Plasma Astrophysics

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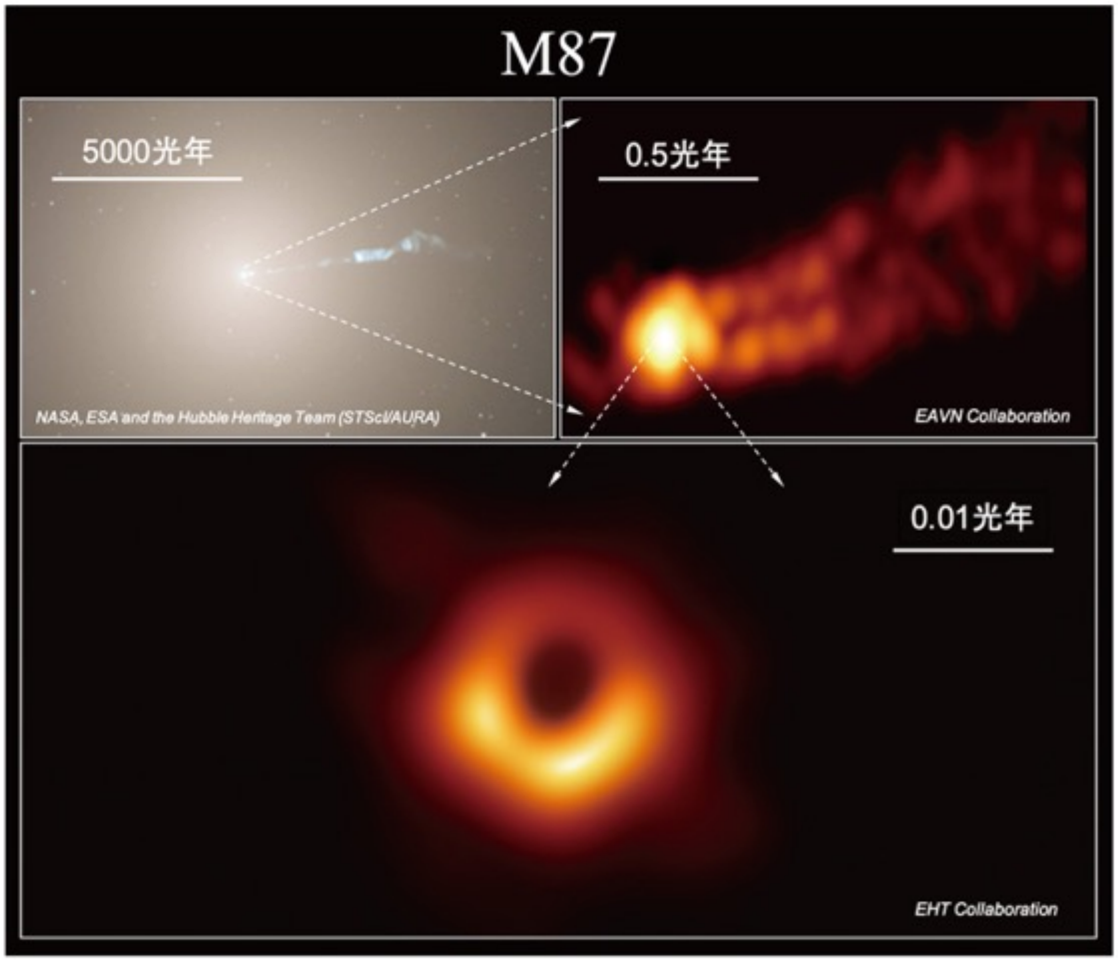
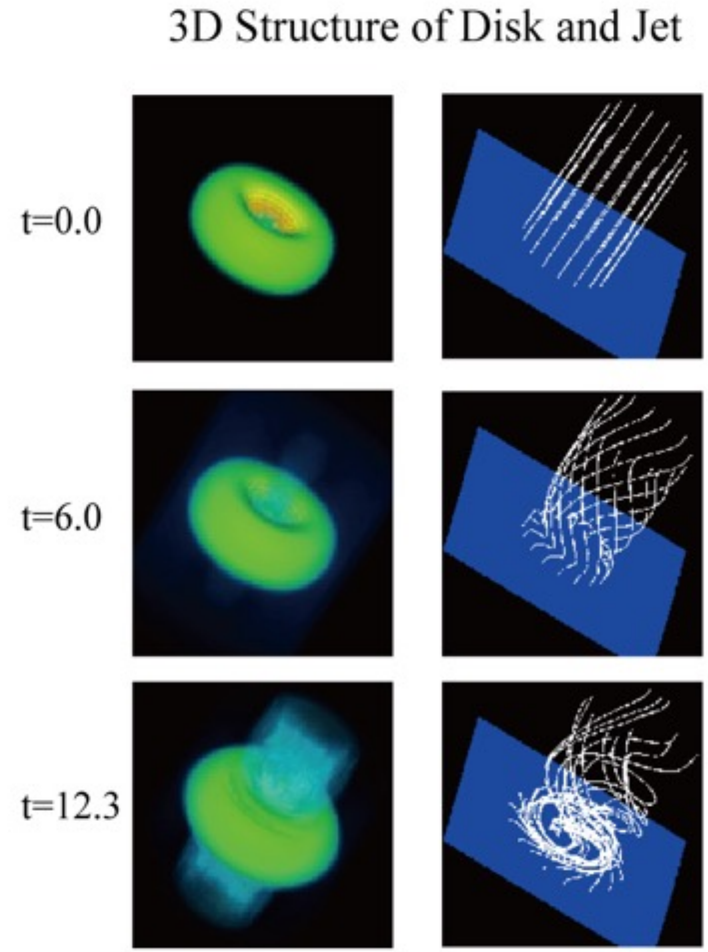
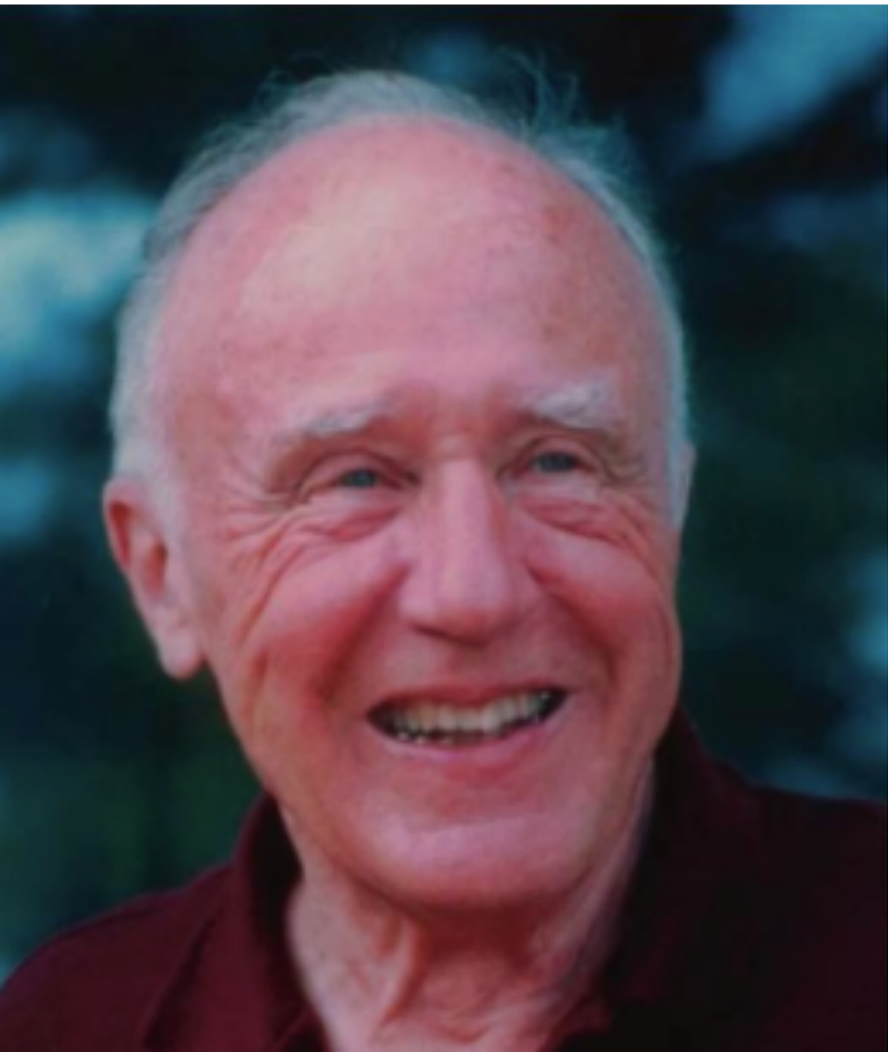
Class 2:PHY249 (2020Spring)





