Lawbreakers? Faster-than-light polarization currents, the electromagnetic "boom" and pulsar observational data

Andrea Schmidt, John Singleton, Joe Fasel, David Bizzozero, **Houshang Ardavan, Pinaki Sengupta, John Middleditch et al.**

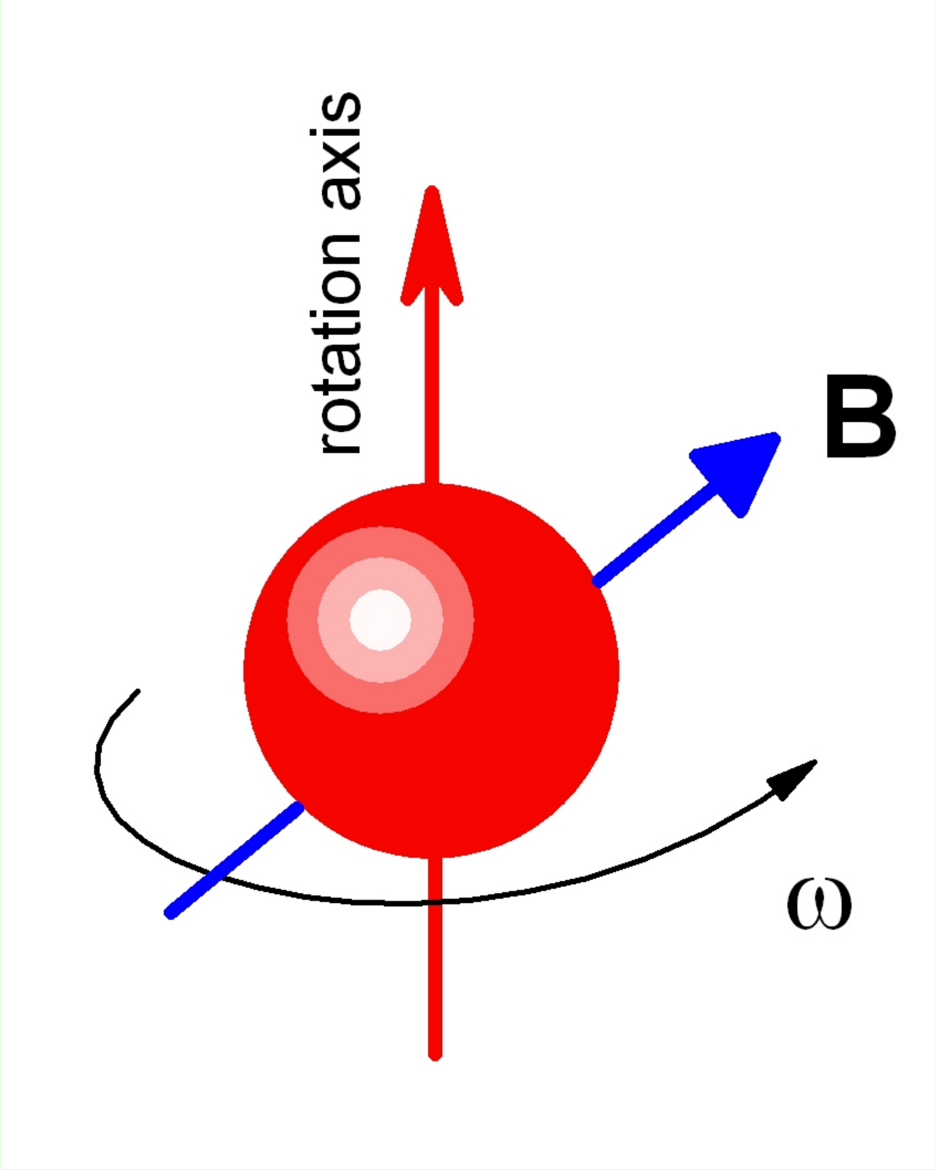
Though pulsars were discovered over 40 years ago, their emission mechanism has remained mysterious.

A melange of disparate models is used to account for different parts of their emission spectra (Rudermann & Sutherland 1975; Cheng et al. 1986; Dyks et. al. 2004 ; Pétri & Kirk 2005; Zavlin 2007; Harding et al. 2008). Jean Eilek (NRAO), "we know why they pulse. But why do they shine? How do they emit such intense coherent radiation?"

Here we describe a single model that seems to account for all aspects of pulsar radiation. This is based on theoretical work by Bolotovskii and Ginzburg (1980s) and Houshang Ardavan (1990s-present).

*Faster than the speed of light *in vacuo*.

Simple picture of pulsars



Pulsar = a rotating neutron star with a very large magnetic field **B** (Tommy Gold, 1969).

Observation: periods of rotation from 1.5 ms to 8.5 s.

=> huge magnetic field rotating through plasma “atmosphere” surrounding neutron star.

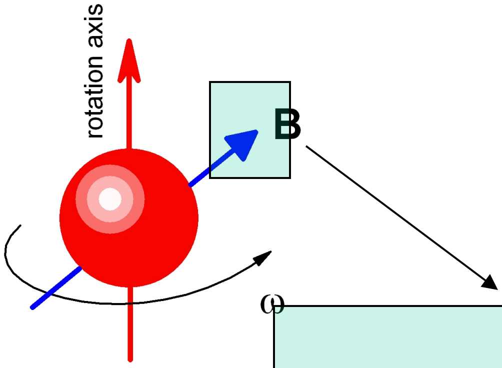
Instantaneous speed of **B:** $v = \omega r$.

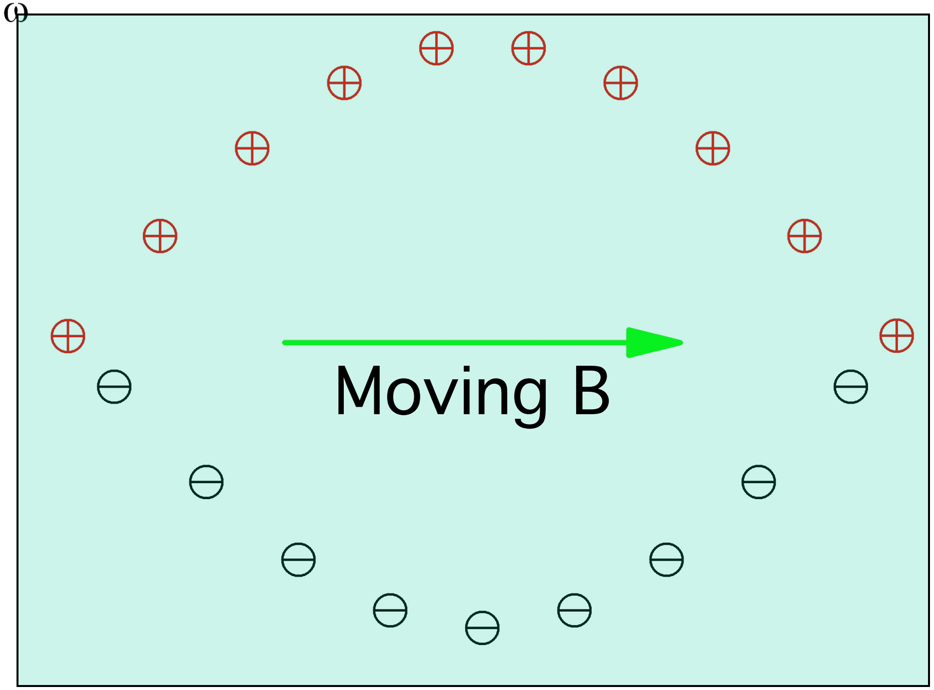
$v > c$ (i.e., faster than the speed of light) for

$r > 75$ km (1.5 ms pulsars)

$r > 400{,}000$ km (8.5 s pulsars)

What does this do to the pulsar's "atmosphere"?





Electromagnetism: moving magnetic field has same effect as electric field.

=>as **B** swings through plasma "atmosphere", -ve electrons and +ve ions displaced in opposite directions.

=>traveling region of electrical polarization **P** with speed *v.*

Trivial solutions of Maxwell's equations show polarized region must keep up with the magnetic field's rotation => $v > c$ for $r > c/\omega$.

NB: displacements small: speed of electrons and ions << *c*. **Polarized region can move faster than *c* even though ions do not.** c.f. Mexican wave, bow wave of boat, laser beam swinging across Moon etc..

Why does this polarized region emit radiation? Maxwell's equations III and IV

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

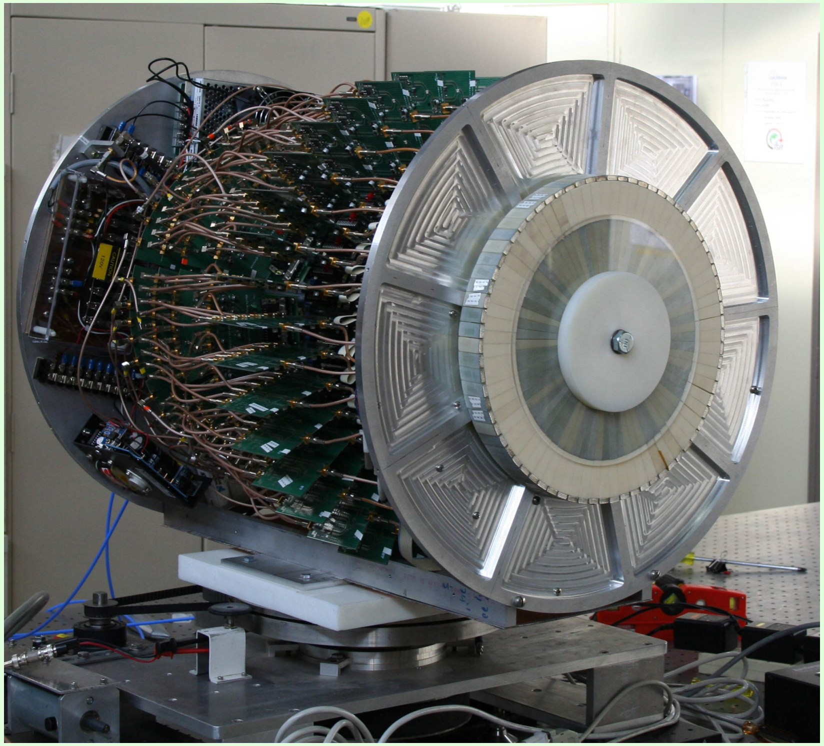
$$\nabla \times \mathbf{H} = \mathbf{J}_{\text{free}} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial \mathbf{P}}{\partial t}$$

Green terms describe wave motion of electromagnetic radiation.

Conventional antennas use free current $\mathbf{J}_{\text{free}}$ of electrons as source. But electrons restricted to $v < c$ (Einstein!).

Polarization current $\partial \mathbf{P}/\partial t$ is an equally good source term, and, as we saw before, it is not restricted to $v < c$. *This is our superluminal source.*

How do we know that this works?



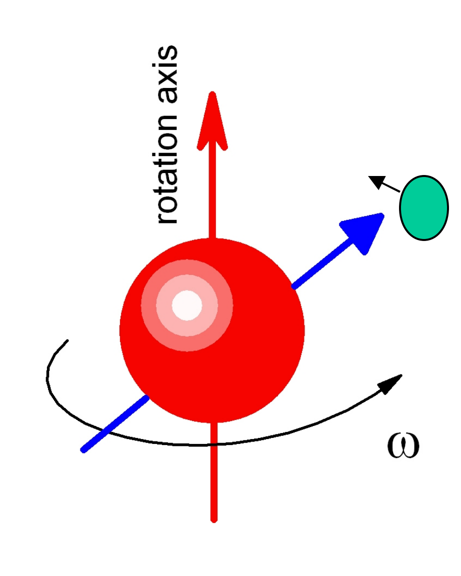
Los Alamos National Laboratory, USA

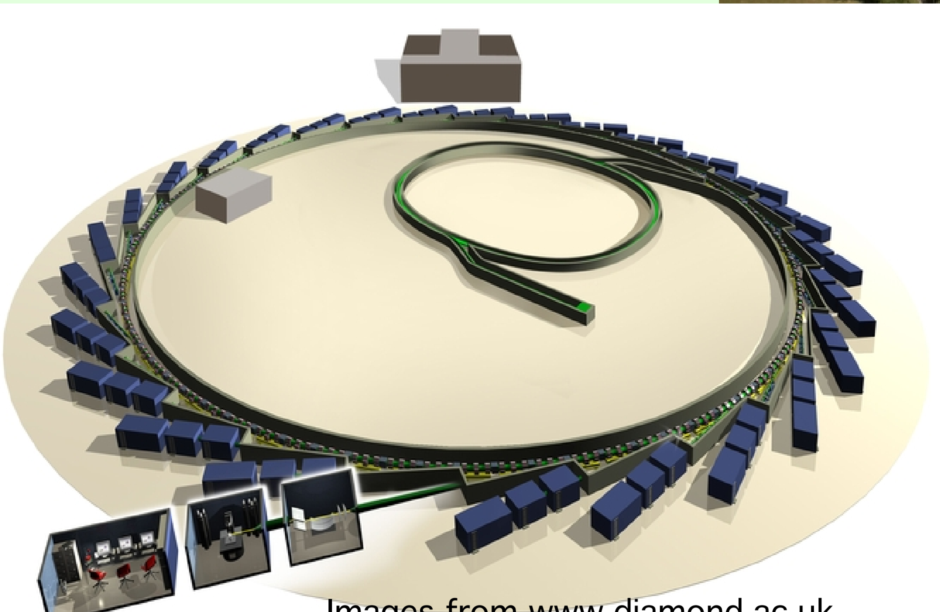
Department of Physics, Oxford University, UK

Ground-based experiments (pulsars!) in the United Kingdom, Russia and the USA have shown that superluminal polarization currents exist and that they emit tightly-focused radiation. Speed record so far: 8*c*.

