Theory of Pulsar Winds

F. Curtis Michel
Rice University

13 July 2005

http://psr.rice.edu/PulsarMech

Valued Coworkers

Bonnie Hausman

Hui Li

Ian Smith

Steve Sturner

Jurgen Krause-Polstorff

Encyclopedia of the Future

Article: “How Radio Pulsars work” (outline).

- Rotating NS + B -> central Q + quadrupole E field
- Neutron star completely surrounded with MHD plasma
- Aligned model good as any (“inclination ads nothing new”)
- Weak particle acceleration because E fields shorted out
- No plausible source of coherent radio emission

Encyclopedia of the Future (alt)

Article: "How Radio Pulsars work" (outline).

- Rotating NS + B -> central Q + quadrupole E field
- Neutron star surrounded by dome/torus of MHD plasma
- Inclined model essential
- Huge particle acceleration because E fields not shorted out except in dome/torus of non neutral plasmas (single sign)
- Particles accelerated and emit synchrotron gamma rays which magnetically convert to pairs and form dense bunches
- Bunches amplify incoherent radiation to provide coherent

THE ASTROPHYSICAL JOURNAL, Vol. 148, April 1967

THE ANGULAR MOMENTUM OF THE SOLAR WIND*

EDMUND J. WEBER AND LEVERETT DAVIS, JR.
California Institute of Technology, Pasadena, California

Received August 29, 1966; revised October 6, 1966

ABSTRACT

A steady-state model of the solar-wind flow in the equatorial plane including the effects of pressure gradients, gravitation, and magnetic forces is developed and solved for both the radial and azimuthal motions. The viscosity is taken to be zero, the electrical conductivity to be infinite, and the energy supply characterized by a polytropic index. The solution must pass through three critical points, whose significance is explained in terms of the characteristic velocities with which disturbances propagate. A numerical solution is obtained for typical parameters The magnetic field produces only a modest tendency toward co-rotation of the outer corona, but the magnetic stresses apply a torque to the Sun equal to that required to produce effective co-rotation out to the radial distance where the radial Alfvénic Mach number equals unity. For typical solar-wind values this will occur between 15 and 50 solar radii out, which implies a substantial loss in the angular momentum of the Sun.

THE ASTROPHYSICAL JOURNAL, Vol. 158, November 1969

RELATIVISTIC STELLAR-WIND TORQUES

F. C. MICHEL
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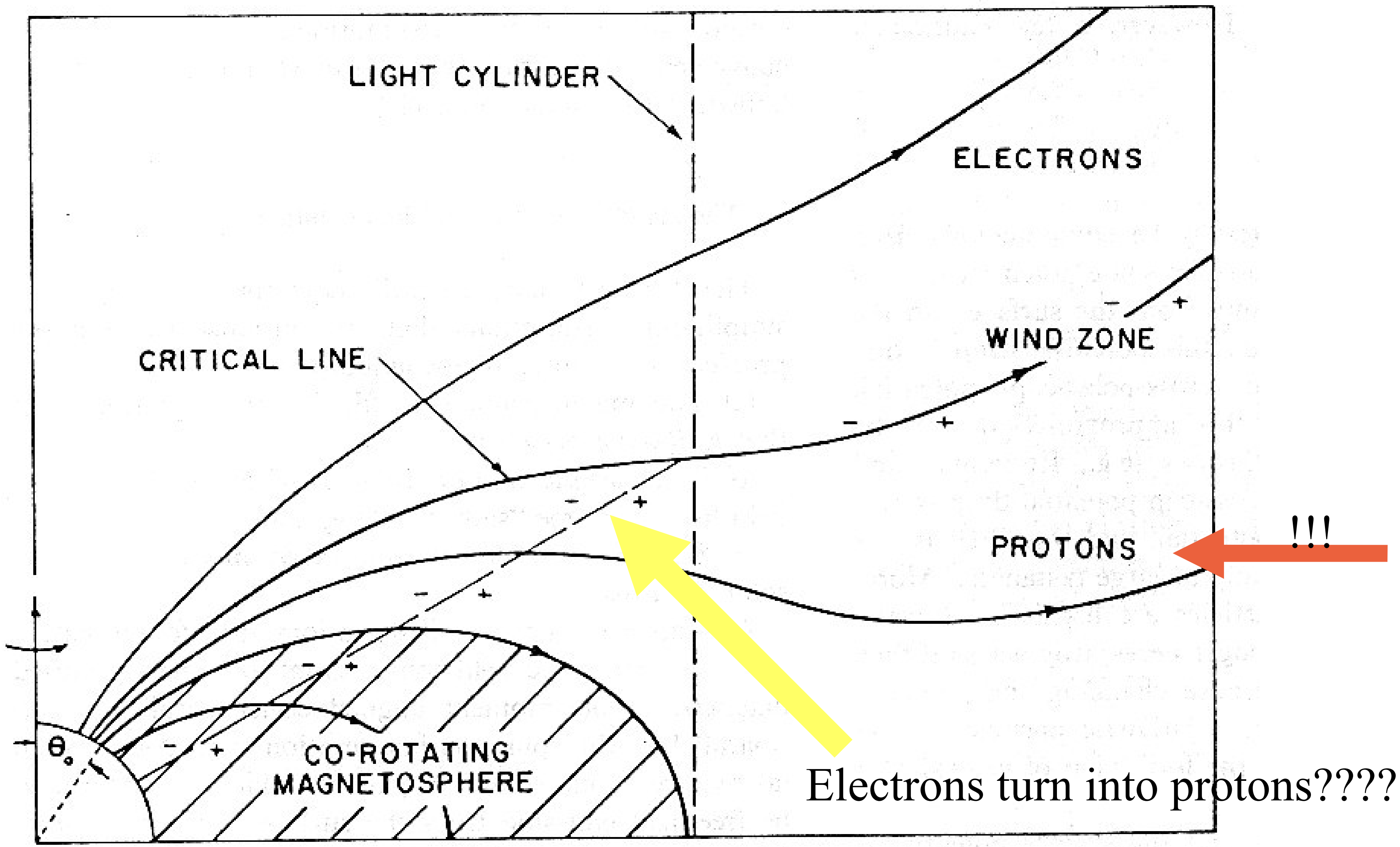
Received 1969 May 7; revised 1969 June 17

