MAGNETIC FIELDS:
A FOUR-PART SERIES

>Astrophysical fundamentals: why magnetic fields matter

>Tracers for measuring fields

>Specifying polarization with Stokes parameters

>Some observational results: Megaparsecs to milliparsecs

MAGNETIC FIELD FUNDAMENTALS

Carl Heiles, UC Berkeley

FORCES ON INTERSTELLAR GAS:

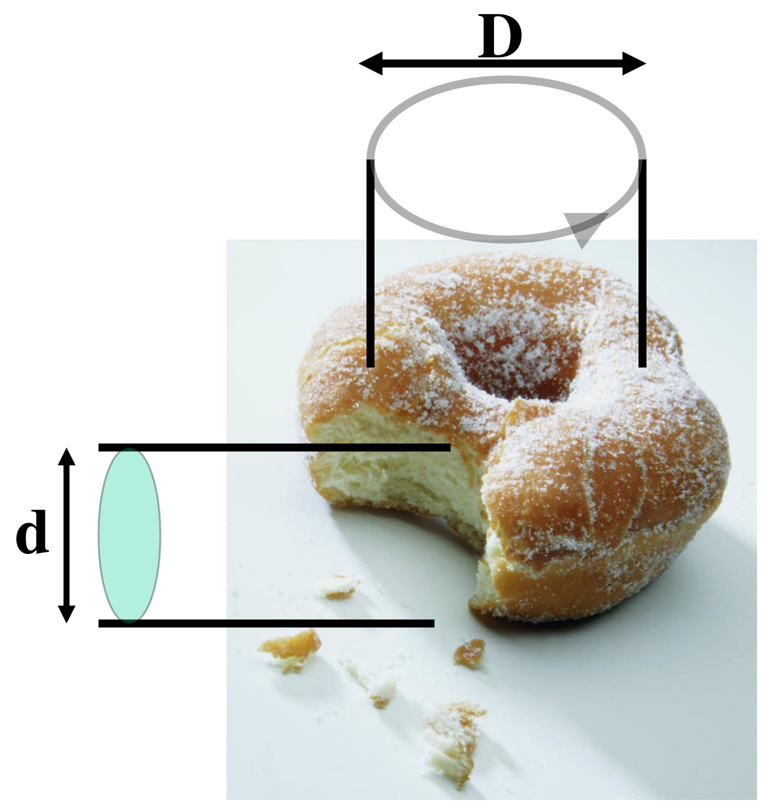
- **Gravity**
- **Pressure**
- **Magnetic Fields**

Consider a current loop in the ISM:

Inductance L ~ D

Resistance ~ D/d^2 ~ 1/D [d ~ D]

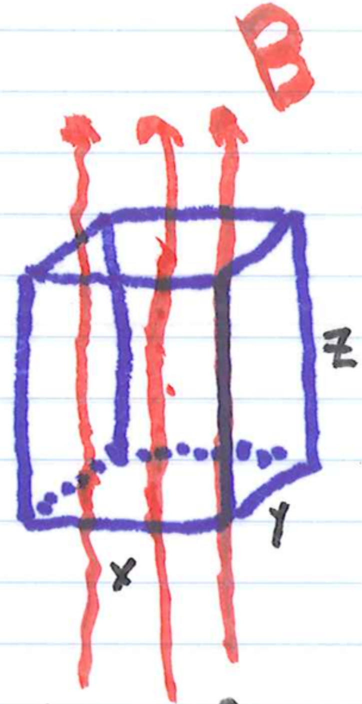
Time constant = L/R ~ D^2



Interstellar structures are BIG.
Even for low fractional ionization, time constant is long, so we have

FLUX FREEZING

Magnetic Pressure and Tension…a simple approach.



$$W_B = \frac{B^2}{8\pi} XYZ$$

$$\frac{dW_B}{dZ} = \frac{B^2}{8\pi} XY \quad - \quad \underline{\text{TENSION}}$$

$$\frac{dW_B}{dx} = \left[\frac{2B}{8\pi} \frac{dB}{dx} + \frac{B^2}{8\pi} \right] YZ$$

$$= -\frac{B^2}{8\pi} YZ \quad - \quad \underline{\text{PRESSURE}}$$

SOME CANONICAL PRESSURES in the DIFFUSE ISM (P/k in units of cm^{-3} K)

Thermal pressure (typical): P/k = nT ≈ 3000 (Jenkins/Tripp)

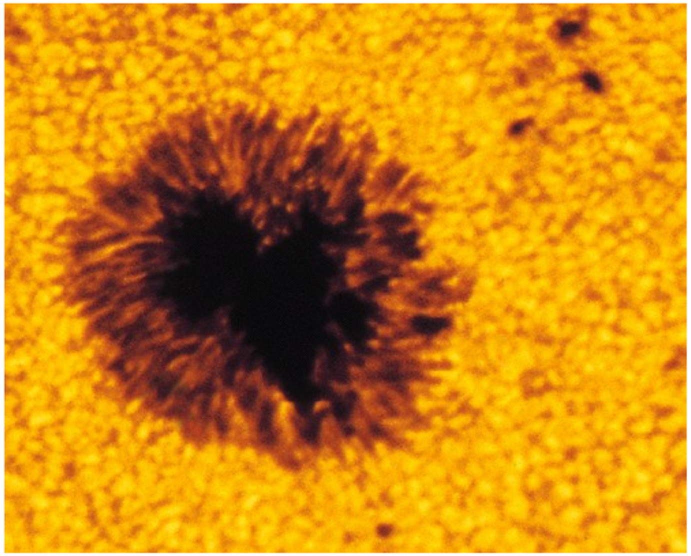
Turbulent Pressure (typical) 10000

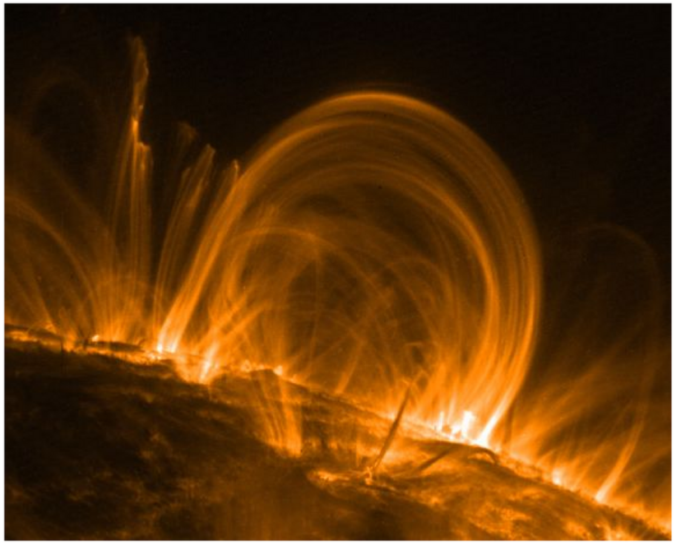
Magnetic Pressure (B = 6 μG) 10000

Galactic Hydrostatic Pressure (Boulares & Cox) 30000

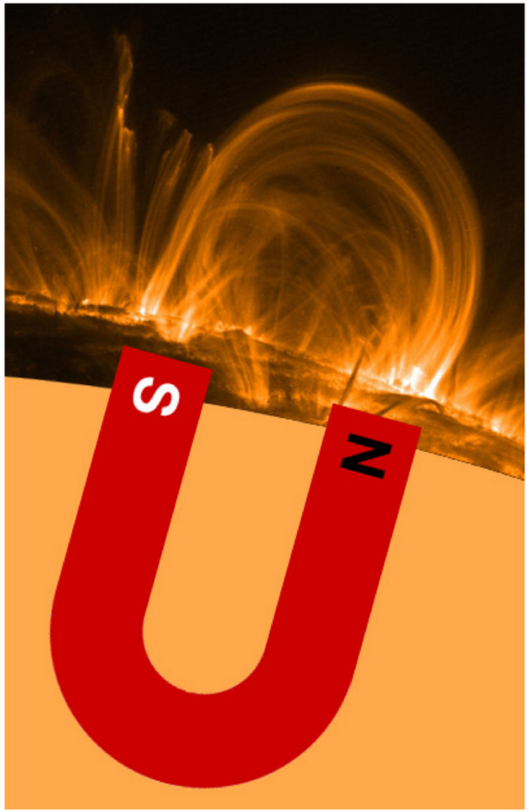
Cosmic Magnetism is a MAJOR FORCE

The interaction of the 3 forces—gravity, pressure, magnetism—produces fascinating and complex phenomenae and is not much understood, in either the terrestrial or astronomical context!





Gravity, Pressure, and Magnetic equilibrium. Solar prominences, sunspots, nice and stable!



