Torsional oscillation of highly magnetized new-born quark-stars as Gamma-Ray Burst Central Engine

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LONG GAMMA RAY BURSTS

Result from certain core-collapse Sne , i.e.

SNIc - BL (with broad lines spectral features)

Only a small fraction of all SNIc

$$E_{iso} = 10^{50} - 10^{54} \text{ ergs}$$

Emission certainly beamed, however

Duration : about a minute or more.

COLLAPSE CAUSES EMISSION OF AN HIGHLY RELAVISTIC JET

For GeV gamma rays to escape against $\gamma + \gamma \leftrightarrow e^+ + e^-$

$$\Gamma = 100 - 600$$

Implies very small baryonic pollution :

$\Gamma = 100$ impossible unless
rest mass energy flux / total energy flux
extremely small *

*** Paczinsky 1990 (APJ 363, 218)**

QUARK STARS CAN « SEPARATE LIGHT FROM MATTER »

Quark star model[*] attractive because baryonic pollution can be zero.

Wind from a q* entirely leptonic-radiative[†]

since baryons are so strongly bound to the quark matter

… We assume q* exist …

[*] **Haensel, Zdunik, Schaeffer 1986 AA 160, 121**

[†] **Haensel, Paczinski, Amsterdamski, 1991, APJ, 375, 209**

GRB's FROM
NEWLY BORN QUARK STARS ?

q* likely to be born from core-collapse SNIc though in possibly small proportion among SNIc's.

q* forms in collapse after a small delay.

Environment at scale 1000 km by then swept up from dense debris

- **GRB could be the external manifestation of the phase transition from nucleonic to strange quark matter**

- **Or could result from electromagnetic activity of fast spinning highly magnetized quark star**

Too much literature to quote !!

OUR CONTRIBUTION

Elaborate on electromagnetic activity resulting from internal differential rotation.

RELATED PREVIOUS IDEAS

- **Millisecond oblique rotator magnetars**

Usov (1992) Nature, 357, 472

- **Differentially rotating n* from WD collapse generates toroidal field of 10^{17} G, emerging episodically by buoyancy, then huge pulsar activity.**

Kluzniak & Ruderman (1998) APJ 505, L113
Ruderman, Tao, Kluzniak (2000) APJ 542, 243.

PERFECT MHD OR NOT ?

Well justified for ordinary quark matter or, if there is colour-superconductivity pairing, when electrons still present.

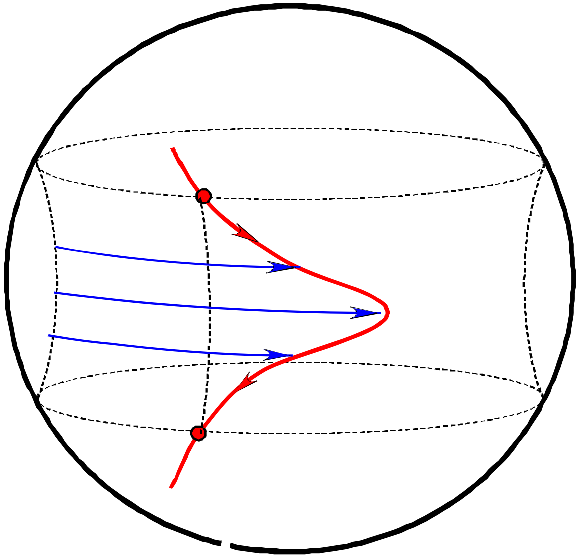
Quark matter is however isolating when there is stressed CFL pairing = quarks only *with* no electrons left, against natural β equilibrium

Stressed pairing arises if gain from the pairing exceeds penalty from the stressing.

Perfect MHD assumed

TORSIONAL OSCILLATIONS

Simulated collapse shows that a 3 ms rotator forms and ≈ 10% of energy in differential rotation *



Differential rotation develops in an alfvénic torsional oscillation **

Period : $P \approx 5 \text{ sec } (B_P / 10^{14})$

Ampl. : $B_\phi \approx 10^{16}$ G for $B_P = 10^{14}$ G

* Obergaulinger et al. (2006) AA 457, 209

Burrows et al. (2007) APJ, 664, 416

** Bonazzola, Villain, Bejger 2007, Class Quant. Grav, 24, S221

BUOYANCY INSTABILITY ?

If star is fully magnetized,

stable against buoyancy if B^{ext} increases with z fast enough.

If initially unstable, leads to marginal stability.

For isolated flux tubes, $\tau_{buoy} < P_{torsion}$

Unless quenched by frozen weak reactions among quarks *

$u + d \leftrightarrow s + u \qquad d \leftrightarrow u + e$

which keep the unequilibrated medium « heavier »

Quenching is effective when gap $\Delta > 14$ MeV and $m_s c^2 > 38$ MeV

Flux brought to the surface does not « escape »

*** Haensel and Zdunik (2007) Nuovo Cimento 121 B, 1349 . Thanks due to L. Zdunik.**

MODULATION OF PULSAR WIND BY TORSIONAL OSCILLATION

Wind is emitted by fast-spinning star and quasistatically modulated if torsional oscillation

Modulation of wind negligible for even torsional oscillations on an even magnetic structure ...

But the star may suffer odd oscillations or the magnetic configuration could be North/South asymmetrical

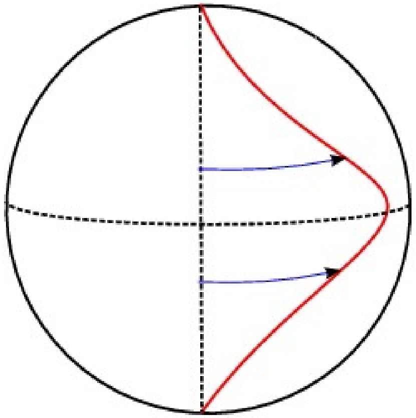
ODD TORSION MODES COULD BE EXCITED

Torsional modes of even parity favoured but not exclusive.

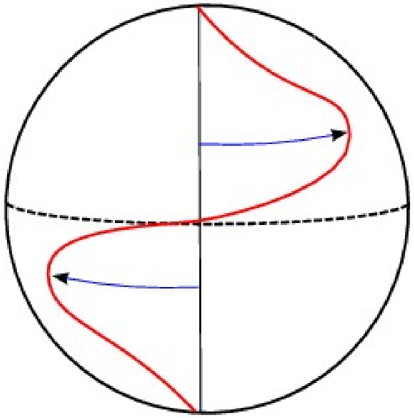
If only « even » collapse n* would not receive a « kick » of 200-500 km/s,

which is about **10^{-3} – 10^{-4}** of momentum ejected from SN

A similar fraction of the energy might go into odd modes



Even



Odd

WHEN TWIST LARGER THAN π
THE MAGNETOSPHERE BREAKS OPEN.