ABSTRACT

Several authors have calculated the torque on the Sun owing to the solar wind. We extend those treatments to encompass both special- and general-relativistic effects. A direct parallel treatment is feasible, and the major correction is, as would be expected, from the increased effective mass density of a relativistic fluid. The treatment may be extended approximately to the limit of zero mass loss, wherein the torque is entirely from the electromagnetic energy radiated by the rotating magnetic moment of the star. Application to rotational models of pulsars is illustrated with the conclusion that NP 0532, for example, would have a magnetic moment of order 3×10^{28} gauss cm^3 (within certain assumptions regarding the rate of mass loss). Centrifugal forces are capable of accelerating the plasma to ultrarelativistic velocities, even in the magnetohydrodynamic approximation. The existence of pulsars therefore suggests a new and highly efficient source of relativistic particles.

Aligned MHD model (GJ)



Well-Known (and Ignored) Pathologies of the Model

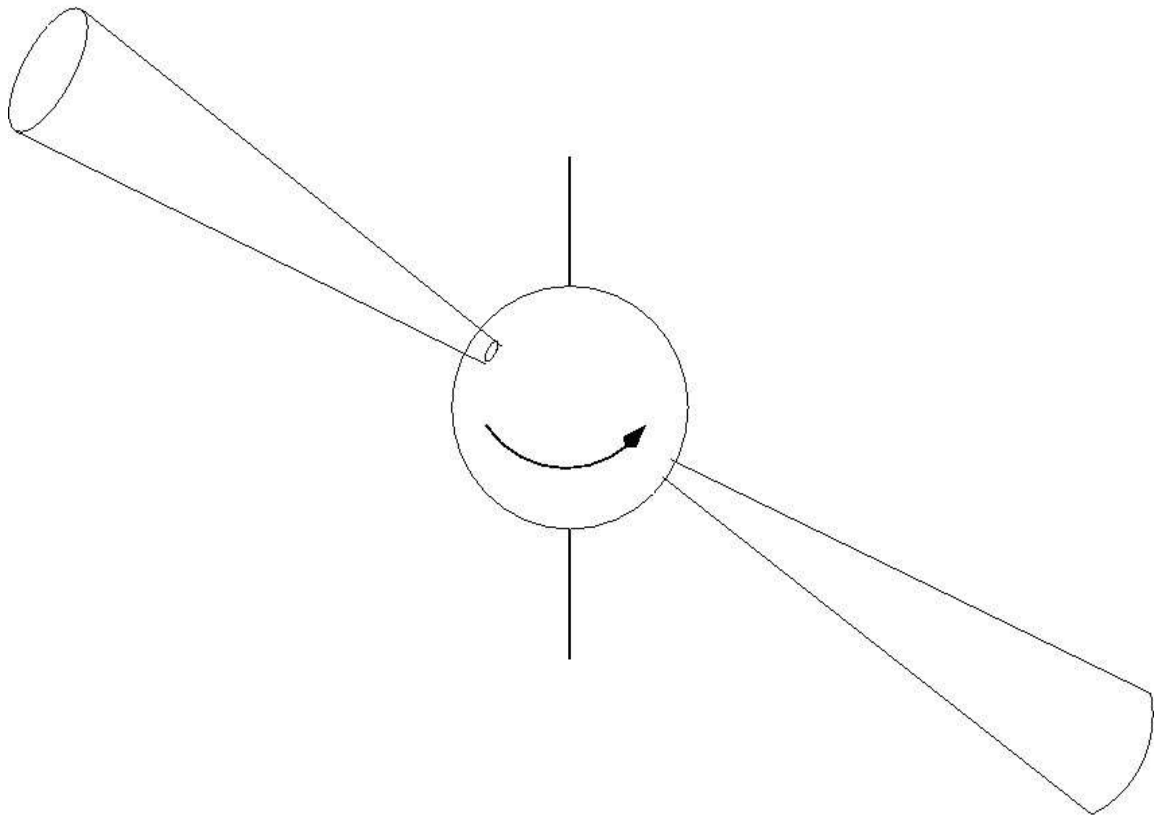
1) Assumes MHD everywhere

2) Assumes particles come from surface! *Easily shown that this is inconsistent with (1) just above*

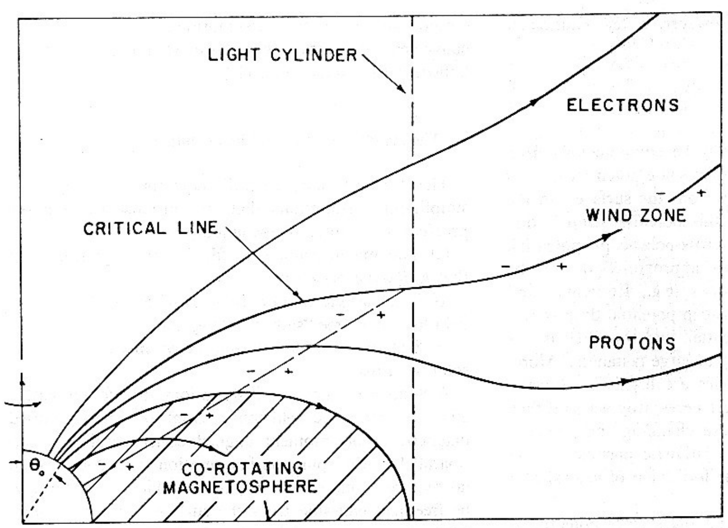
3) Assumes flow changes sign across a boundary!!