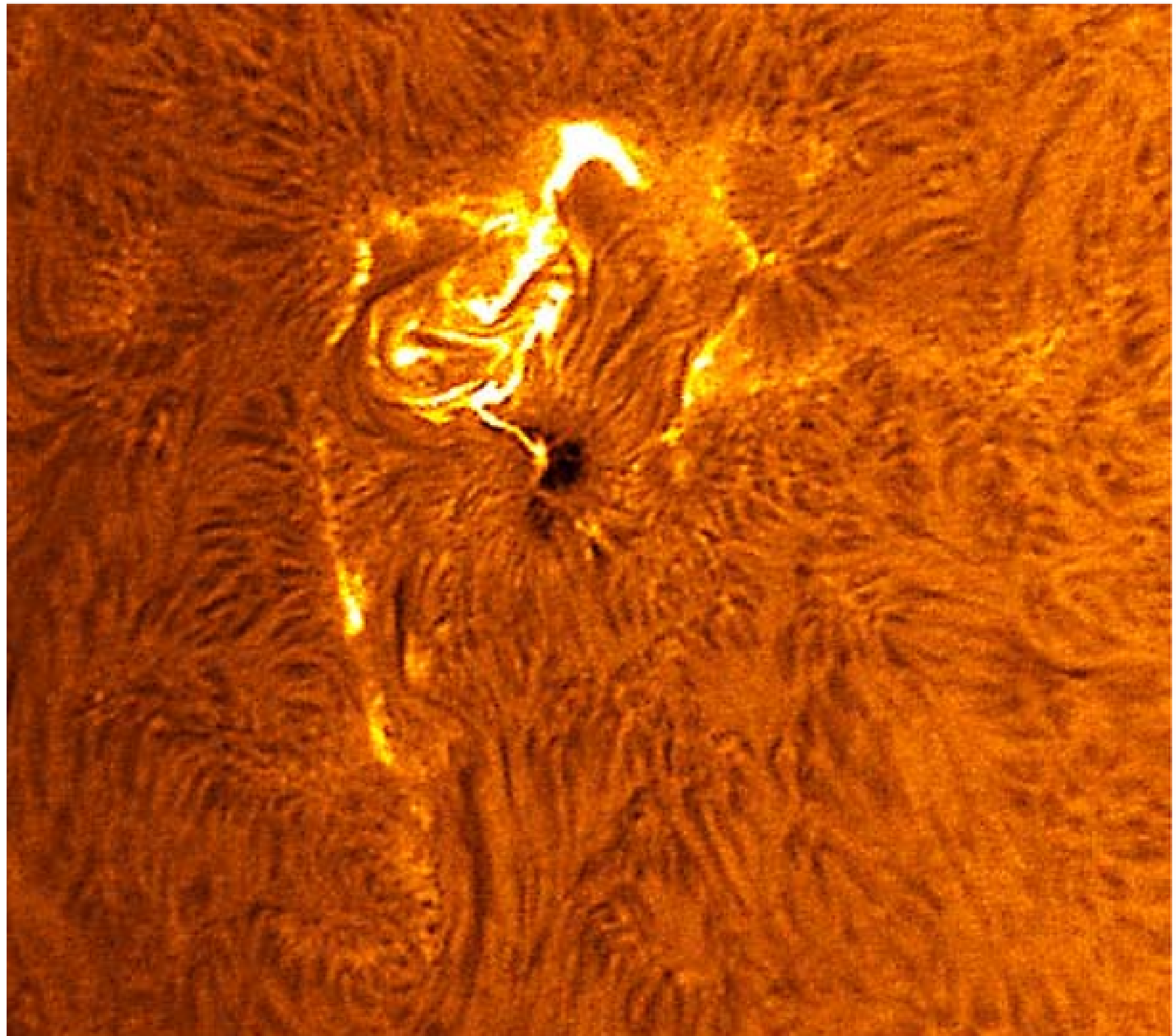
"FLUX FREEZING'' – the magnetic lines more with the gas. And vice-versa. Nice ordered flows give nice ordered fields; or, if the field is strong, nice ordered fields give nice ordered flows.

But there can be...

TURBULENCE!!

and INSTABILITY!!

SOLAR FLARE – the N and S poles attract! NOT so nice and stable!



