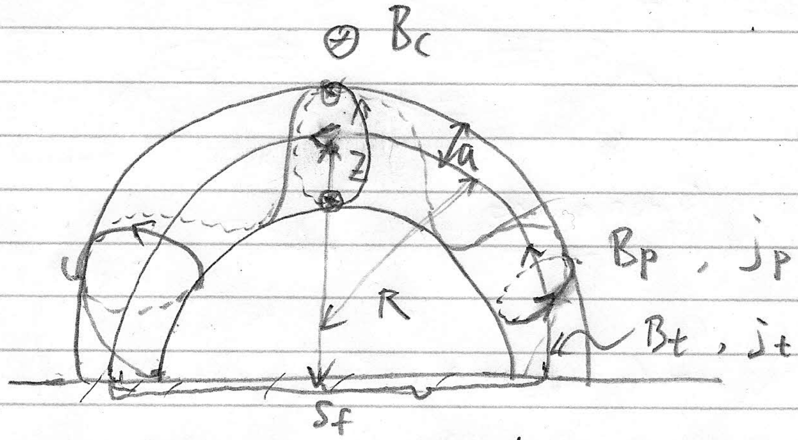
Dec. 2, 2010

CME models

* See PPT presentation for a review on
  - flare models
  - flare - CME models
  - CME models, including ICME

* CME eruptive flux rope model (Chen 2003)
  essentially 3-D



B_t: toroidal magnetic field

B_p: poloidal magnetic field

j_t: toroidal current

j_p: poloidal current.

→ Inside the flux rope, helical field line, helical current

B_c: external magnetic field

Z: height of apex

R: major radius

a: minor radius

S_f: footpoint seperature.

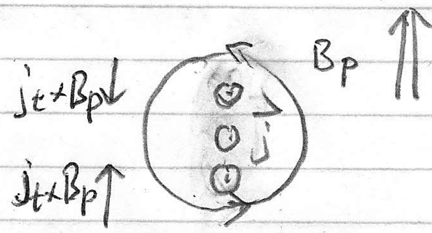
(2)

In this model, forces need to be considered

* Lorentz self-force $\vec{J} \times \vec{B}$

① $J_t \times B_p$

always outward, since B_p is stronger in the inner part of the torus



② $J_p \times B_t$.

always inward, since J_p is stronger in the inner part

① + ② ⇒ magnetic hoop force, Lorentz self-force tends to eject the flux rope

③ $J_t \times B_c$: Lorentz force from background magnetic field

holds down the flux rope

typically, ① + ② = ③

* other forces.

④ gravity force ; not important

⑤ drag force : only important in the outer corona when one study CME evolution

$$F_d = C_d \, n_a \, m_i \, a \, (V_c - V) \, |V_c - V| \; ;$$

C_d: drag coefficient : 0.5 ~ 5

n_a: ambient plasma density

V_c: background solar wind speed

V: CME speed.

put all forces together, momentum equation $\Rightarrow$

$$M \frac{d^2 z}{dt^2} = \frac{I_t^2}{c^2 R}\left[\ln\left(\frac{8R}{a}\right) + \frac{1}{2}\beta_p - \frac{1}{2}\frac{B_t^2}{B_p^2} + 2\left(\frac{R}{a}\right)\frac{B_c}{B_p} - 1 + \frac{\xi_i}{2}\right] + F_g + F_d \quad \text{--- (1)}$$

Similarly, for minor radius momentum equation

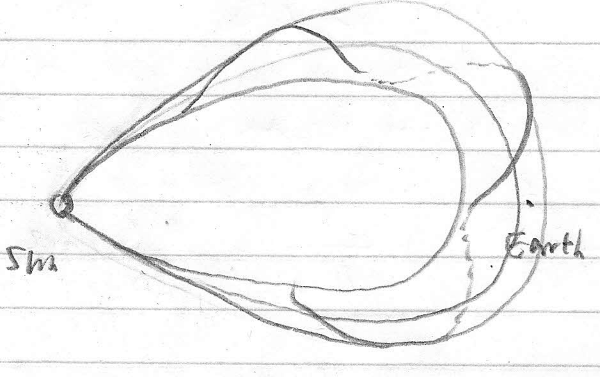
$$M \frac{d^2 a}{dt^2} = \frac{I_t^2}{c^2 a}\left(\frac{B_t^2 - B_p^2}{B_p^2} + \beta_p\right) \quad \text{--- (2)}$$

(1) and (2) are coupled second $\boxed{\text{order differential equation}}$ which can be solved numerically.

Many calculations have been done using this model, and good consistency has been found with observations.

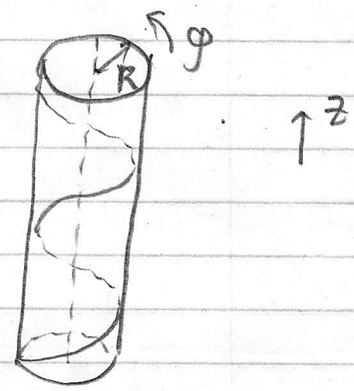
Flux rope from in-situ observation: internal structure

often called magnetic cloud (Lepping 1990)



global

Local $\Longrightarrow$



local

flux rope at local scale can be approximated by a cylinder

Assuming Linear force free: $\vec{J} \times \vec{B} = 0$. α: constant

$$\nabla \times \vec{B} = \alpha \vec{B}$$

$$\nabla \times (\nabla \times \vec{B}) = \nabla \times (\alpha \vec{B})$$

$$\nabla(\nabla \cdot \vec{B}) - \nabla^2 \vec{B} = \nabla\alpha \times \vec{B} + \alpha \nabla \times \vec{B}$$

$\alpha \alpha \vec{B} \rightarrow \alpha^2 \vec{B}$

$$\Rightarrow \nabla^2 \vec{B} + \alpha^2 \vec{B} = 0$$

In cylindric geometry, this equation exists Lundquist solution

$$\vec{B} = (B_R, B_A, B_T)$$

radial ($\hat{R}$), axil ($\hat{z}$) ~~azimuthal~~, tangential ($\hat{\varphi}$)

$$\Rightarrow \begin{cases} B_R = 0 \\ B_A = B_0 J_0(\alpha R) & \text{zero-order Bessel function} \\ B_T = B_0 H J_1(\alpha R) & \text{First order Bessel function} \end{cases}$$

$H = \pm 1$, the sign of helicity or handedness

At $R = R_0$,

$$\begin{cases} B_R = 0 \\ B_A = 0 \\ B_T = B_0 H \cdot J_1(\alpha R_0), \text{ and } \alpha R_0 = 2.4 \end{cases}$$

Field is purely poloidal

$$R_0 = \frac{2.4}{\alpha}.$$ R_0: define the size of flux rope

This model can be obtained from observation

Lepping's 7-parameter magnetic cloud fitting (1990).

(1) θ: the latitude of the axis

(2) φ: the longitude of the axis

(3) Y_0: distance of the spacecraft from the axis

(4) B_0: B at the axis, purely axial ($\hat{z}$)

(5) α: force free α ($R_0 = \frac{2.4}{\alpha}$)

(6) H: ± 1 - sign of helicity

(7) t_0: the time at the closest approach of spacecraft to the axis