Odd oscillation OR

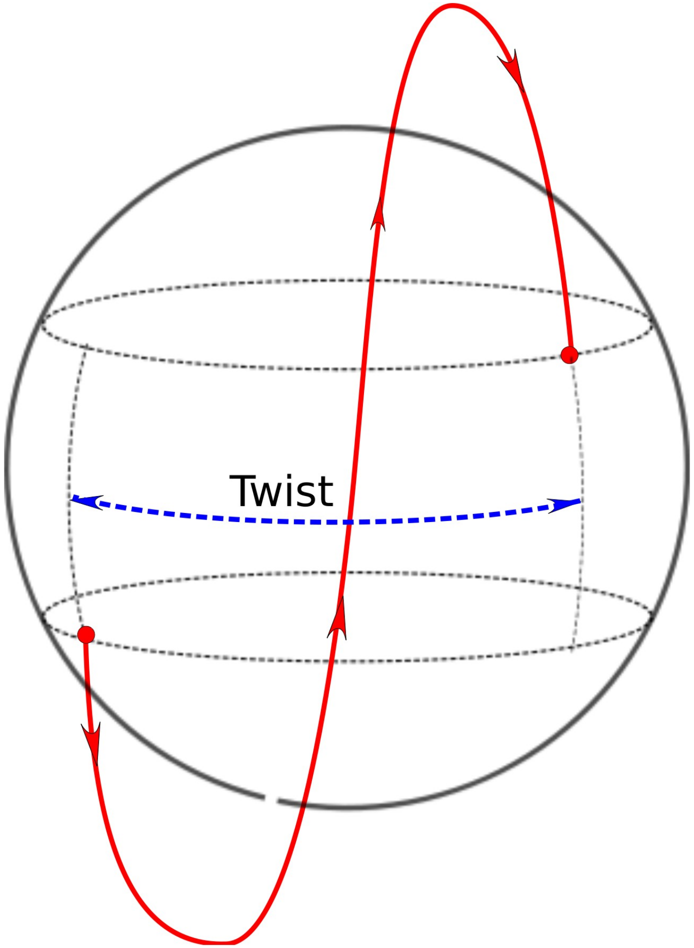
Different latitudes of foot points

causes « twisting »

of magnetospheric field lines.

Induces electric current, which deforms magnetosphere and...

… blows it open when twist exceeds a threshold of about π *



*** i.e. Wolfson, 1995, APJ 443, 810**

FIELD OPENING IS EASY !

Magnetosphere opens under odd modes as soon as

$\sin \Omega_T t > 10^{-2}\ (P^*/1\ \mathrm{ms})\ (10\ \mathrm{s}\ /\ P_T)\ (\ \alpha_{odd}\ /\ 10^{-4})^{-1/2}$

Magnetosphere does not open at all only if $\alpha_{odd} < 10^{-8}$

Magnetosphere opens because of asymmetrical N/S magnetic structure if

$\delta\theta_{foot\ points} > (\pi/2)\ 10^{-4}\ (P^*/1\ \mathrm{ms})\ (10\mathrm{s}\ /\ P_T)\ (\ \alpha_{even}\ /\ 10^{-1})^{-1/2}$

Dipole off-centered by $10^{-3}\ R_*$ is enough

CONSEQUENCES OF MAGNETOSHERIC BLOW UP

When in « closed » state,

pulsar wind + Poynting power from polar caps

$$P_{closed} = B_p^2 R_*^6 \Omega_*^4 / 4 c^3$$

When in open state,

pulsar wind + Poynting power from all star surface

$$P_{open} = 2 B_p^2 R_*^4 \Omega_*^2 / 15 c \approx 100 P_{closed}$$

For 3. 10^{14} G and 3 millisec rotation

$$P_{open} \approx 1.7\ 10^{48} \text{ erg s}^{-1}$$

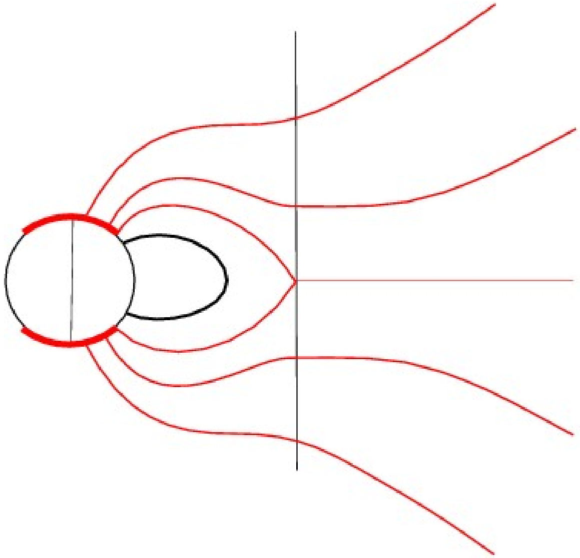
Poynting flux drives a centrifugally-driven

leptonic wind,

which Lorentz force

will focus into a jet

at large distances.

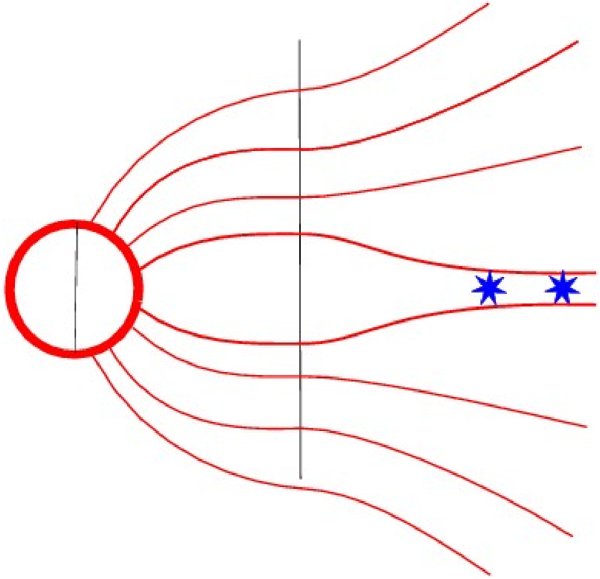


Episodic reconnection in

equatorial plane

and immediate re-openings

causes large variability.



DURATION OF HIGH EPISODE

Large Poynting power losses
damp global rotation $\Omega_*(t)$
and differential rotation $\delta\Omega_*(t)$.

Characteristic time scale is :

$$\tau = 3\,c\,I_* / (B_P^2 R_*^4) \sim 150 \text{ sec } (B_P/10^{14})^{-2}$$

The « high » event ceases when differential rotation becomes too weak to open magnetosphere
By then, rotation period ~ 5-10 millisec

TO SUM UP :

q* hypothesis, but

No need of emerged 10^{17}G fields to get high enough luminosity.

$B_P = 3\ 10^{14}$ to $3\ 10^{15}$ G is enough.