4) Magnetic field lines near and beyond light cylinder

Phenomenological Hollow Cone Model



Only the most generic connection with this model



It's all been done before:

Proceedings of the American Physical Society

University of California, Los Angeles, California, January 2-3, 1948

Phys. Rev. 73, 536 1948

D4. Stellar Electromagnetic Fields. LEVERETT DAVIS, JR., *California Institute of Technology.*—The electromagnetic field in the neighborhood of a rotating magnetized body such as the earth or sun is best treated in an inertial system, one that does not rotate with the body. The stellar model considered is one in which the magnetic field is that of a dipole parallel to the axis of rotation, the field strength at the surface of the star at the pole being B_p. Rationalized m.k.s. units will be used. If the field due to the ions in the neighborhood of the star is negligible, the electrostatic potential outside the star is $V = V_p(a/r)^3P_2(\cos\theta)$ where $V_p = B_p\omega a^2/3$, a is the radius of the star, ω its angular velocity, and (r, θ, ϕ) are spherical polar coordinates. Consideration of the motion of the ions in such a field shows that a space change will accumulate that cannot be neglected. When a steady state has been attained, if one neglects the effect of unionized interstellar material, it appears that the external space charge rotates with the same angular velocity as does the star, that the change in the magnetic field is very small, but that the electrostatic potential is now, to a first approximation, $V = -\frac{3}{2}V_p(a/r)\sin^2\theta$.

Journal of Geophysical Research Vol. 70, No. 19 October 1, 1965

Electric Field Generated by a Rotating Magnetized Sphere

Edward W. Hones, Jr., and John E. Bergeson

Department of physics and Astronomy
State University of Iowa, Iowa City

"Davis [1947, 1948] showed that plasma surrounding a rotating, conducting
magnetized sphere will rotate with the sphere if the plasma particles are
is constra

$$\rho = -\frac{\mu\omega}{2\pi c r^3}\{[3\cos^2\theta - 1]\cos\gamma + [3\sin\theta\cos\theta\cos(\phi - \omega t)]\sin\gamma\} \quad (17)$$

Summary to here

- Aligned MHD model usually credited with “charge density” but this was worked out 21 years earlier and revived 4 years earlier.
- Model clearly assumes particles from surface, but clearly particles from low latitudes (+) trapped close to star on huge B fields (torus)
- Particles from high latitudes (-) could escape but don't owing to positive charge on star (domes)
- MHD true, but only where there is (non neutral) plasma and completely wrong everywhere else

NB: L. Davis, Jr. and P. Goldreich both physics professors, Caltech, 1967-2003

THE ASTROPHYSICAL JOURNAL, 227:579–589, 1979 January 15

VACUUM GAPS IN PULSAR MAGNETOSPHERES*

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Departments of Space Physics and Astronomy, of Physics, and of Mathematical Science, Rice University
Received 1978 May 26; accepted 1978 August 1

ABSTRACT

We show, by giving several explicit examples, that a charge-separated magnetosphere about a star can have vacuum voids within it. These can range from the small polar "gaps" discussed by Ruderman and Sutherland to being so large that the charge particles are confined to a disk or even a ring about the central object. Insofar as the pulsar problem is concerned, the possible existence of such structuring appears to remove one of the outstanding roadblocks to the construction of self-consistent models.

Subject headings: hydromagnetics — plasmas — pulsars

THE QUIET ALIGNED ROTATOR*

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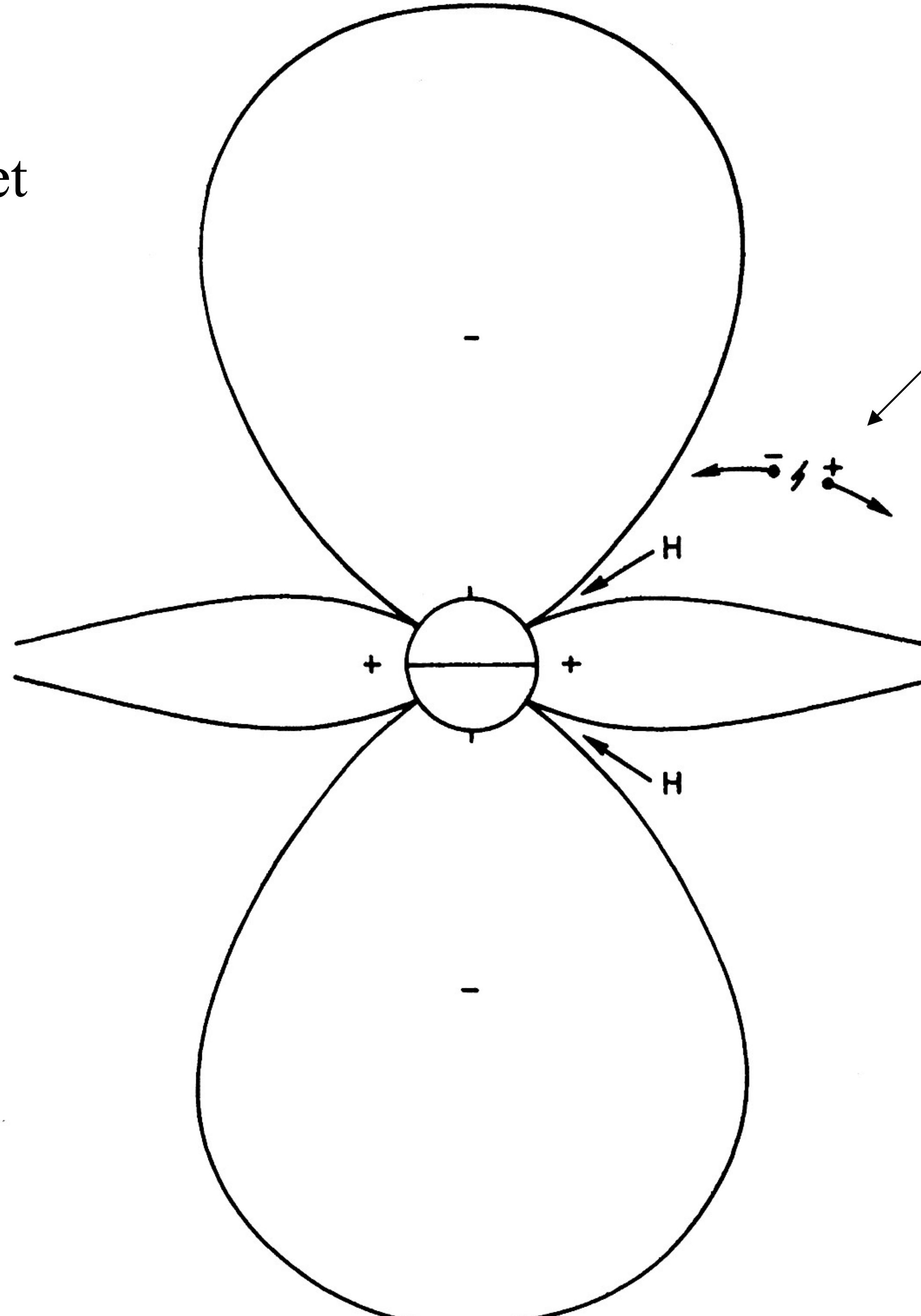
Plateau de Palaiseau, Palaiseau, Cedex, France

