



IMPRS Retreat 2011

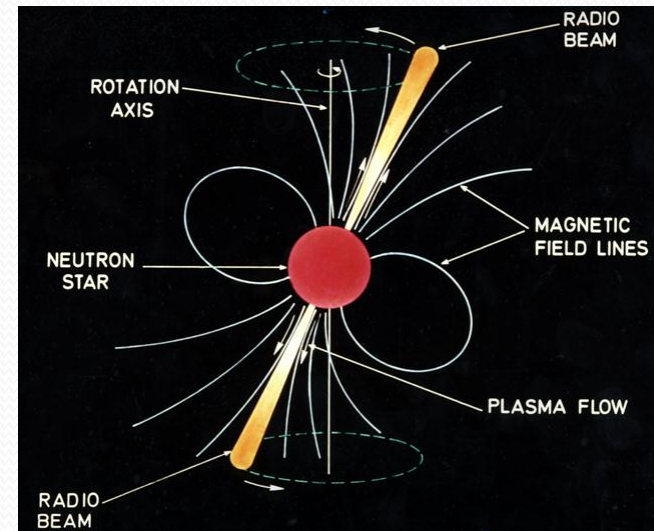
Astro-particles III.

Astro-particles & Pulsars

Cherry Ng
26th October, 2011

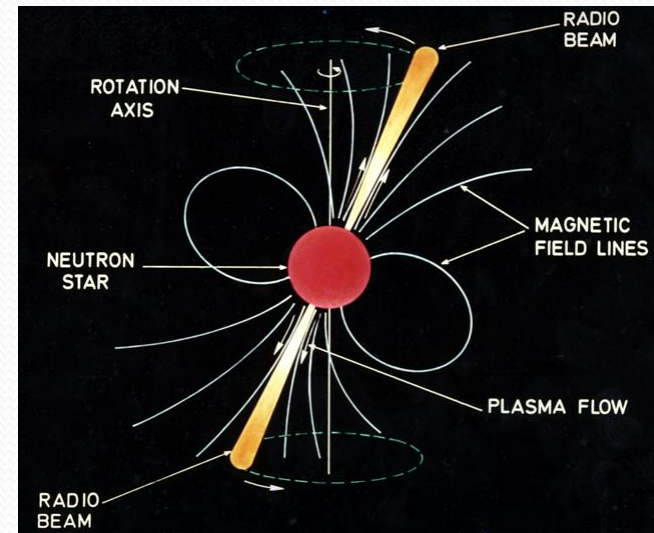
Pulsars, more than just radio pulsation...

- Enormous magnetic fields ($> 10^{20}$ G)
- High rotation rates
- -> powerful unipolar generators
- Charges stripped off highly-conductive surface
- accelerated above stellar surface
- Along B-field lines \rightarrow emit curvature radiation
- Scatters with B-field, produces e^+e^- cascade
- Cascade produces radio beam
- High energy protons \rightarrow photomeson production
- Beam of μ neutrinos \rightarrow neutrino pulsars?



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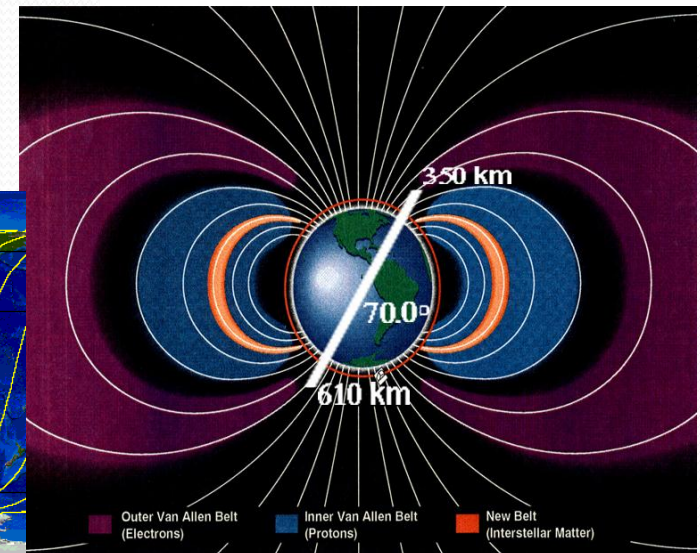
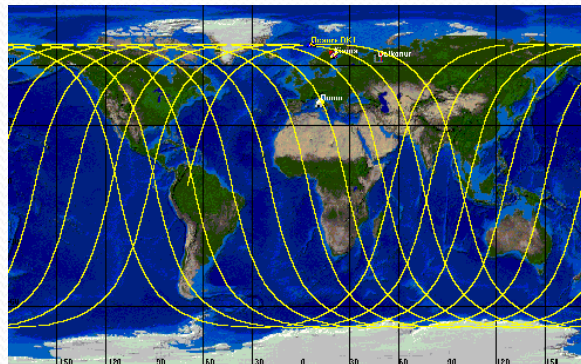