NB: in the above experiments, the material that hosts the polarization current is alumina, rather than a plasma, but the physics is the same. The Russian experiment uses a real plasma.

Pulsar's rotating polarization current is like a synchrotron



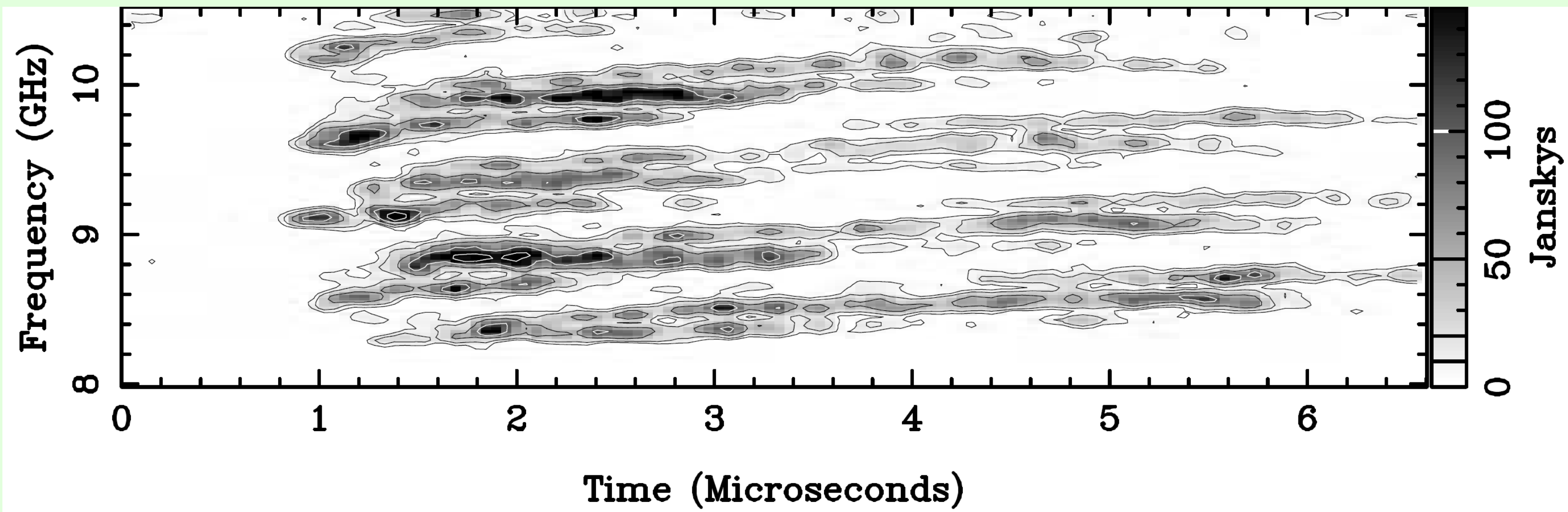


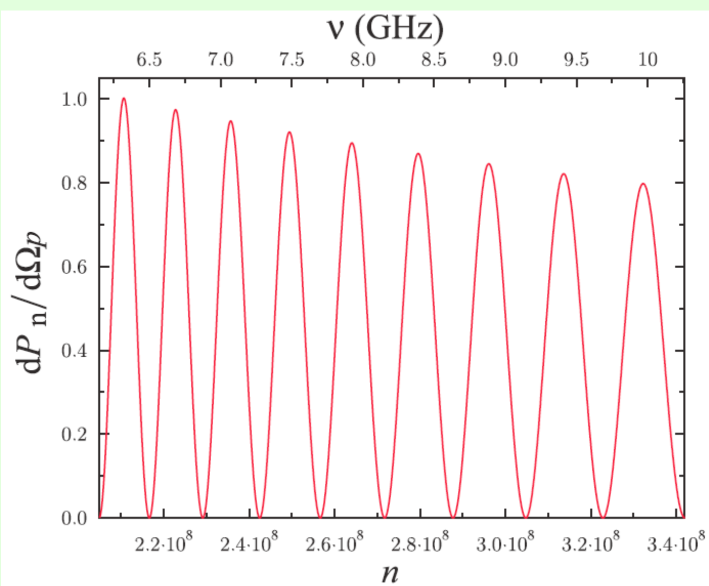
Images from www.diamond.ac.uk

A synchrotron is a very **broadband** radiation source

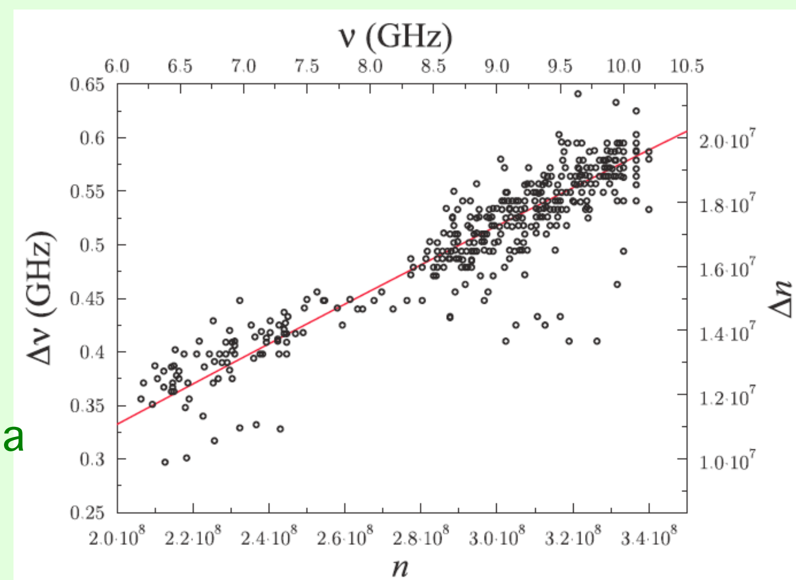
=>Our analogous model of pulsars produces radio frequencies to X-rays using a single mechanism.

Important difference of superluminal ($v > c$) pulsar emission versus conventional synchrotrons: Lorentz factor $\gamma = 1/[1-(v/c)^2]^{1/2}$ imaginary. => Intensity oscillates as a function of frequency. These oscillations are observed in Crab interpulses (Hankins and Eilek, 2007).





Predictions (left) fit observations (right) very well. Beside the (known) rotation frequency, only one adjustable parameter (plasma freq.) is needed for the fit.



Complete frequency spectrum of Crab pulsar.

- By fitting GHz observations (prev. slide- one adj. parameter), we reproduce Crab's emission spectrum up to $\nu = 10^{14}$ Hz.
- One further parameter (electron cyclotron frequency) used to fit peak at higher ν.

=>Superluminal model accounts *quantitatively* for Crab's emission over 16 orders of magnitude of ν using **just two adjustable parameters.**

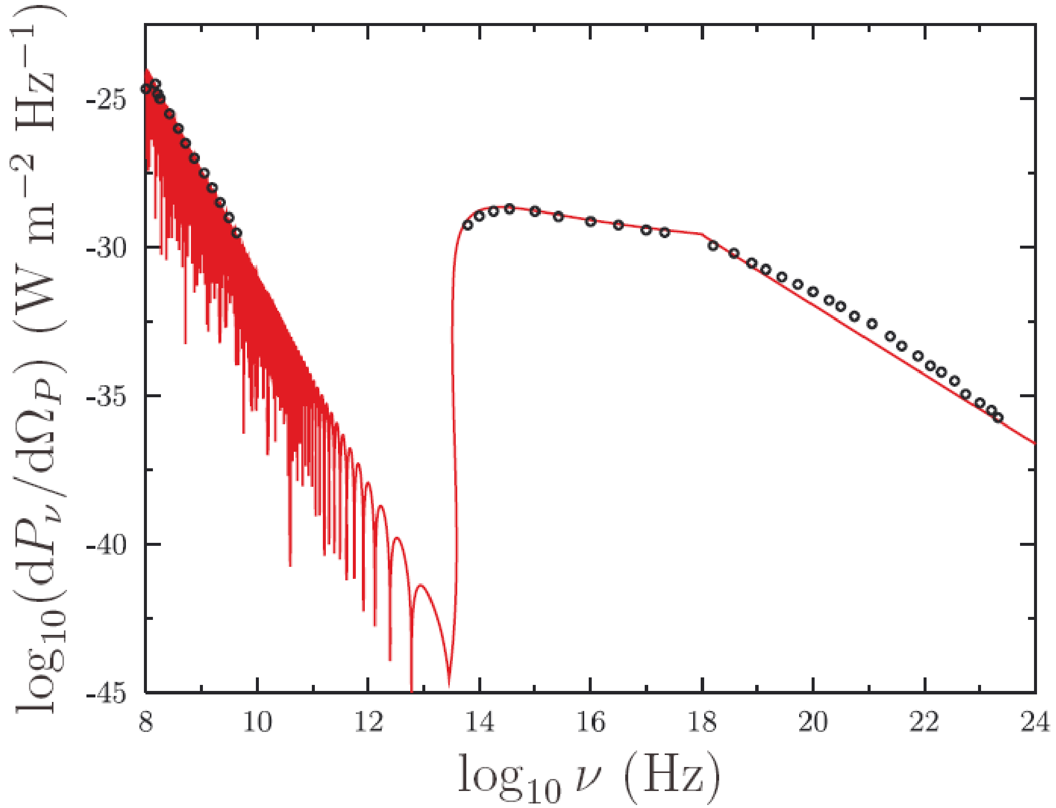
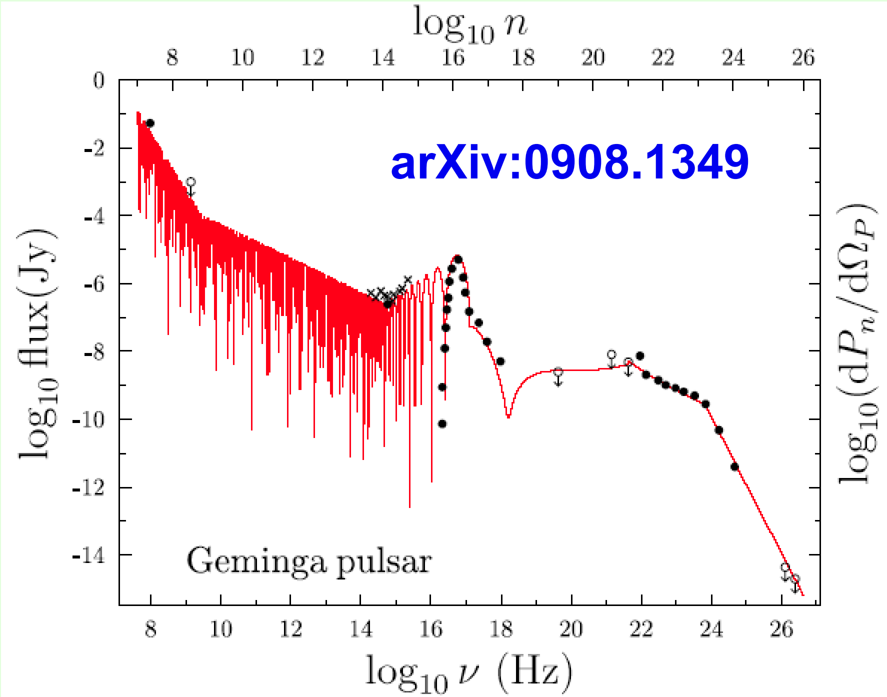
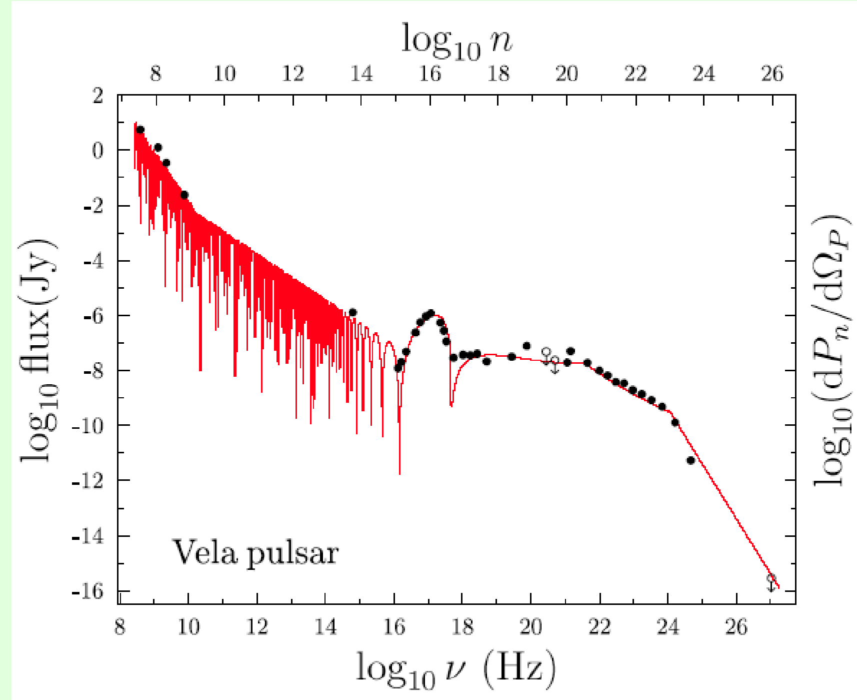


