Excitation of Supernova Remnants by Twisting of the Neutron Star Dipole Magnetic Flux

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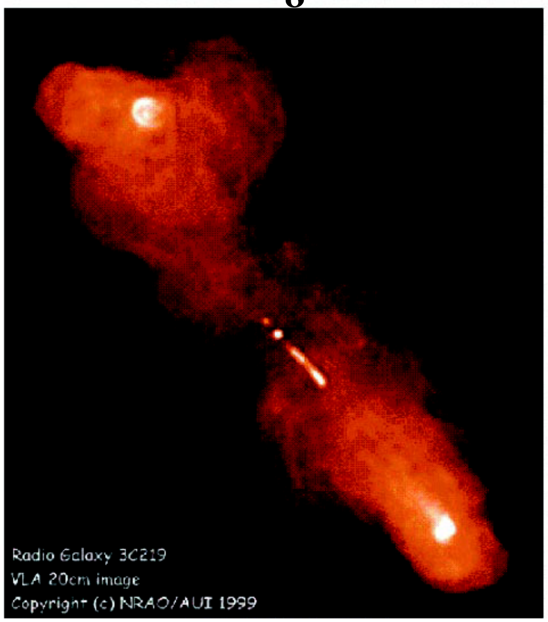
Extra galactic cosmic rays, AGN jets, and Radio Lobes are all possibly produced from the free energy of formation of Super Massive Black Holes. In our view these are the result of the twisting of the magnetic field produced by a large scale dynamo within the accretion disk forming the MBH.

Similarly it is suggested that the relative winding of the magnetic flux attached both to the neutron star and to the ejecta of the supernova will supply free energy comparable to the ejecta and produce similar non-thermal x-rays and gamma rays.

Winding of magnetic flux in a low density conducting medium, produces force free magnetic fields. The magnetic energy is transformed efficiently to particle energy by J. E, E(parallel to B) acceleration.

This is the comparison: Will the winding of the NS flux make the nebula?

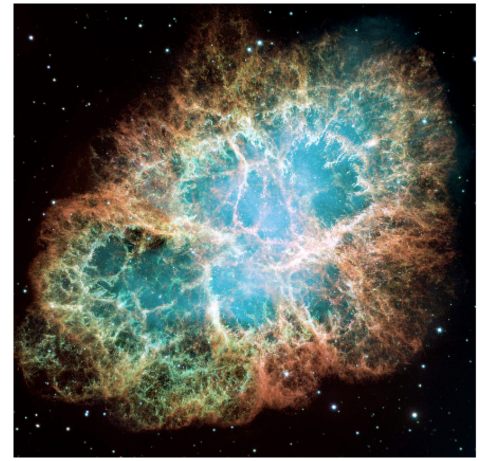
Radio Lobe, ~ 10^{61} ergs, ~ 10% $M_8\,c^2$



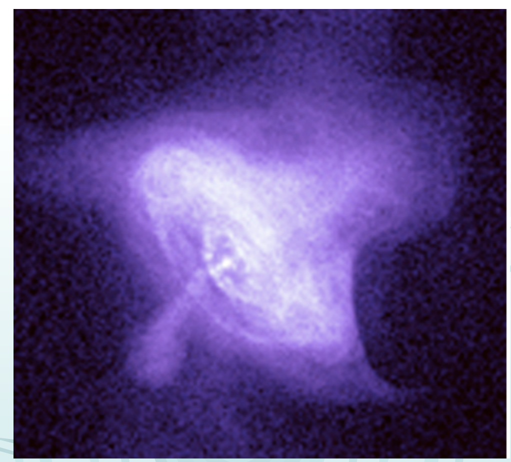
An alpha-omega dynamo in The accretion disk; the winding of a force-free magnetic helix, ~10^{12} turns, reconnection, dissipation, and acceleration, finally Synchrotron emission gives the radio flux.

3c219 Radio Lobe
Synchrotron radiation.
B=5×10^{-6} G, (Faraday)
Electrons, E ~ 10^4 mc^2 .
Compton CMB = x-rays