Positrons from Pulsars?

“Hasan Yuksel and Todor Stanev at the University of Delaware and Matthew Kistler at Ohio State University claim that the source of these positrons [excess] is Geminga — a nearby and rapidly rotating neutron star. The results also represent the first time that astronomers can link cosmic rays to a specific source.”

PAMELA – Positron excess

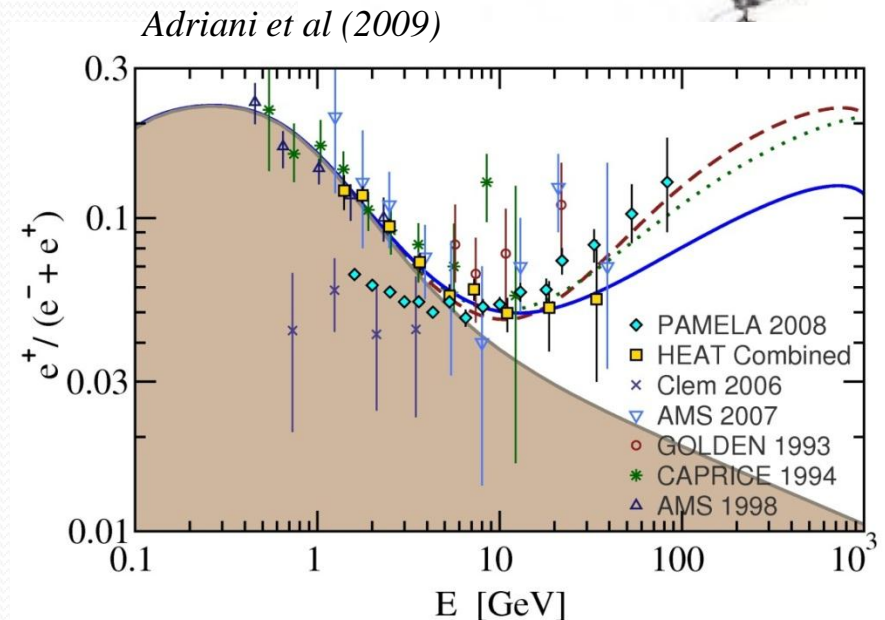
- "piggy-back" on board of Russian Resurs-DK1 satellite for Earth Observation
- launched on 15th June, 2006
- quasi-polar (inclination 70.4°), elliptical orbit
- main purpose:
measurement of antiproton and positron components of cosmic rays in an energy range and with a statistics never before achieved



PAMELA – Positron excess

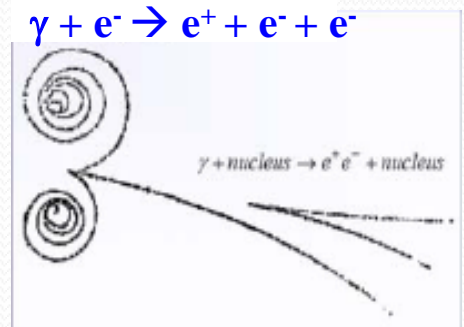
- In 2008, observed excess positrons from 10-100 GeV in cosmic ray spectrum
- Adriani et al (2009 Nature)
- Similar trend had been observed (AMS, HEAT etc.)
- Results could not be explained by standard models of cosmic ray origin and propagation in the Milky Way
 - Excess e^+ than expected in context of secondary e^+ production
- Suggested a nearby 'source' of high energy positrons.

→ Some primary sources are needed!