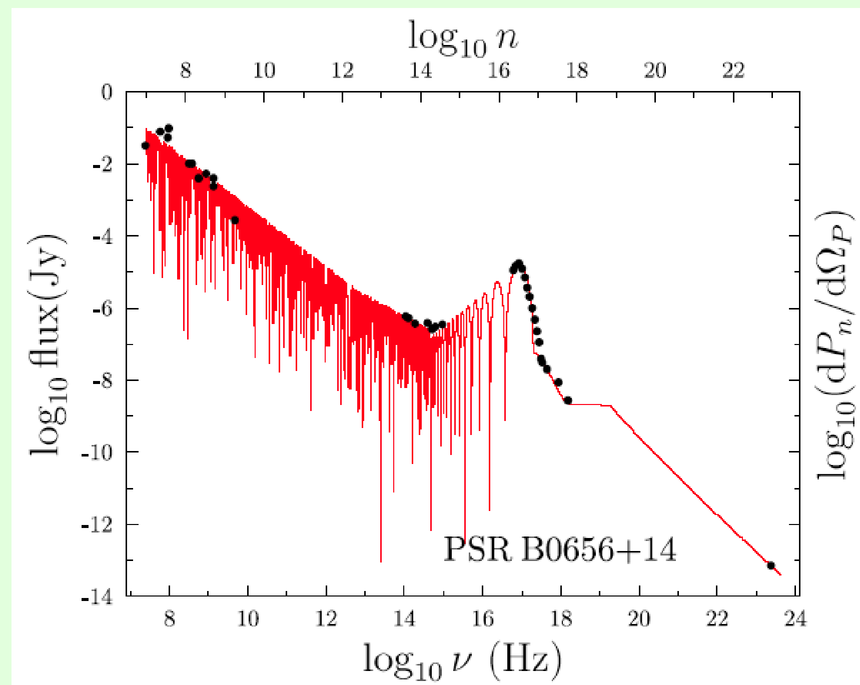
Figure 6. The spectral distribution $\log(dP_\nu/d\Omega_P)$, predicted by equation (33), versus $\log\nu$ for $\nu = n\omega/(2\pi) \simeq 30n$ Hz appropriate for the Crab pulsar. The points show observational data (where available) of the spectrum of the Crab pulsar (Lyne & Graham-Smith 2006). In the model, the recovery of intensity at the ultraviolet peak at $\sim 10^{15}$ Hz is caused by resonant enhancement due to the azimuthal modulation frequency $m\omega/2\pi$

Overall characteristics of pulsar emission determined by *superluminal nature* of the source: only the *details* depend on the pulsar "atmosphere", i.e. resonances in its relative permittivity.

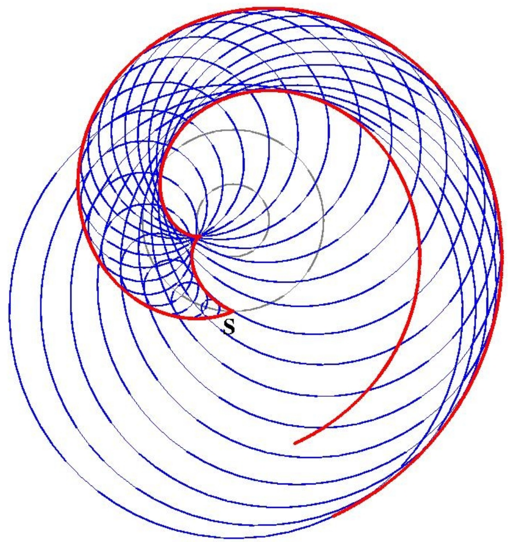


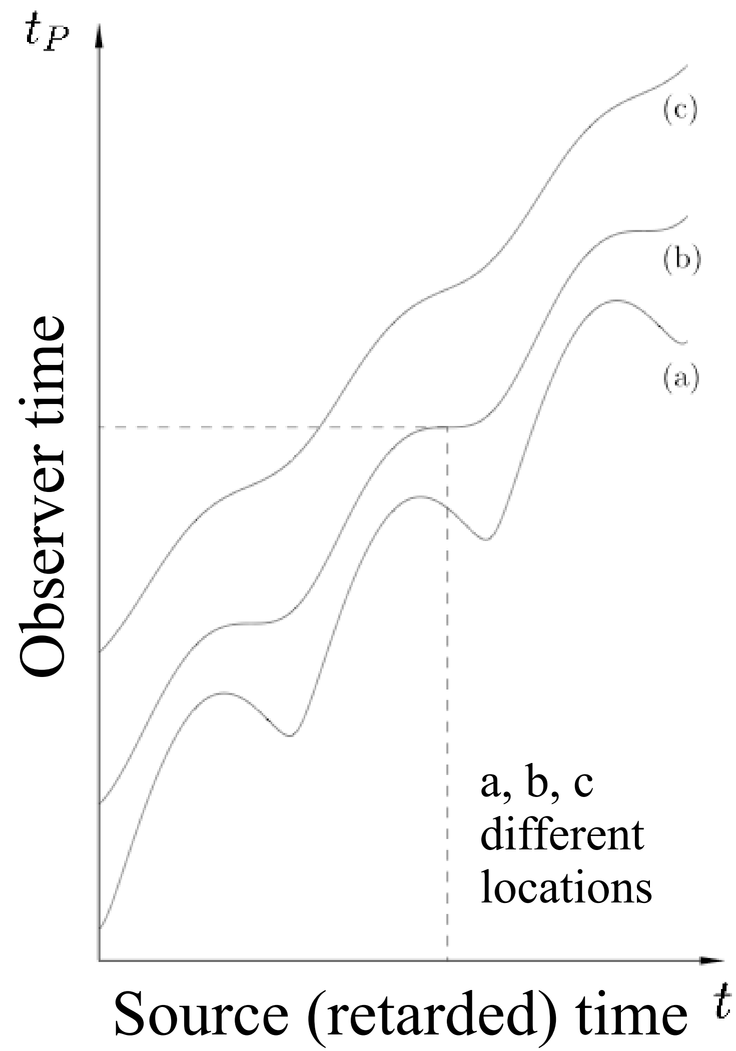


- Same Model (---) fits *all* pulsars with broadband data (•, 9 in total).
- Overall behavior given by superluminal nature of source;
- Coarse features scale as (rotational period)^3 => ms pulsars emit only RF; slow pulsars emit out to X-ray (true!)
- Detail differences due to resonances in pulsar atmosphere (plasma freq., electron cyclotron resonance).



Why does the superluminal emission dominate pulsar observations? Why the sharp pulses?





- Spherical wavelets from rotating source.
- Cross-section of envelope in orbit plane.
- Orbit and light cylinder ($r = c/\omega$).

Source: $r = \text{const}, \quad z = \text{const.}, \quad \varphi = \hat{\varphi} + \omega t$

Observer: $r_P,\ z_P,\ \varphi_P$

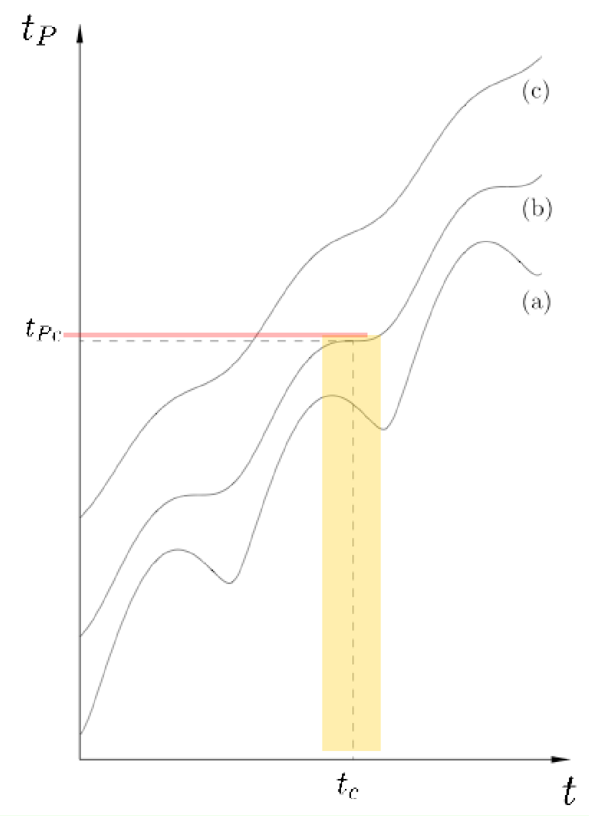
Separation, source to observer:

$$R(t) = [(z_P - z)^2 + {r_P}^2 + r^2 - 2 r_P r \cos(\varphi_P - \hat{\varphi} - \omega t)]^{\frac{1}{2}}$$

Obs. time t_P = source t + dist/c = $t + R_P/c$ =

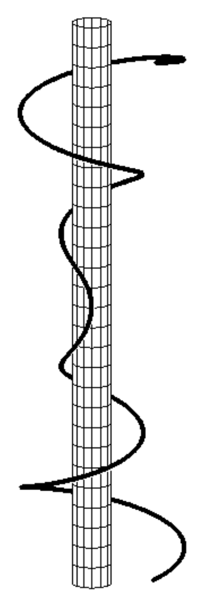
$$t + [(z_P - z)^2 + {r_P}^2 + r^2 - 2 r_P r \cos(\varphi_P - \hat{\varphi} - \omega t)]^{\frac{1}{2}}/c$$

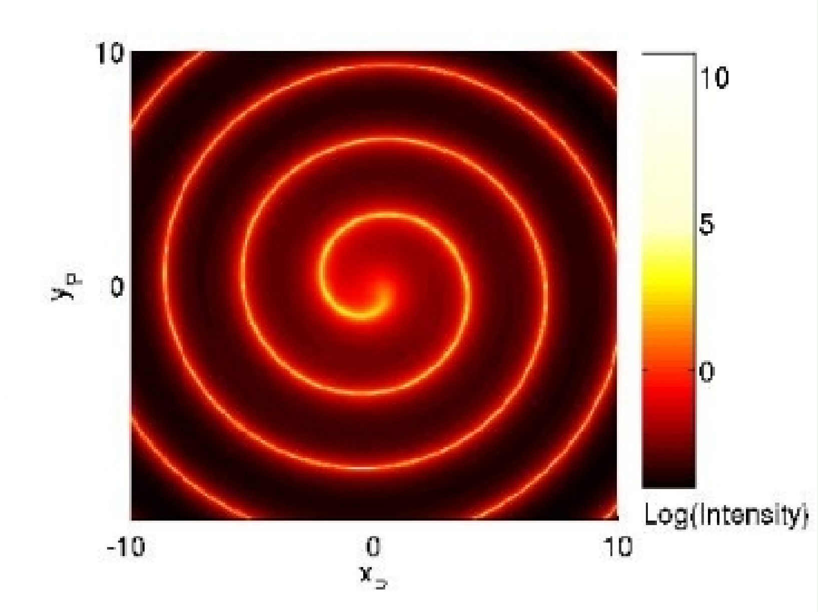
Notice the concentration of energy for case (b)



The electromagnetic "boom"

For (b), observer receives radiation in a very short time period emitted over a much longer period of source time. There is a huge concentration of energy (temporal focusing). This EM "boom" spirals out from the pulsar. When it hits Earth we receive a very short, intense pulse.