Magnetosphere opens for very small asymmetry,

very small odd mode amplitude

or very small asymmetry of magnetic field.

Time scale satisfactory : Relatively short duration event

Fluctuating output

Fluctuations on all time scales built-in,

from millisec. (reconnection) to seconds (cycle open/closed)

Similarities to Ruderman et al. (2000), but cause of episodic activity different.

THANKS

SUPPLEMENTS

ENERGETICS

$$E_{iso} = 10^{50} - 10^{54}\ \text{ergs}$$

Emission certainly beamed, however

Long burst duration :
from a few seconds
to minutes or more.

COLLAPSE CAUSES EMISSION OF AN HIGHLY RELAVISTIC JET

For GeV gamma rays to escape against $\gamma + \gamma \leftrightarrow e^+ + e^-$

$$\Gamma > 100 - 600$$

600 infered from observations in some well studied cases *, by demanding $\tau_{\gamma\gamma} < 1$.

*** Abdo et al. , the Fermi LAT collab. (2009) Science, 323 1688**

VERY SMALL BARYONIC POLLUTION IS NEEDED

$\Gamma = 100$

impossible unless

rest mass energy flux / total energy flux

extremely small *

Total wind baryon load should be less than $10^{-5}\,M_{sun}$

* Paczinsky 1990 (APJ 363, 218)

PERFECT MHD OR NOT ?

Well justified for ordinary quark matter or, if there is colour-superconductivity pairing, when electrons still present.

Quark matter is however isolating when there is stressed CFL pairing = quarks only *with* no electrons left, against natural β equilibrium

Stressed pairing arises if gain from the pairing exceeds penalty from the stressing. Mass of s-quark is too small to enforce presence of electrons against the gap approx. when*:

$$m_s^2 c^4 / 4 \langle\mu\rangle < \Delta$$

Perfect MHD assumed

*** Rajagopal Wilczek (2001), Phys Rev Lett, 86, 3492**
***Alford, Schmitt, Rajagopal, Schaeffer Rev Mod Phys 2009**

WHAT IS A GAMMA RAY BURST?

A short, strong γ ray emission ($\tau = 10^{-3} - 10^{3}$ s.)

Hard X – MeV gammas (sometimes to GeV's)

About one per day @ present sensitivity

Initially, no obvious counterpart seen, but…

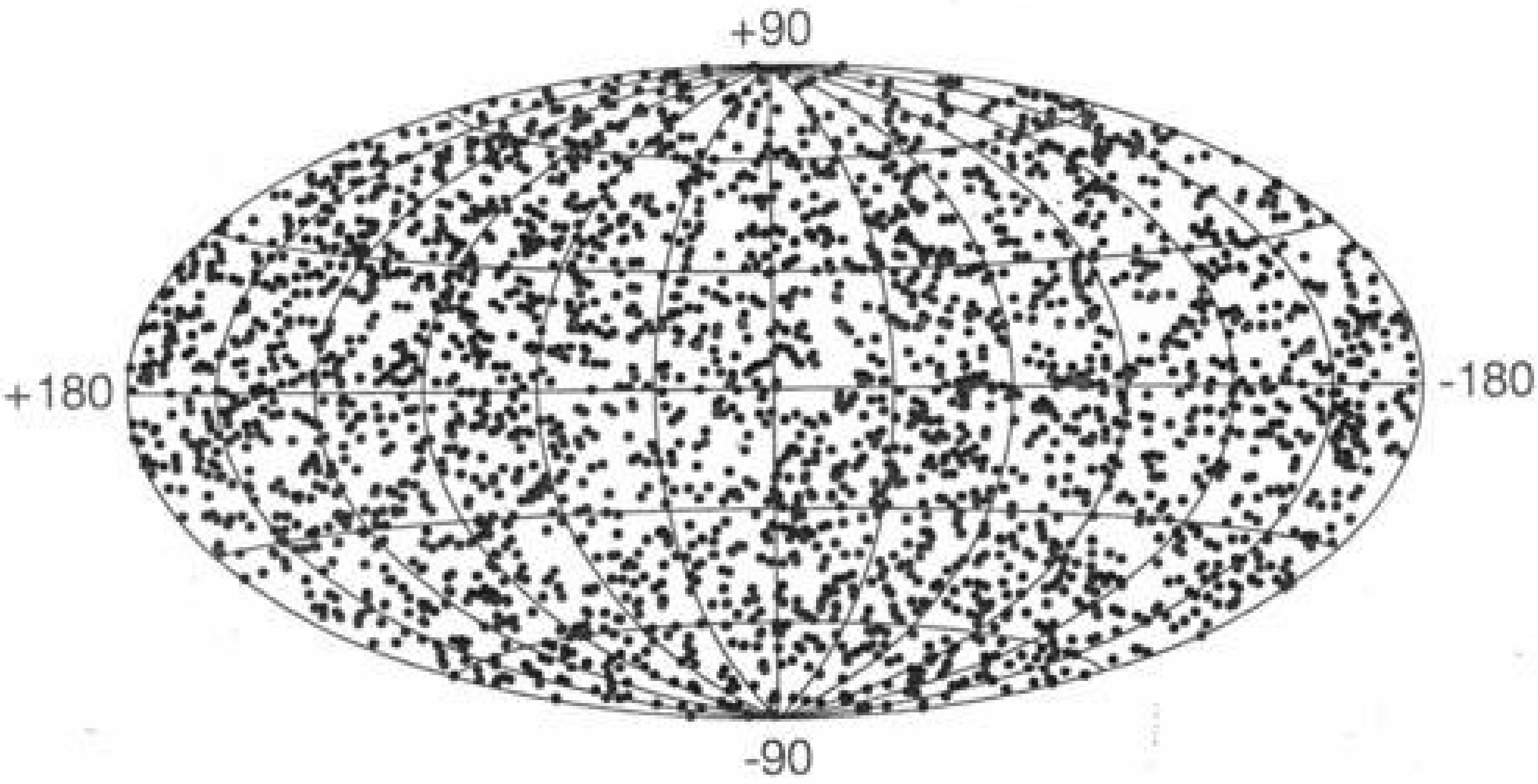
except March 5th 1979 in 30 Doradus in LMC