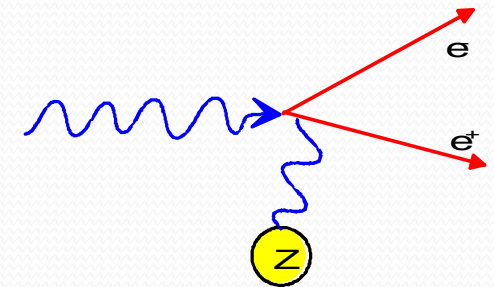


Positrons Pair Production

- Every particle has antiparticle, if encounter, annihilate and give off gamma rays
- Reverse of this process = pair production
- Formation of e^\pm pair from high energy photon (usually in vicinity of an atomic nucleus / atomic e^-)
- Dominant photon interaction process at high energies
- Threshold energy: $E_\gamma = 2mc^2$ near a nucleus
- $h\nu > 2 m_e c^2 = 2 \times 0.51 \text{ MeV} = 1.02 \text{ MeV}$



$\gamma + \text{nucleus} \rightarrow e^+ + e^- + \text{nucleus}$



Pair Production in Pulsars – Polar Cap Model

- Strong E-fields induced by rotating neutron star
- Electrons are extracted from star outer layer and accelerated
- e^\pm pairs produced in magnetosphere and accelerated by E-fields and/or pulsar wind.

(Chi+ 1996; Zhang & Cheng 2001; Grimaud 2007; Hooper+ 2008; Profumo 2008 etc)

- Open field lines originate at polar caps
- e^\pm pair production can escape into ISM contributing to CR e^- and e^+ components
- Energy spectrum of these particles expected to be harder than that of the secondary positrons
 - pulsar-originated e^+ can dominate high energy end of CR positron spectrum

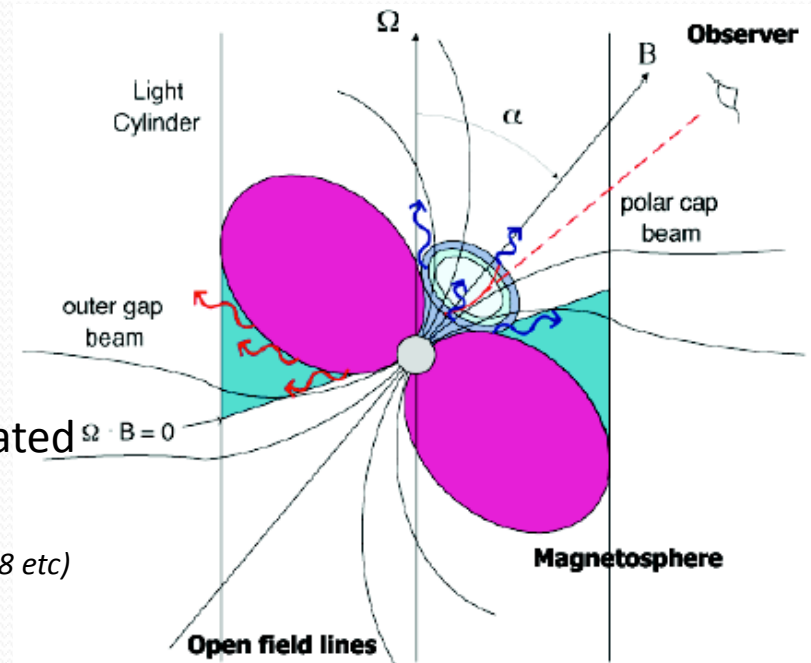
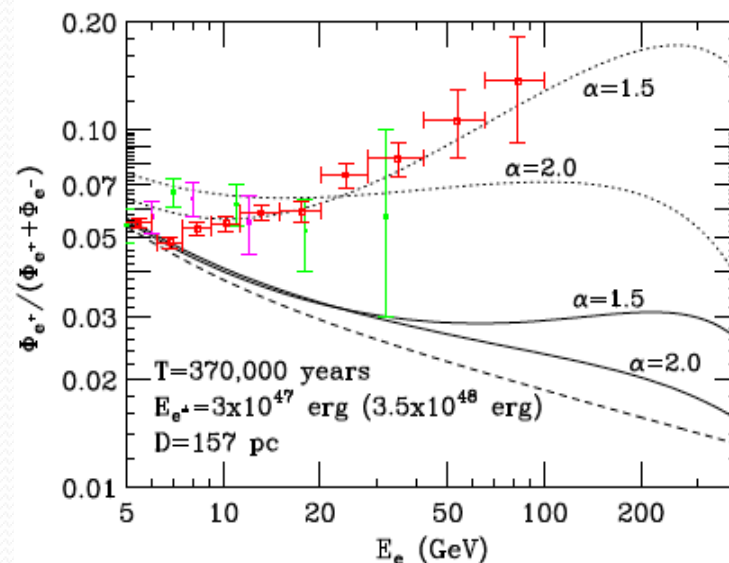