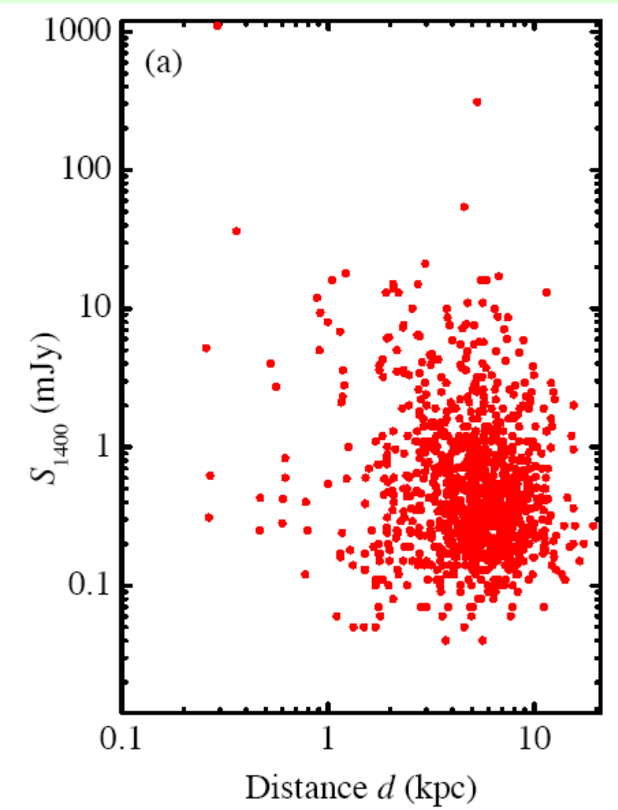


Simulations: this radiation has an intensity I ∝ $1/d$ (d = distance) rather than as $1/d^2$. This is why we see it from Earth.

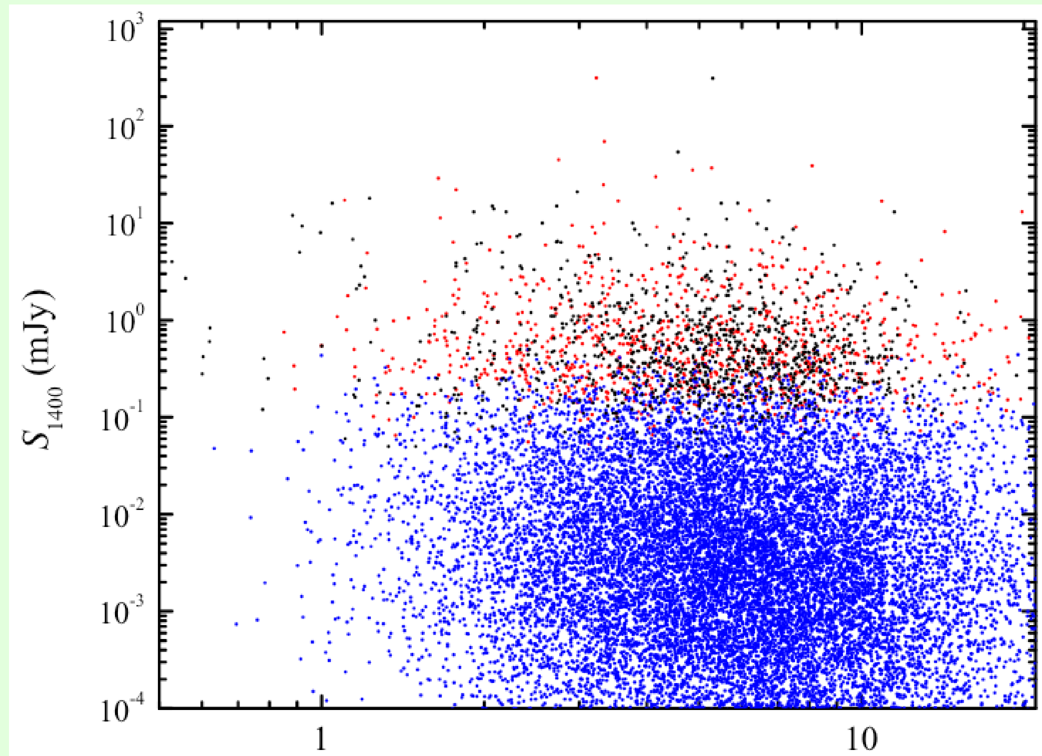
Analogous effect known in acoustics (left): the intense, localized "boom" of an supersonic airplane.

Can we detect the component with $I \propto 1/d$?

Use Parkes Multibeam Survey, data for ≈ 1100 Galactic pulsars incl. flux ($\propto I$) at 1400 MHz (S_{1400}) and dispersion measure (DM). DM gives d via a method (NE2001) that does not assume the inverse-square law.



(Jy = 10^{-26} Wm^{-2}Hz^{-1})



Singleton et al. Fig. 4

(1 pc =3.26 ly)

Left: Parkes Survey. Right: Bayesian analysis of Synthetic Galaxy using Parkes characteristics: ● undetected pulsars, ● detected pulsars, ● real data.

Note the Malmquist bias- Parkes misses increasing fraction of weaker pulsars as d increases. Naive analysis will get the wrong power law!

To get around the Malmquist bias, use **Maximum Likelihood Analysis**, originally applied to redshifts of very distant objects by George Efstathiou and colleagues.

Mon. Not. R. astr. Soc. (1988) **232,** 431–461

Analysis of a complete galaxy redshift survey – II. The field-galaxy luminosity function

G. Efstathiou *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*
Richard S. Ellis *Physics Department, University of Durham, Science Laboratories, South Road, Durham DH1 3LE*
Bruce A. Peterson *Mt Stromlo and Siding Spring Observatories, The Australian National University, Woden ACT 2606, Australia*

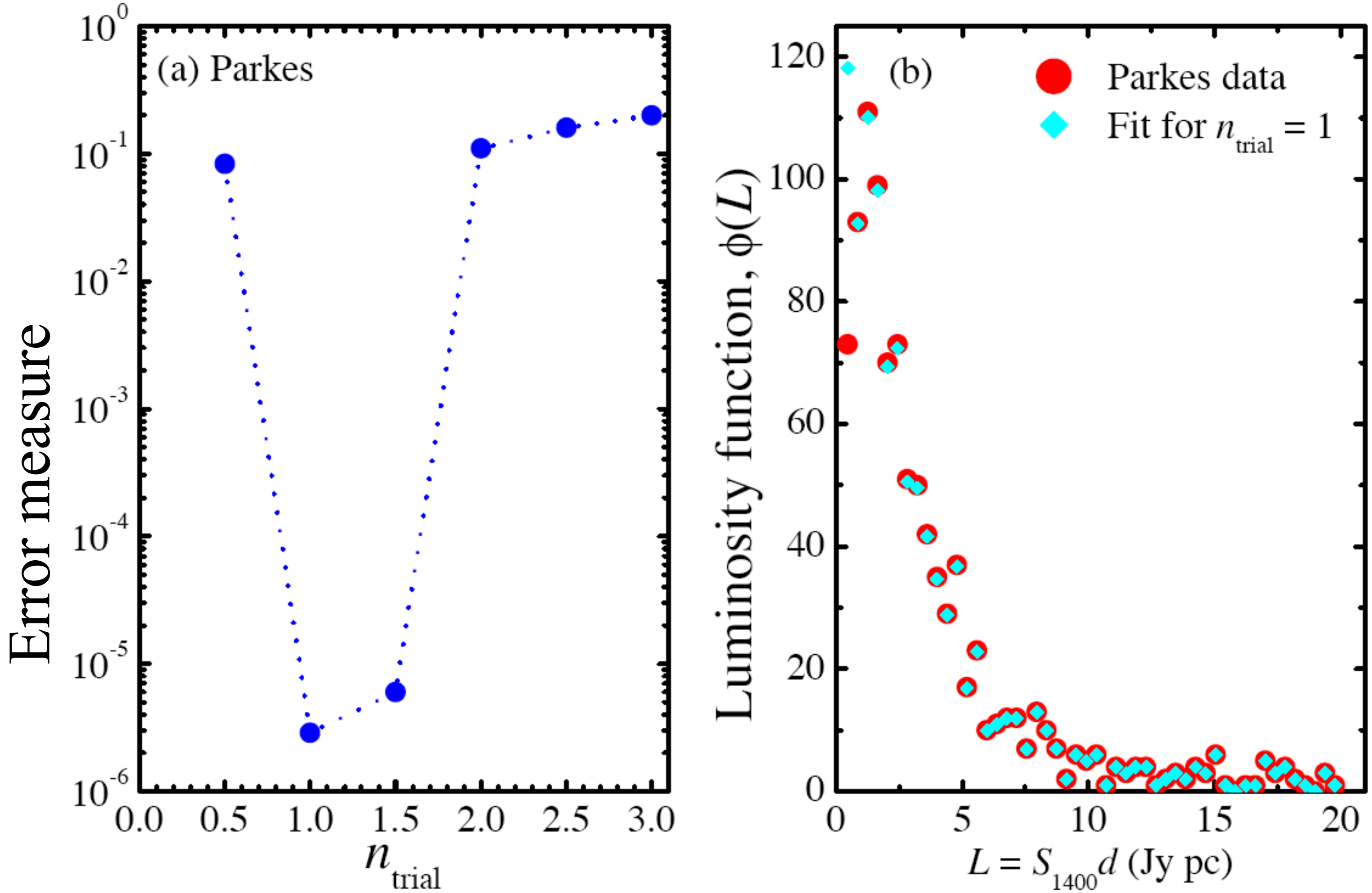
Accepted 1987 November 25. Received 1987 September 14

Maximum Likelihood Analysis (MLA) determines an initially unknown luminosity function $\Phi(L)$ (i.e. fraction of pulsars with a particular luminosity) that best fits all of the Parkes pulsar data.

- Use $S \propto 1/d^{n}_{n}$ in MLA; luminosity L given by $L=d^{n}S_{1400}$
- Run with n = 0.5, 1, 1.5, 2, 2.5, 3.
- Best mapping of pulsar data onto a luminosity function gives n.

$n < 2$ supports the superluminal model; $n = 2$ implies conventional inverse square $S \propto 1/d_{2}$.

Results of Maximum Likelihood Analysis



- The error measure is ~ 10 times better for n = 1 and n = 1.5 than for the inverse square law, n = 2. The best fit is for n = 1.
- Strongly suggests that the flux of pulsars observed from Earth contains a component whose intensity falls off as 1/d, adding further support for the superluminal model.

Successes of the Superluminal Model for Pulsars

1. Reproduces emission spectrum quantitatively over 16-18 orders of magnitude of frequency for nine pulsars; limitation is comprehensive observational data. V. few adjustable parameters.
2. General property: frequency spectrum depends on the rotational period cubed: low speed pulsars (e.g. Geminga) - gamma emitters; millisecond pulsars - RF emitters (correct!).
3. Gives a flux-distance relationship that seems to account for all pulsar data in the Parkes Multibeam Survey (S is proportional to $1/d$).
4. Predicts Stokes parameters for pulsars semi-quantitatively (e.g. swing in position angle is correct).
5. Can understand other aspects of pulsar radiation- e.g. the apparent radiation temperature.

Acknowledgements: Quinn Marksteiner, Larry Earley, Zhi-Fu Wang, Frank Krawczyk, Arzhang Ardavan.

Further information, see arXiv:0912.0350, arXiv:0908.1349, arXiv:0903.0399, Mon. Not. Roy. Ast. Soc. 388 873, 2008.

Extra slides for use in the question and answer sessions.

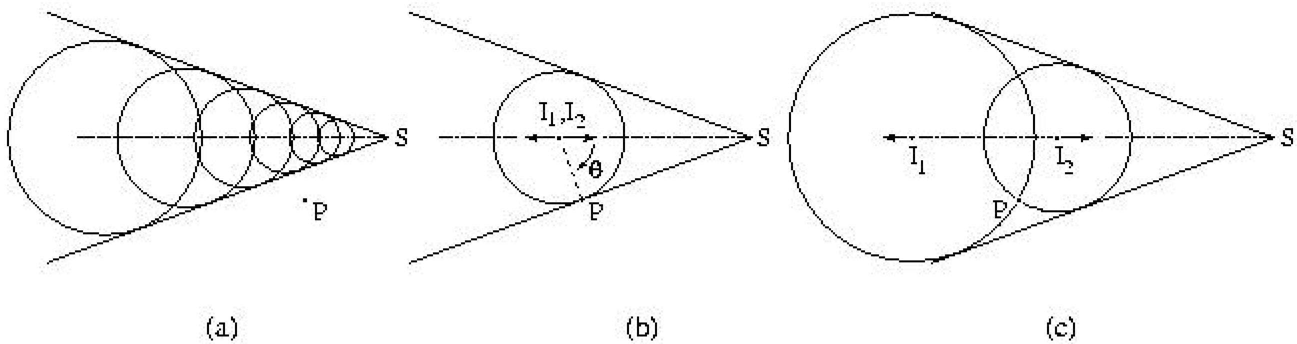
There is a very important way in which superluminal sources differ from subluminal ones.

Superluminal sources can make *more than one* contribution to the electromagnetic fields received at an instant by an observer. We show two examples.