No recurence, except a few remarkable and exceptional ones

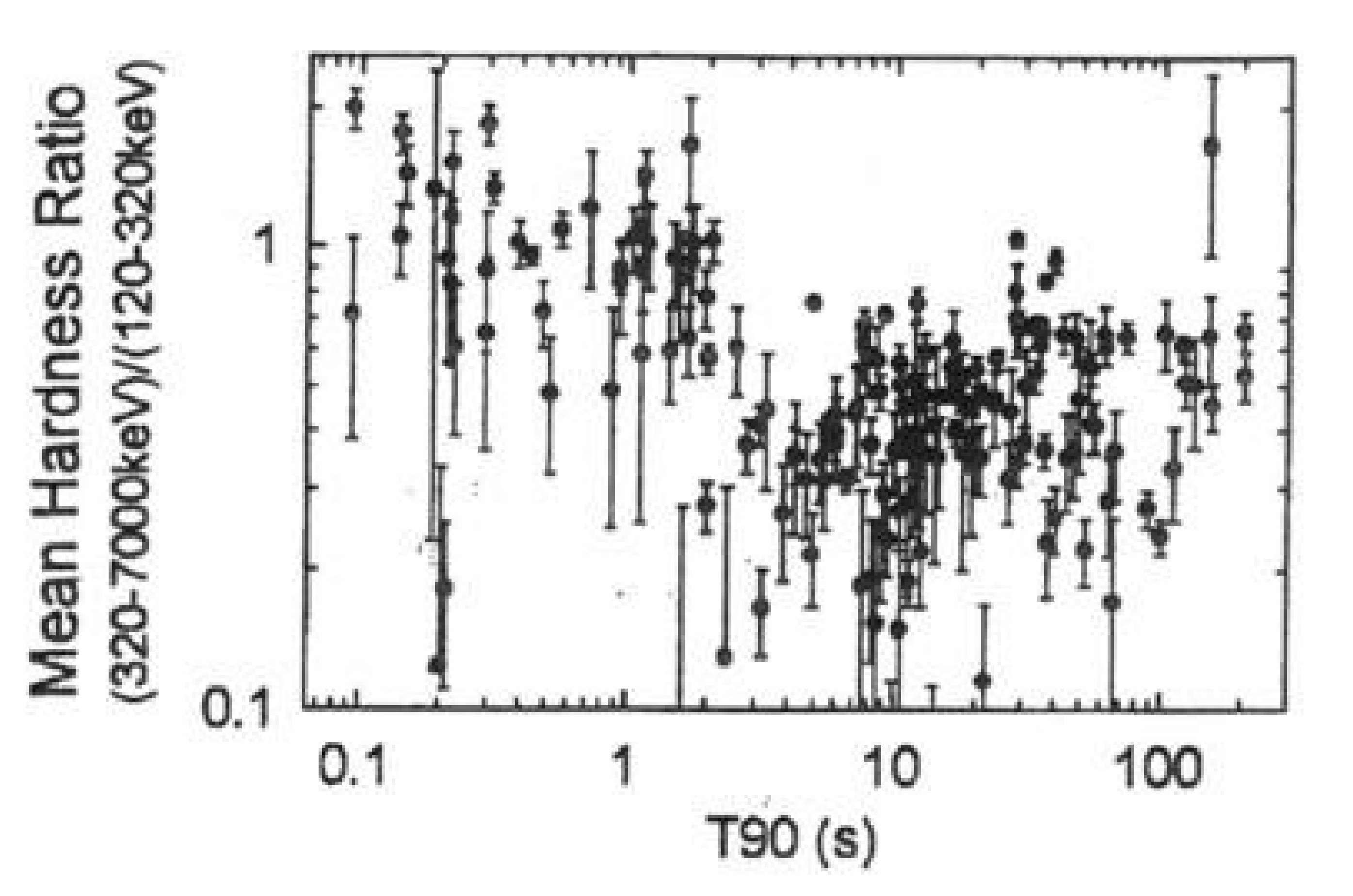
WHERE ARE GAMMA RAY BURSTS?

BATSE: ISOTROPIC DISTRIBUTION

⇒ @ **Cosmological distances** !!

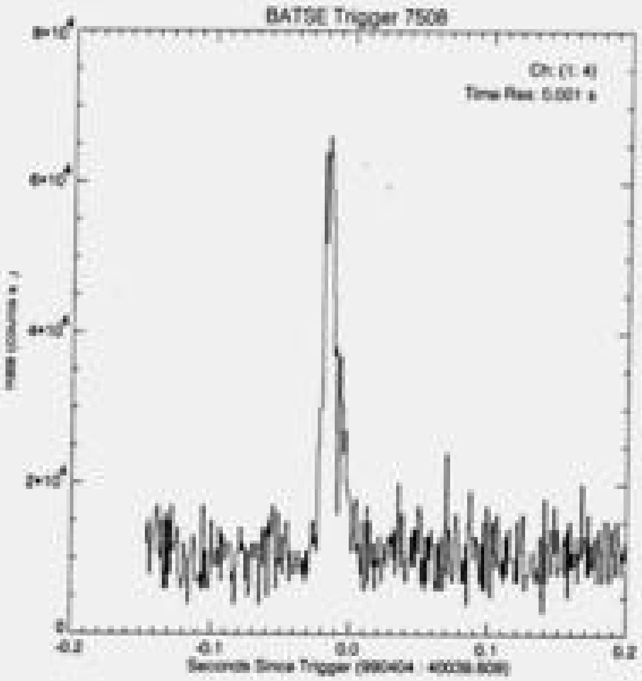


LONG AND SHORT BURSTS

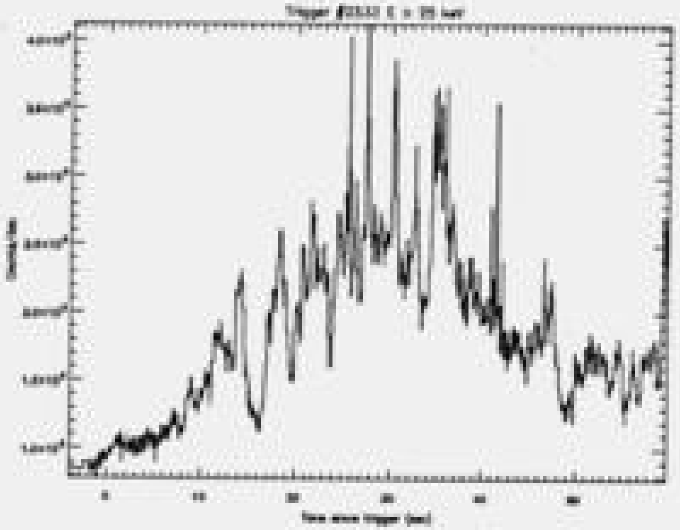


∃ 3d class : Soft Gamma ray Repeaters (galactic)

SHORT AND LONG
GAMMA RAY BURST LIGHT CURVES



1 graduation = 0.01 sec



1 graduation = 1 sec

THE FIRST OPTICAL «AFTERGLOW»