The Crab, ~ 10^{47} ergs

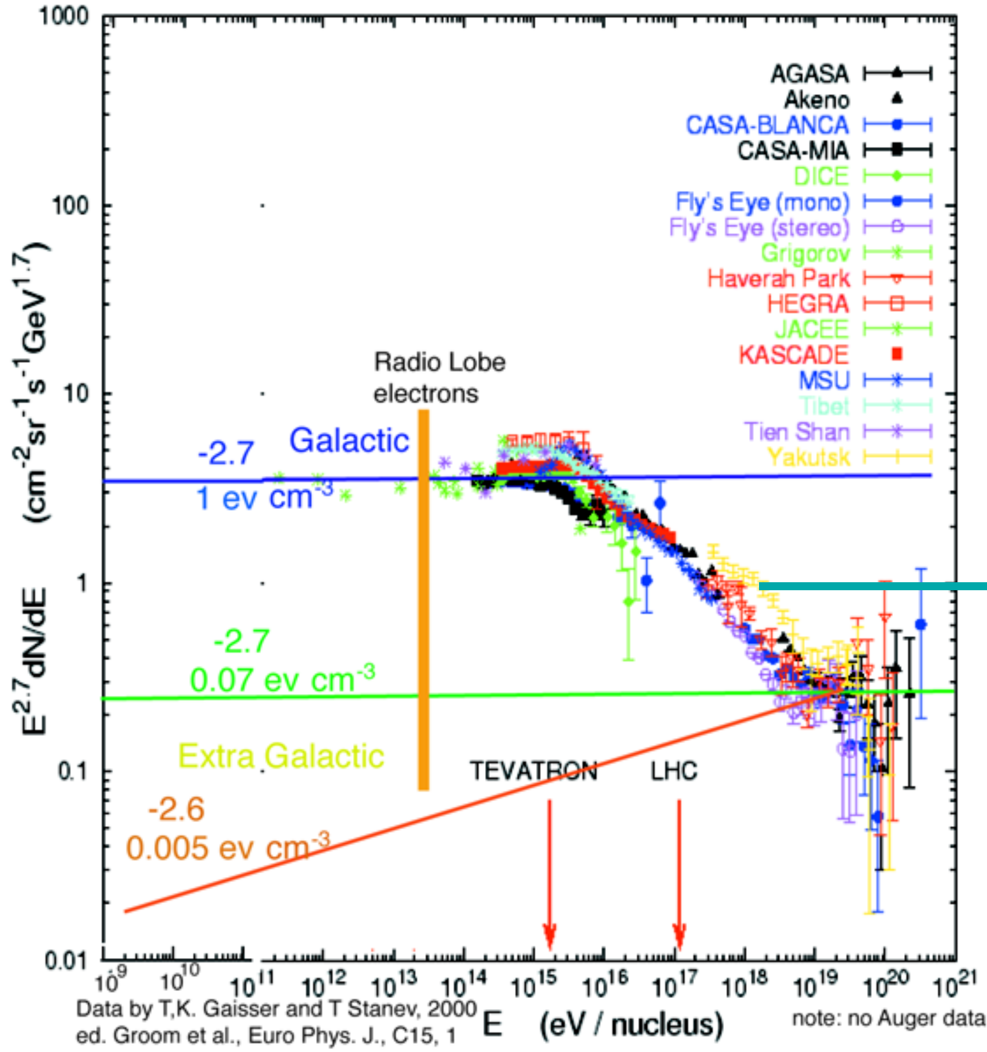


Optical/x-rays



Do twisted fields power the nebula?

Total Energy of Extra Galactic Cosmic Rays, $\sim 10^{60}$ to 10^{61} ergs, ~ 1% to 10% $M_{MBH}\, c^2$



$\Gamma = -2.7$, galaxy

$\Gamma = -2.6$ extra galactic

Spallation ~ 10% loss per e-fold

$W_{CR} = 8\times10^{-15}$ ergs cm^{-3}

$* \ 10^{74}$ cm^3 = 8×10^{59} ergs

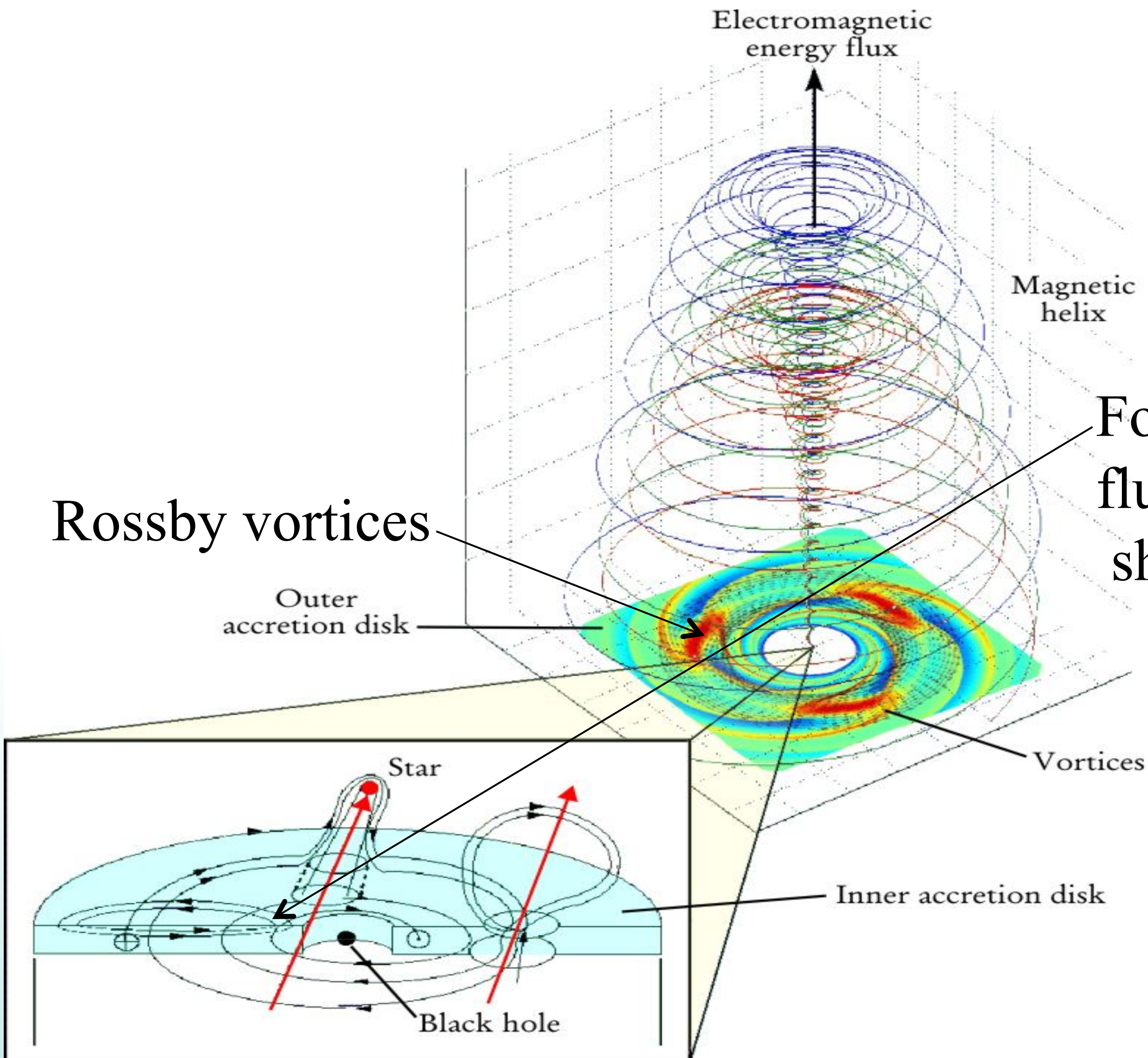
Progressive leakage from Galaxy to metagalaxy