Example 1: linear motion

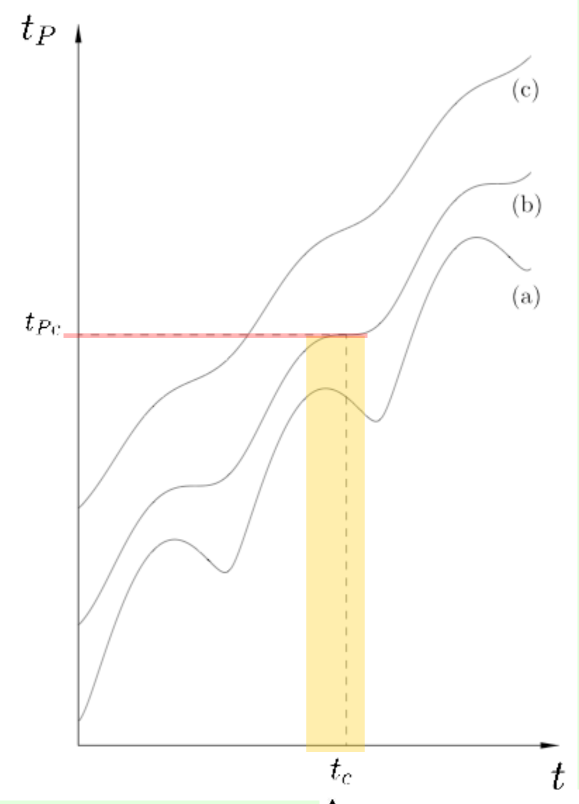
Source time versus reception time; Picard's manoeuvre and multiple images.

Envelope of spherical wavefronts from superluminal ($v > c$) source



- (a) Nothing observed at P.
- (b) Two coincident images observed at P.
- (c) Two distinct images observed at P.

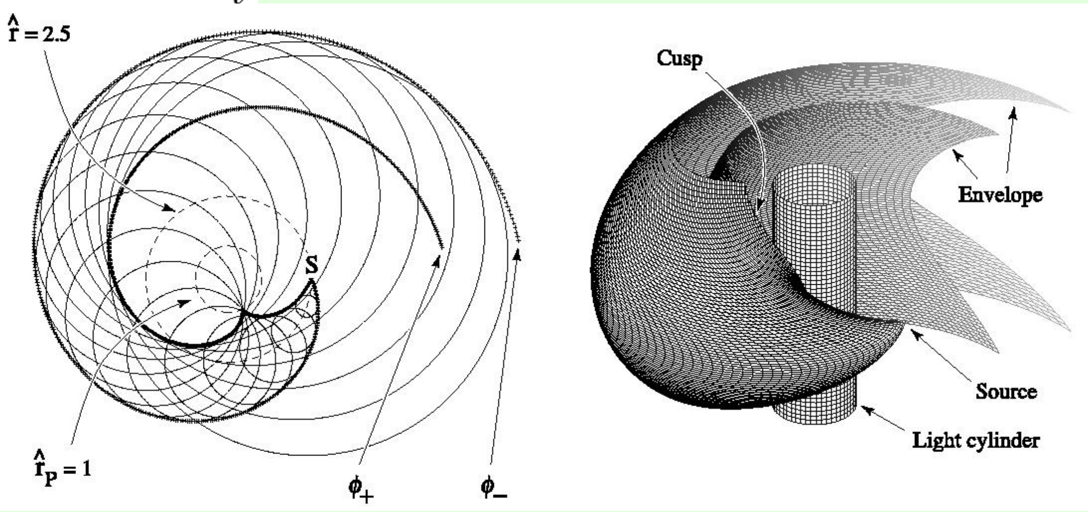
The cusp: a unique property of accelerated superluminal sources

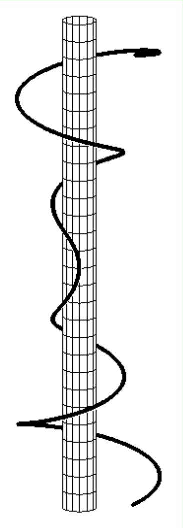


•On the cusp (b), the observer receives radiation in a very short time period that was emitted *over a considerably longer period of source time*. ⇒ There is a concentration of energy on the cusp.

•The cusp is due to source points approaching the observer at *c* and at zero acceleration. It is the fold seen in the envelope below, which spirals out from the source.

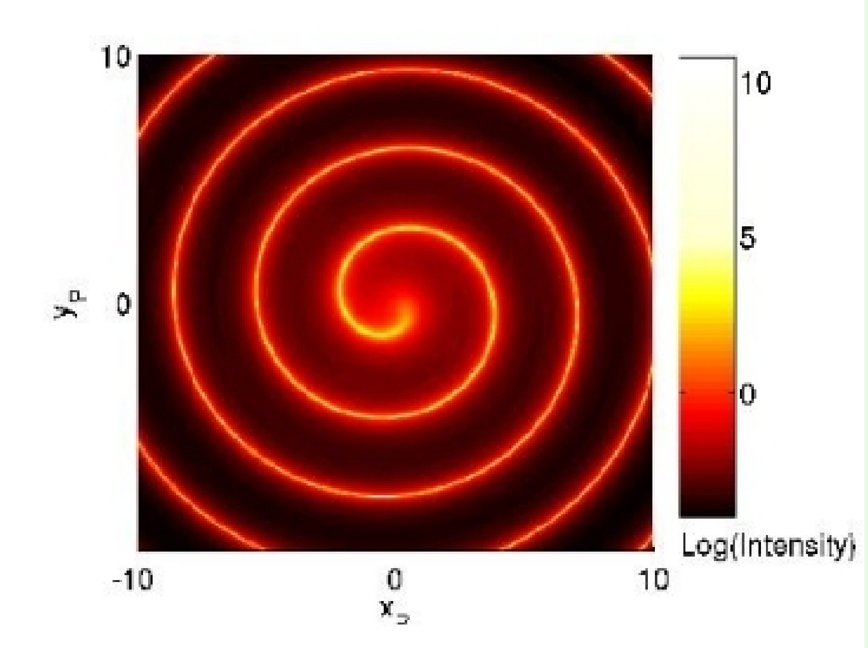
•On the cusp, all phase information collapses: the source looks coherent.





Solving for the radiation on the cusp:

Solve Liénard-Wiechert numerically (right) and analytically (below).
Analytical solution involves asymptotic expansion of Green's functions in time domain, followed by evaluation of Hadamard's finite part of the integral representing the radiation field.



Final result: =>
E-field of radiation varies as 1/√R,
i.e. <u>the power varies as 1/*R*.</u>
(c.f. conventional transmitters: power varies as $1/R^2$. On cusp, source is intrinsically bright.)

$$\mathbf{E}^{\rm ns} \sim \frac{4}{3}(2\pi)^{\frac{1}{2}}\hat{R}_P^{-\frac{1}{2}}|\sin 2\theta_P|^{-1}\exp(\mathrm{i}\Omega\varphi_C/\omega)\times$$
$$\sum_{\mu=\mu_\pm}|\mu|^{\frac{1}{2}}\,\mathrm{sgn}(\mu)\exp(\mathrm{i}\tfrac{\pi}{4}\,\mathrm{sgn}\,\mu)$$
$$\times\exp[-\mathrm{i}\mu(\hat{R}_P-\omega t_P+\varphi_C)]\{(\mathrm{i}\bar{s}_\varphi+\Omega\bar{s}_r/\omega)\hat{\mathbf{e}}_\parallel$$
$$-[(\mathrm{i}\bar{s}_r-\Omega\bar{s}_\varphi/\omega)\cos\theta_P+\Omega\bar{s}_z\sin\theta_P/\omega]\hat{\mathbf{e}}_\perp\} \qquad (57)$$

Laboratory demonstration that superluminal polarization currents emit radiation

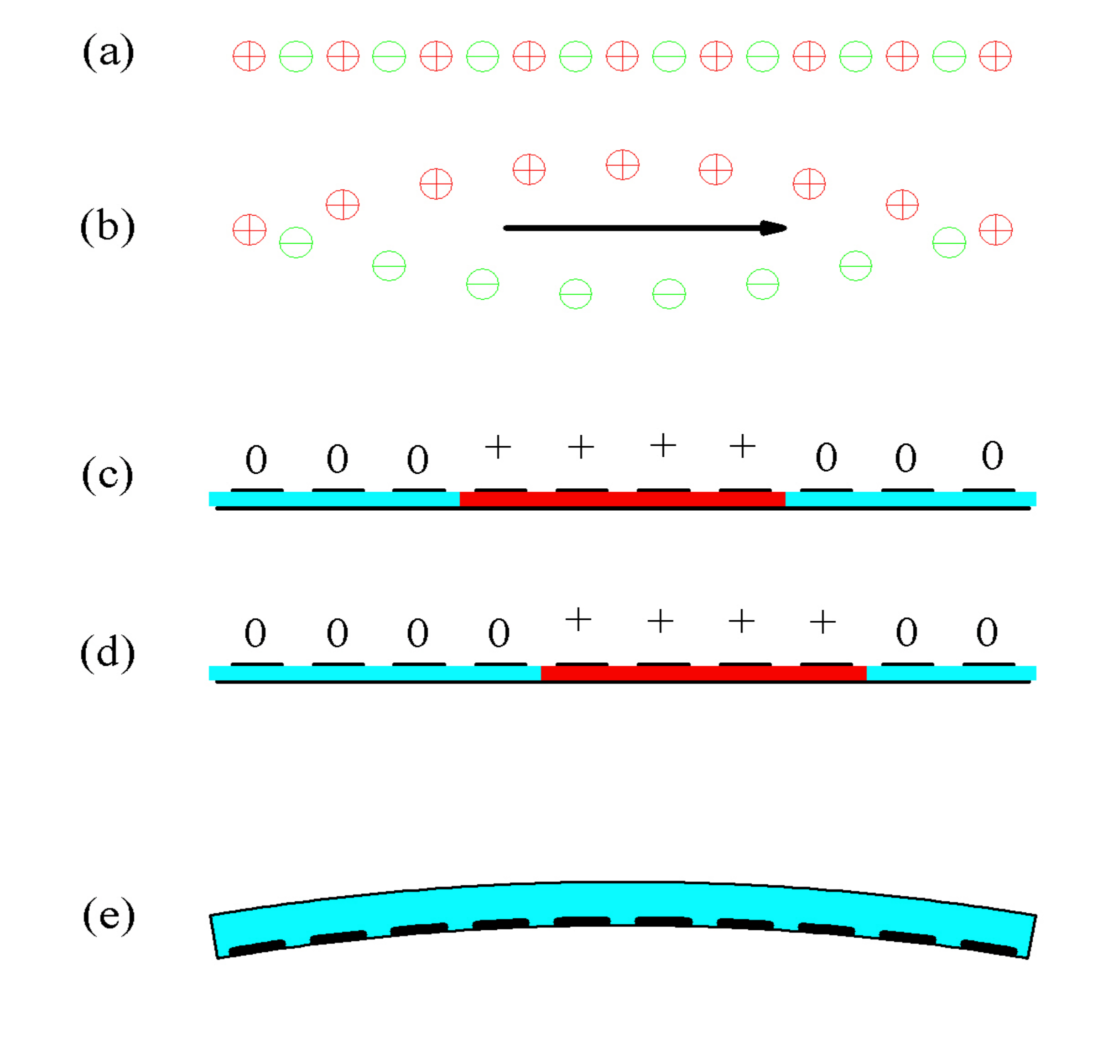
(a) Unpolarized solid containing ions.

(b) Turn on varying *E*-field => region of finite **P** that can be moved along arrow.

(c) Experimental realisation; electrodes above and below a strip of dielectric.

(d) Switch plates on and off; polarized region moves.

(e) Curvature of dielectric gives centripetal accel.