08 May 1997 : GRB 970508 (a 15 s one)

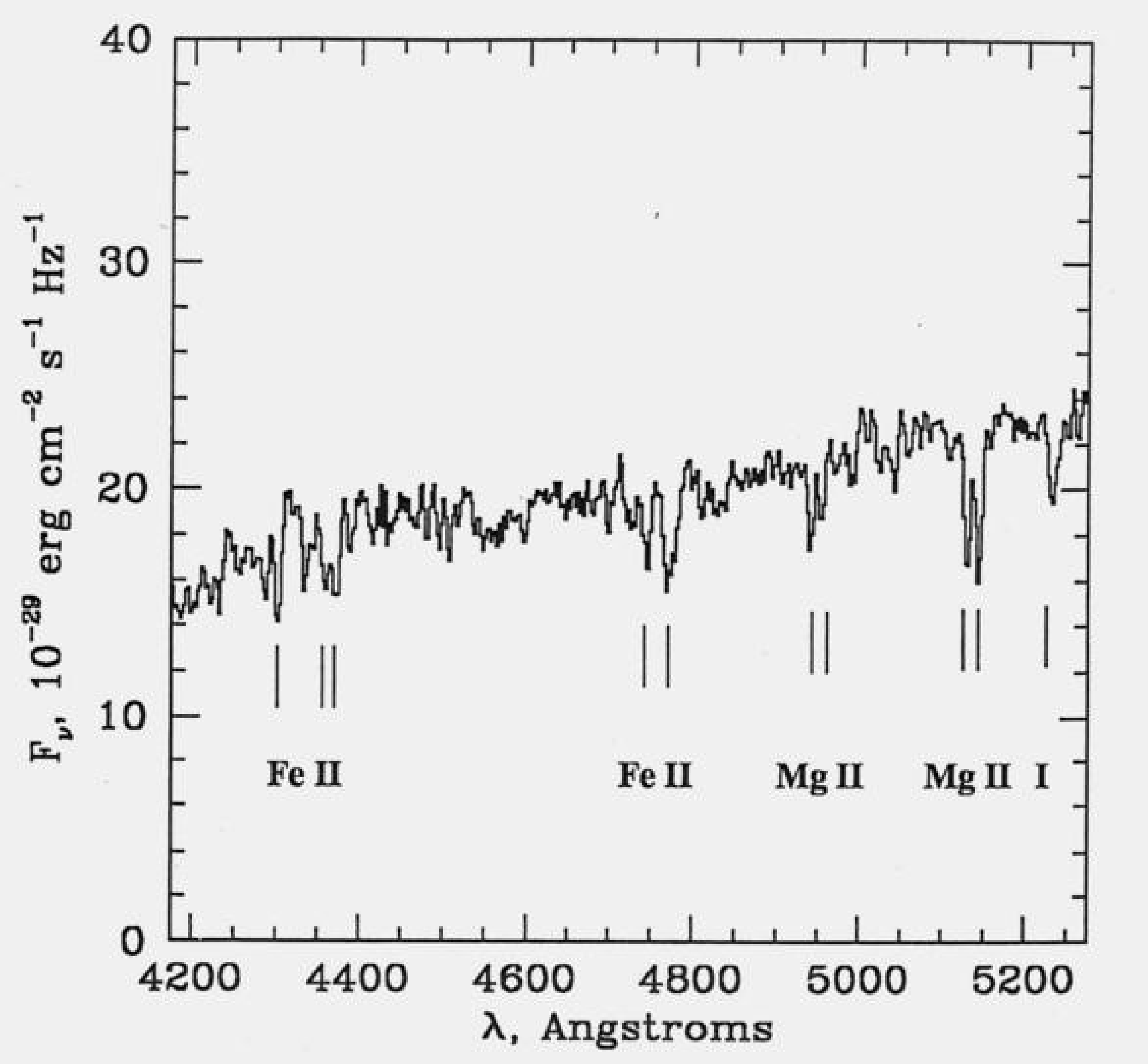
X COUNTERPART IN REAL TIME
BY BEPPO SAX

OPTICAL OBSERVATIONS FEW HOURS AFTER
OPTICAL COUNTERPART « AFTERGLOW » SEEN FOR 5 DAYS
Maximum on May 10th, Declines as 1/t .

KECK SPECTRUM ON MAY 11th ⇒

FE II AND MG II ABSORPTION
SYSTEMS @ Z = 0.835!!
In a star-forming Dwarf Galaxy at D > 3.5 Gpc

If isotropic emission $E = 7\ 10^{51}$ ergs emitted


F_ν, 10^{-29} erg cm^{-2} s^{-1} Hz^{-1}
0
10
20
30
40
4200
4400
4600
4800
5000
5200
λ, Angstroms
Fe II
Fe II
Mg II
Mg II
I

MORE COUNTERPARTS

BEPPO-SAX:

About 40 X-optical-radio afterglows observed in 2 years

$Z = 0.4 - 4.5$

All in the «long» class and in Dwarf Galaxies

SWIFT :

About 50 redshifts determined (as by Jan 2006)

Highest $Z = 6.29$ (GRB 050904)

Counterpart of short bursts : @ edge of
an old, red host galaxy. Not in star forming regions.
Not really at cosmological distances ($Z < 1$)

THE JET PARADYGM

It is believed that the collapse eventually causes the emission of a very relativistic jet.

Bulk motions of very high Lorentz factors are needed
to allow the escape of high energy gamma rays
from the very luminous gamma-ray environment of the burst
against $\gamma + \gamma \leftrightarrow e^+ + e^-$
Otherwise huge opacity

$\Gamma > 600$
Have been infered in some well studied cases, demanding that $\tau_{\gamma\gamma} < 1$.

Opacity for $\gamma + \gamma \leftrightarrow e^+ + e^-$ huge
if the source is at rest:

$$\tau_{\gamma\gamma} = n_\gamma \sigma_T R = (L_\gamma / 4\pi R^2 h\nu c)\, \sigma_T R \approx \mathbf{10^{14}\,!!}$$

Initially : very opaque hot fireball
with little radiation through gamma-ray photosphere.
Starts to expand relativistically ≈ adiabatic (4/3)

FIREBALL EXPANDS RELATIVISTICALLY..

… pushed by huge radiation pressure in it .

$\tau_{\gamma\gamma}$ **in the relativist. expanding wind is much less than at rest because**….

a- **Energy of each photon is less in the matter's rest frame by the Lorentz** γ **and the fraction of photons able to create pairs is less** (by a factor which depends on the slope -s of the photon spectrum)

b- **The apparent variability time in lab frame is longer than variability time** t_{var} **in the frame of the moving matter by** γ

Altogether the optical thickness of the moving source is $\gamma^{(2s+2)}$ **smaller.**

$\Rightarrow$ For it to become γ–ray transparent,
$\Rightarrow \gamma = 100$ needed.

Models not explicitly based on the fireball idea also involve relativistic winds, with similar γ's.

Fireball expands relativistically pushed by huge radiation pressure in it .

$\tau_{\gamma\gamma}$ in the relativistic expanding wind

is much less than at rest

For it to become gamma–ray transparent,

$\gamma = 100$ needed.

Models not explicitly based

on the fireball idea

also involve relativistic winds,

with similar γ‘s.