John A. Wheeler



"Toshi, do you know what a professor is about?
A professor is a person who learns from students."

Sept., 1980,
Prof. Wheeler at Univ. of Texas at Austin

What part of astrophysics?

- Frontiers of astrophysics only (that are not yet well understood):

  highest energy particles (e.g. of cosmic rays > 10^20eV, high energy neutrinos)

  highest energy photons (e.g. γ-rays up to TeV /PeV)

  most violent processes (e.g. disruptive accretion; jets)

  episodic and eruptive (e. g. γ-ray bursts)

  young objects (e. g. AGN, Blazars)

  neutron-star x neutron-star collision→ plasma plays essential role

  ……….

- I have no time to cover:

  old objects (e.g. our galaxy, our Sun, our solar system), gravitational dominants

  quiet, steady-state objects

  objects where little plasma such as the Moon ("the older, the less plasma")

  single particle interacts with astronomical object (cf. collective interaction N^2)

  ………..

(our textbook covers some of both kinds)

What can/should we do by the end of the Quarter? (if you are lucky)

- What magnetic fields do in active Universe? Why are they there?
- Why B-fields important? What do B-fields do?
- What kind of structure formations? Accretion disks, jets, collisions of stars (and galaxies),…….
- Survey nonlinear plasma evolution
- What are the Universe's long standing nonlinear structures?
- Why wakefields are among them and there (does not disappear) and robust?
- Imagine where Mother Nature wishes to excite wakefields?
- Predict (in addition to interpret) what happens if you make violent plasma excitation?
- Acceleration, emission of gammas, protons, neutrons
- What can you predict from all these?
- ………

Distinction between gravity ←→ EM

- Both: range can be **infinite** ← Gauss law
- Strong and weak interactions:

  → range O(fermi = fm)
- Grav: **no** negative mass; EM: + and **–,** but can be combined;

  no magnetic monopole **→** magnetic force range finite
- EM: if combined +/- → atoms : range O(Å)
- EM: +/- → Debeye screening: range O(v_t/ω_p)

  → collisionless skindepth: range O(c/ω_p)