Figure:

<http://coss.gsfc.nasa.gov/images/epo/gallery/pulsars/>

Potential candidate - Geminga

- Not too far away ...
- CR e^\pm propagate via diffusion in our Galaxy deflected by B-fields
- e^\pm cannot propagate far \leftarrow energy losses by synchrotron & inverse Compton emission
 \rightarrow sources should be located nearby ($< 1\text{kpc}$)
- The right age ...
- Pulsar young enough to still produce high-energy particles
- Old enough that multi-GeV e^\pm from its more active past could have made it to Earth
 \rightarrow increasing fraction of middle-aged pulsars lies outside their host remnants as a function of age
- Pulsar Geminga:
- 800ly from Earth, 300,000 years old
- Milagro γ -ray observatory: seen halo of high energy γ -ray sources around Geminga
- Nearest known γ -ray source to Earth (excluding solar system bodies)
- Implies e^\pm pairs being produced near pulsar, accelerated to very high energies



Hooper et al. (2009)

Conclusion 1

- Positron excess observed by PAMELA (2008) could be attributed to nearby pulsars
- Geminga: First time astronomers can link CR positron to specific source?
- PAMELA positron data insufficient to distinguish between astrophysical primary sources such as pulsars or DM annihilation
- Future observations needed (AMS-02, CALET on ISS, CTA on ground...)

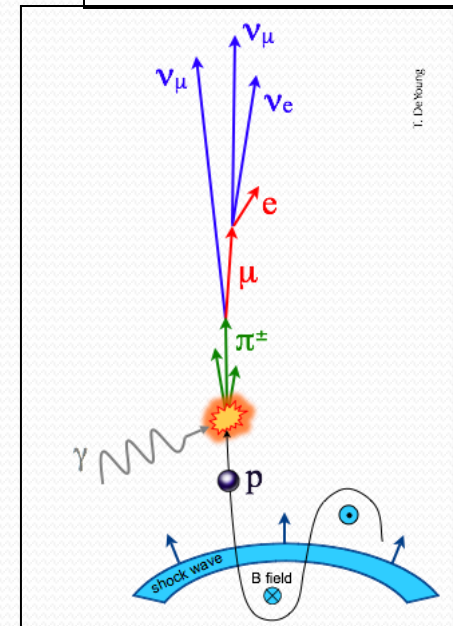
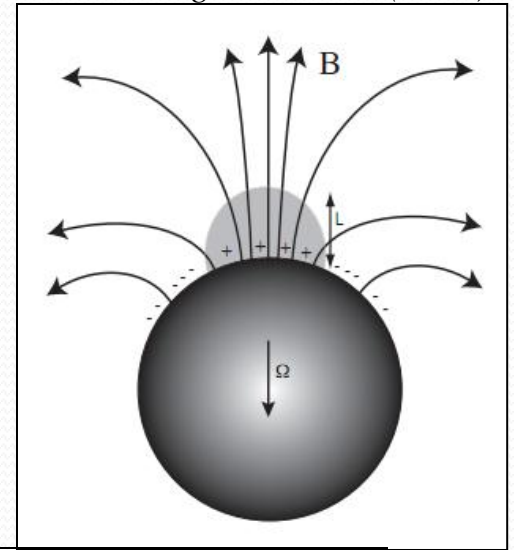
Neutrino Pulsars?

Young, rapidly rotating pulsars could be the brightest sources of high-energy neutrinos (~ 50 TeV) ... Can a radio pulsar also be a “neutrino pulsar”?