HIGH LORENTZ FACTORS INVOLVED

Strong beaming of the emission required for the energy emitted in gamma rays to always be < $M_{sun}c^2$

If not, any « stellar » model of GRB should be rejected.

Jet opening angle can be indirectly inferred from the **rate of decline in time of the afterglow emission.**

Jet opening angle ≈ 5°- 20°

Equals Doppler boosting angle at that time, giving $\gamma \approx 20$ at that stage

Points to $\gamma \approx 100$ at the base of the wind.

Strong beaming of the emission is required for energy emitted in γ rays to remain < $M_{sun}\ c^2$

Doppler beaming angle during the afterglow can be infered from the rate of decline in time of the emission. The afterglow emission comes from the shock surface running towards the observer at relativistic speed. When the Lorentz factor is still very high the observer only sees a part of that surface, due to the smallness of the relativistic angular beam of emission. When the Lorentz factor decreases, this observable surface increases and eventually covers all the emitting surface. The transition from one to the other regime is observed as a change in the time decline of the intensity of the afterglow emission, which can be used to infer the opening angle of the jet, which is found to be of order of 5°, which corresponds, at the time when the afterglow changes its rate of temporal decline, to $\gamma = 20$. This points to higher Γ at the origin of the wind.

VERY SMALL BARYONIC POLLUTION IS NEEDED

High Γ impossible unless mass flux/energy flux very small

Very super-Eddington winds from n* calculated * as a function of rest mass loss rate $M'c^2$ and injected power L_{in} show that

Γ=100 only reached when $L_{in} > 100\ M'c^2$

Total wind baryon load should be less than $10^{-5}\ M_{sun}$

Bucciantini et al. (MNRAS **368** 1717) consider centrifugally driven radial relativistic magnetized MHD winds.

In ultra relativistic limit, terminal γ is

$$\gamma_\infty = (\Phi^2 \, \Omega^2 / \; M' c^3)^{1/3}$$

γ_∞ **= 100 for a 3 millisec rotator needs baryon density**

$$n_p < 4 \;\; 10^{23} \text{ cm}^{-3} B_{14}{}^2$$

at the base of the wind. The lepton density in a pair-creating fireball (at $T \geq 10^9$ K, say) is $\leq$ $\mathbf{n_{lept} = bT^3 = 1.5 \; 10^{28} \; cm^{-3}}$

In our model there is no base fireball, but electron density is a (small) fraction of that in quark matter (**3.10**^{33} **cm**$^{-3}$ for a mass of the s-quark of 100 MeV).

CENTRAL ENGINE = QUARK STAR?

Phase transition from nucleonic to strange quark matter ?

Cheng & Dai (1996) : **Conversion of n* to q* caused by accretion**

Bombaci & Datta (2000) : **Conversion of n* to q***

Wang, et al. (2000): **Conversion of a rapidly spinning n* into q* by spin down**

Lugones, G. Dal Pino et al (2002): **Anisotropic deflagration in presence of B fields** when normal matter converted to strange matter. Strong anisotropy drives a jet-like neutrino outflow in polar directions wich generates a leptonic jet..

Ouyed, Dey & Dey (2002) : **Quark Novae**: Transition to strange u,d,s matter as a result of the collapse of a n* core. Free fall of « envelope » causes the release of the binding energy to the strange quark matter state. Quark Nova ejecta ramming in SN ejecta cause GRB.

ABOUT VERY DENSE MATTER

Nature of the matter changes with increasing density :

Ordinary nuclei

Neutron-enriched nuclei

Mainly free neutrons, neutronized by reaction in equilibrium

$$n \Leftrightarrow p + e + \text{anti } \nu_e$$

Muons partially replace electrons by

$$e \Leftrightarrow \mu + \nu_e + \text{anti } \nu_\mu$$

Negative hyperons replace leptons (deleptonisation) by e.g.

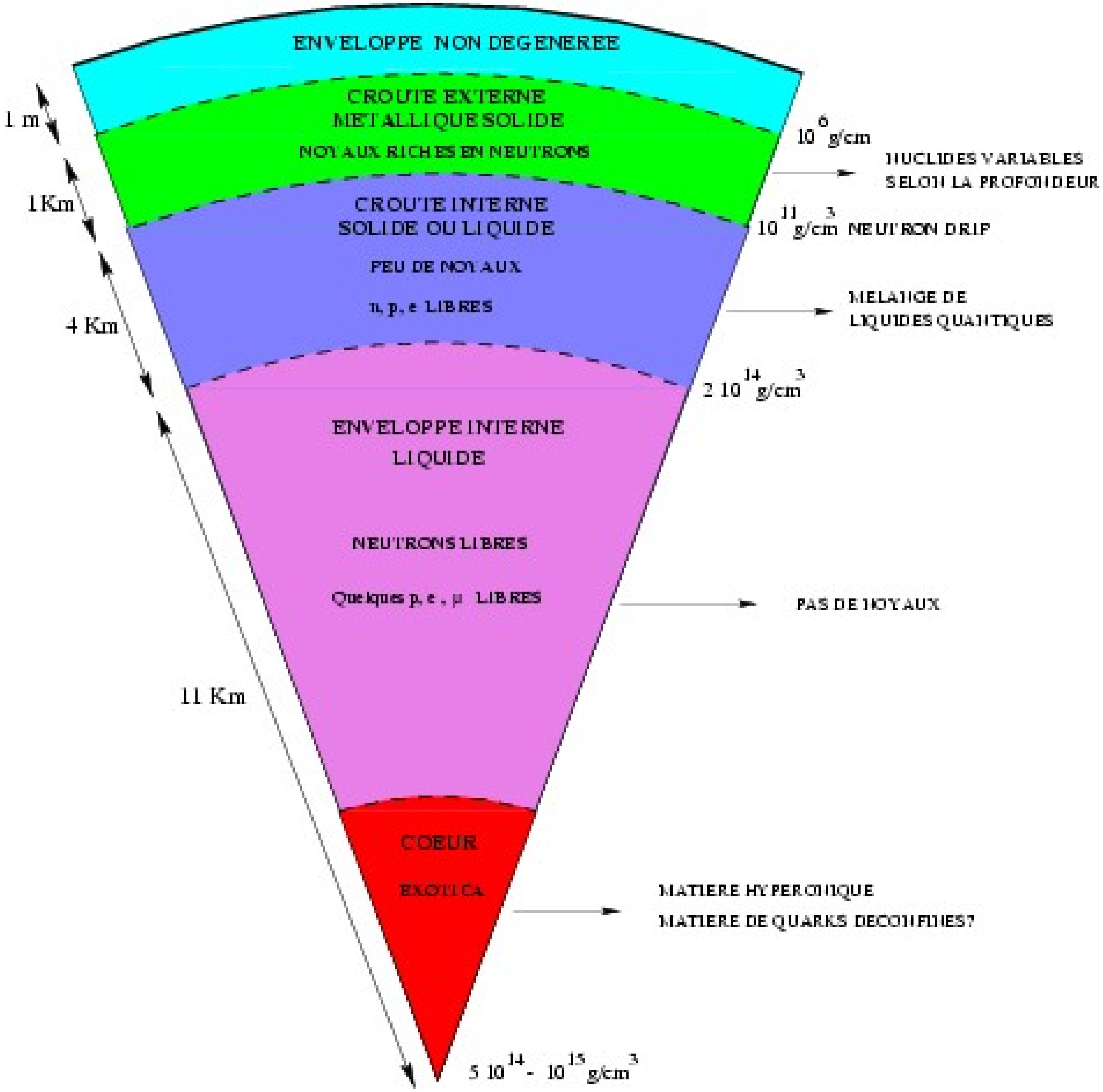
$$n + e \Leftrightarrow \Sigma^- + \nu_e$$