  → EM radiation infinite range

However,

- With B : fields screening **removed** ← **Alfven** effect

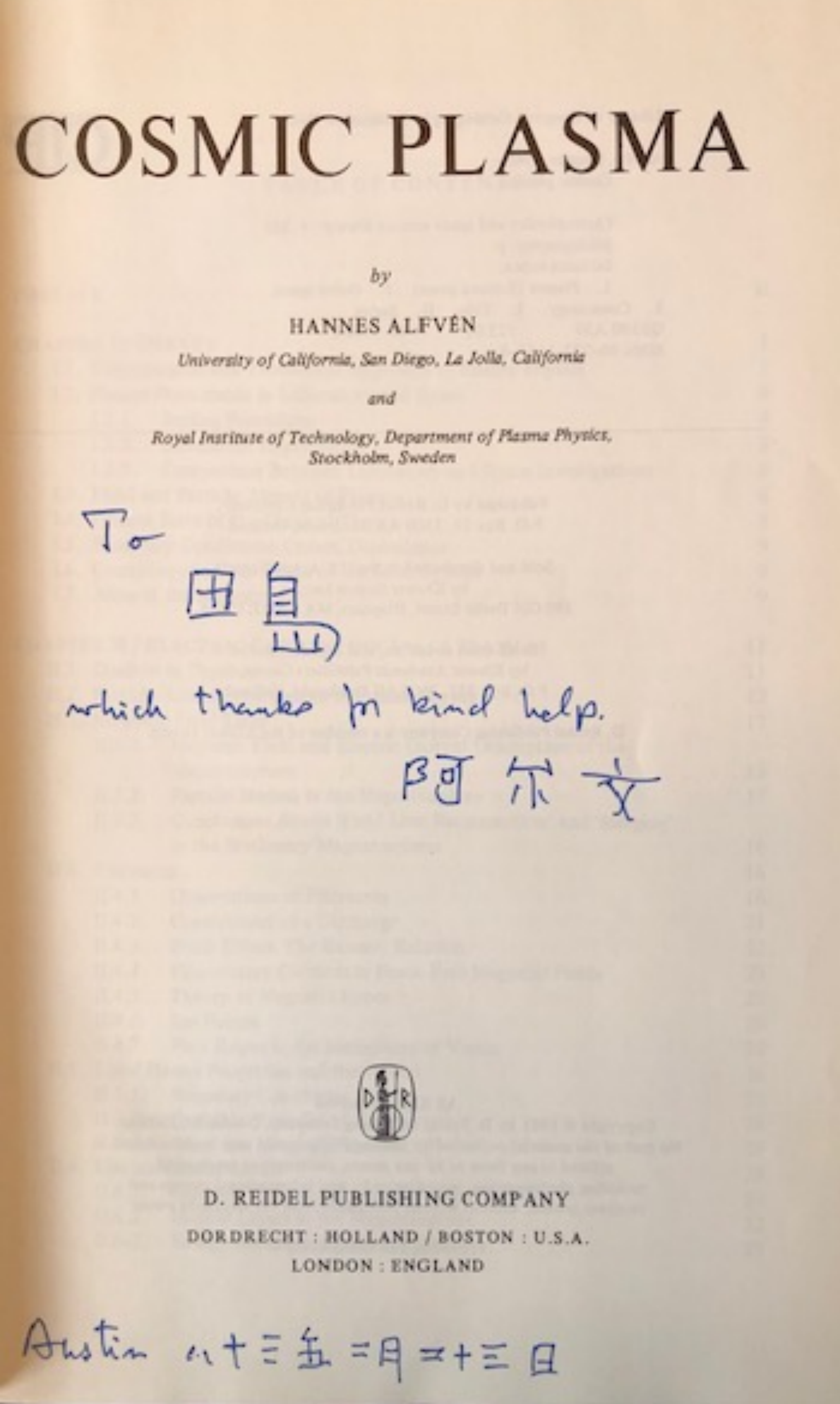
  mediated @ v_A

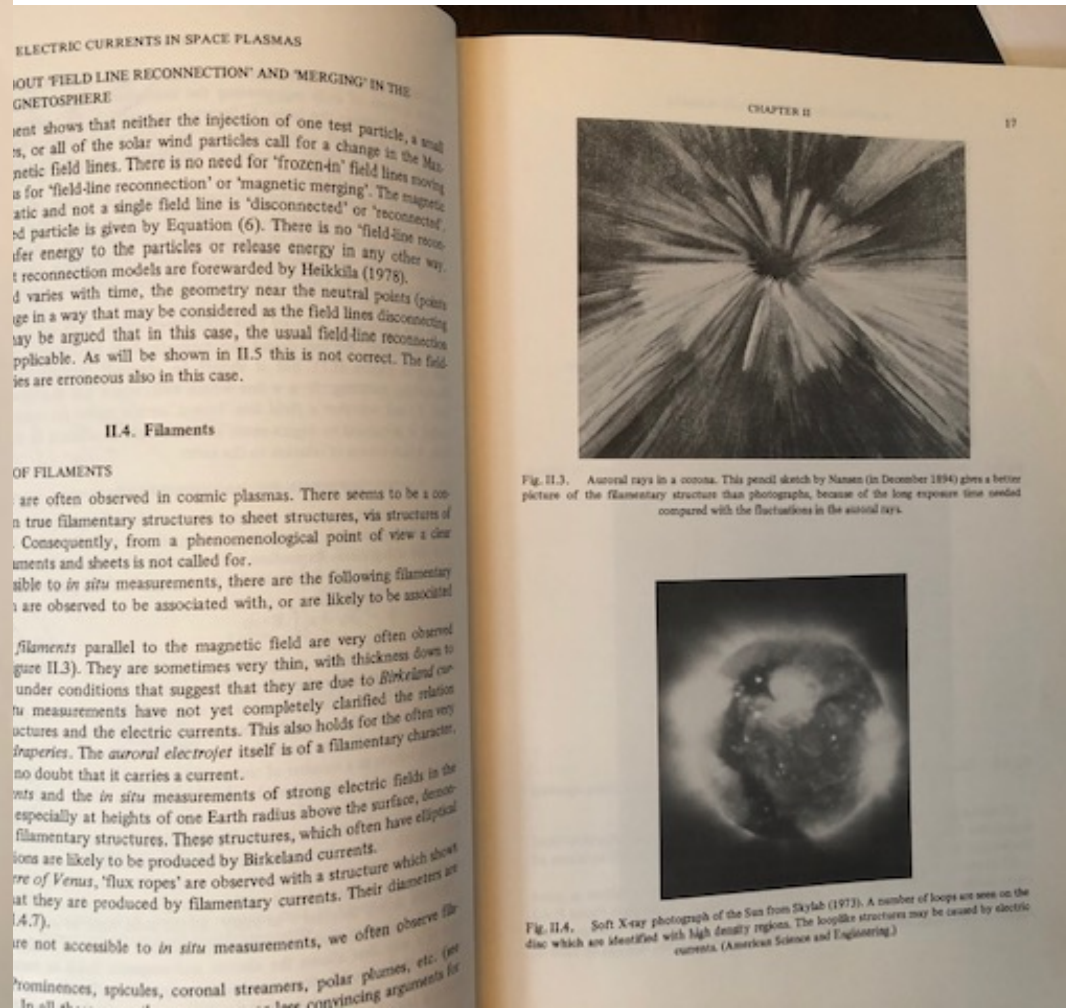
  : texture appears
- **Collective**/ violent proc. → ephemeral struct. or

  → robust struct = **wake** @ c

Alfven’s legacy

Importance of **filaments** / **texture** in plasma!





Structure Formation of Universe

- Gravitational : Well known
- Plasma-mediated: Not yet well known

e.g. AGN (prior to becoming a Galaxy) with plasma as the disk, or formation of cluster of AGNs.

even stellar formation out of plasma.

e.g. **collaboration** of gravity and plasma

(plasma ← **amorphous**, and thus anti-structure entity in blood, as well as in ionized gas)

But!

↓

plasma + B : provides **texture** to weave the structure of the Universe on

(many examples in textbook)

Structures in Universe

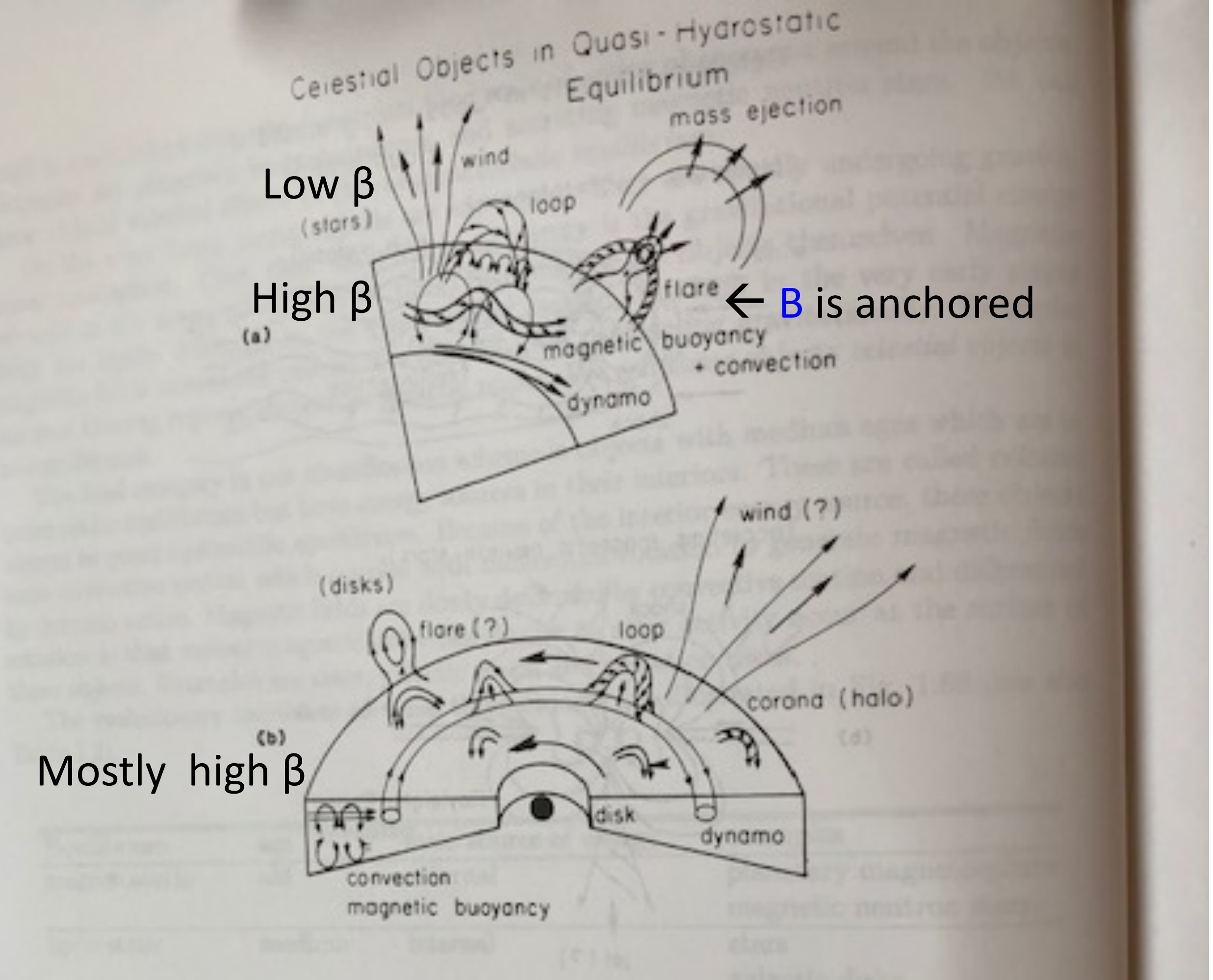


FIGURE 1.8 The structure of objects in quasi-hydrostatic equilibrium.