Neutrino Pulsar ?

- 1. Strong accelerating field
- B-field lines anti-parallel to spin axis (half of neutron stars)
→ positive ions accelerated off surface
- Acceleration *near the surface* (high density of radiation field)
- 2. High energy proton ($\sim 1\text{PeV}$)
- Young pulsars → surface still emit soft X-ray
- Protons scatter with surface X-ray
- Photomeson production -- “ Δ resonance”
- $p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+ \rightarrow n\nu_\mu\mu^+ \rightarrow n\nu_\mu e^+\nu_e\bar{\nu}_\mu$
- Accelerated proton far more energetic than radiation field, neutrino produced would move in nearly same direction
→ Produce beam of neutrinos

Burgio and Link (2006)

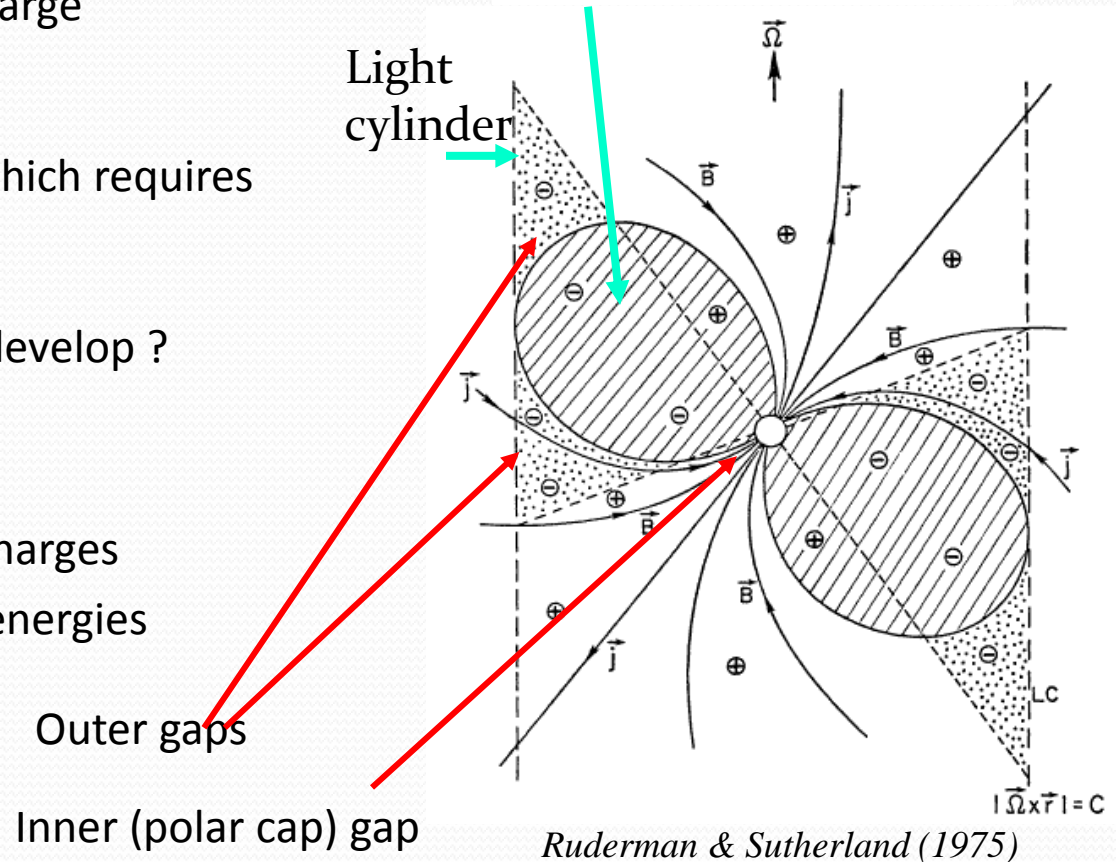


Neutrino Pulsar ?