Some aspects of some situations are clear. Examples include…

***Shocks**

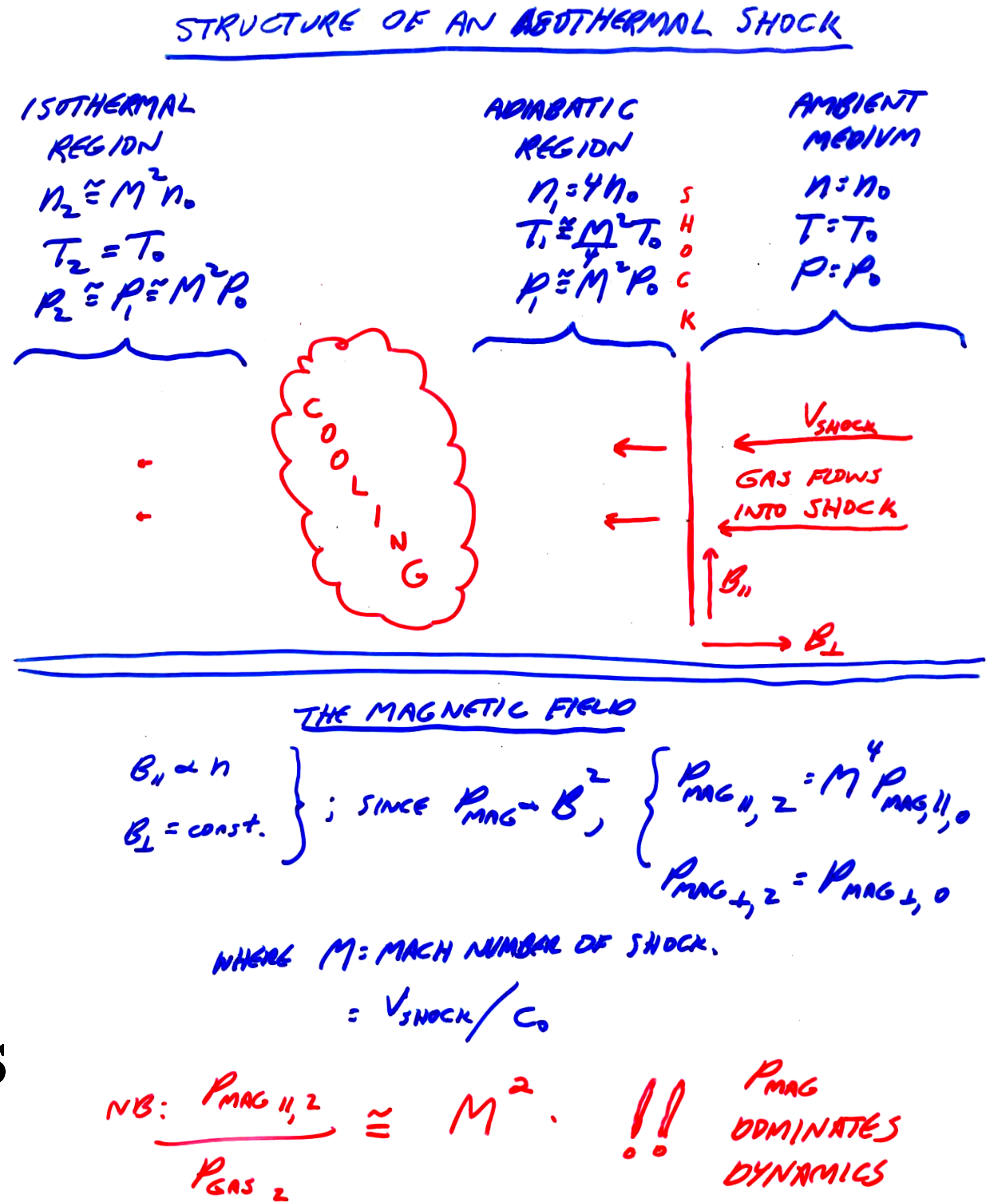
***Parker instability**

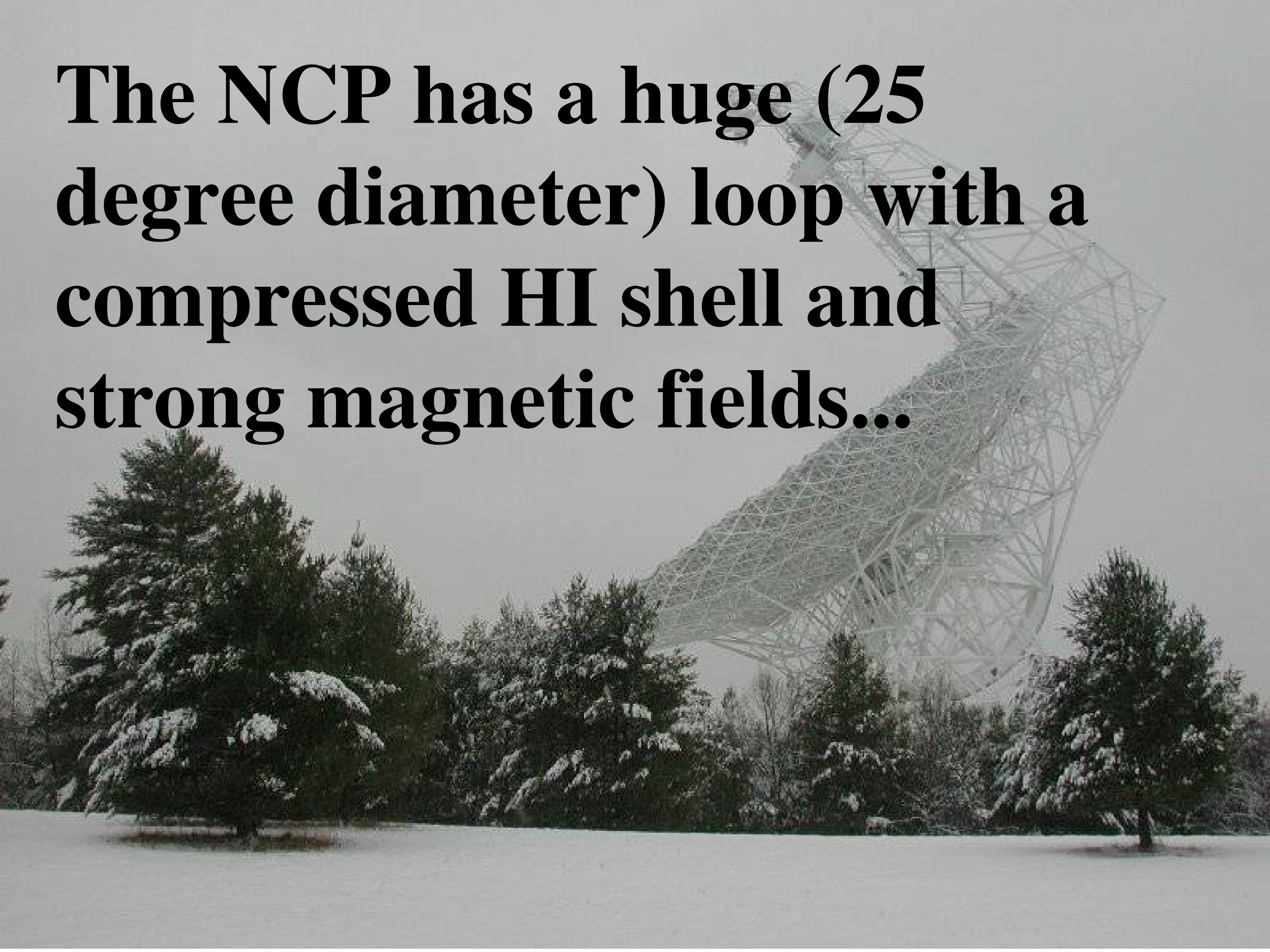
***Virial Theorem**

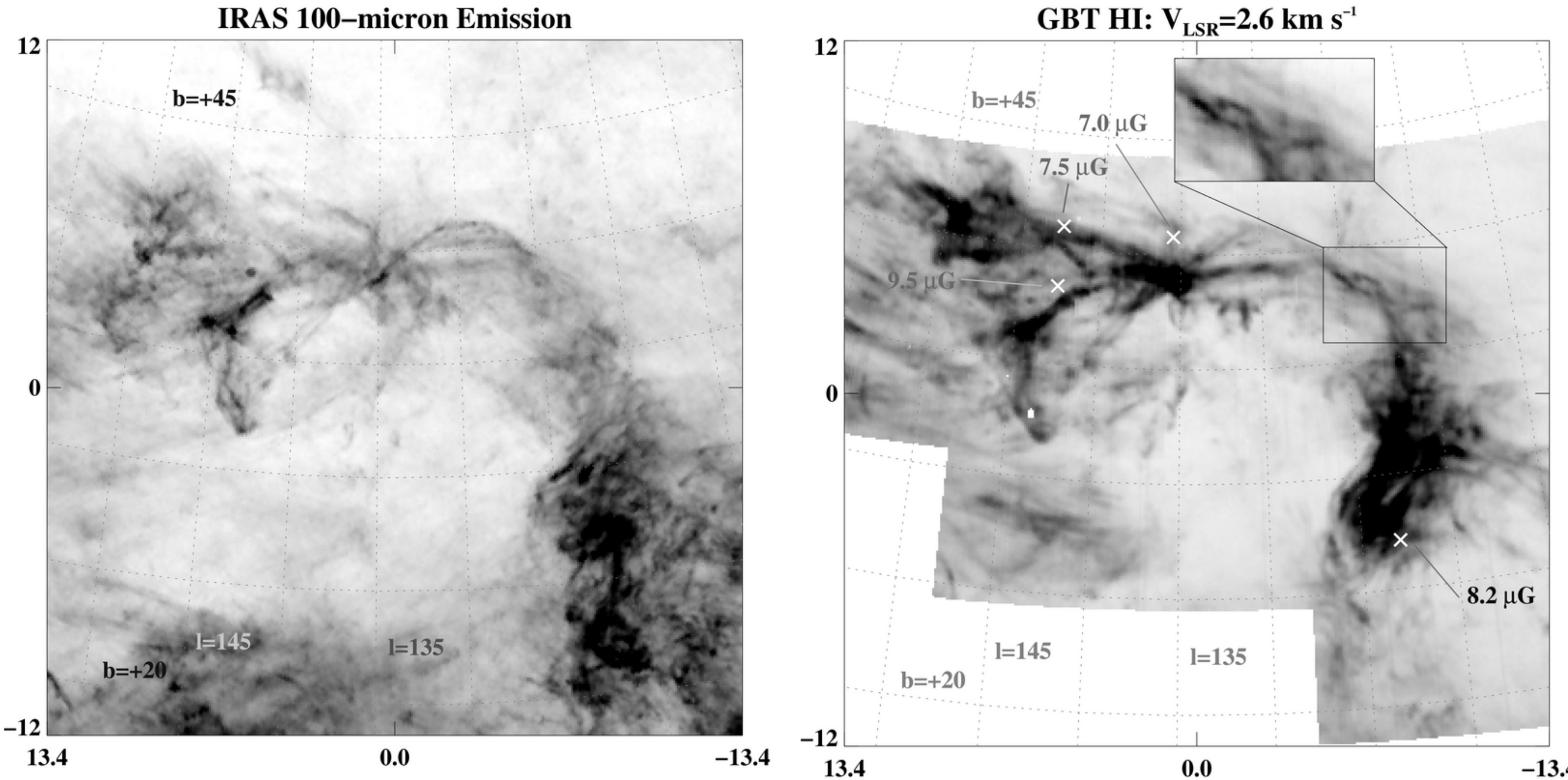
***Angular momentum transport**

***Field generation by Dynamos**

In a magnetically-dominated shock, the final gas density can be greatly reduced: the post-shock pressure is magnetic, not thermal, goes as (Mach nr)^2.




The NCP has a huge (25 degree diameter) loop with a compressed HI shell and strong magnetic fields...



26 deg

A beautiful example of shock-magnified magnetic field and density.

The Parker Instability. Cosmic Rays inflate the field, clouds drag it down, all tied together by magnetic tension

discrete character of the interstellar gas is self-gravitation of the individual clouds,[8] but there is the problem that in many cases the cloud masses inferred from the observations do not seem to be large enough to maintain the cloud in equilibrium by self-gravitation alone (see Kahn and Dyson 1965). For instance, the self-gravitation of a spherical cloud with a diameter of 20 pc and a density of 10 hydrogen atoms/cm^3 can hold the cloud together only if the internal motions are 0.7 km/sec or less. A higher density of 100 atoms/cm^3 can contain internal motions of only 2.2 km/sec. But even the thermal velocities are this large, to say nothing of the 10-km/sec motions expected from collisions between clouds and from the passage of hot luminous stars through the region. So there is some question as to the means by which the apparent identity of the smaller, more tenuous, interstellar gas clouds is maintained. The new point arising in the galactic field configuration presented in this paper is that the self-gravitation of the individual gas clouds is supplemented, in the configuration shown in Figure 2, by the gravitational field of the Galaxy as a whole.

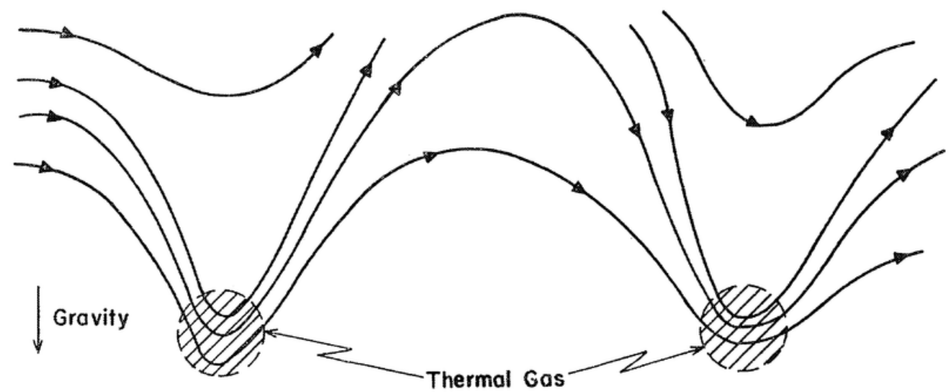


FIG 2.—Sketch of the local state of the lines of force of the interstellar magnetic field and interstellar gas-cloud configuration resulting from the intrinsic instability of a large-scale field along the galactic disk or arm when confined by the weight of the gas.