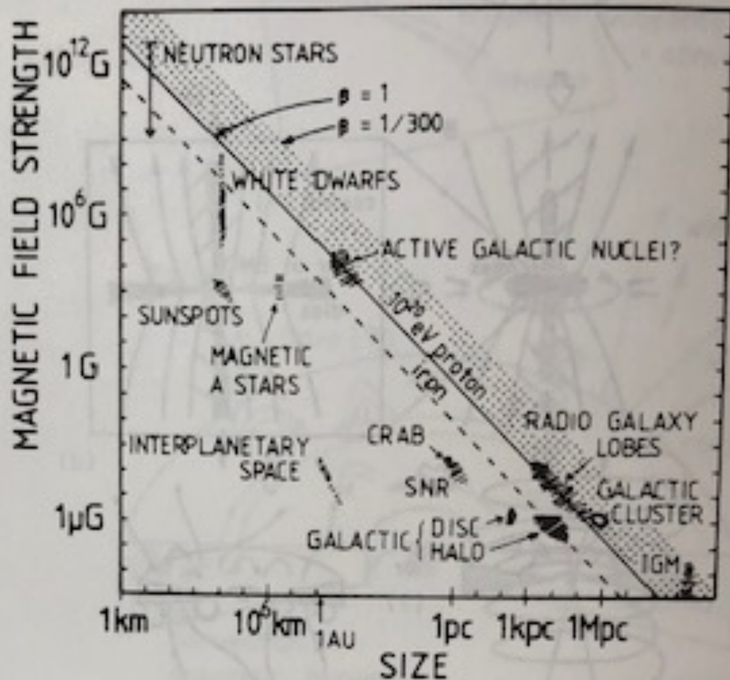
	ideal or nonideal MHD	steady	nonsteady
low β region	nonideal MHD	corona	flare
	ideal MHD	wind	mass ejection (jet)
high β region		magnetic structure	
		magnetoconvection	
		magnetic buoyancy ↑ dynamo ↑ differential rotation	

- Interplay of **gravity** and **B**

Examples:

- Stellar dynamics (see: NB)
- AGN disk dynamic

Magnetic fields and astrophysical objects:



.10 Magnetic field strength of various celestial objects as a function of their sizes (fr

On the other hand, an example of quasi-steady release of magnet
nal loop. If the loop is open to interplanetary space, a wind is cre
ough there are many uncertainties in the disks (especially in the
ne possibility is that the disk has a structure similar to the sol
e as illustrated in Fig. 1.8b.

Fundamental Processes in Objects in Non-Equ

prototype of these objects is the *star forming region*, we will sur
ysics of star forming regions (Fig. 1.9). (The same basic physics m
ation of galaxies.) In the first stage of gravitational contraction o

Magnetic field B vs size of objects

Globally,

B ~ 1/ λ

why?

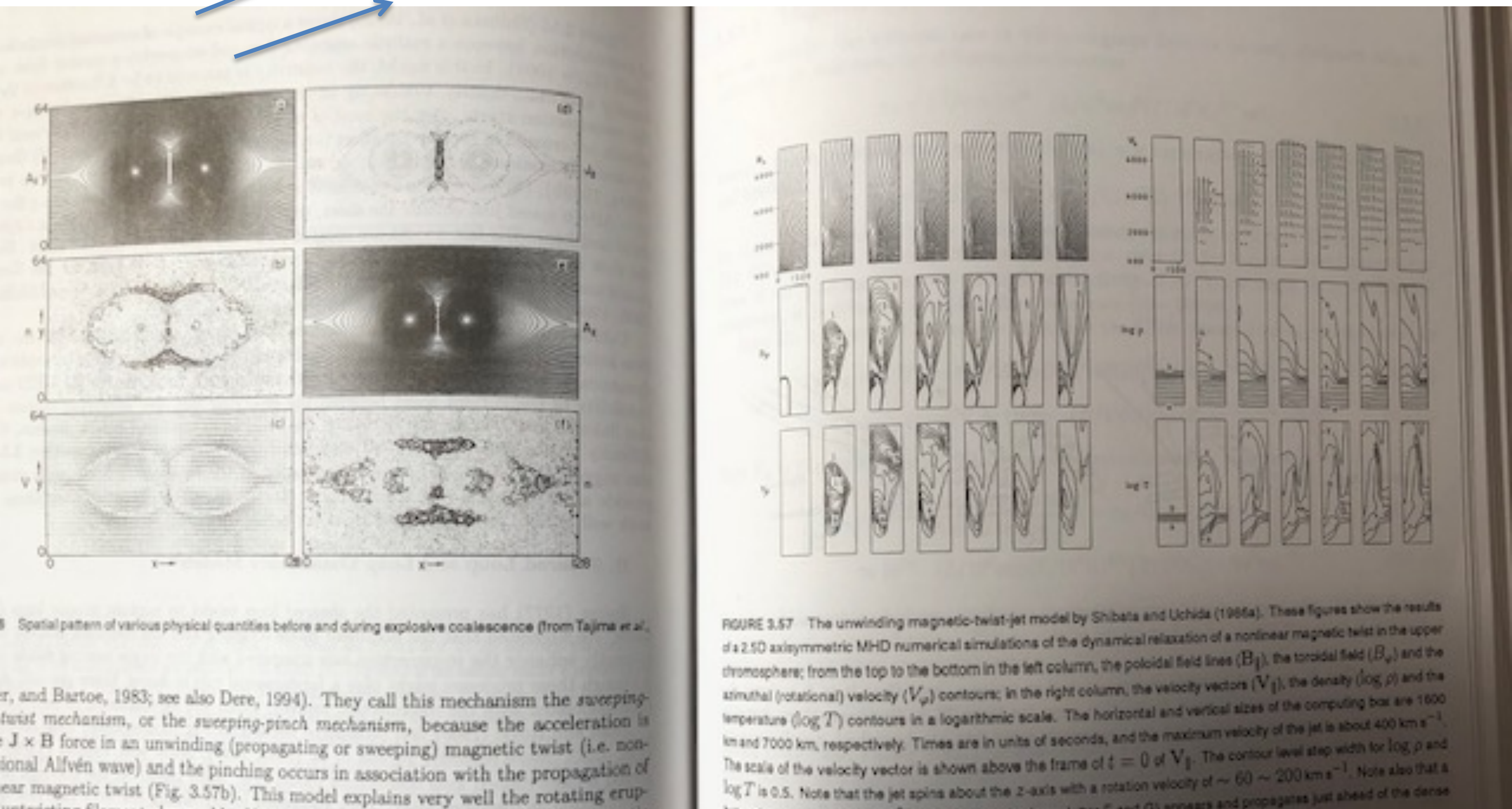
NB:

current tube-current tube interaction

Tube coalescence (and reconnection)