Acceleration in force-free fields

CRs lost to voids in 1/100 Hubble time. ? GZK cut-off;

$dN/N = -\,\Gamma\, dE/E$, $N = N_0\, E^{-\Gamma}$

AGN Force-Free Helix; Grad-Schfanov calc.
10^{12} turns, L= 10Mpc, $3*10^4$ G, $r_0 = 10^{14}$ cm, $r_1 = 10^{18}$



Rossby vortices

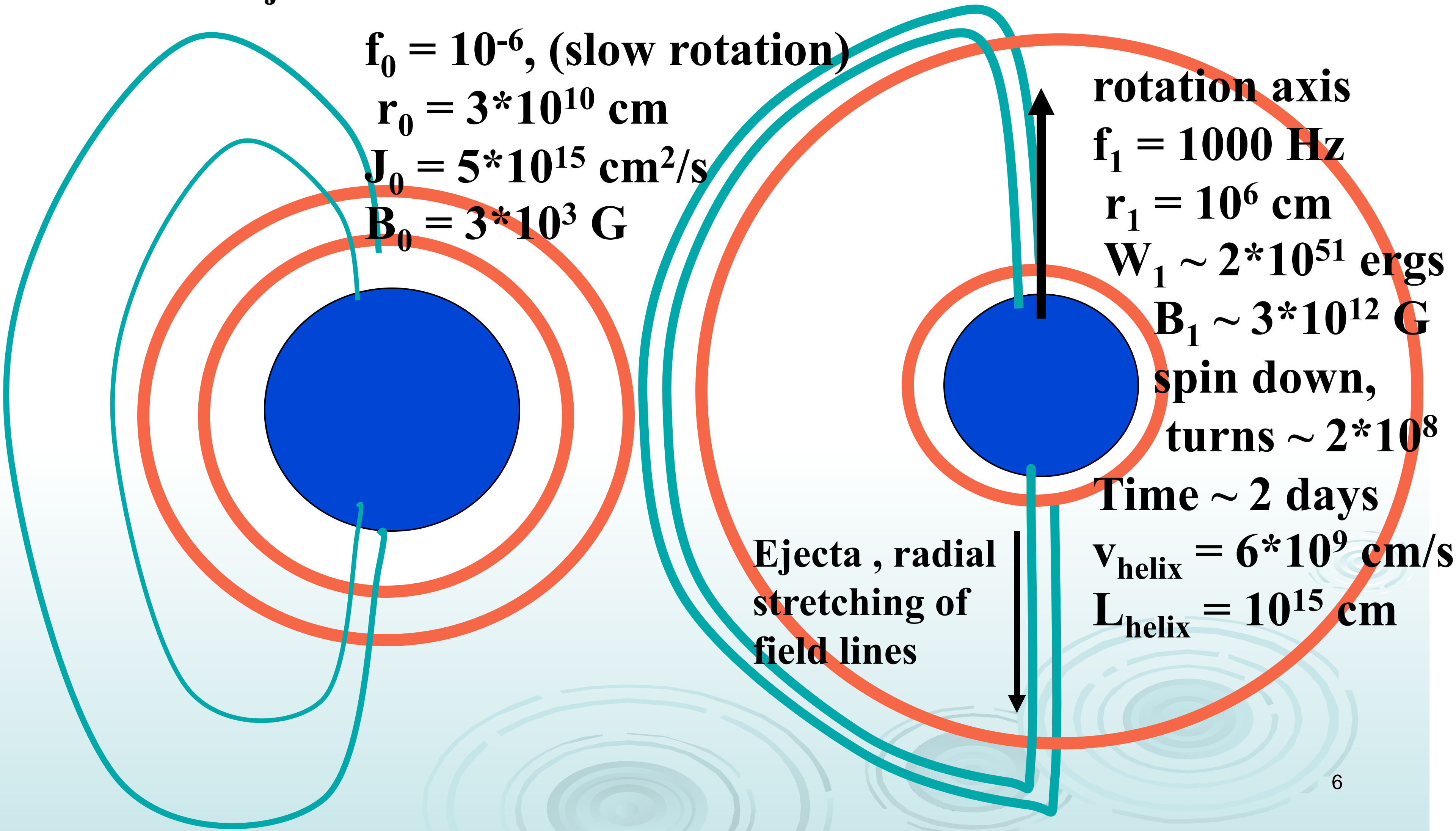
Foot prints of poloidal flux wound by Keplerian shear