(Received 18 February, 1980)

Abstract. We conclude that the magnetospheric structure around an aligned rotating magnetized neutron star, in the case of a completely charge-separated plasma, consists of a dome of charge about the polar caps and an equatorial disk of opposite charge which, together, entirely envelope the surface but do not fill the magnetosphere. Although the aligned rotator is a 'standard model' for analyzing pulsar emission, the magnetosphere we obtain need not emit particles and need not generate a stellar wind, contrary to previous expectations. Pair production only seems to modify the detailed shape of the dome and disk, such modification serving to shut off further pair production. Such a magnetohydrodynamically inactive object may have difficulty simulating pulsar emission.

Fig. 1 from Quiet Aligned Rotator

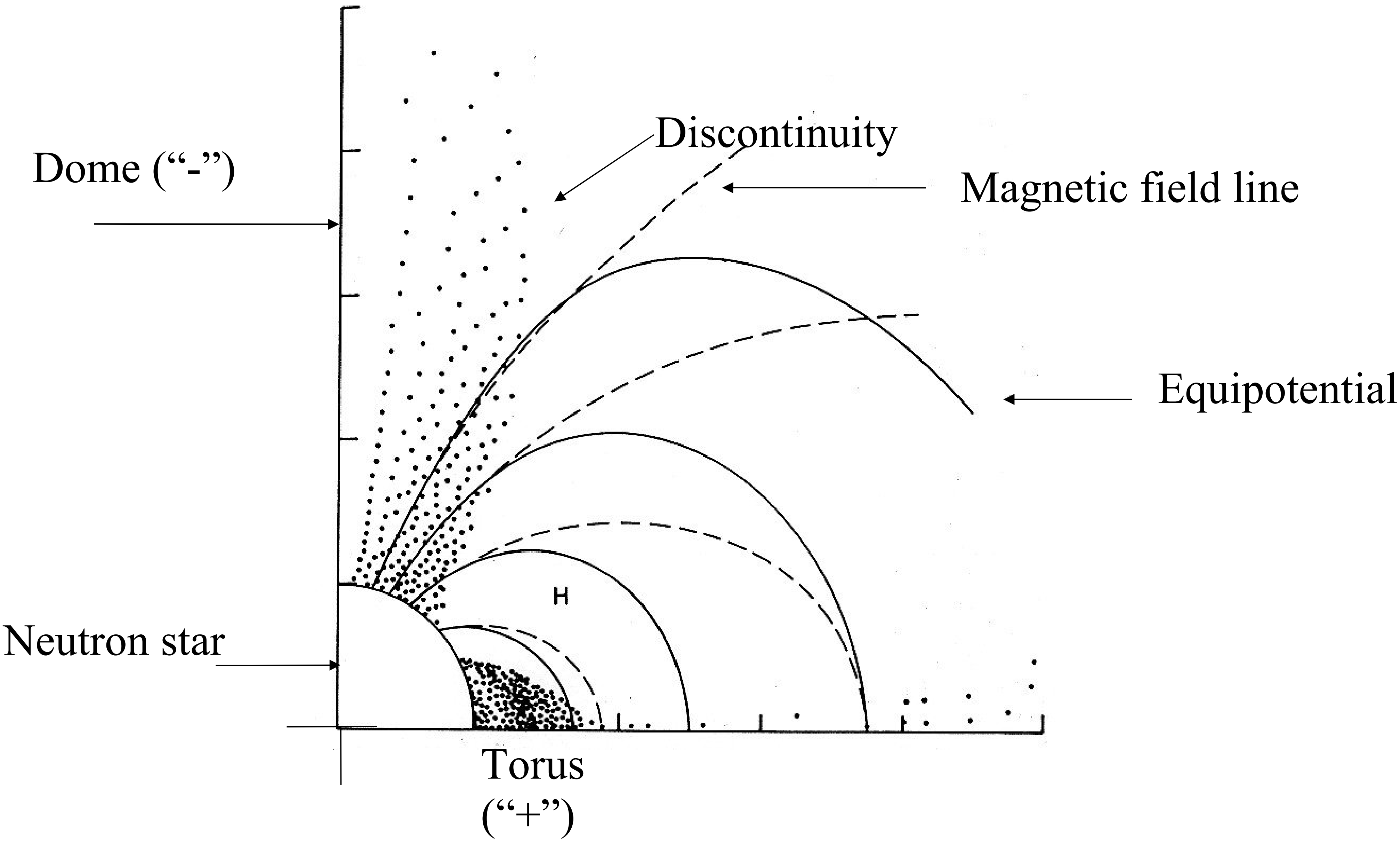
Pair production can't change result significantly