Flux twist and untwist

pp.220-221



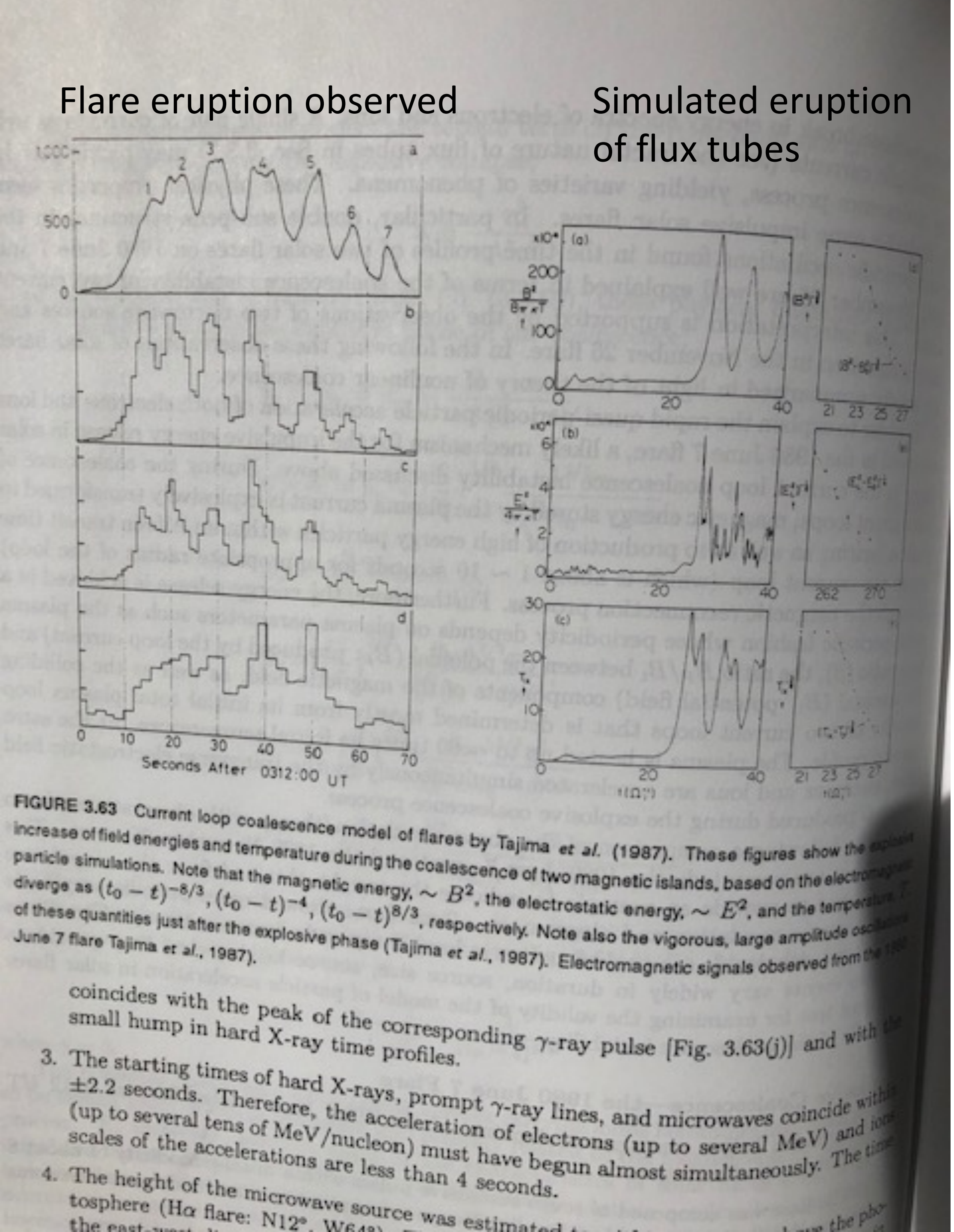
NB:

Solar flare eruption

(example of stellar dynamics)

Flare eruption observed

Simulated eruption of flux tubes



Coalescence of current tubes

Explosive coalescence (and reconnection)

low β

(no toroidal field)

p.236

Examples of base processes

Parker instability
(ballooning instability) → **Flux buoyancy**

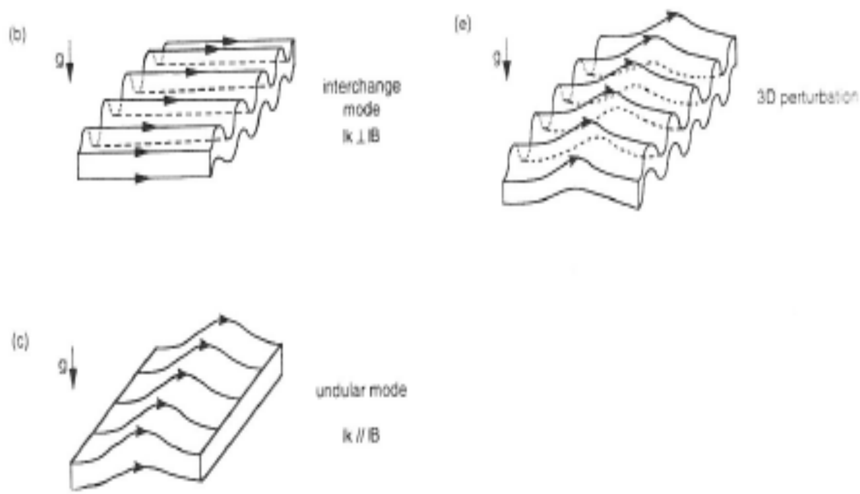


FIGURE 3.18 Interchange mode and undular (Parker) mode of magnetic buoyancy instability.

3.2.1.2 Magnetic Buoyancy Instability and Parker Instability

MRI → twisted magnetic amplification; jet formation

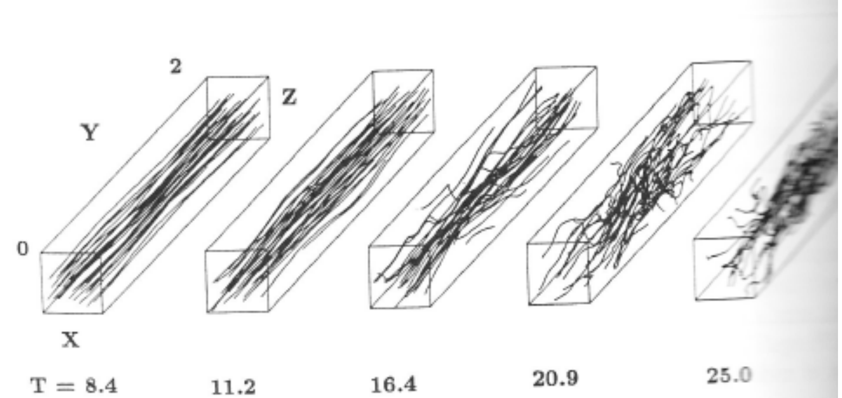


FIGURE 4.27 Magnetic field lines for model T in the eigenmode growth state $[t = (8.4 - 16.4$ ... saturation stage $[t = (20.9 - 25.0/\Omega]$ (Matsumoto and Tajima, 1995).