- In the equilibrium magnetosphere (co-rotating magnetosphere), there is no charge acceleration ($\mathbf{E} \cdot \mathbf{B} \approx 0$).
- For acceleration, need $\mathbf{E} \cdot \mathbf{B} \neq 0$, which requires $n < n_{GJ}$ somewhere.
- How and where does this *gap* develop ?
 - Inner gaps vs. outer gaps.
 - Charge-depleted gaps \rightarrow charges accelerated to relativistic energies

Corotating charge density:

$$n_{GJ} \cong 7 \times 10^{13} B_{12} p_{ms}^{-1} \text{cm}^{-3}$$



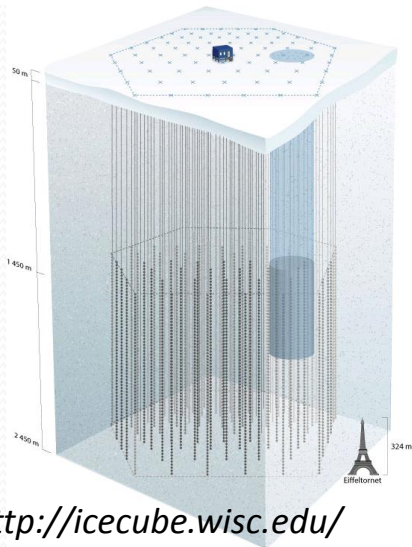
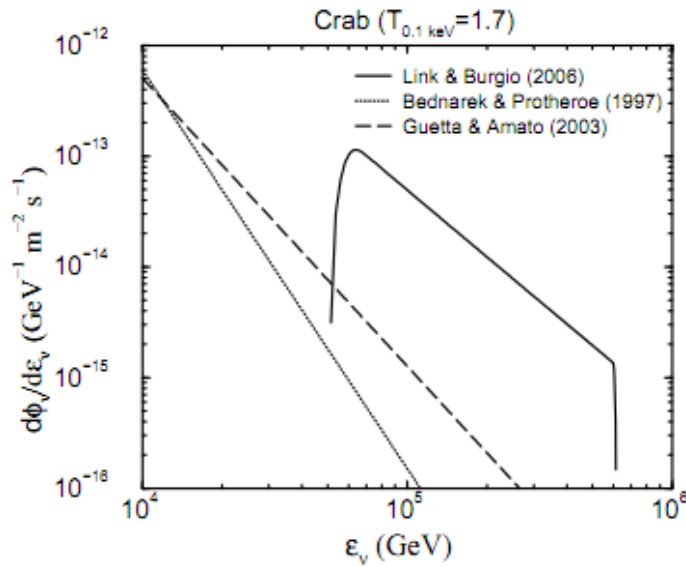
Regions of particle acceleration!

Neutrino Pulsar ?

- Threshold for photomeson reaction: $\varepsilon_p \geq \left(\frac{T_\infty}{0.1 \text{ keV}} \right)^{-1} \text{ PeV}$
- Is it possible to get protons to $\sim 1 \text{ PeV}$?
- 64 known pulsars within 10 kpc younger than 10^5 yr (Parkes Radiopulsar Survey)
- 9 pulsars within 5 kpc, younger than 10^5 yr , and that satisfy $T_\infty = 0.1 \text{ keV}$
- Some promising candidates: (Burgio and Link 2006)

Source	Hemisphere	estimated μ flux on Earth $\text{dN/dAdt} \text{ (km}^{-2} \text{ yr}^{-1})$
Crab	northern	45
J0205+64	northern	1
Vela	southern	25
B1509-58	southern	5

Neutrino Pulsar ?



<http://icecube.wisc.edu/>

- Typical proton energies required to reach resonance $\sim 1 \text{ PeV}$
- Expected neutrino energies will be $\sim 50 \text{ TeV}$ (5% energy of proton)
- Sharp rise predicted at 50 TeV (Burgio & Link 2006)
- Detection:
- AMANDA-II detected 10 events (over background of 5.4) from direction of Crab pulsar, energy $> 10 \text{ GeV}$
- Intriguing but not statistically significant
- Future:
- IceCube confirm / refute this results
- Null results also provide bound on accelerating potential near neutron star surface

Conclusion 2

- Young, rapidly rotating pulsars could be the brightest sources in the sky above ~ 50 TeV. They might be the first sources detected
- Further observations needed e.g. IceCube
- Detection would allow direct constraints on the physical conditions in the neutron star magnetosphere
- Lack of detection would also allow constraints



Thank you!