2. The Virial Theorem for a Uniform Spherical Cloud

$$\underbrace{|W_G| + 3P_0V}_{Holding\ Together} = \underbrace{2T + W_B}_{Blowing\ Apart}$$

V = Volume of cloud

W_G = Gravitatioal Potential Energy $= -\left[\frac{3GM^2}{5R}\right] \propto [\rho^2 \times R^5] \propto [(\rho R)^2 \times R^3] \propto \underbrace{[N^2 \times R^3]}_{note!}$

$3P_0V$ = External Gas Pressure Term

$2T$ = Internal Kinetic Energy (Gas Pressure)

W_B = Magnetic Energy $= \underbrace{\left[\frac{B^2}{8\pi}R^3\right]}_{note!}$ + [Surface Term (can be + or −)]

Both $|W_G|$ and $W_B \propto \frac{1}{R}$

$\frac{|W_G|}{W_B} \propto \frac{N}{B}$ ← independent of size!

SUBCRITICAL means W_B dominates. **SUPERCRITICAL** means $|W_G|$ dominates

For a critical cloud,

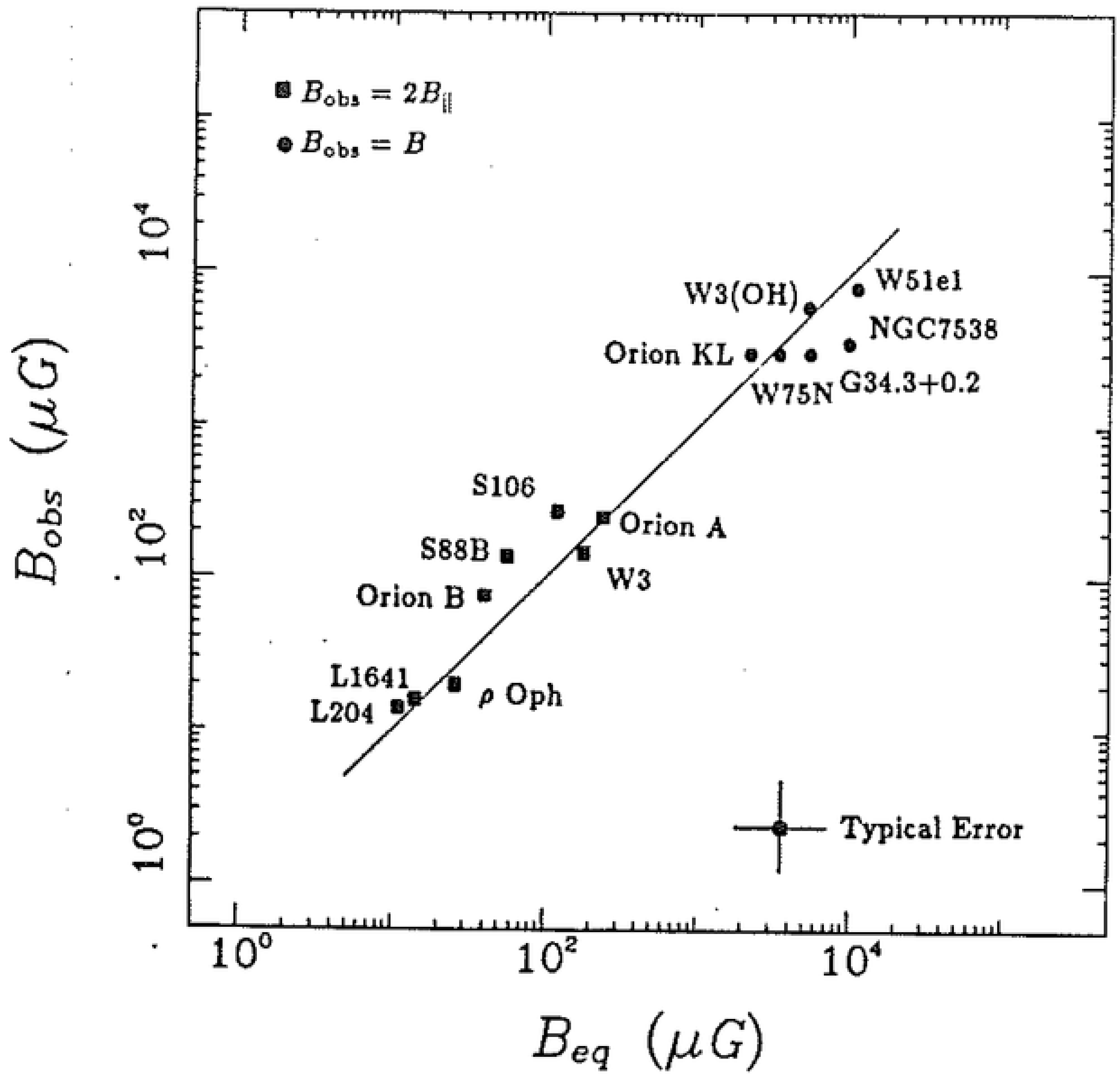
$$B_{cr} = \frac{N_{H-nuc}}{3\times10^{20}} = 6\,A_V \quad \mu\text{G}$$

or, in terms of line width,

$T = \frac{2\pi}{3} R^3 \rho \Delta v^2$, so

$$B_{cr} = \left(\frac{40\pi^2}{9G}\right)^{1/2} \frac{\Delta v^2}{R}$$

Observed clouds tend to be close to $B_{critical}$



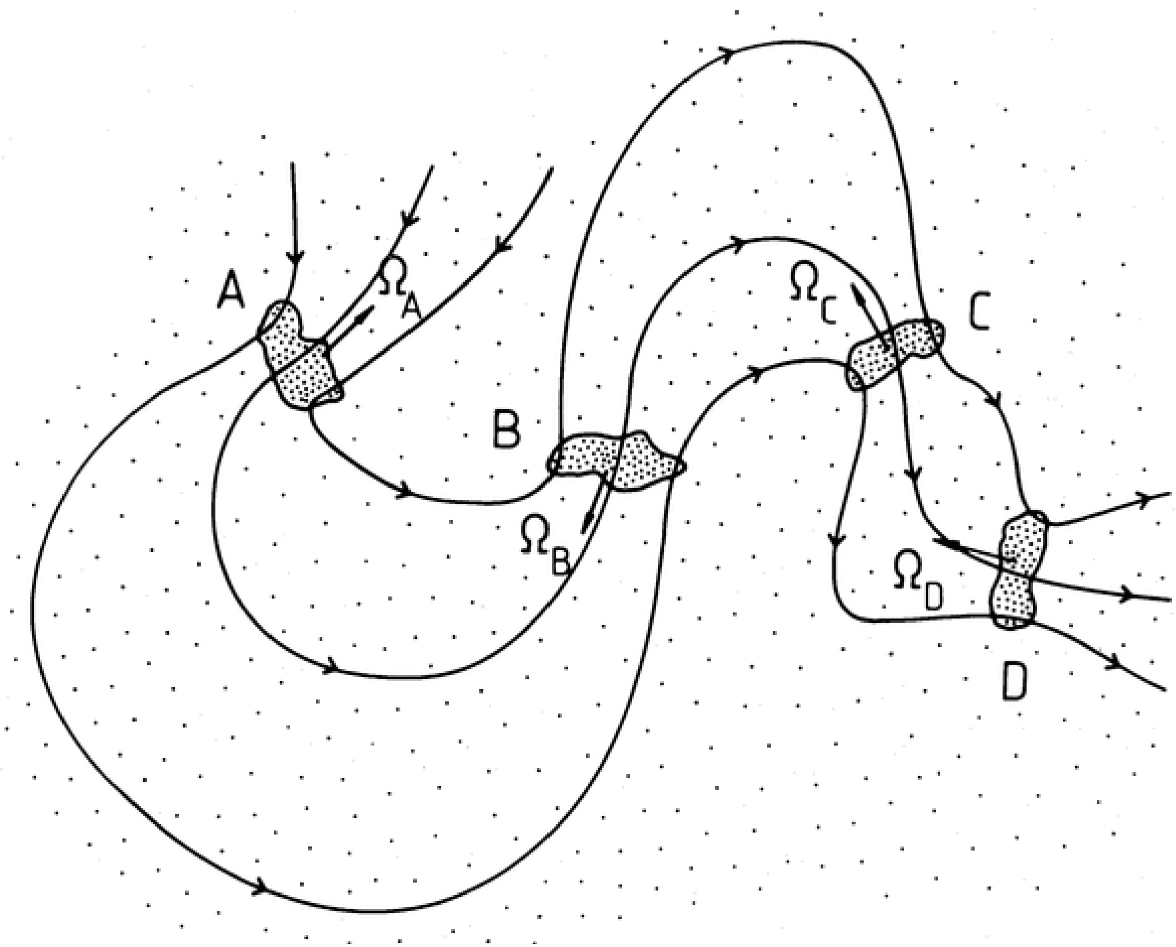
Magnetic fields play a crucial role in transporting angular momentum during star formation.