The first practical machine: "the Polarization Synchrotron"

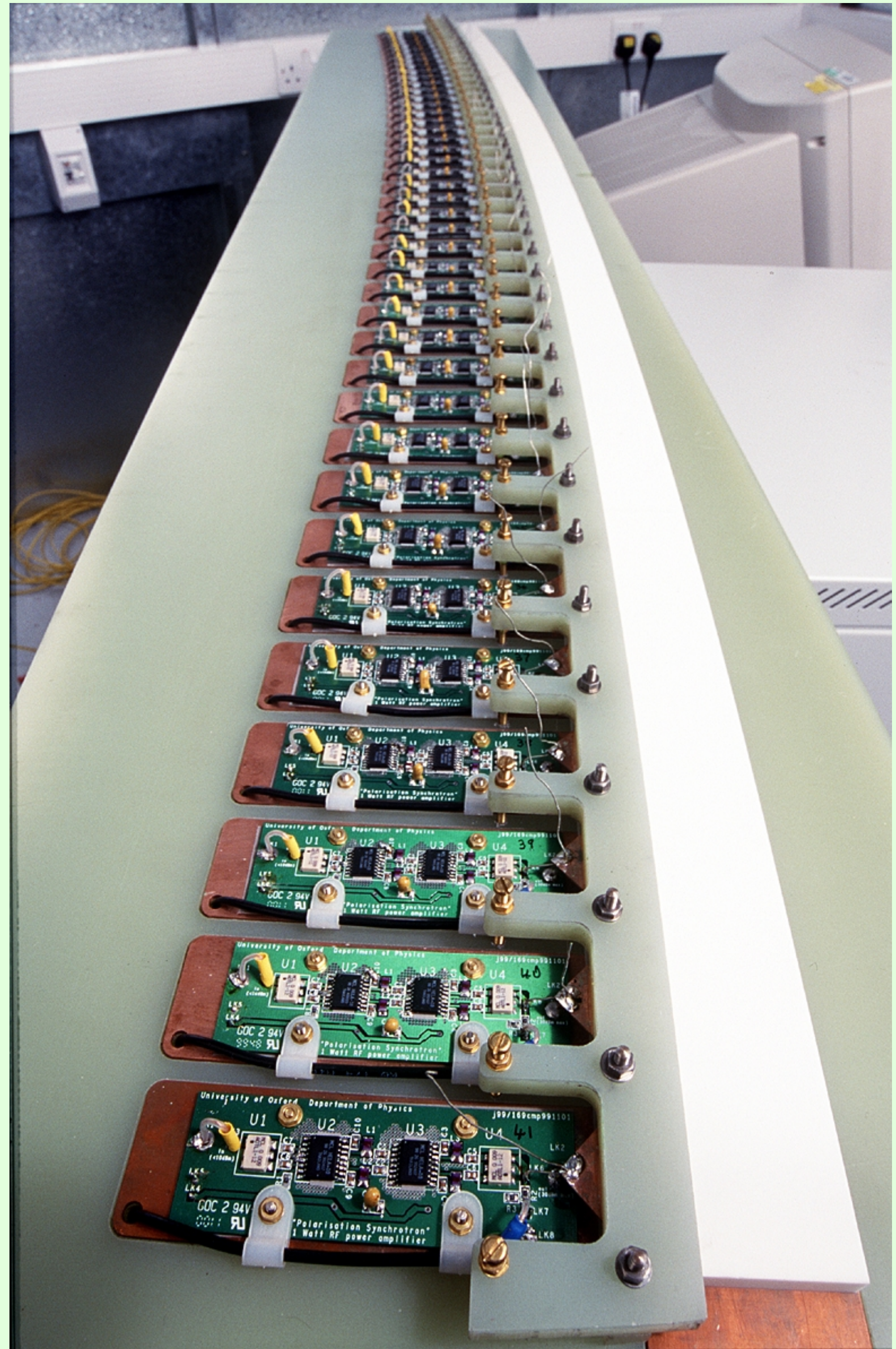
The dielectric is a 10 degree arc of a 10.025 m radius circle of alumina ($\varepsilon_r = 10$).

There are 41 electrodes, driven by 41 amplifiers.

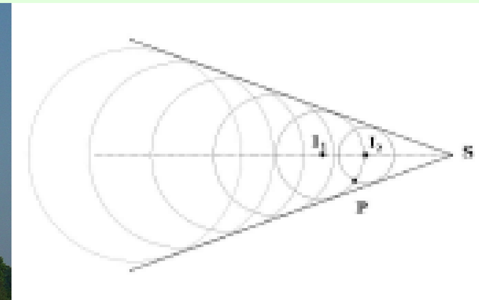
The speed of light is exceeded very easily using frequencies in the MHz range.

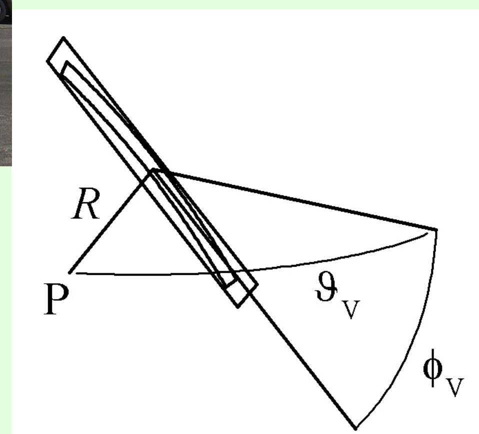
Many successful experiments carried out with this machine.

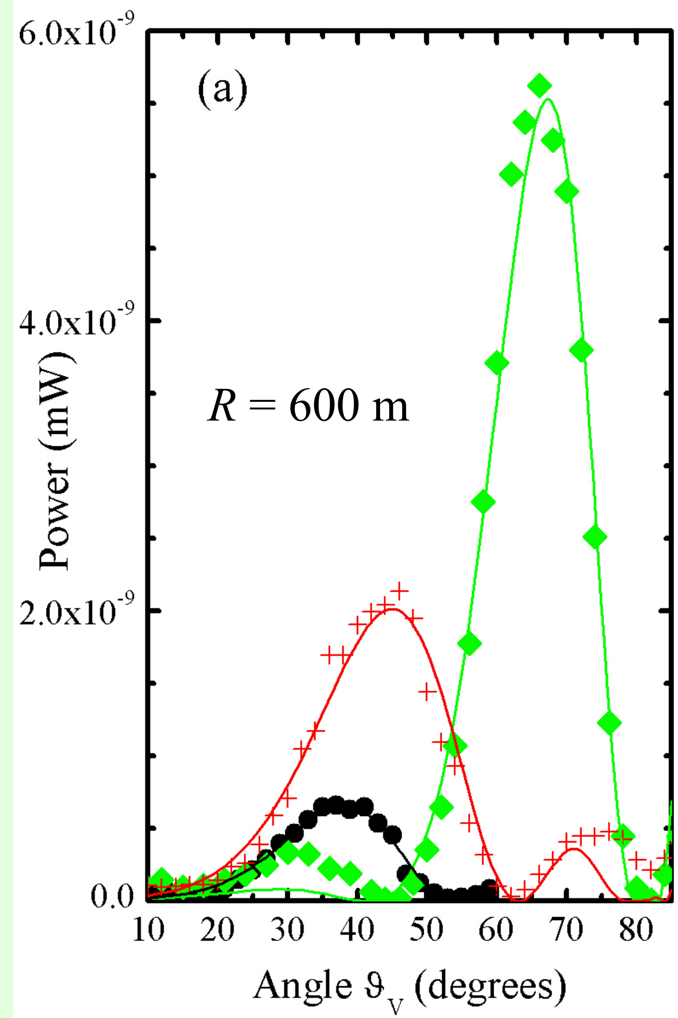
Constructed by Ardavan, Ardavan, Singleton et al. at Oxford University.



Does it work? Simplest test: can we get Cerenkov radiation into the vacuum? Yes!







Expect Çerenkov-like emission peaked at θ V = arcsin{*R/R*P [1-(*mc/nv*)] } with

n = 2π *f/ω* ; *m* = *η/ω* . Data are for *η*/ 2π = 552.654 MHz, Ω/ 2π = 46.042 MHz

and *f* = |*Ω*+*η*|/ 2π : speed *v/c* = 1.06 (dots), 1.25 (crosses), 2.00 (diamonds).

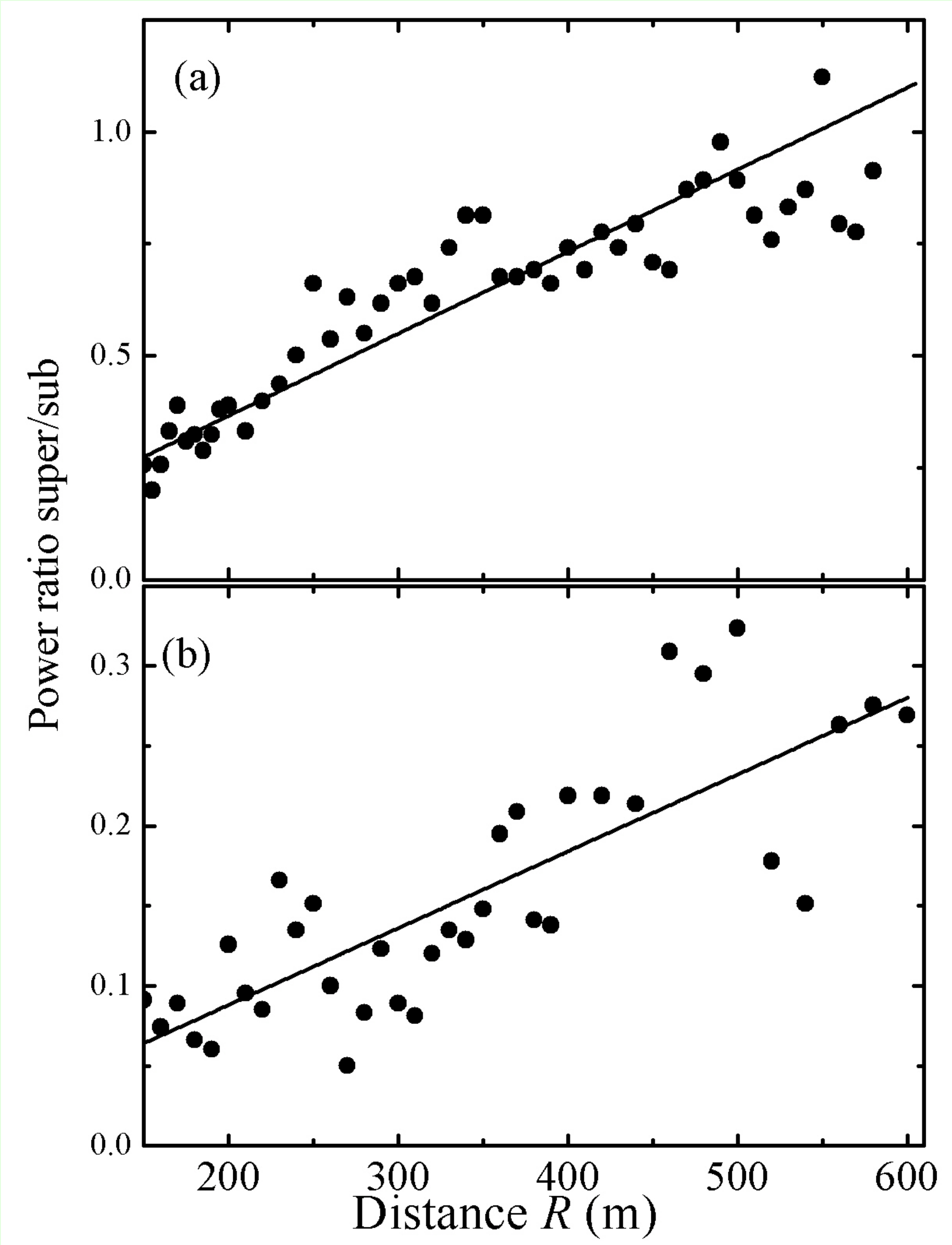
Emission moves to higher angles as *v* increases. *Curves are model with source*

Characterizing the cusp

Both figures show data recorded along the expected cusp direction. (The weather conditions differed between (a) and (b).)
Data are plotted as the ratio of the power with the machine running superluminally ($v/c = 1.06$) to that with it running subluminally ($v/c = 0.875$). (Frequencies as previous figure.)

The line is a fit to the function (power ratio) = CR with µ = 1.