αω dynamo, poloidal flux ~ 10^{-13} toridal flux

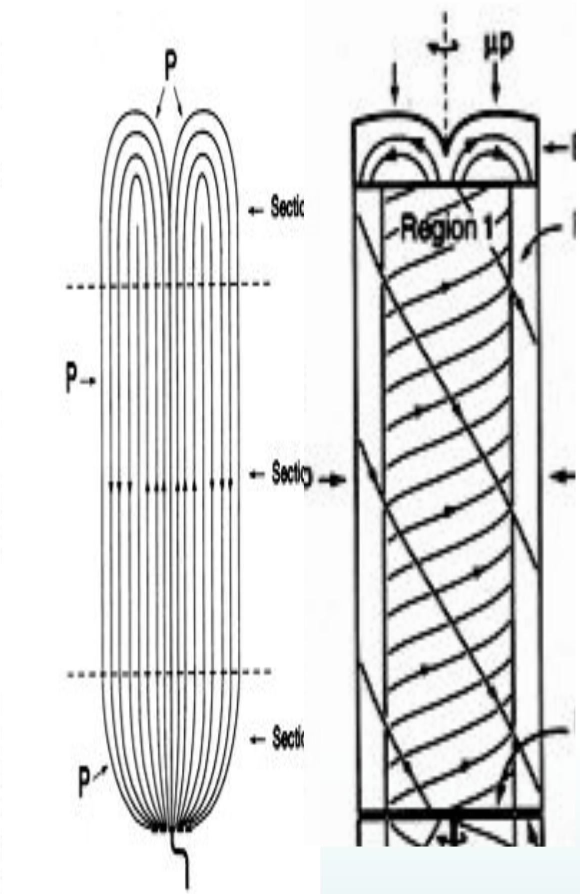
Magnetized Neutron Star and Supernova Ejecta

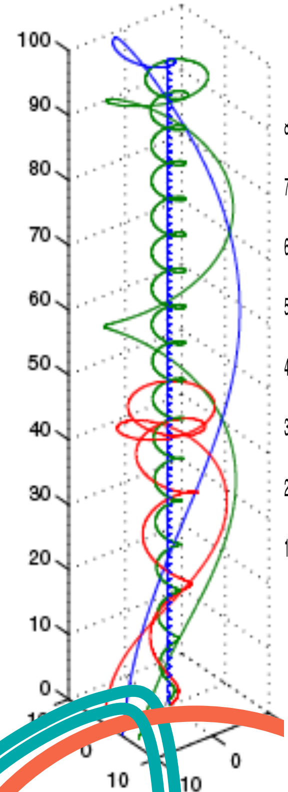
collapse of supernova with magnetic flux imbedded both in the neutron star and in the ejected mass.

The radial stretching of the flux trapped in the neutron star by the explosion ejecta

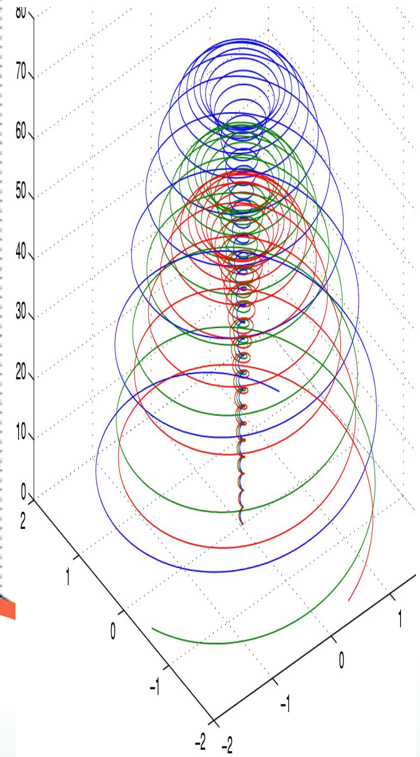


Twisting of Flux Column by the Neutron Star





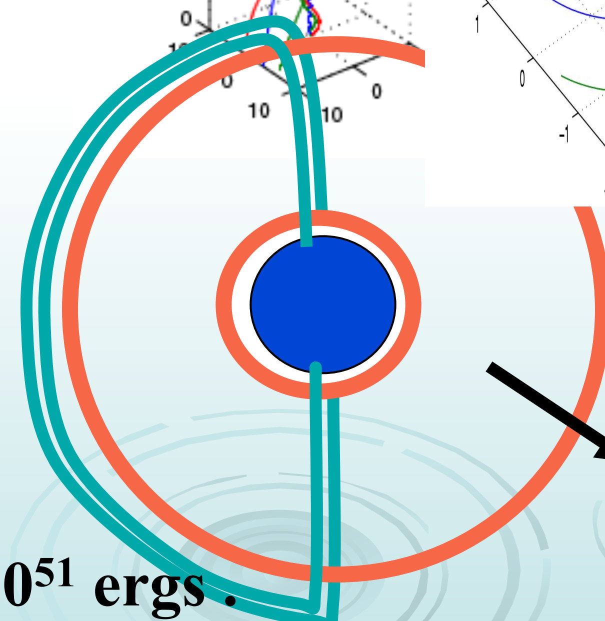
Grad-Schafranov force-free calculation, Hui Li.