Négative mésons may appear by

$$n \Leftrightarrow p + \pi^-$$

Λ_0 hyperons partially replace neutrons (hypéronisation) by

$$n + p \Leftrightarrow p + \Lambda_0$$


ENVELOPPE NON DEGENEREE
CROUTE EXTERNE
METALLIQUE SOLIDE
NOYAUX RICHES EN NEUTRONS
CROUTE INTERNE
SOLIDE OU LIQUIDE
PEU DE NOYAUX
n, p, e LIBRES
ENVELOPPE INTERNE
LIQUIDE
NEUTRONS LIBRES
Quelques p, e , µ LIBRES
COEUR
EXOTICA
1 m
1 Km
4 Km
11 Km
10^6 g/cm
NUCLIDES VARIABLES
SELON LA PROFONDEUR
10^11 g/cm^3 NEUTRON DRIP
MELANGE DE
LIQUIDES QUANTIQUES
2 10^14 g/cm^3
PAS DE NOYAUX
MATIERE HYPERONIQUE
MATIERE DE QUARKS DECONFINES?
5 10^14 - 10^15 g/cm^3

QUARKS

Particles consist of 3q (baryons) or q+ anti q (mésons)

Quarks are characterized

by « flavour » **u, d, s, c, t, b**

and « colour » **R, B, G** Existing (observed) particles are « white »

They have fractional elementary charge

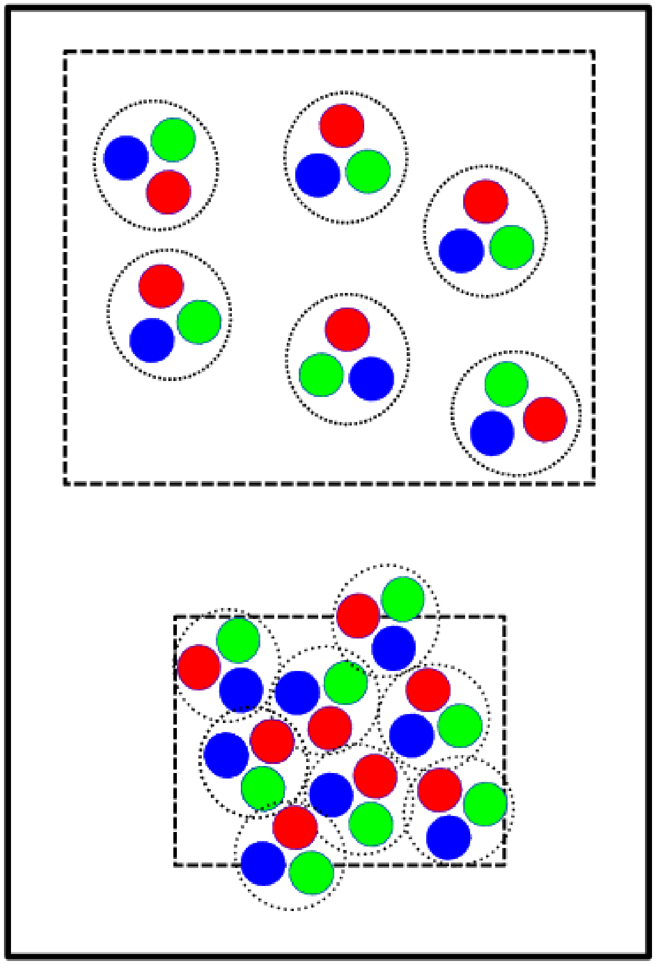
u = + 2/3 d = -1/3 s = -1/3

The s-quark has strangeness -1

Quarks enjoy « asymptotic freedom »

But this really happens only at densities much marger than the nuclear density

STRANGE QUARK MATTER



Quark deconfinement:

$\Rightarrow$ **strange quark matter**

Proportion of quarks of different flavours adapts by equilibrium of reactions such as :

$$u + e \Leftrightarrow d + \nu_e$$
$$u + e \Leftrightarrow s + \nu_e$$
$$u + d \Leftrightarrow s + u$$

For massless quarks, solution is no leptons, equal numbers of u, d, s. Ensures electric neutrality !

If $m_s \neq 0$, electrons are present.

MIT BAG MODEL

Quarks, confined or not, assumed to live free and UR (all 3 flavours) in bags, the volume of which may change with pressure. Mutual attraction represented by fictitious (constant) « bag pressure » B exerted by the outside on the inside of bags :