This implies that the power on the cusp falls off as $1/R$ *as predicted by the theory papers.*



Computational studies

The Liénard-Wiechert field of a point source in uniform superluminal rotation at $(\mathbf{x}_p, t_p)$ is given by:

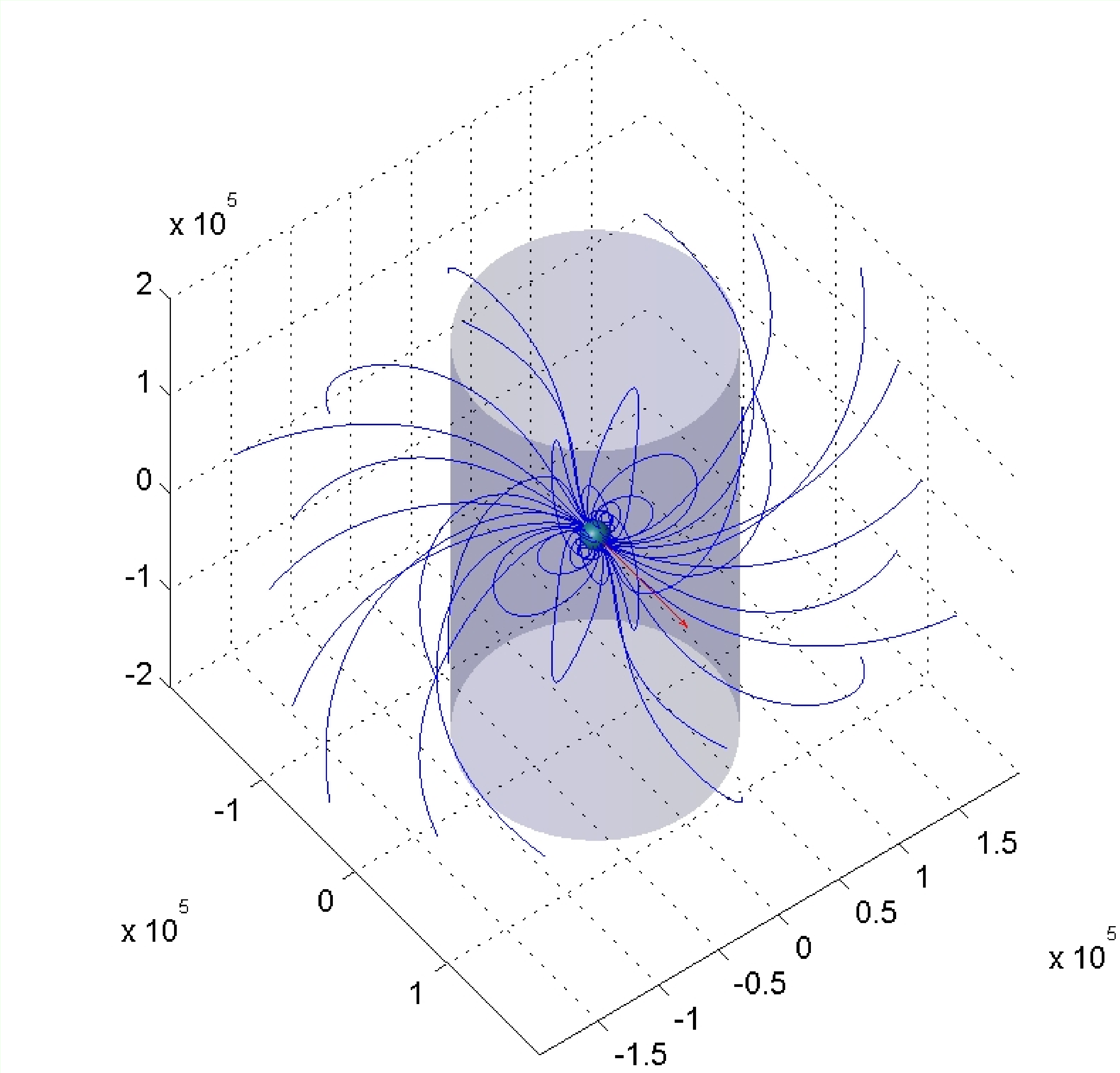
$$E(x_P, t_P) = q \sum_{t_{ret}} \left[\frac{\left(1 - |\dot{x}|^2 / c^2\right) u}{|1 - \hat{n} \cdot \dot{x} / c|^3 R^2(t)} + \frac{\hat{n} \times (u \times \ddot{x})}{c^2 |1 - \hat{n} \cdot \dot{x}|^3 R(t)} \right],$$

$$B = \hat{n} \times E.$$

Here, $R(t) \equiv x_P - x,\ \dot{x} \equiv dx/dt,\ u \equiv \hat{n} - \dot{x}/c,$ and the unit vector $\hat{n} \equiv R/R$ designates the radiation direction.

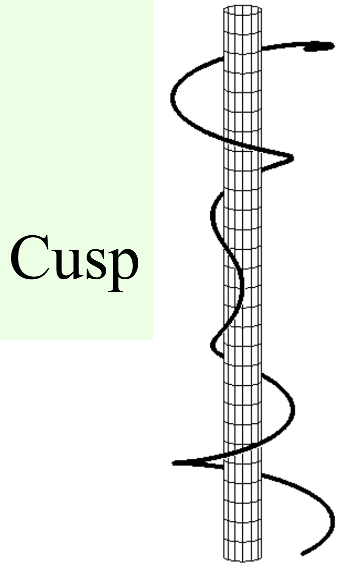
A unique characteristic of superluminal sources is that the radiation received at any given observation point can contain contributions from more than one retarded time.

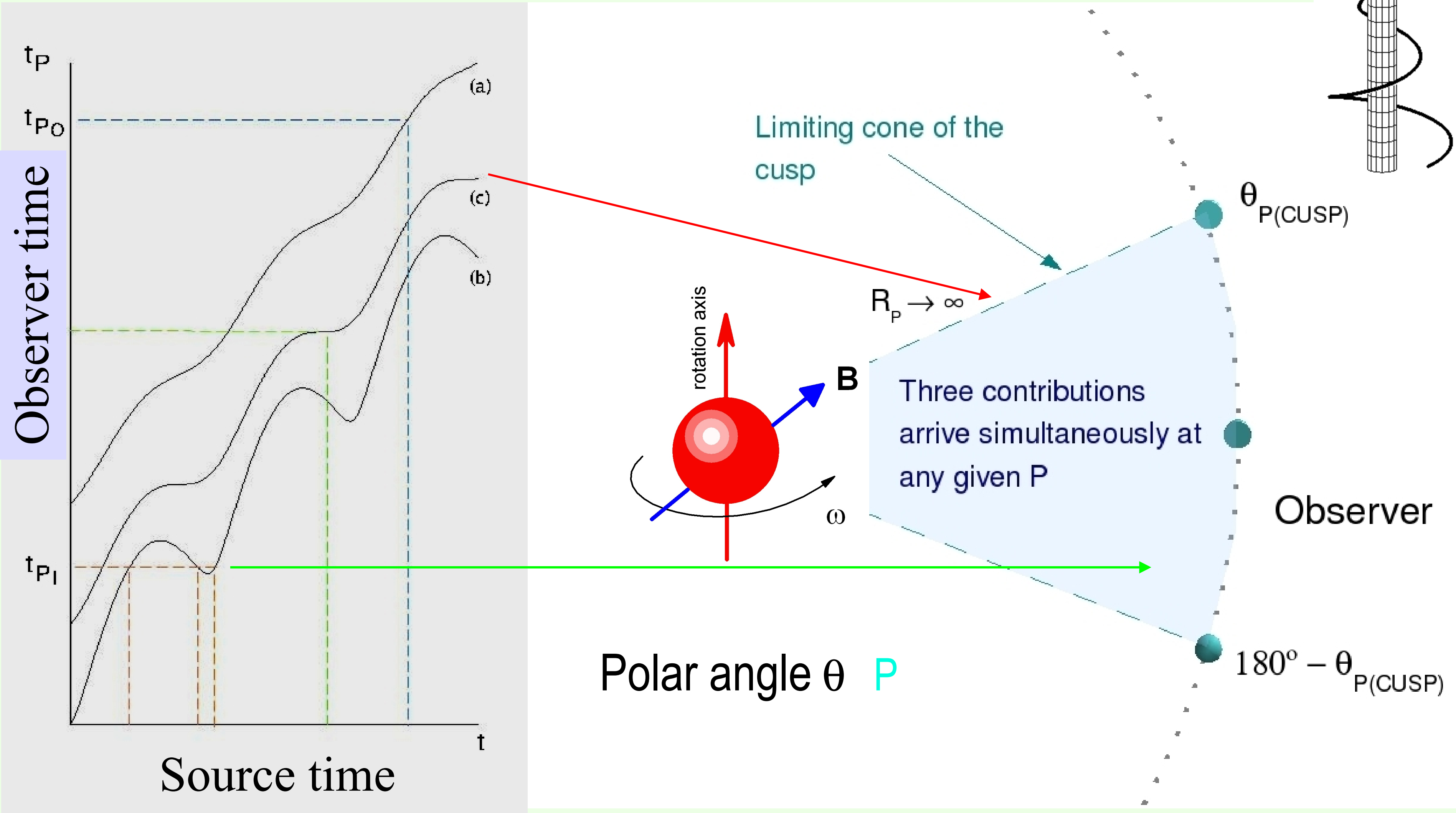
Relativistic simulations by Petr Volegov (P-21); grey denotes the light cylinder.



Numerical simulations:

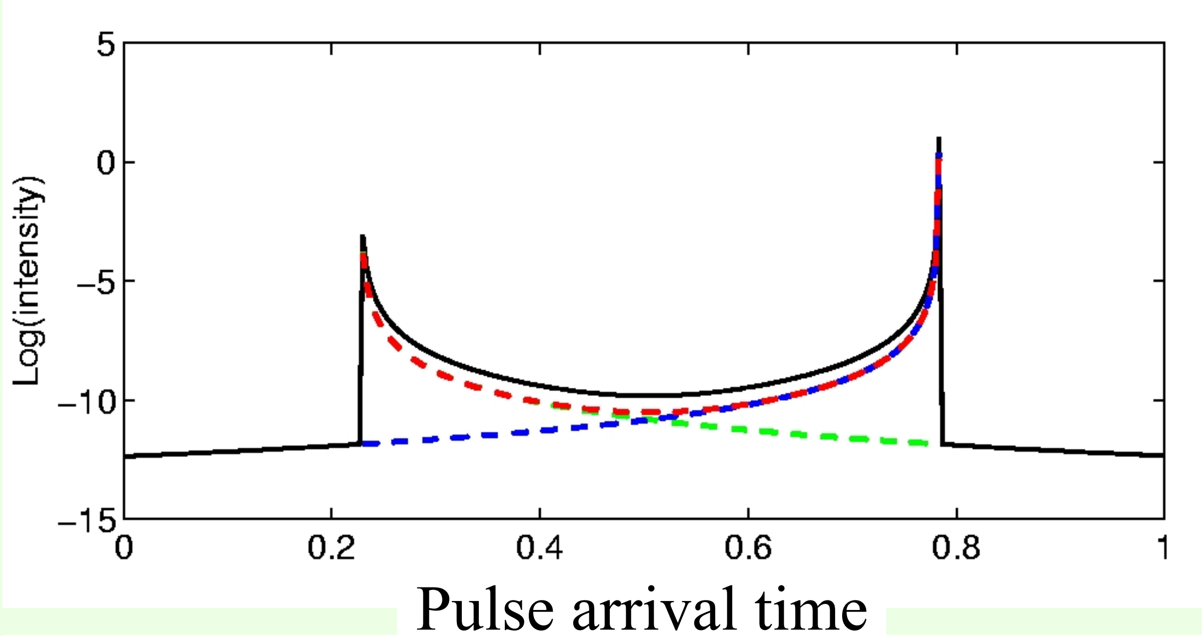
Calculate Liénard-Wiechert fields for a compact source moving on a circular path faster than the speed of light. Solutions shown will be for polar angles where three retarded times are observable and for v. large *R*.



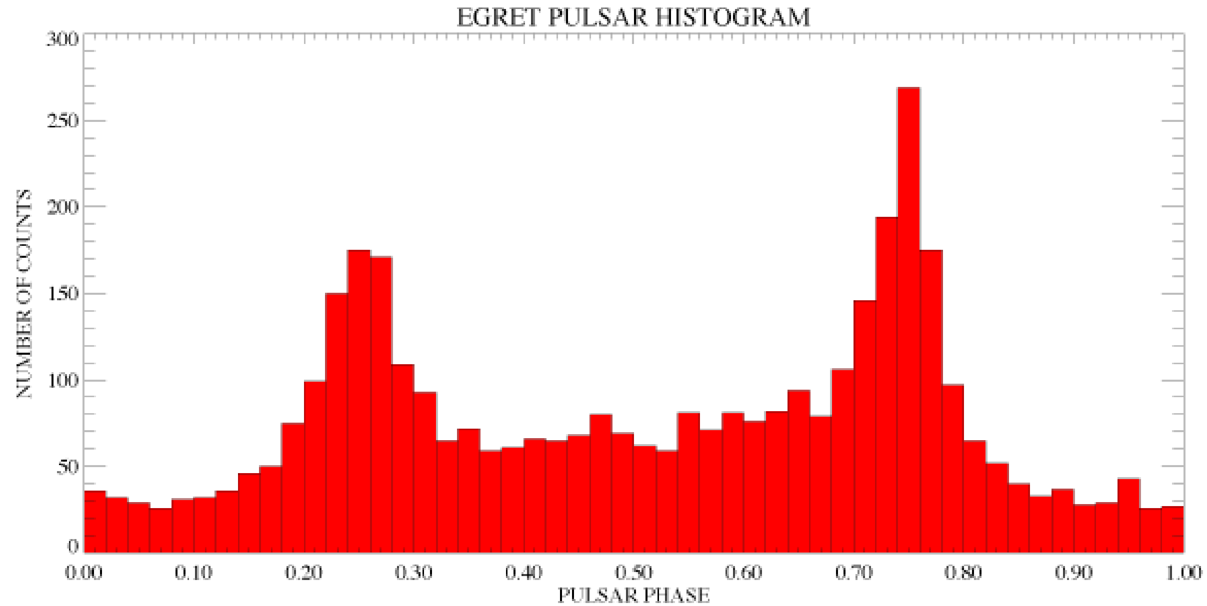


Results of numerical calculations:

Top: Calculated intensities of the contributions from the three retarded times (colour) and their resultant (black).



Bottom: Observation of gamma-ray intensity from Geminga detected by by the EGRET instrument on the Compton Gamma Ray Observatory (Hankins and Rankin, 2006).