Supernova ejecta stretches the imbeded dipole quadrupole flux.

The neutron star winds its imbedded flux differentially relative to the expanding return flux imbedded in the ejecta.

Vacuum cavity forms by twisting a line-tied pinch



Core is neutron star radius, ~10^6 cm; energy= 2×10^8 turns x $(B^2/8\pi)\ 6 * r^3 = 4 \times 10^{51}$ ergs .

Explosion expansion of ejecta

Properties of force-free helix

Flux conservation: compression of dynamo flux, 10^4G in main-sequence star to neutron star. Collapse from 3 x 10^{10} cm to 10^6 cm.

Then B_0 = 3 x10^{12} gauss (issues with crust strength for dipole B>~10^{13}G. (Ruderman and Flowers, ~ 1963))

No differential rotation or winding during collapse because of convection in nuclear burning.

Magnetic core of helix is radius of NS, $r_0 = 10^6$ cm.

Diffusion: Bohm diffusion = maximum diffusion at ($T_{e,i}$ ~ 1 gev): D = 1.4 x 10^4 cm^2/s = resistivity = η; at maximum temperature;

Then the life time of helix, $t_{helix} = r^2/D$ = 2 years, or greater, but spin-down time = 2 days, 2*10^5 s .

Axial velocity of helix, progression, = $\omega\, r_0$ = 6*10^9 cm/s.

Properties of force-free helix, cont.

Length, $L_{helix} = t_{spin}\, \omega\, r_1 = 10^{12}$ cm

Number of turns = f x t_{helex} = 1.8×10^9
= amplification of Flux generated by helical winding:

The dissipation of this flux is then the luminosity of the Crab nebula.

Power = $\omega_1 (B_1^2 / 8\pi)(\pi r_1^2) = 2 \times 10^{38}$ ergs/s.

Electric field, volts = $\omega_1 r_1 B_1 \times 10^{-8} = 2 \times 10^{14}$ volts/cm.

Particles are accelerated and lost by diffusion : an alternate way to make cosmic rays, electrons and x-ray sources.

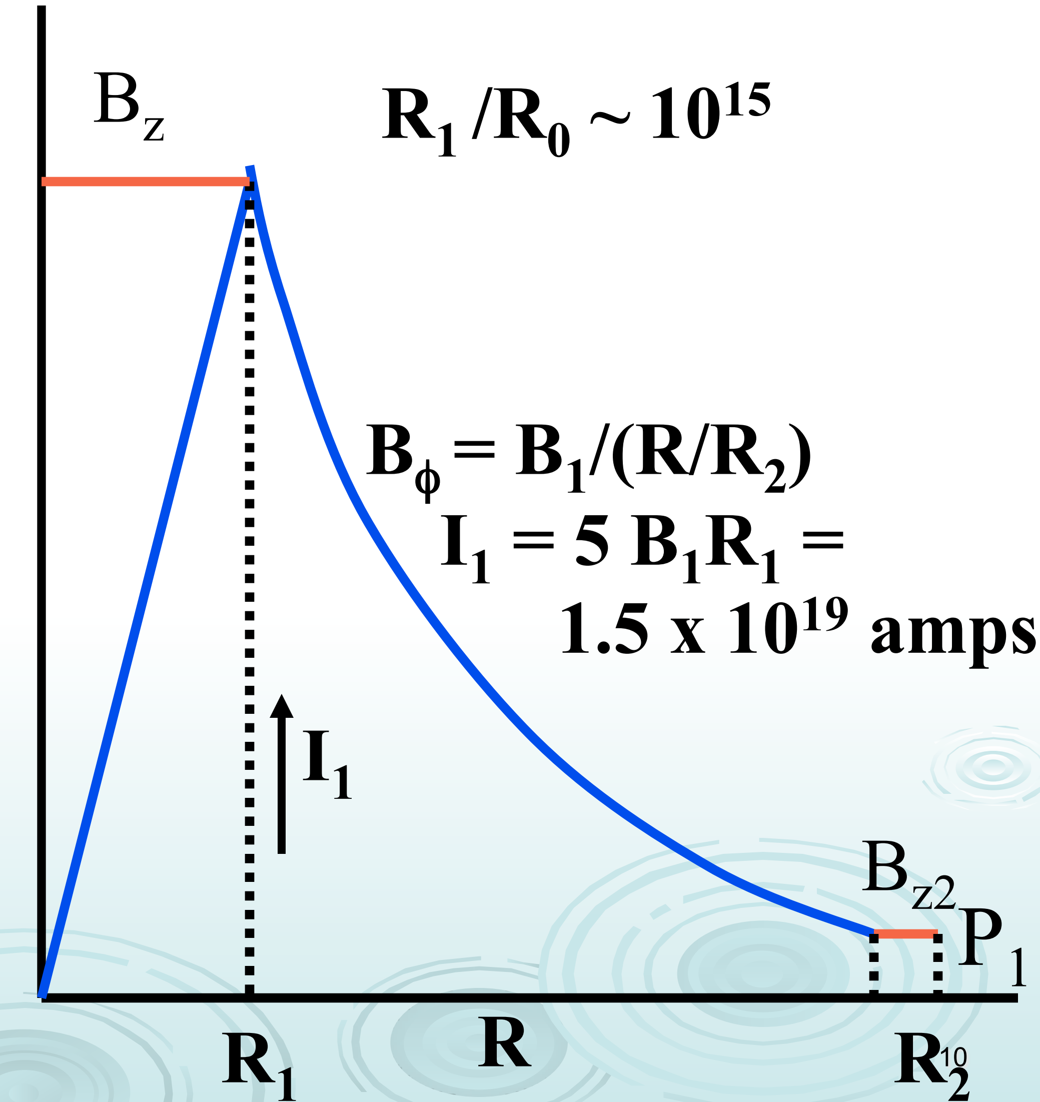
Geometry of Force-free Neutron Star Driven Helix