***quasi-equilibrium models**

***dynamics: protostellar jets**

***dynamics: Magneto-Rotational Instability (MRI)**

MAGNETICALLY LINKED ROTATORS. II.



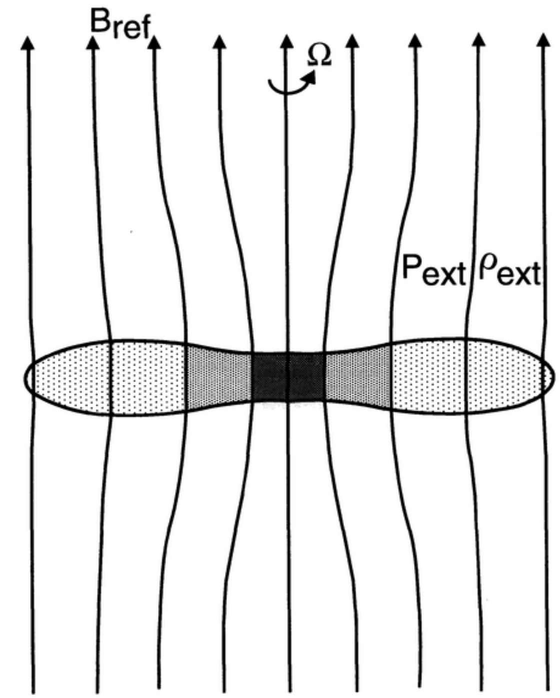


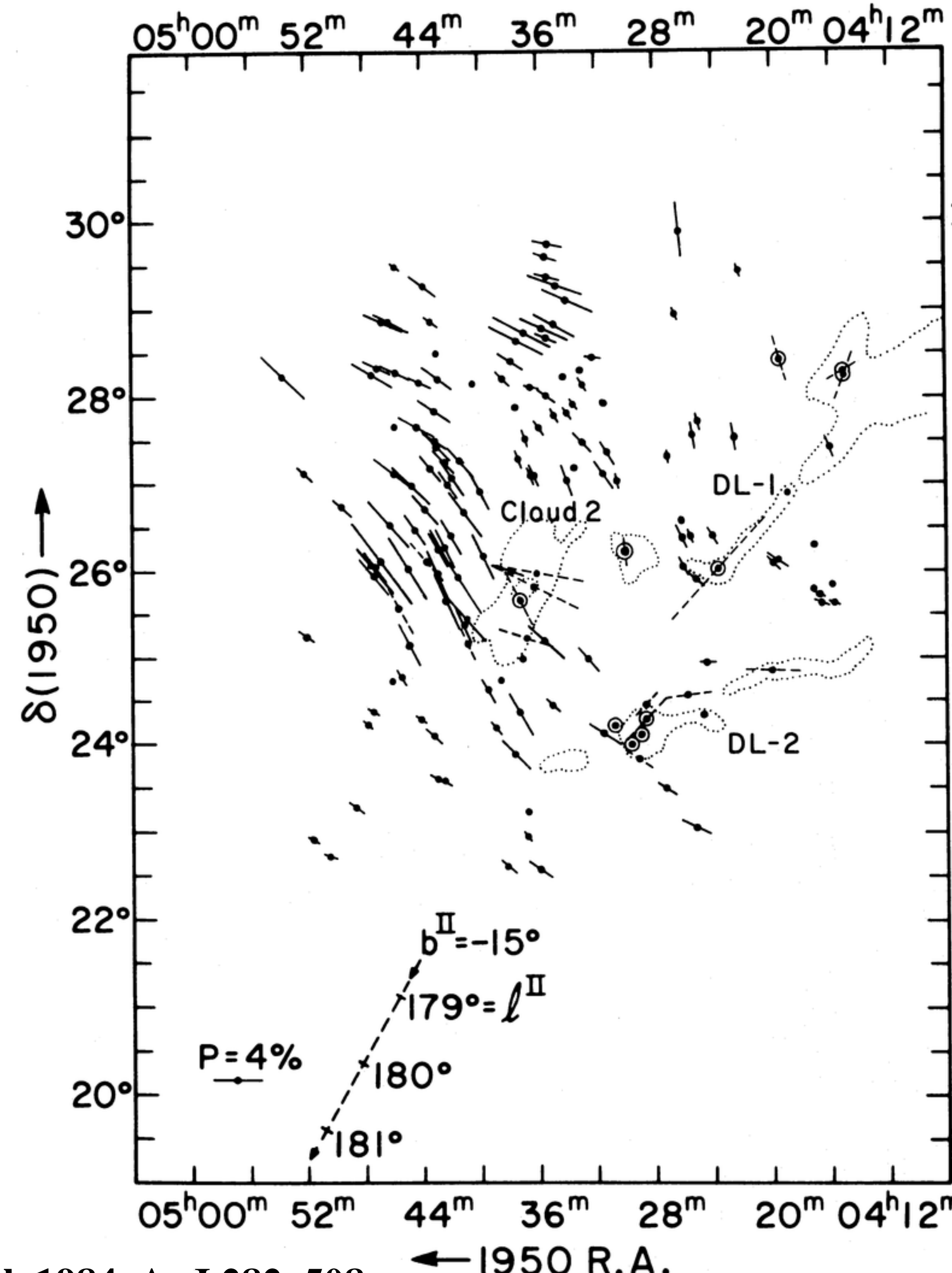
FIG. 1.—Schematic view of an axisymmetric cloud that has flattened along the common direction of rotation and an ambient magnetic field which, far from the cloud, has a uniform "reference" value B_{ref}. The cloud is bounded by an external medium of pressure P_{ext} and density ρ_{ext}.

Quasi-equilibrium: transfer by winding the field with circularly-polarized Alfven waves (Mouschovias, Basu)

Left, Mouschovias 1985 ApJ 298, 205; Right, Basu & Mouschovias 1995, ApJ 453, 271.

Field lines thread and connect clouds in real life!

MONETI *ET AL.*



Moneti et al. 1984, ApJ 282, 508

MAGNETOCENTRIFUGALLY DRIVEN FLOWS FROM YOUNG STARS AND DISKS. I. A GENERALIZED MODEL

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ABSTRACT

We propose a generalized model for stellar spin-down, disk accretion, and truncation, and the origin of winds, jets, and bipolar outflows from young stellar objects. We consider the steady state dynamics of accretion of matter from a viscous and imperfectly conducting disk onto a young star with a strong magnetic field. For an aligned stellar magnetosphere, shielding currents in the surface layers of the disk prevent stellar field lines from penetrating the disk everywhere except for a range of radii about $\varpi = R_x$, where the Keplerian angular speed of rotation Ω_x equals the angular speed of the star Ω_*. For the low disk accretion rates and high magnetic fields associated with typical T Tauri stars, R_x exceeds the radius of the star R_* by a factor of a few, and the inner disk is effectively truncated at a radius R_t somewhat smaller than R_x. Where the closed field lines between R_t and R_x bow sufficiently inward, the accreting gas attaches itself to the field and is funneled dynamically down the effective potential (gravitational plus centrifugal) onto the star. Contrary to common belief, the accompanying magnetic torques associated with this accreting gas may transfer angular momentum mostly to the disk rather than to the star. Thus, the star can spin slowly as long as R_x remains significantly greater than R_*. Exterior to R_x field lines threading the disk bow outward, which makes the gas off the mid-plane rotate at super-Keplerian velocities. This combination drives a magnetocentrifugal wind with a mass-loss rate $\dot{M}_w$ equal to a definite fraction f of the disk accretion rate $\dot{M}_D$. For high disk accretion rates, R_x is forced down to the stellar surface, the star is spun to breakup, and the wind is generated in a manner identical to that proposed by Shu, Lizano, Ruden, & Najita in a previous communication to this journal. In two companion papers (II and III), we develop a detailed but idealized theory of the magnetocentrifugal acceleration process.