Stokes parameters provide a description of the polarization state of electromagnetic radiation: widely used for astrophysical data.

$$I = |E_{pa}|^2 + |E_{pp}|^2$$

$$\frac{Q}{I} = \frac{|E_{pa}/E_{pp}|^2 - 1}{|E_{pa}/E_{pp}|^2 + 1}$$

$$\frac{U}{I} = \frac{2|E_{pa}/E_{pp}|\cos\delta}{|E_{pa}/E_{pp}|^2 + 1}$$

$$\frac{V}{I} = \frac{2|E_{pa}/E_{pp}|\sin\delta}{|E_{pa}/E_{pp}|^2 + 1}$$

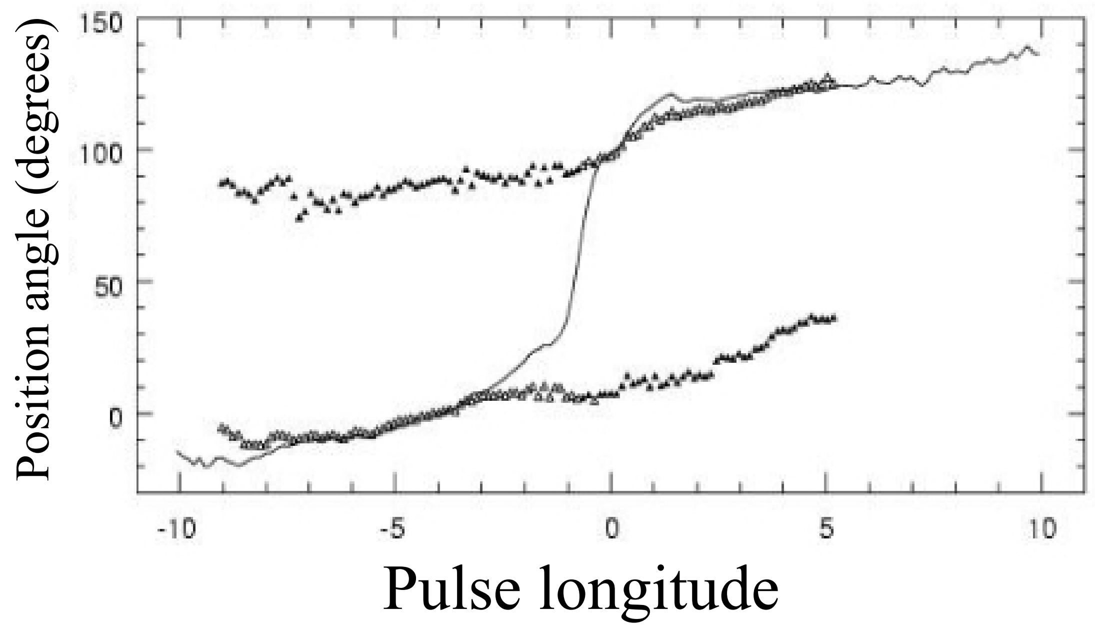
(pa = parallel, pp = perpendicular)

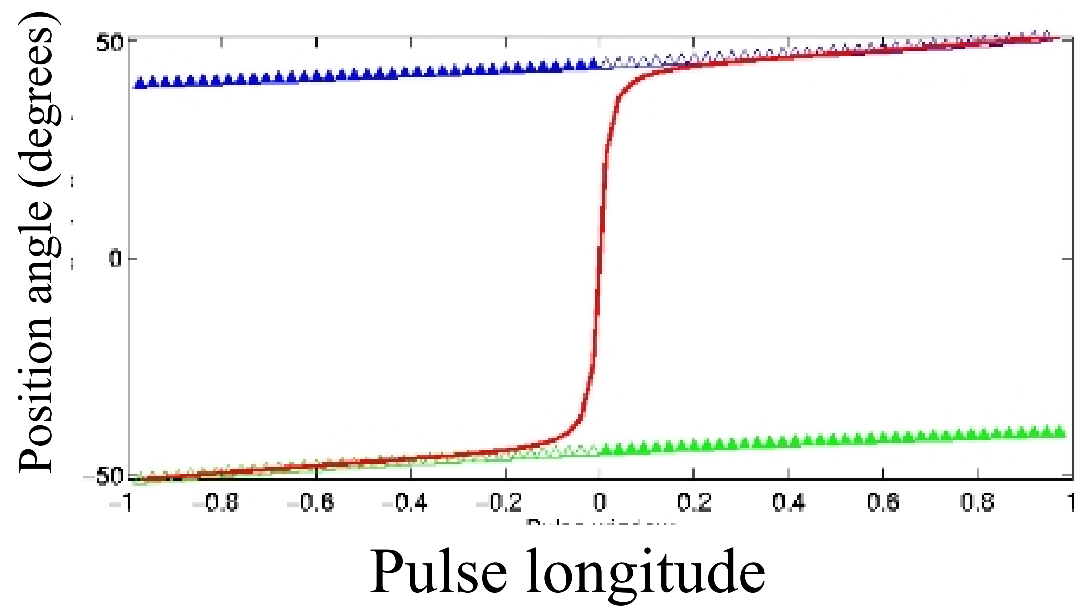
- Degree of circular polarization: V / I
- Degree of linear polarization: $L / I = (Q \quad + U \quad) \quad /I$
- Polarization position angle: $(1/2)\ \arctan(U/Q)$

Stokes parameters of observations are reproduced

Data: position angle histogram of PSR 2016+28 at 1404 MHz. [McKinnon: Astrophys. J. 590:2, 1026]. Presence of “mystery third component” bridging the middle of the pulse.

Calculation: the three retarded times reproduce all of the features of the observational data, including the 90 degree swing.





Use **Maximum Likelihood Analysis** to determine luminosity function $\phi(L)$.

Analysis allows for instrumental sensitivity.

The luminosity L is related to the flux by
$L = d\ S_{1400}$.

n = 1 supports the superluminal model; n = 2 implies conventional inverse square.

The probability that a pulsar at distance d and luminosity L_i is observed is given by

$$p_i \propto \phi(L_i) / \int_{L_{min}(z_i)}^{\infty} \phi(L) dL. \qquad (24)$$

We can define a likelihood function

$$\mathcal{L} = \prod_i p_i$$

We utilize a technique that does not assume a simple functional for $\phi(L)$. Instead we parameterize the luminosity function as N_b steps.

$$\phi(L) = \phi_k, \quad L_k - \frac{\Delta L}{2} < L < L_k + \frac{\Delta L}{2}, \quad k = 1, ..., N_b \qquad (25)$$

The maximum likelihood function assumes the form

$$\ln \mathcal{L} = \sum_{i=1}^{N_p} W(L_i - L_k) \ln \phi_k - \sum_{i=1}^{N_p} \ln \left(\sum_{j=1}^{N_p} \phi_j \Delta L H[L_j - L_{min}(z_i)] \right) + const. \qquad (26)$$

where N_p is the total number of pulsars in the Parkes survey.

$$H(x) = \begin{cases} 0, & -\Delta L/2 \le x \le \Delta L/2 \\ 1, & \text{otherwise} \end{cases}$$

and

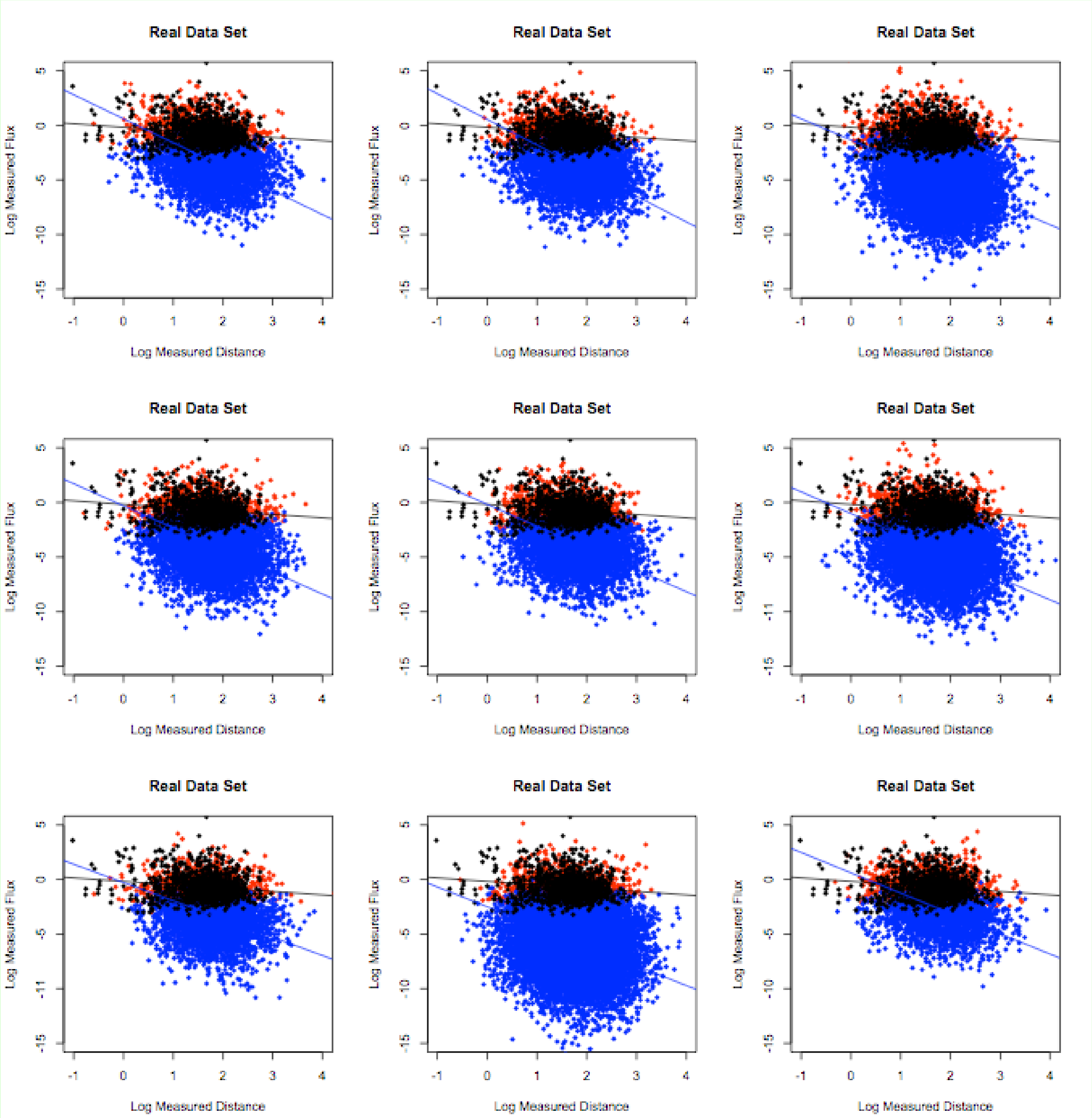
$$W(x) = \begin{cases} 0, & x \le \Delta L/2 \\ (x/\Delta L + 1/2), & -\Delta L/2 \le x \le \Delta L/2 \\ 1, & x \ge \Delta L/2 \end{cases}$$

The parameters ϕ_k determining the luminosity function are given by the self-consistent set of equations

$$\phi_k \Delta L = \frac{\sum_i W(L_i - L_k)}{\sum_i \left(H[L_k - L_{min}(z_i)] / \sum_{j=1}^{N_b} \phi_j \Delta L H[L_j - L_{min}(z_i)] \right)}, \qquad k = 1, ..., N_b (27)$$

The above equations are solved iteratively to obtain the luminosity function.

Results of Bayesian analysis (Todd Graves): need for better telescopes!



Nine possible pulsar populations in our Galaxy: blue and red points are simulated data.

- Blue points represent pulsars which *would not* be detected by the Parkes Multibeam Survey due to instrumental limitations.
- Red points are simulated pulsars that Parkes *would* detect.
- Black points are real observations.

A brief history of superluminal emission.

- Emission from charged particle with $v > c$ studied by Sommerfeld in 1904.
- Work ignored, as Einstein's Special Relativity, forbidding $v > c$, published a few months later (1905).
- Several authors point out that no superluminal source can be point-like ($E = \infty$ on wavefronts from it).
- Ginzburg, Bykov and Bolotovskii (Soviet Union, 1979-1990); no physical principle forbids *extended*, massless superluminal sources.
- H. Ardavan publishes a model of pulsars based on superluminal emission.
- First practical device built in Oxford (UK) by Ardavan, Ardavan, Fopma, Halliday and Singleton (2002).

The "Lawbreakers?" in the title comes from a report on our being funded (approx. $500K) by the EPSRC (UK) to build the first practical device. This can be read in the *Economist* magazine (1 Sept, 2000). The article commences "You cannot break the laws of physics. But that is exactly what a group of… researchers is trying to do…"

Later in the article, an eminent astronomer refers to the project as "a waste of tax-payers' money!"

As we shall see, no laws of physics are broken by this experiment.