4.2.3.6 Effects of the Parker Instability*

When the vertical gravity is included, magnetic field escapes from the disk ... due to the Parker instability (the magneto-buoyancy instability; see Sec. 3.2 ... growth rate of the Parker instability is $2 - 5H/v_A$, the growth rate of the Parker ... becomes comparable to that of the magnetic shearing instability as β approaches ...

Text p.158-196

Text p. 329-342

Parker Instability

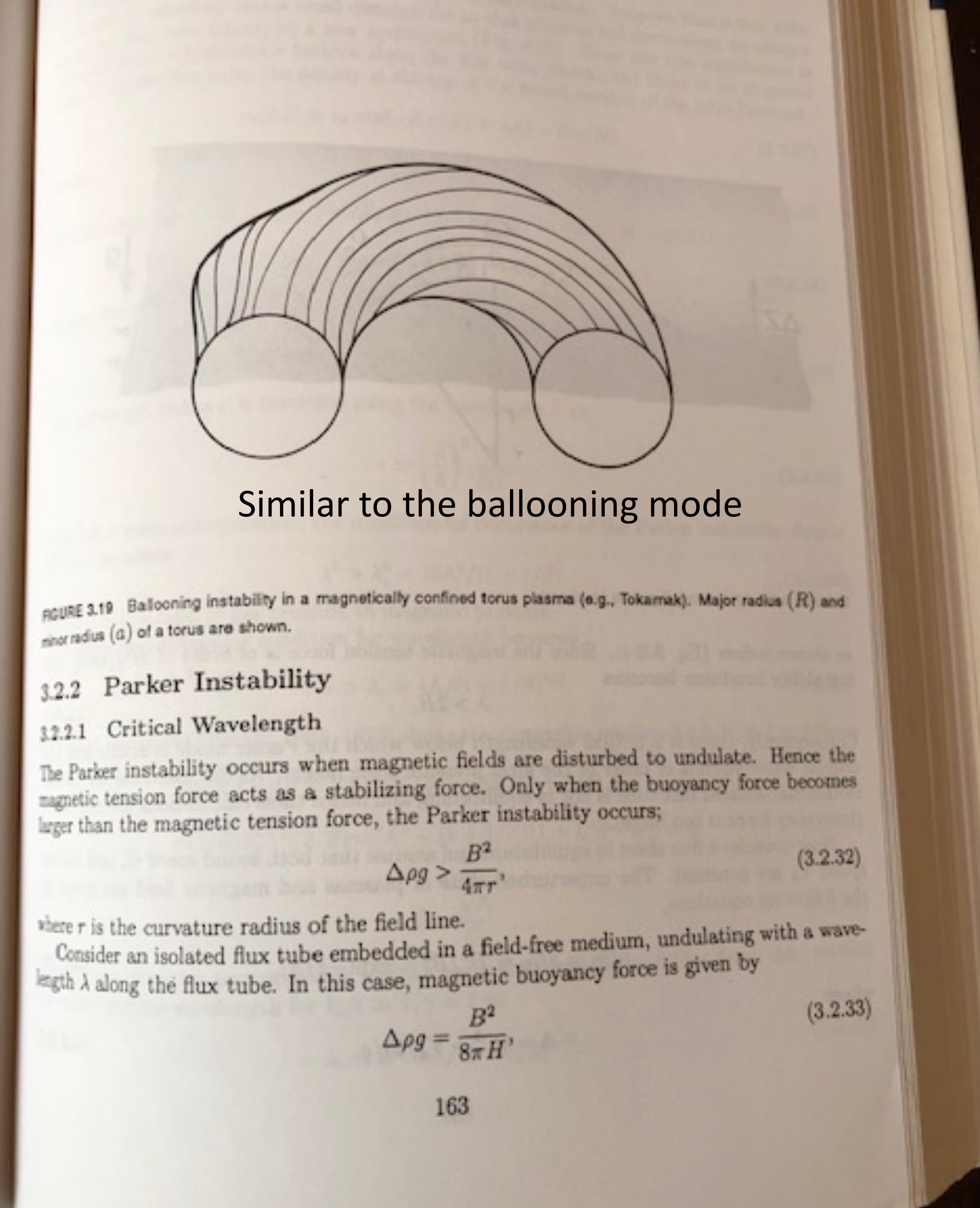


FIGURE 3.19 Ballooning instability in a magnetically confined torus plasma (e.g., Tokamak). Major radius (R) and minor radius (a) of a torus are shown.

3.2.2 Parker Instability

3.2.2.1 Critical Wavelength

The Parker instability occurs when magnetic fields are disturbed to undulate. Hence the magnetic tension force acts as a stabilizing force. Only when the buoyancy force becomes larger than the magnetic tension force, the Parker instability occurs;

$$\Delta\rho g > \frac{B^2}{4\pi r}, \qquad (3.2.32)$$

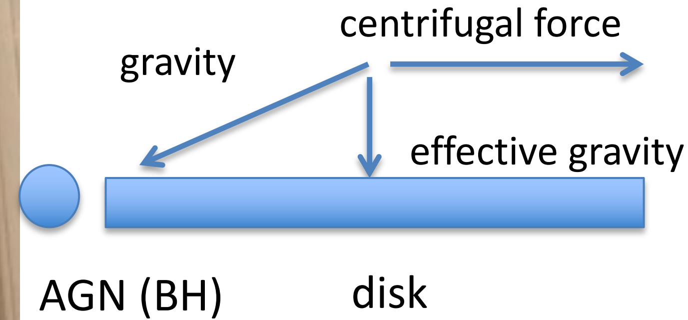
where r is the curvature radius of the field line.

Consider an isolated flux tube embedded in a field-free medium, undulating with a wavelength λ along the flux tube. In this case, magnetic buoyancy force is given by

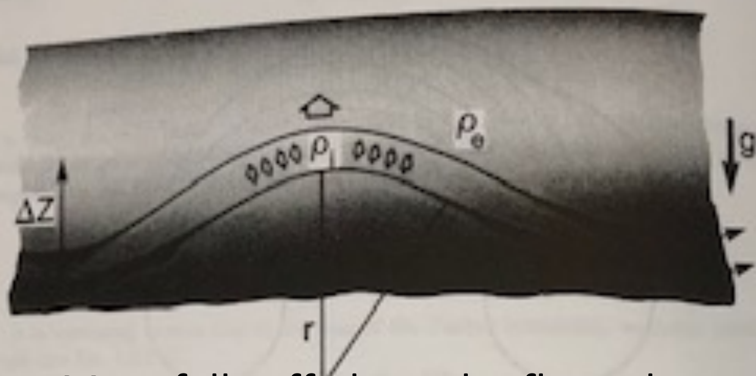
$$\Delta\rho g = \frac{B^2}{8\pi H}, \qquad (3.2.33)$$

163

Similar to the ballooning mode



Nonlinear evolution of Parker Instability



Mass falls off along the flux tube

→ Stimulate further growth of balloon

→ ”overshoot”

FIGURE 3.20 Undulating flux tube (or sheet).

as shown before (Eq. 3.2.4). Since the magnetic tension force is of order of $B^2/(4\pi\lambda)$, the instability condition becomes

$$\lambda > 2H. \quad (3.2.34)$$

Consequently, there is a critical wavelength below which the Parker mode is stable and the critical wavelength is of order of the local pressure scale height. As discussed earlier, above isothermal isolated flux tube is not in equilibrium, and hence these calculations are not exact (buoyancy force is too large).