Need for quantitative Results

- Had Jurgen Krause-Polstorff working at Rice Univ. with Prof. Dick Wolf while FCM on sabbatical in France
- Program was to directly simulate the aligned MHD model by releasing charges from surface of rotating magnetized NS
- Equilibrium conditions imposed by relaxation (to give MHD)
- Particles released until none left (self terminating program)

The dome/torus of Krause-Polstorff

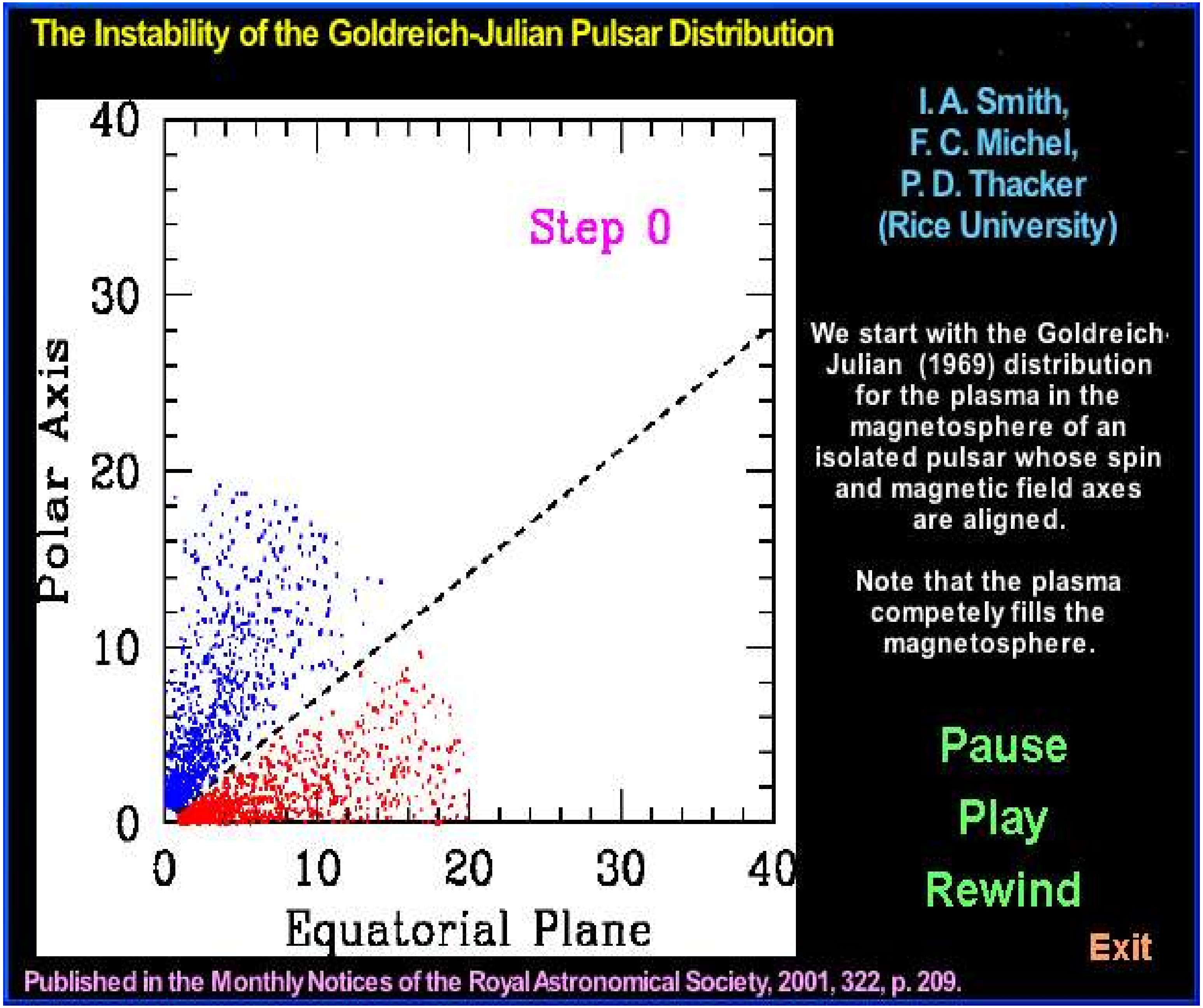


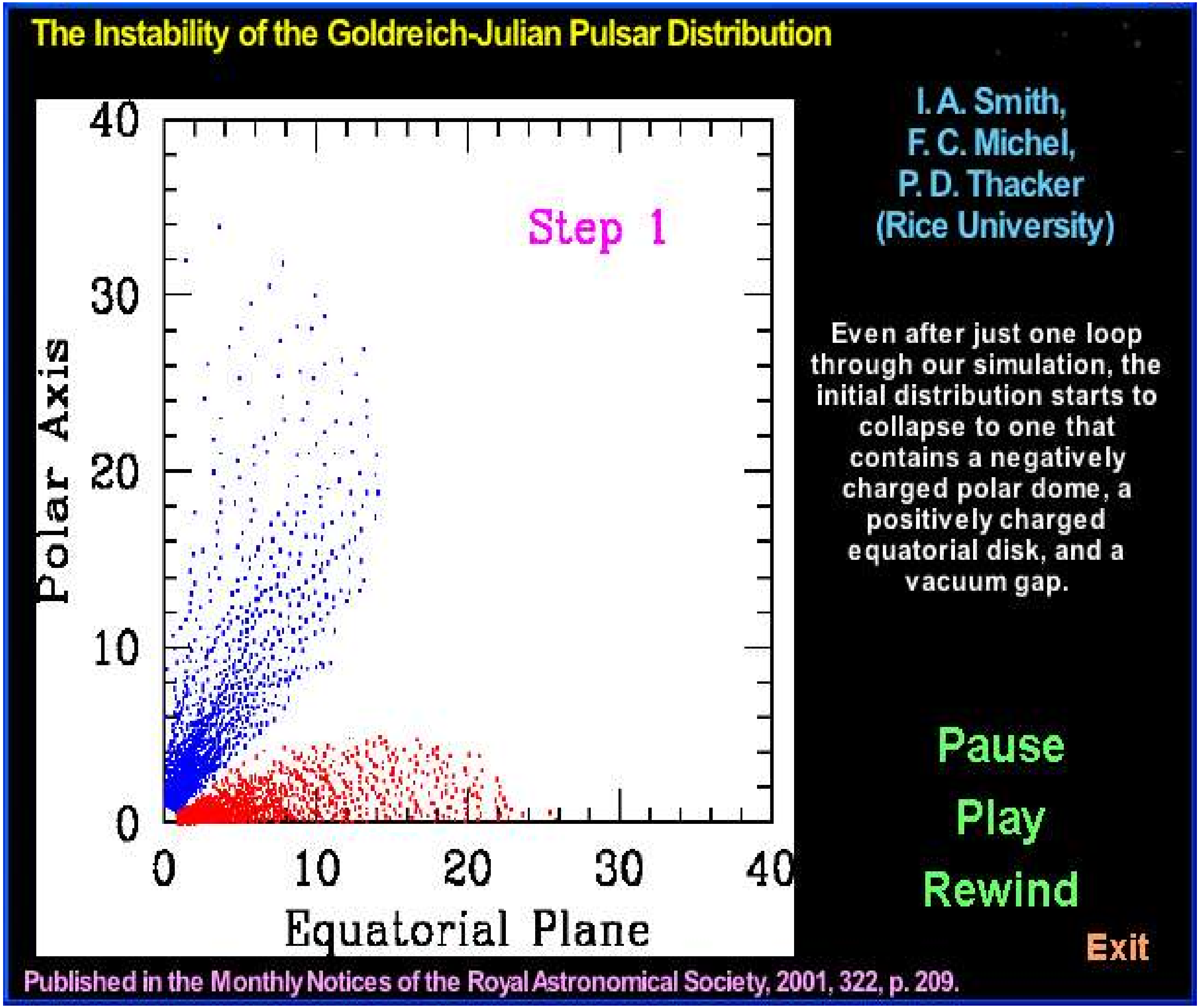
Which is right?

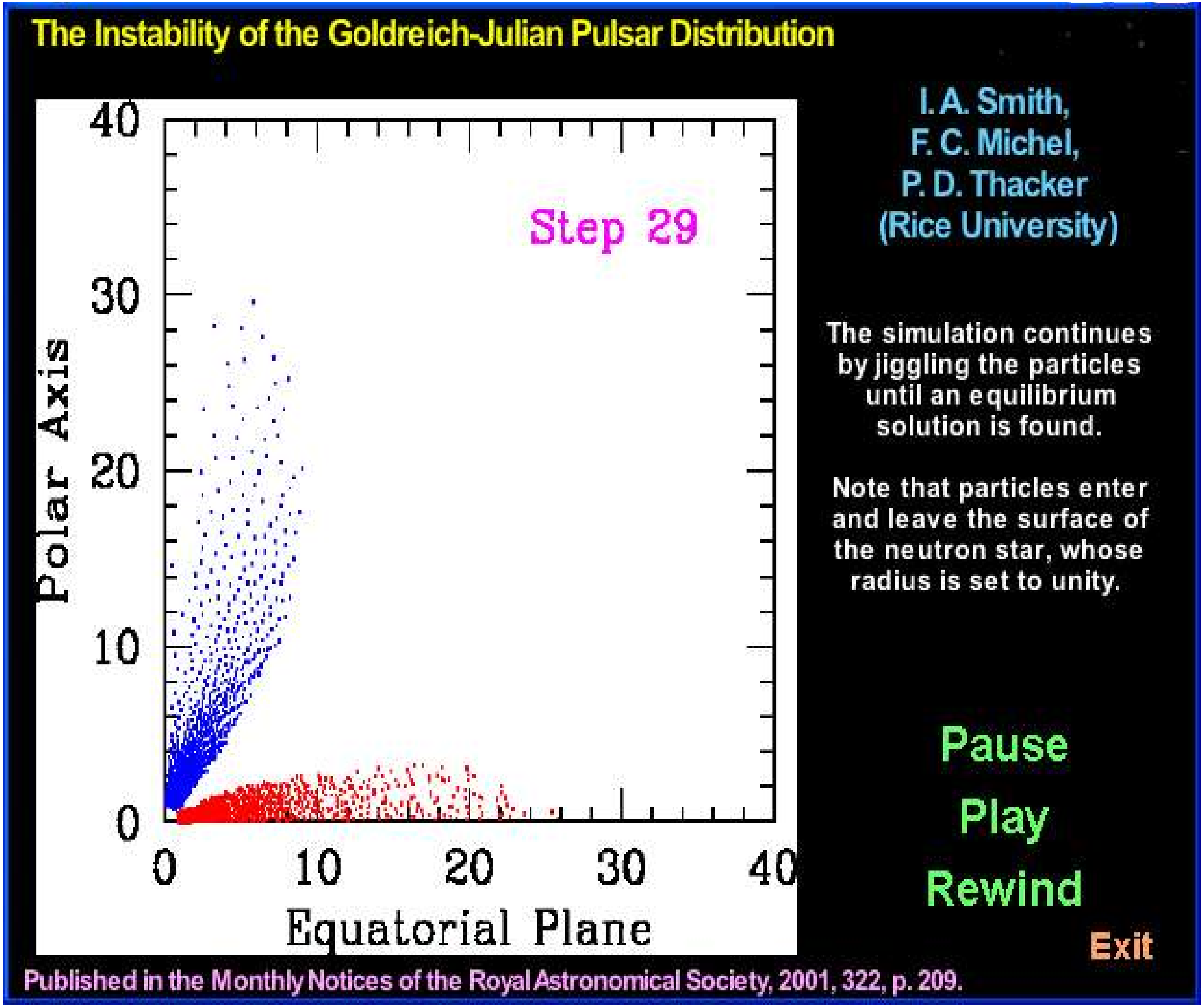
- Myth: MHD (everywhere) has to be true so plasma has to be everywhere
- Completely inconsistent with plasma-pulled-from-surface (has to be non neutral!).
- Modified program to act "dynamically" to show that even if one *forced* the solution to be that of the aligned MHD, it simply fell apart!