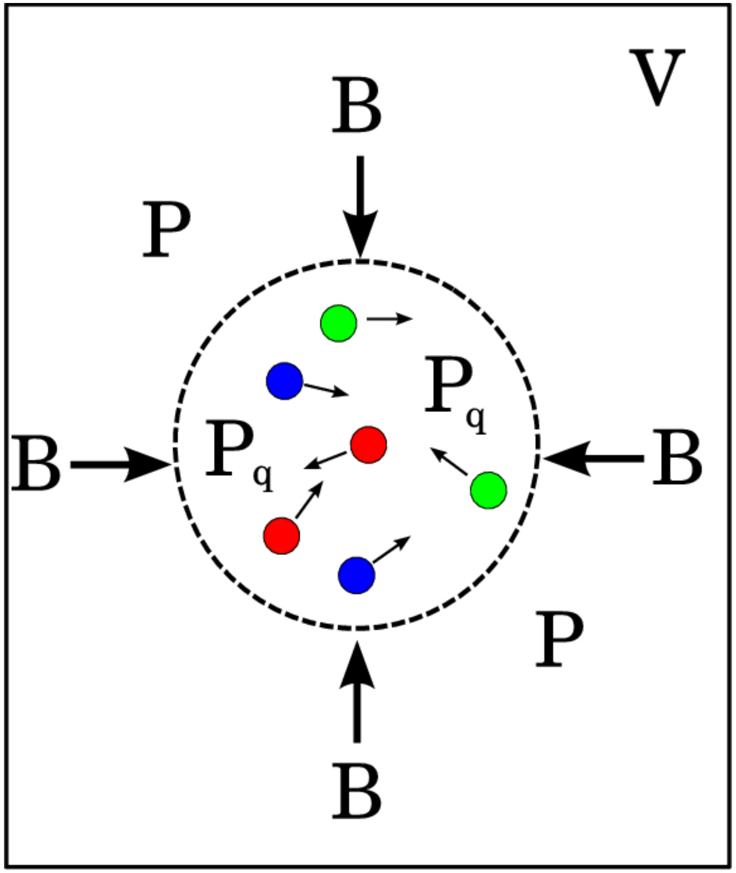
$$\mathbf{P + B = P_q}$$

When volume of all system changes by dV

$$dU = - P\, dV = - (P_q – B)\, dV = dE_q + B\, dV$$

$$\Rightarrow\ U = E_q + BV\ \Rightarrow\ \boldsymbol{\varepsilon = 3P_q + B}$$

$$\Rightarrow \varepsilon = 3P + 4B$$



QUARK STARS

Not known whether central regions of n* consist of quark matter.
Transition possible only at $\rho_c > 6 - 9\ \rho_0$ (ρ_0 = nuclear density)

If yes, $\exists$ hybrid neutron-quark stars.

Nucleonic cold matter at zero pressure has $\varepsilon_{nucl} \approx \rho_0 c^2$

with $\rho_0 = 2.8\ 10^{14}$ g/cm^3

Quark cold matter at zero pressure has $\varepsilon_{quark} \approx 4\ B$

If $4B < \rho_0 c^2$, quark matter more bound than nucleonic matter ! Happens if B < 40 MeV fm^{-3}

If yes, must $\exists$ quark-stars
(fully made of strange quark matter from surface to center).

GRB POWERED BY (DIFFERENTIAL) ROTATION ?

Rotation and/or differential rotation?

Usov (1992) : **Millisecond magnetars (oblique rotators)**

Kluzniak & Ruderman (1998) : Differentially rotating n* generates toroidal field of 10^{17} G emerging out episodically by buoyancy.

Dai & Lu (1998) : Diff. rot. in quark star generates 10^{17} G toroidal field and causes flux emergence and associated fireball, then millisec. pulsar activity.

Spruit 1999:

n* spun up by accr. develops diff. rotation from an r-mode instability.
Generates 10^{16}- 10^{17} Gauss toroidal magnetic field by winding up in a few months.
Then buoyancy causes situation similar to Ruderman et al. above.

Ruderman et al. (2000) : Collapse of accr. magn. WD to diff. rotating n*
Diff. rotation generates 10^{17} G toroidal fields, which emerges by buoyancy to generate huge pulsar activity. Diff. rotation and flux emergence opens and closes the doors for bursts of powerful episodic pulsar winds.

DAMPING BY BULKVISCOSITY ?

Even the quark superfluid suffers « bulk viscosity », due to **finite time it takes to restaure equilibrium of reactions** such as:

$$\mathbf{u + d \Leftrightarrow s + u}$$

The torsional wave is linearly incompressible, but a small compression results from non-linear effects.

The damping time which results from this NL compression has been shown to be **of order 10^{10} sec.**

EMISSION OF A LOW-FREQUENCY ELECTROMAGNETIC WAVE BY TORSIONAL OSCILLATION ?

We calculate **electromagnetic emission in vacuo** generated by the torsional oscillation. The BC is continuity of E_θ.

Inside the star $E_\theta = - v_\phi x B_r$.

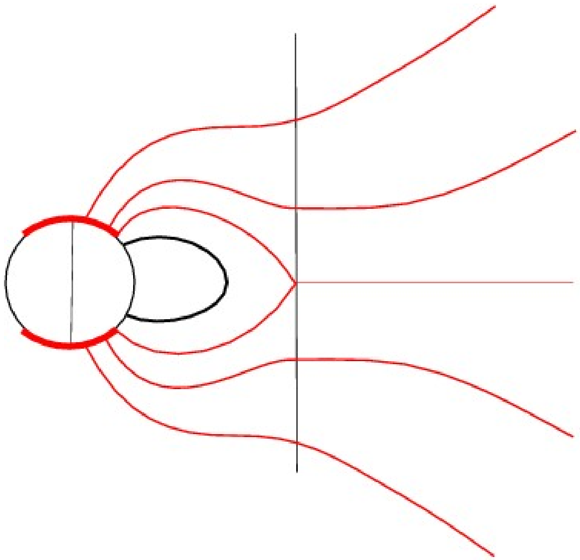
A very weak radiative Poynting flux results because

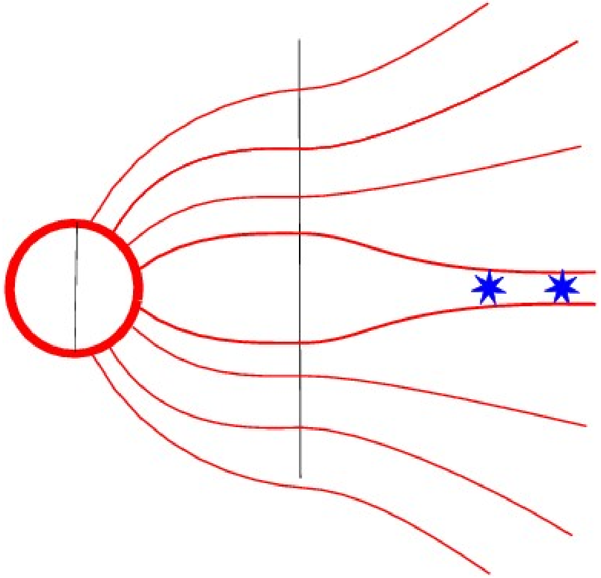
Low frequency of the wave.

Impedance mismatch between the inside and the outside of star

Quadrupolar character of the emission.

Same if emission takes place in an expanding, resistive, spherical, relativistic leptonic wind with a toroidal field.





For open magnetosphere, these equations are:

$$d\Omega_*/dt = -\,(1/15)\,[B_p{}^2 R_*{}^4/cI_*]\ \ \Omega_*$$

$$d^2y/dt^2\ +\ (4/21)\,[B_p{}^2 R_*{}^4/\,cI_*]\ \ dy/dt\ +\ \Omega_T{}^2\, y = 0$$

The emitted Poynting power declines on a time scale

$$t_d = (15/2)\,(cI_* / B_p{}^2 R_*{}^4) = 2\ 10^4\ \mathrm{sec}\ (I_{45}\, B_{p14}{}^{-2}\, R_{10}{}^{-4})$$

Matches duration of long bursts for
B = 3 10^{14}G to several 10^{15} G.

Intense energy shedding stops when the
amplitude of odd oscillation becomes unable to open the magnetosph.
Star has by then lost almost all of its rotational energy
and has been slowed down
to about 5-10 milliseconds period (for B = 3 10^{14} G)
It then becomes an ordinary (unvisible) pulsar