Winding of radial flux, at the "nose"; end of helix, produces azimuthal flux and a current, $I_1 = 10^{19}$ amps .

Pressure equilibrium in the core, r_0 ,
$B_z^2 + B_\phi^2 = B_1^2$.

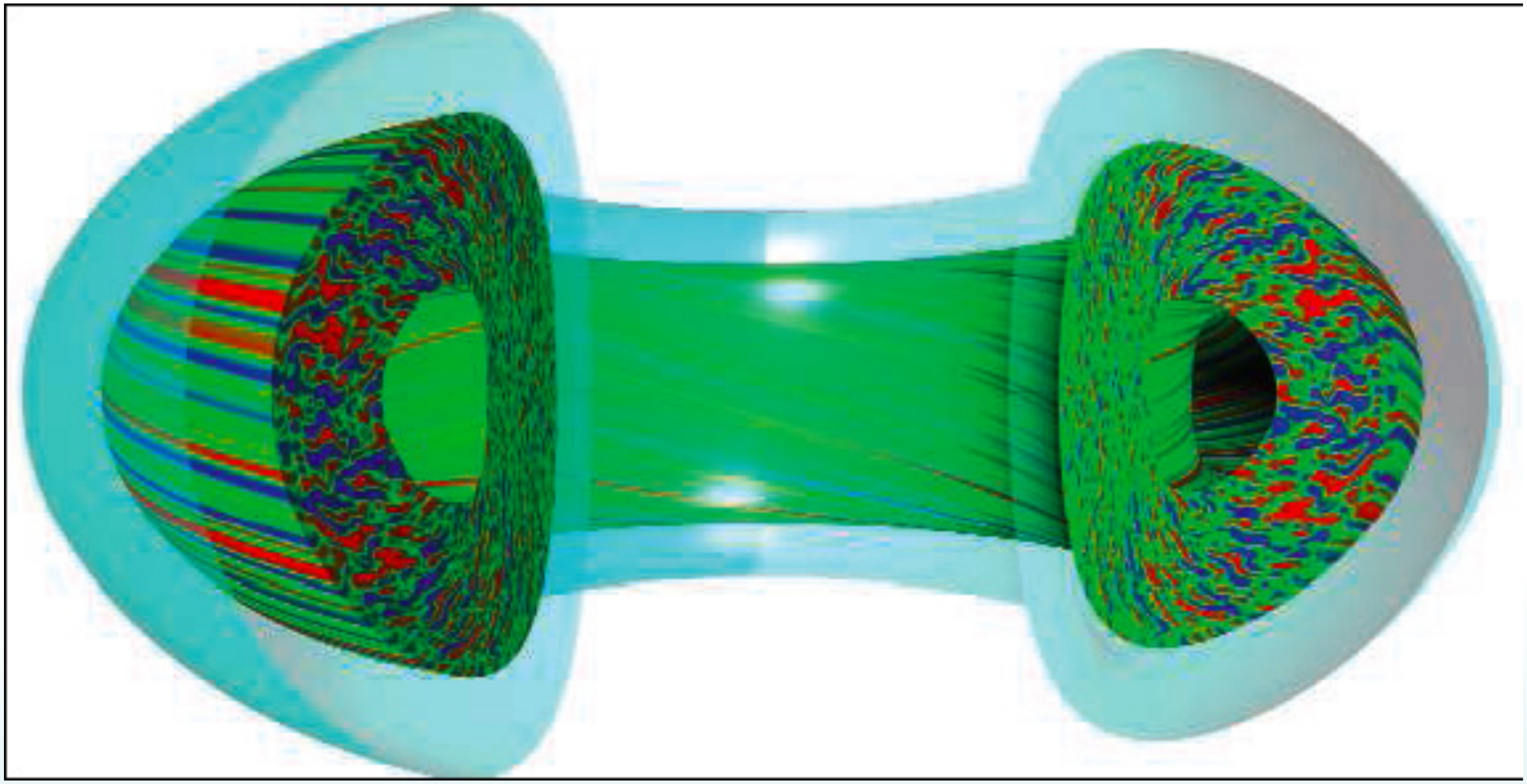
Pressure equilibrium at the outer boundary, r_2 ,
$P_2 = B_{\phi 2}^2 = B_{z2}^2$.