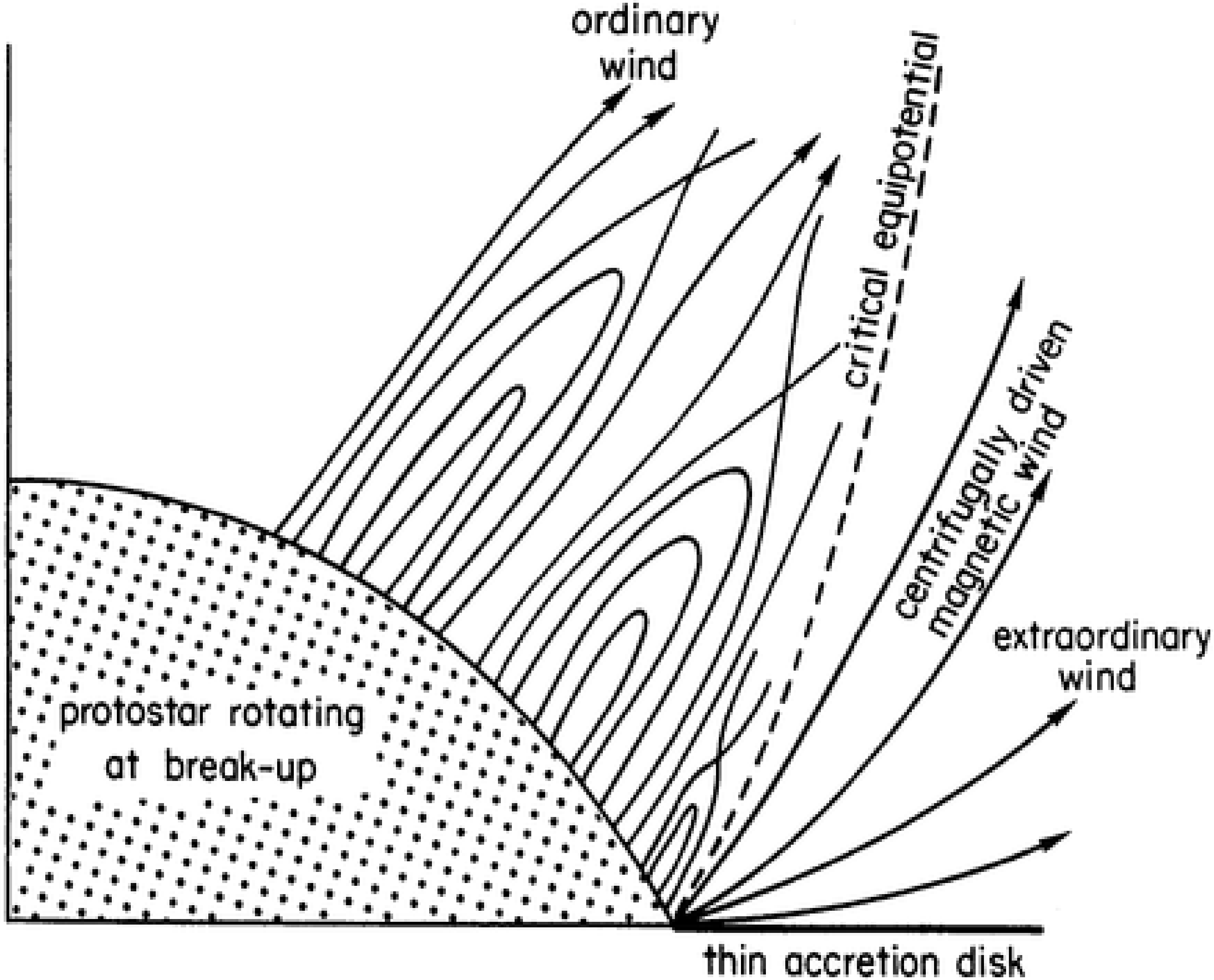


FIG. 1.—A complex geometry of open and closed field lines exists over most of the surface area of a protostar, with an ordinary wind (O-wind) blowing out along the open field lines. This wind intensifies into an extraordinary wind (X-wind) driven by magnetocentrifugal effects if open field lines protrude from the equatorial region of a star spun to breakup by heavy accretion from a thin accretion disk.

1. The MagnetoRotational Instability (MRI)

Two masses (1,2) in orbit around a central mass M connected by a magnetic field in tension (a spring).

Mass M, Radius R, Velocity V, Angular Momentum Ω, Angular Momentum L

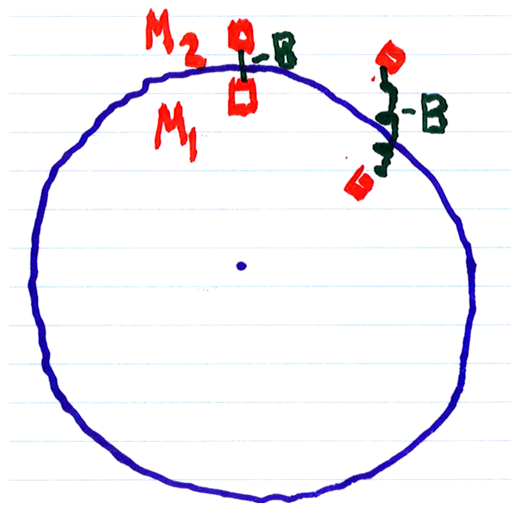
$R_1 < R_2$

$V \propto \left[\frac{1}{R^{1/2}}\right]$ so $V_1 > V_2$

$\Omega \propto \left[\frac{V}{R}\right] \propto \left[\frac{1}{R^{3/2}}\right]$ so $\Omega_1 > \Omega_2$

$L \propto [V \times R] \propto \left[R^{1/2}\right]$ so $L_1 < L_2$

The magnetic field (spring) pulls M_2 forward, increasing L_2 and also R_2. This stretches the spring; the spring pulls harder, increasing the torque pulling M_2 forward. It's a runaway instability.



and it transfers angular momentum OUTWARDS

Breakdown of flux freezing must occur in star formation and dynamos…

The Role of Magnetic Fields in the Protostellar Accretion Phase

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Abstract. We summarize recent work addressing the role of magnetic fields in the process of star formation and disk accretion. After a short review of the basic observational results, we concentrate on the efficiency of magnetic braking during cloud collapse and its consequences on the formation of centrifugally supported disks around young stars. Then, we relate this issue to the well-known magnetic flux problem of star formation, and we show that the introduction of non-ideal MHD effects is a necessary step toward the development of self-consistent models for the collapse of molecular clouds and the formation of disks. Finally, we discuss the structure and evolution of magnetized accretion disks around young stars that have dragged their magnetic field in the phase of gravitational collapse and we focus on two main diffusive processes: viscous stresses that redistribute mass and angular momentum, and the resistive diffusion of mass across magnetic field lines.

However, a correct physical description of these processes requires the introduction of non-ideal MHD effects, either micro- or macroscopic, to avoid the two most unwanted consequences of field-freezing, namely (*i*) the catastrophic magnetic braking of circumstellar disks, and (*ii*) the huge concentration of magnetic flux in protostars, both contrary to observations.

Galli et al. 2010, in "Plasmas in the Laboratory and in the Universe"

Let's take a pictorial look at COSMIC DYNAMOS. The master is Eugene Parker. We extract from two of his papers, ApJ 122, 293 (1955) & ApJ 163, 255 (1971)

HYDROMAGNETIC DYNAMO MODELS

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Received October 18, 1954; revised May 11, 1955

ABSTRACT

The purpose of this paper is to investigate the steady-state amplification of magnetic fields in a fluid It is shown that a rotating sphere of conducting fluid can regenerate a dipole magnetic field. It is sufficient for the angular velocity of rotation to vary with distance from the axis of rotation and for cyclonic fluid motions to be present The nonuniform rotation generates a toroidal field from the dipole field; the cyclones generate, from the toroidal field, loops of flux in the meridional plane which coalesce to amplify the dipole field The rotating sphere is discussed in relation to the liquid core of the earth and the geomagnetic dipole field. If, instead of a rotating sphere, one has a prismatic volume of fluid, it is possible to construct migratory dynamo waves The dynamo waves are discussed in relation to the solar convective zone; it is shown that such waves can account for many of the principal features of the observed solar magnetic activity

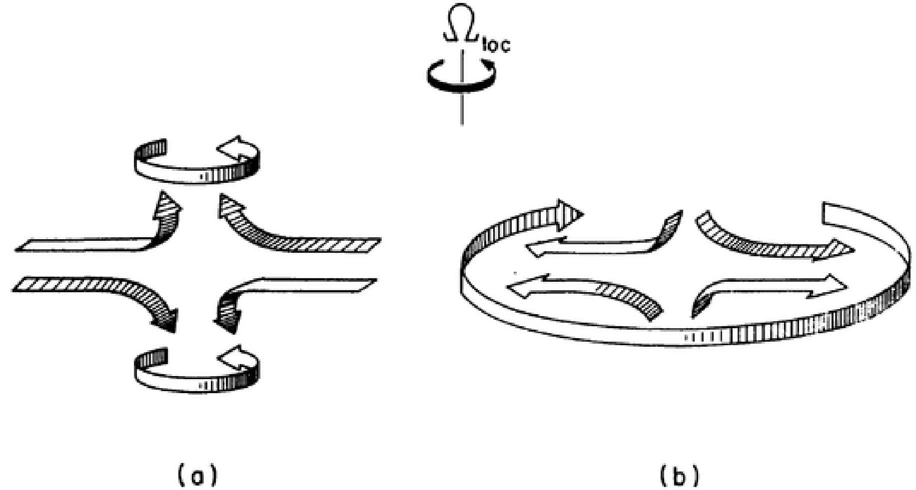


FIG. 1.—Sketch of the change in angular velocity, (*a*) in a converging flow and (*b*) in a diverging flow, in a region where the overall angular velocity Ω_{loc} is indicated by the arrow in the center (clockwise when looking in the $+z$-direction).