Now consider a flux sheet in equilibrium and assume that both sound speed C_s and Alfvén speed V_A are constant. The unperturbed state of plasmas and magnetic field are given by the following equations,

$$p/p_0 = \rho/\rho_0 = B^2/B_0^2 = \exp(-z/\Lambda), \quad (3.2.35)$$

where

(3.2.36)

... obtained from a hydrostatic balance along the flux tube (sheet) and there is no magnetic force along the flux tube, the density at the top of the raised portion of the tube becomes

$$\rho_i(\Delta z) \simeq \rho_0 \exp(-\Delta z/H) \simeq \rho_0(1 - \Delta z/H), \quad (3.2.37)$$

where

$$H = C_s^2/g. \quad (3.2.38)$$

On the other hand, the density outside the tube (sheet) at the same height (Δz) is

$$\rho_e(\Delta z) \simeq \rho_0 \exp(-\Delta z/\Lambda) \simeq \rho_0(1 - \Delta z/\Lambda). \quad (3.2.39)$$

Hence, the net density depression at the top of the loop is

$$\Delta\rho \simeq \rho_e(\Delta z) - \rho_i(\Delta z) \simeq \rho_0 \Delta z\left(\frac{1}{H} - \frac{1}{\Lambda}\right). \quad (3.2.40)$$

The curvature radius r is rewritten using the wavelength λ as

$$r \simeq \left(\frac{\lambda}{4}\right)^2 \frac{2}{\Delta z}. \quad (3.2.41)$$

Then after some manipulation, the condition for occurrence of the Parker instability $\Delta\rho g > B^2/4\pi r$ becomes

$$\lambda^2 > \lambda_c^2 = 16\Lambda^2/(1 + 1/\beta), \quad (3.2.42)$$

where β is the ratio of gas pressure to magnetic pressure.

Finally the instability condition for wavelength becomes

$$\lambda > \lambda_c = 4\Lambda/(1 + 1/\beta)^{1/2}. \quad (3.2.43)$$

An exact treatment (Parker, 1966, 1979) shows the dispersion relation for $k_y\Lambda \gg 1$ as follows

$$(2/\beta + \gamma)\Omega^4 + [(4/\beta)(1/\beta + \gamma)(k_x^2\Lambda^2 + 1/4) + \gamma - 1]\Omega^2$$
$$+ (2/\beta)k_x^2\Lambda^2[(2/\beta)\gamma k_x^2\Lambda^2 - (1 + 1/\beta)(1 + 1/\beta - \gamma)] = 0, \quad (3.2.44)$$

where

$$\Omega = \frac{\omega\Lambda}{C_s} \quad (3.2.45)$$

and y is the direction perpendicular to both vertical and magnetic fields. From this, we find the exact critical wavelength for $k_y\Lambda \gg 1, \gamma = 1$ as

Magnetic buoyancy (simple derivation)

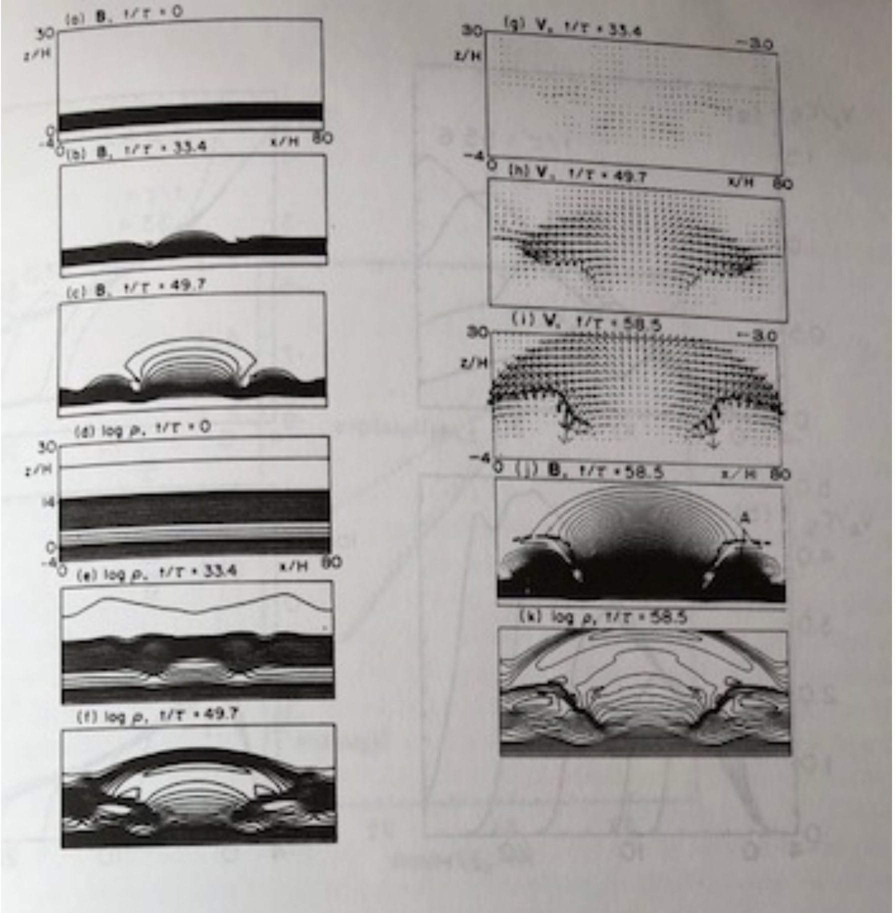
Pressure equilibrium: $\rho_i = \rho_e - B^2 / 8\pi H$, where the scale height $H = T / Mg$

Buoyancy force: $\Delta\rho\, g = B^2 / 8\pi H$

The Parker instability: $\Delta\rho\, g > B^2 / 4\pi r$, where r the tube curvature

The unstable wavelength for Parker: $\lambda > 9H$ when $\beta \gg 1$

(p. 166)



he nonlinear simulation results of the Parker instability triggered by the localized perturbat
t in Fig. 3.30. (a) The magnetic field lines $\mathbf{B} = (B_x, B_z)$. (b) the velocity vector $\mathbf{V} = (V$
($\log \rho$). Note that the magnetic flux expands approximately self-similarly (from Shibata et a

ctive-Parker instability (Nozawa et al., 1992) and in the 3D Parker in
interchange mode (Matsumoto et al., 1993; see Sec. 3.2.2).
ind that the Alfvén speed in the rising loop increases with height. Thi
ma β decreases with height and explains why we have a low β coror
p. As magnetic loop expands, it tends to be current free since both the
forces become smaller than the magnetic force as the loop rises (see e
(3.2.81).
Shibata et al. (1989a) found these results assuming isolated magnetic
the same results are found also by assuming continuous magnetic fie

Loop brightening

Further nonlinear manifestation of Parker process

Feet of the flux loop emit EM signals by bombardment of plasma to the disk surface