P_1 = expanding nebula pressure.



Tokamak, Tangled field Drift waves

Weakly tangled field allows run-aways to random-walk out of field.
Drift waves too weak for $\beta \sim 10^{-11}$; plasma = current carriers only, $n_e \sim 10^{15}$/cc



A new twist. Gyro-kinetic simulation of plasma density fluctuations in a shaped tokamak. Image shows a cut-away view of the density fluctuations (red/blue colors indicate positive/negative fluctuations). The blue halo is the last closed magnetic flux surface in the simulated tokamak. Krulsnick & Cowley, 2005,[11] Science 309, 1502

The Current-Carrier Starved Helix

A high temperature, 100 Mev, can support a plasma above a NS.

Matter will fall back until an electric field supports it against $g=10^{14}$ cm/s^2 (Starvation). $Ee = 10^{14} \times 1.6 \times 10^{-24}$; E= 100 volts/cm, or 100 Mev, produced by a trivial charge separation.

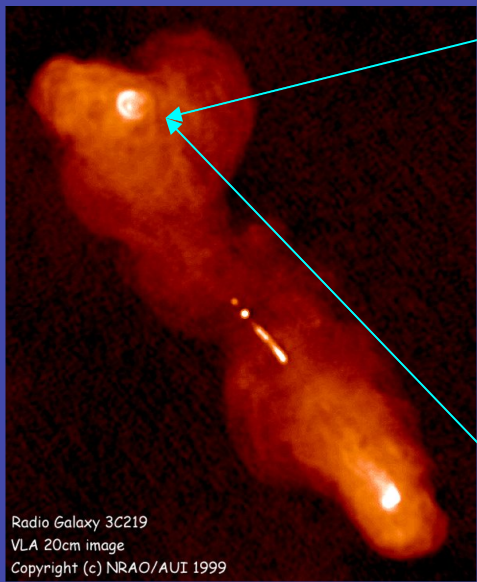
The inductive electric field due to a diffusion time of 2 years becomes: $E = L\,(dI/dt)$; $L = \sim 3\times10^{-8}$ henries/cm, $I = B\,5\,r_g$ = 1.5×10^{19} amperes, / $t = 6 \times 10^{7}$ s, = 7×10^{3} volts/cm.

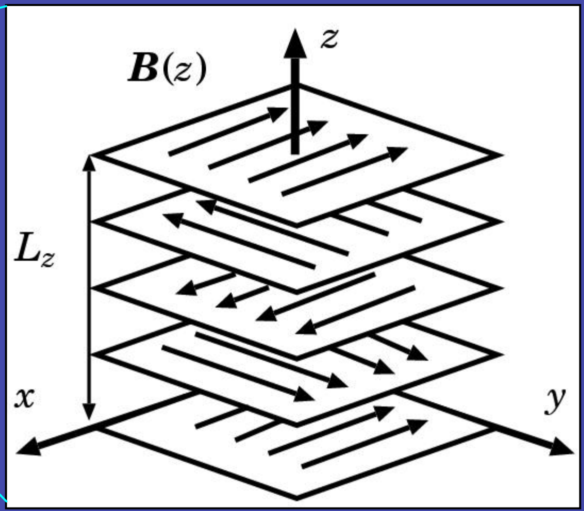
A voltage of $E\,L = 4.5 \times 10^{18}$ volts, enough for galactic cosmic rays.

Starvation of current carriers leads to drift velocity c.
$n_{e,i} = (I \times 6\times10^{18})/(\pi\, r^2\, c) = 10^{15}$ /cc.

How to find such a diffusion coefficient.?

An idealized Problem, helical shear





Sheet Pinch:

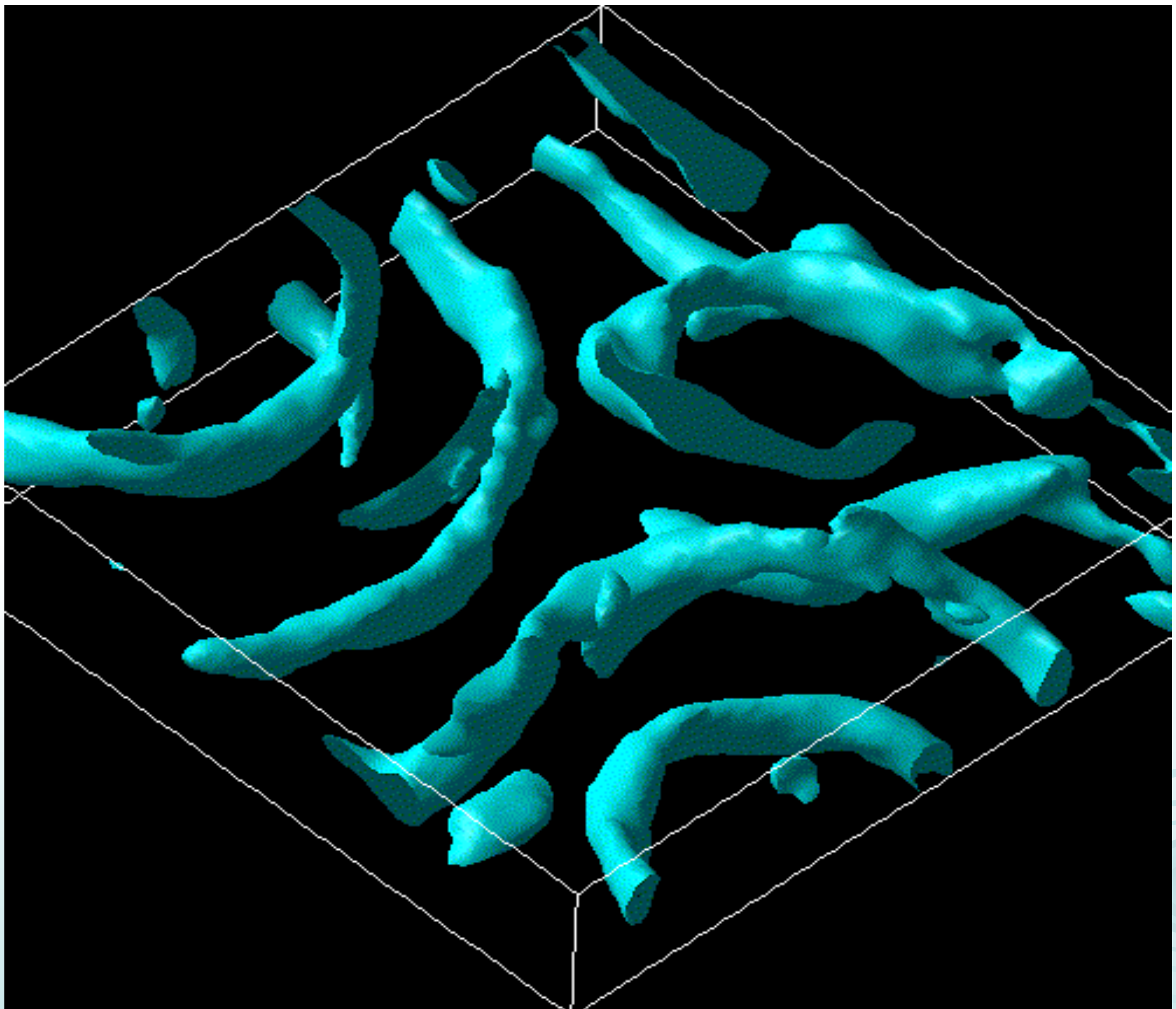
$$B_x(z) = B_0 \cos \alpha z$$
$$B_y(z) = B_0 \sin \alpha z$$
$$B_z(z) = 0$$

Sheet-pinch is force-free, with a constant, continuous shear.

Q: Is this sheet-pinch configuration stable? no
Q: If so, how does it convert B^2 into particle energy?

Li, H.; Nishimura, K.; Barnes, D. C.; Gary, S. P.; Colgate, S. A. 2003, Phys of Plamas, 7, 2763

Current Filaments on the scale of d_i the ion collisonless skin depth = c/ω_{pi}



Li et al. 03

$t\ \omega_{pi} = 8$

Current filament diffusion; at the collisionless skin depth

The currrent, J, supporting the sheared field is unstable to filamentation at a size $d_i = c/\omega_{pi}$, the ion collisionless skin depth, (distance of separation of electrons from ions in a magnetized plasma).

In the current carrier starved helix, $d_i = c/\omega_{pi} = c/(3\text{x}10^{11}\ \text{Hz}) = 0.1$ cm.

Run-away current carriers at velocity c follow tangled field lines of force out of, (into) the core, or plasma $\sim R_0$.

The random step size $\langle x \rangle = d_i\ (\Delta B/B)$.

$\Delta B = J\ (\pi\ d_i^2)\ /\ d_i = J\ (\pi\ d_i)$; and $B = I\ /5R_0 = J\ (\pi\ R_0^{\ 2})/5R_0$;

Hence $(\Delta B/B) = 5\ d_i\ /\ R_0 = 5\text{x}10^{-7}$;
And so the random step size $\langle x \rangle = 5\text{x}10^{-8}$ cm.

The Diffusion coefficient $\eta = c \langle x \rangle/3 = 500\ \text{cm}^2/\text{s}$.
The diffusion time or energy conversion time becomes $R_0^2\ /\eta = 2\text{x}10^8$ s = 6 years.

Conclusion

Magnetic flux is trapped during the stellar evolution leading to imbedded, compressed flux in the pre supernova star.

During the explosion hydrodynamic forces initially exceed Magnetic forces by many orders of magnitude and stretch this flux radially within and ahead of the SN ejecta.

We consider the result of differential winding, twisting of this trapped flux external to the NS.

We find that the total magnetic flux is increased by ~ x10^9 Before spin down limits twist.

The dissipation of this helical flux leads to acceleration through E parallel to J, of electron, ion, run-aways, non-thermal spectra, x-rays, gamma rays, and cosmic rays.