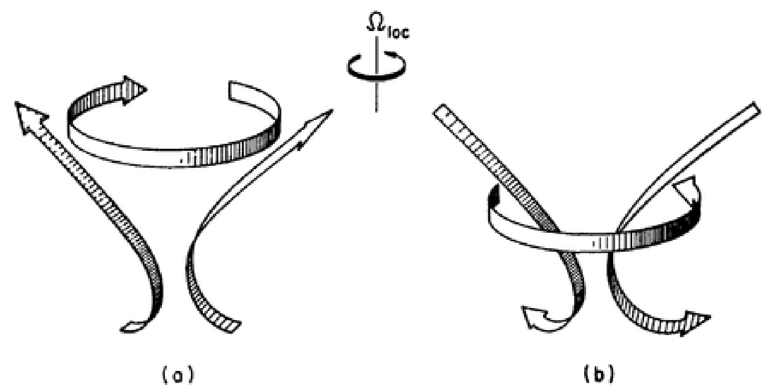
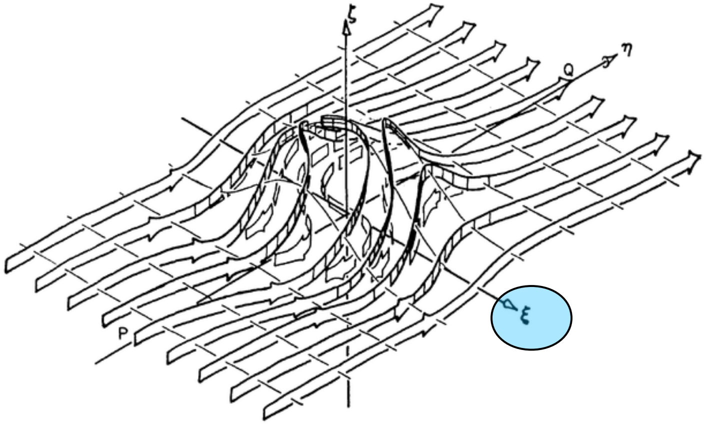
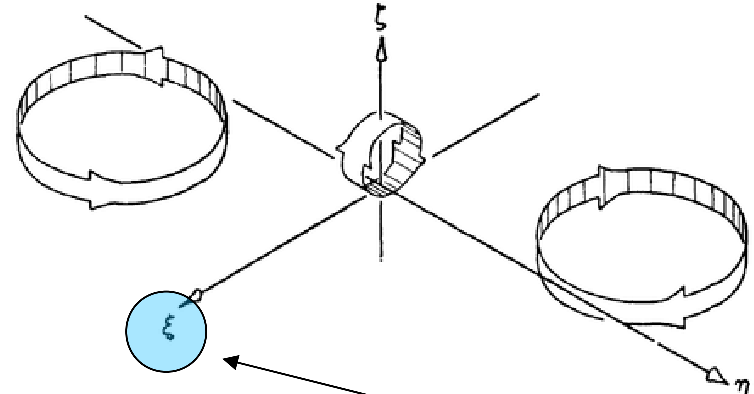


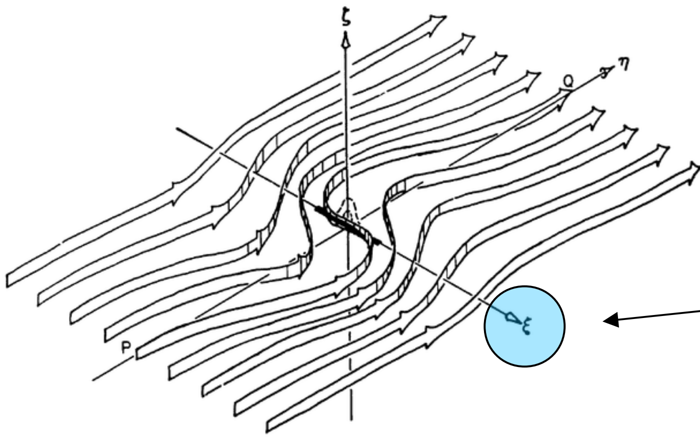
FIG. 2.—Sketch of the change in angular velocity in a flow extending (*a*) vertically upward, and (*b*) vertically downward, across one or more scale heights in the gas density ρ.

A turbulent cell in the Galaxy expands as it rises from z=0; it rotates because of the Coriolis force



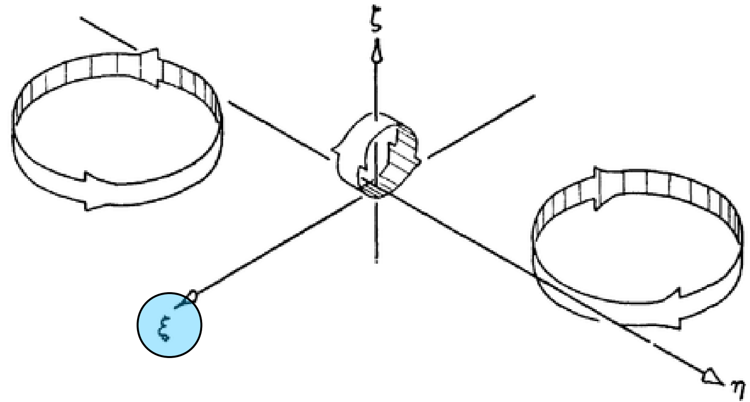
-The deformation of a slab of toroidal field by cyclonic fluid motion. The ri
ent $-\boldsymbol{\beta}$.





(Note the rotated coordinate system!)

The cell drags the field with it, distorting as on the left. This distortion is represented by the loops on the right.



The two 'horizontal' loops are of opposite sense. With a large number of cells <u>whose fields reconnect</u>, these cancel and disappear. In contrast, all of the 'vertical' loops have the same sense; their fields reconnect and

<u>they add up to give a meriodonal (radial) field. This radial field is stretched by differential rotation to make an azimuthal field, which amplifies the original one.</u>

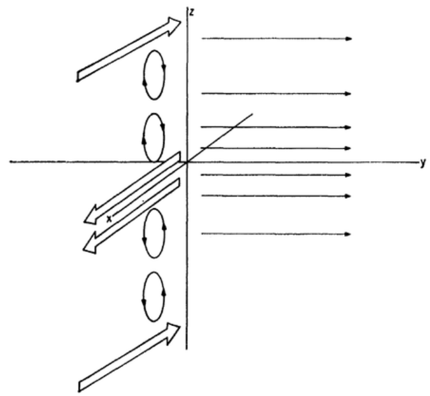


FIG. 4.—Schematic drawing of the fields in the lowest even mode in the galactic disk. Straight arrows in the (y, z)-plane represent the dominant azimuthal field. Circles in the (x, z)-plane represent the loops of flux produced by the cyclonic motions. Ribbons in the (x, z)-plane represent the field from the coalescence of the loops. The azimuthal field is produced from the ribbons as a result of the combination of the shear dV_y/dx and the losses out of the upper and lower surfaces of the disk.