Magnetic buoyancy and twist in jets from accretion disk

A consequence of Parker process

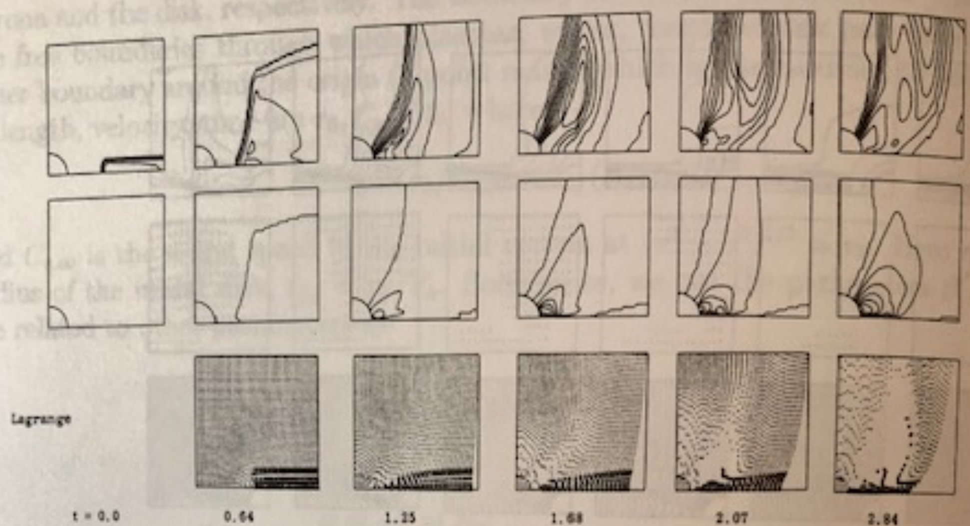


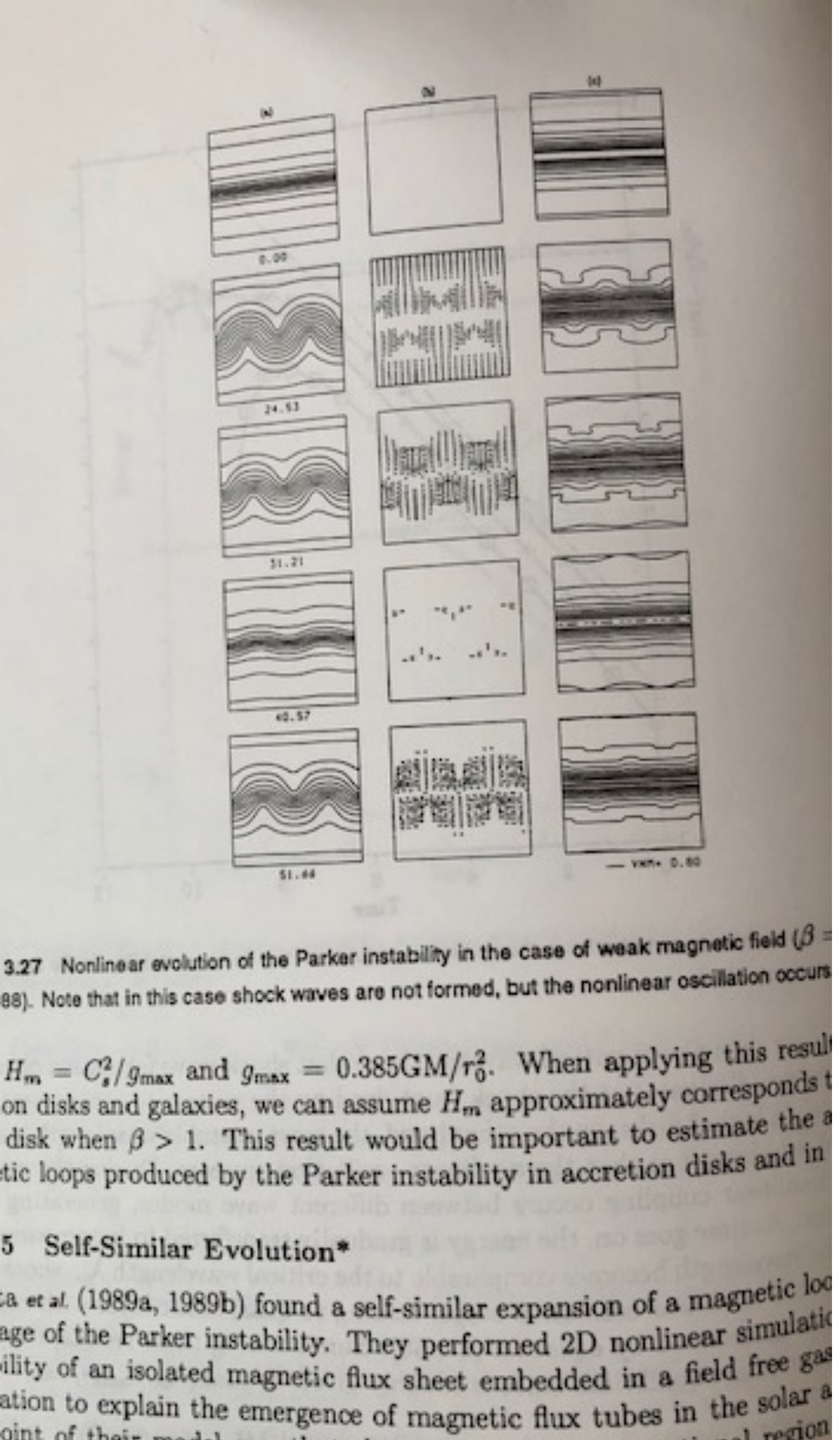
FIGURE 4.53 2.5D MHD sim. of magnetic twist jet (Shibata and Uchida, 1986a): v_φ, B_φ, Lagrange.

of jet.

Figure 4.55 shows the dependence on the plasma β. It is seen that the magneti more rigid in low $\beta(= 0.3)$ case, while it is more undulating in high $\beta(= 5)$ case. I found that the velocity of jet is higher in low β case than in high β case. Empirica is written as

$$V_{\rm jet} \sim \beta^{-0.3\sim-0.4} \sim B^{0.5\sim0.7}.$$

Interestingly, this relation is roughly in agreement with the relation of Michel's mi energy solution for a fast rotator (equation (4.3.35) in previous subsection). Accordin and Shibata (1986, unpublished), the low β jet is accelerated mainly by the centrifuga whereas the high β jet is by the magnetic pressure gradient force. The dependence initial rotational velocity is shown in Figure 4.56. From this, we find that even the ir Keplerian case leads to contraction due to magnetic braking and hence eventually t though the velocity of the jet is slower than the sub-Keplerian case. More detailed comp between the jet formation and the Balbus-Hawley mchanism (or Velikhov-Chandras



3.27 Nonlinear evolution of the Parker instability in the case of weak magnetic field (β =
88). Note that in this case shock waves are not formed, but the nonlinear oscillation occurs

$H_m = C_s^2/g_{max}$ and $g_{max} = 0.385GM/r_0^2$. When applying this resul
on disks and galaxies, we can assume H_m approximately corresponds t
disk when $\beta > 1$. This result would be important to estimate the a
tic loops produced by the Parker instability in accretion disks and in

5 Self-Similar Evolution*

a et al. (1989a, 1989b) found a self-similar expansion of a magnetic loo
age of the Parker instability. They performed 2D nonlinear simulati
ility of an isolated magnetic flux sheet embedded in a field free gas
ation to explain the emergence of magnetic flux tubes in the solar a

Beginning of **structure formation**

via Parker process

Consequences:

→ 1. the escape of amplified B-field in the disk

2. pinching of plasma radially accentuated, forming **streaks** of dense regions

3. allow accentuated magneto-rotational instability onset

4. assist jet formation

5. assist **accretion of clumped matter**