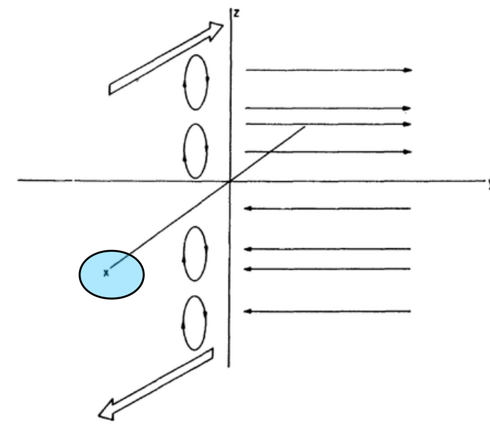


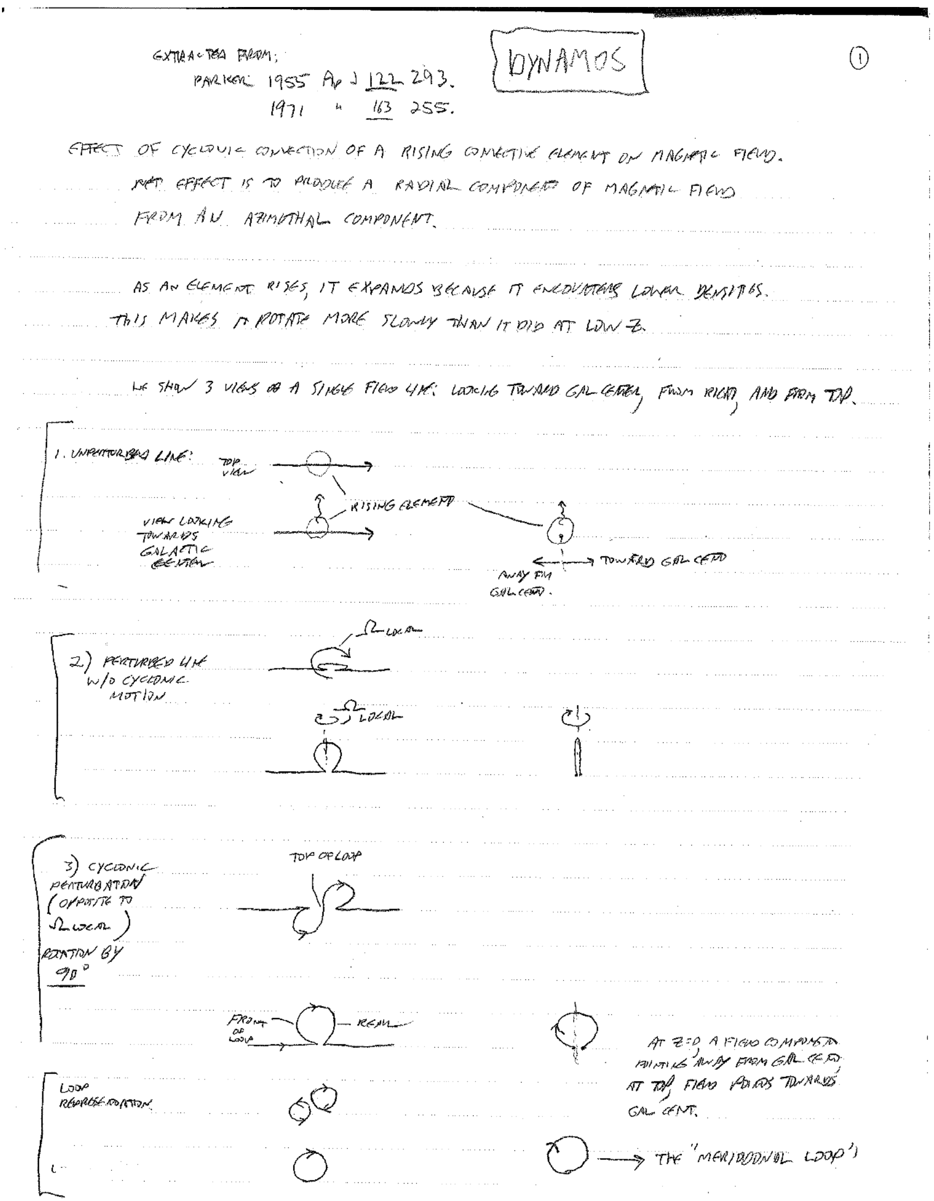
FIG. 6.—Schematic drawing of the fields in the lowest odd mode in the galactic disk. Straight arrows in the (y, z)-plane represent the dominant azimuthal field. Circles in the (x, z)-plane represent the loops of flux produced by the cyclonic motions. Ribbons in the (x, z)-plane represent the field from the coalescence of the loops. The azimuthal field is produced from the ribbons as a result of the shear dV_y/dx.

Lowest-order Even Mode

Lowestorder Odd Mode

There are different dynamo modes. Note that, for the even mode, the fields are opposite at high z. These fields must leave the Galaxy for this mode to work.

My handwritten notes, which may or may not help…



EXTRACTED FROM:
PARKER 1955 ApJ 122 293.
1971 " 163 255.

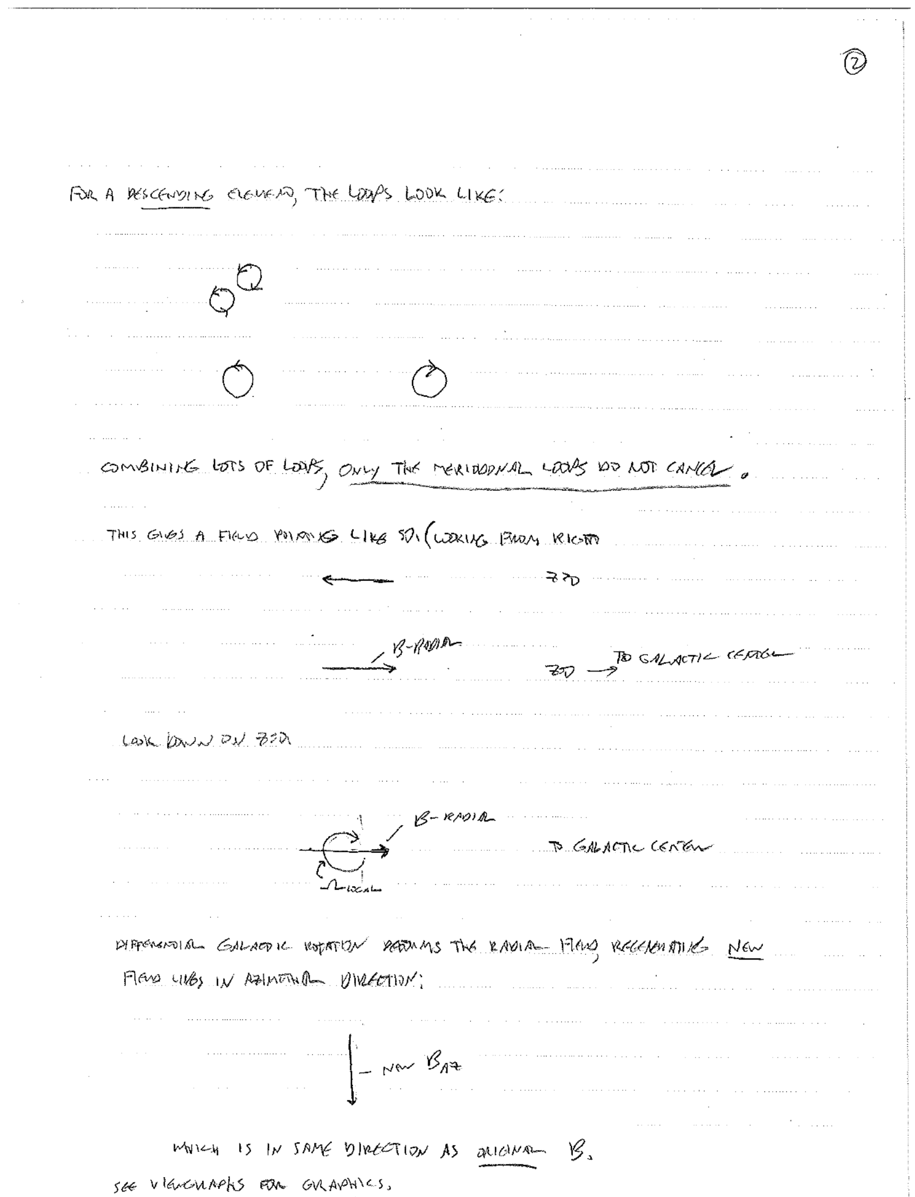
DYNAMOS

1

EFFECT OF CYCLONIC CONVECTION OF A RISING CONVECTIVE ELEMENT ON MAGNETIC FIELD.
NET EFFECT IS TO PRODUCE A RADIAL COMPONENT OF MAGNETIC FIELD FROM AN AZIMUTHAL COMPONENT.

AS AN ELEMENT RISES, IT EXPANDS BECAUSE IT ENCOUNTERS LOWER DENSITIES. THIS MAKES IT ROTATE MORE SLOWLY THAN IT DID AT LOW Z.

WE SHOW 3 VIEWS OF A SINGLE FIELD LINE: LOOKING TOWARD GAL CENTER, FROM RIGHT, AND FROM TOP.



2

FOR A DESCENDING ELEMENT, THE LOOPS LOOK LIKE:

COMBINING LOTS OF LOOPS, ONLY THE MERIDIONAL LOOPS DO NOT CANCEL.

THIS GIVES A FIELD POINTING LIKE SO: (LOOKING FROM RIGHT)

LOOK DOWN ON Z>0

DIFFERENTIAL GALACTIC ROTATION DEFORMS THE RADIAL FIELD, REGENERATING NEW FIELD LINES IN AZIMUTHAL DIRECTION:

WHICH IS IN SAME DIRECTION AS ORIGINAL B.

SEE VIEWGRAPHS FOR GRAPHICS.

IMPORTANT POINTS common to ALL dynamos:

***Differential Rotation and an azimuthal field (maybe a 'seed' field)**

***Rising convective elements subject to Coriolis force, producing cyclonic motions**

***Generation of B-field loops in 3 orthogonal planes**

***Coalescence of loops and DESTRUCTION OF FIELD LINES---REQUIRES FIELD DESTRUCTION**

***Production of a meriodonal (radial) field**

***Differential rotation stretches the radial field, producing an azimuthal field in the same sense as the original---FIELD AMPLIFICATION.**

***The lowest EVEN mode has no azimuthal reversal at z=0---but at high z, the azimuthal lines are in opposite directions and THE HIGH-Z LINES MUST ESCAPE FROM THE SYSTEM!**

***The lowest ODD mode does not require this escape.**

The Galaxy's field seems to be even…

Breakdown of flux freezing—reconnection, field destruction—is essential for the Universe to exist as we know it. The mechanisms are not well-understood. THIS IS THE LEAST WELL-UNDERSTOOD ASPECT OF COSMIC MAGNETIC FIELDS.

Some possibilities:

***3d turbulent mixing of field lines to create small-scale structure in B**

***Ambipolar Diffusion: ions are tied to B, neutrals are not, ion/neutral collisions are rare so they can slip past each other.**

***Hall Diffusion: E fields exist from charged grains (which have large collisional cross sections). Ions and electrons drift in different directions in response to both B and E.**

***Resistive diffusion**

Fin