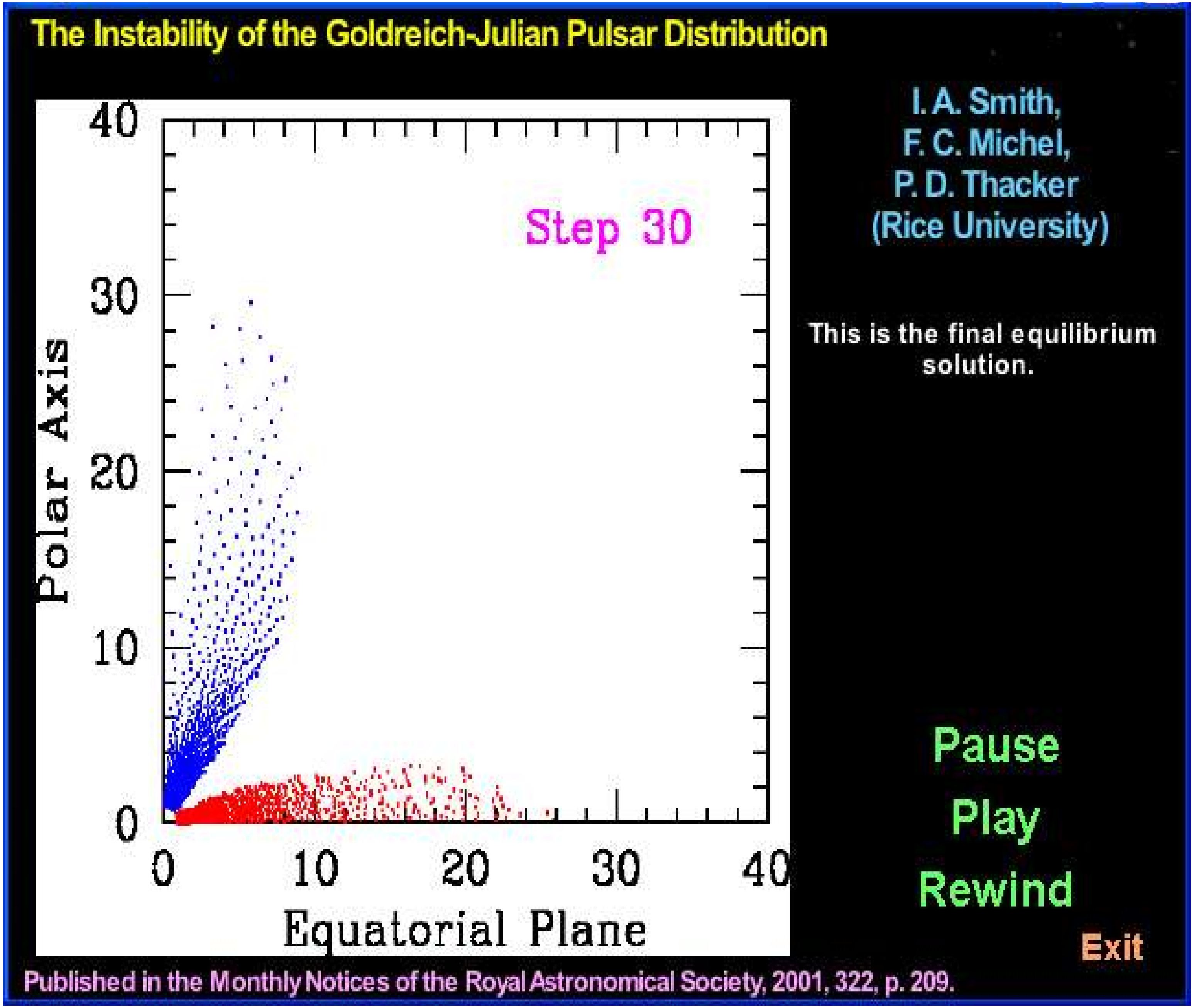
Collapse of GJ to Dome/Torus

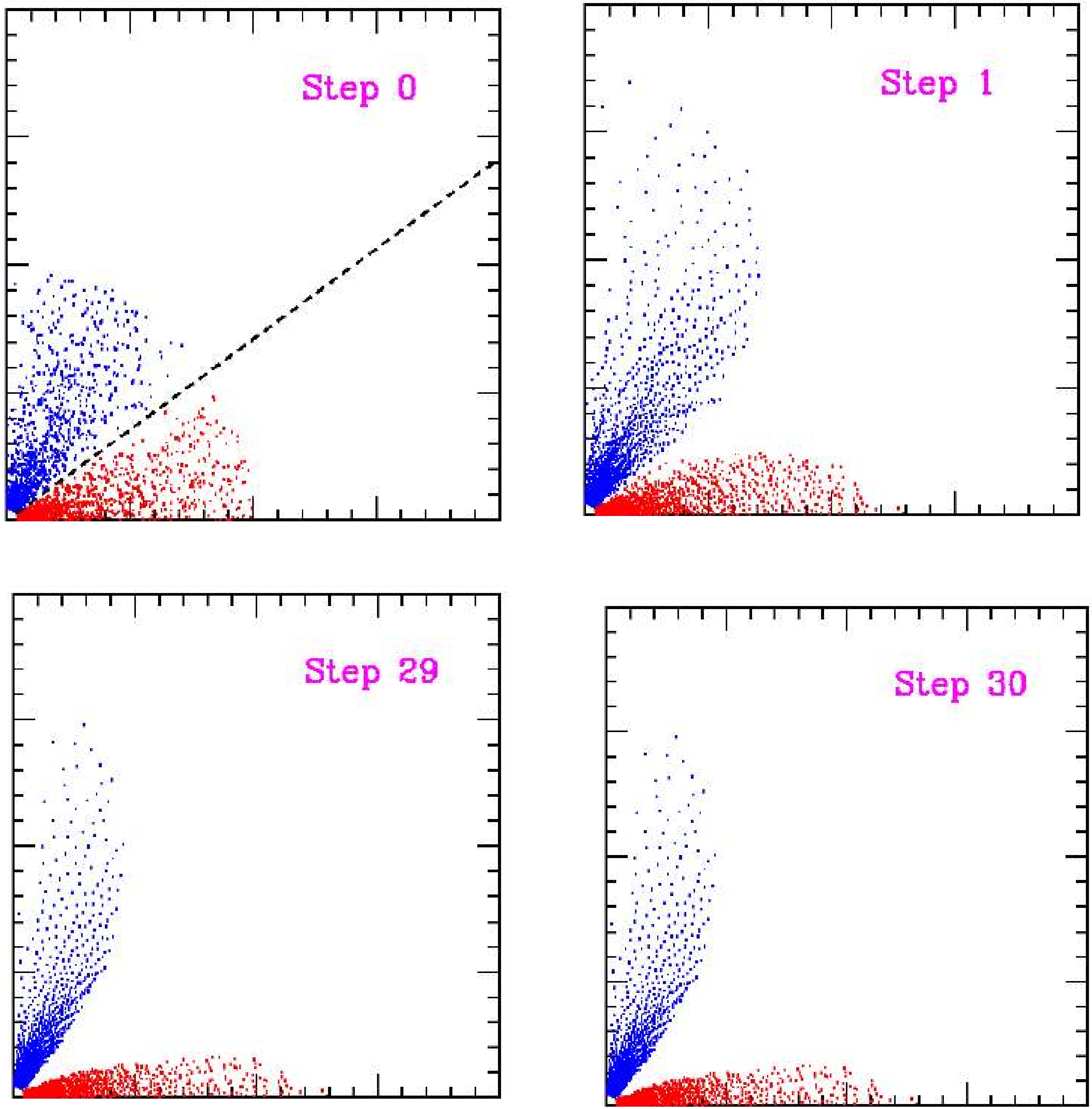
Backup Stills of GJ collapse to Dome/Torus




The Instability of the Goldreich-Julian Pulsar Distribution
I. A. Smith,
F. C. Michel,
P. D. Thacker
(Rice University)
Step 1
Polar Axis
Equatorial Plane
0
10
20
30
40
Even after just one loop through our simulation, the initial distribution starts to collapse to one that contains a negatively charged polar dome, a positively charged equatorial disk, and a vacuum gap.
Pause
Play
Rewind
Exit
Published in the Monthly Notices of the Royal Astronomical Society, 2001, 322, p. 209.


The Instability of the Goldreich-Julian Pulsar Distribution
I. A. Smith,
F. C. Michel,
P. D. Thacker
(Rice University)
Step 29
Polar Axis
Equatorial Plane
0
10
20
30
40
The simulation continues by jiggling the particles until an equilibrium solution is found.
Note that particles enter and leave the surface of the neutron star, whose radius is set to unity.
Pause
Play
Rewind
Exit
Published in the Monthly Notices of the Royal Astronomical Society, 2001, 322, p. 209.


The Instability of the Goldreich-Julian Pulsar Distribution
I. A. Smith,
F. C. Michel,
P. D. Thacker
(Rice University)
Step 30
Polar Axis
Equatorial Plane
0
10
20
30
40
This is the final equilibrium solution.
Pause
Play
Rewind
Exit
Published in the Monthly Notices of the Royal Astronomical Society, 2001, 322, p. 209.


Step 0
Step 1
Step 29
Step 30

Others who have discovered dome/torus

Shibata, 1989

Rylov, 1989

Zachariades, 1993

Neukirch, 1993

Thielheim and Wolfensteller, 1994

Spitkovski & Arons, 2002

The “Pulsar Equation”

Rip van Winkle all over again! 1985 to 2005

What has changed? Nothing!

1. Ignore problem (often observational papers)

2. Insist aligned MHD everywhere works (e.g. Mestel et al.)

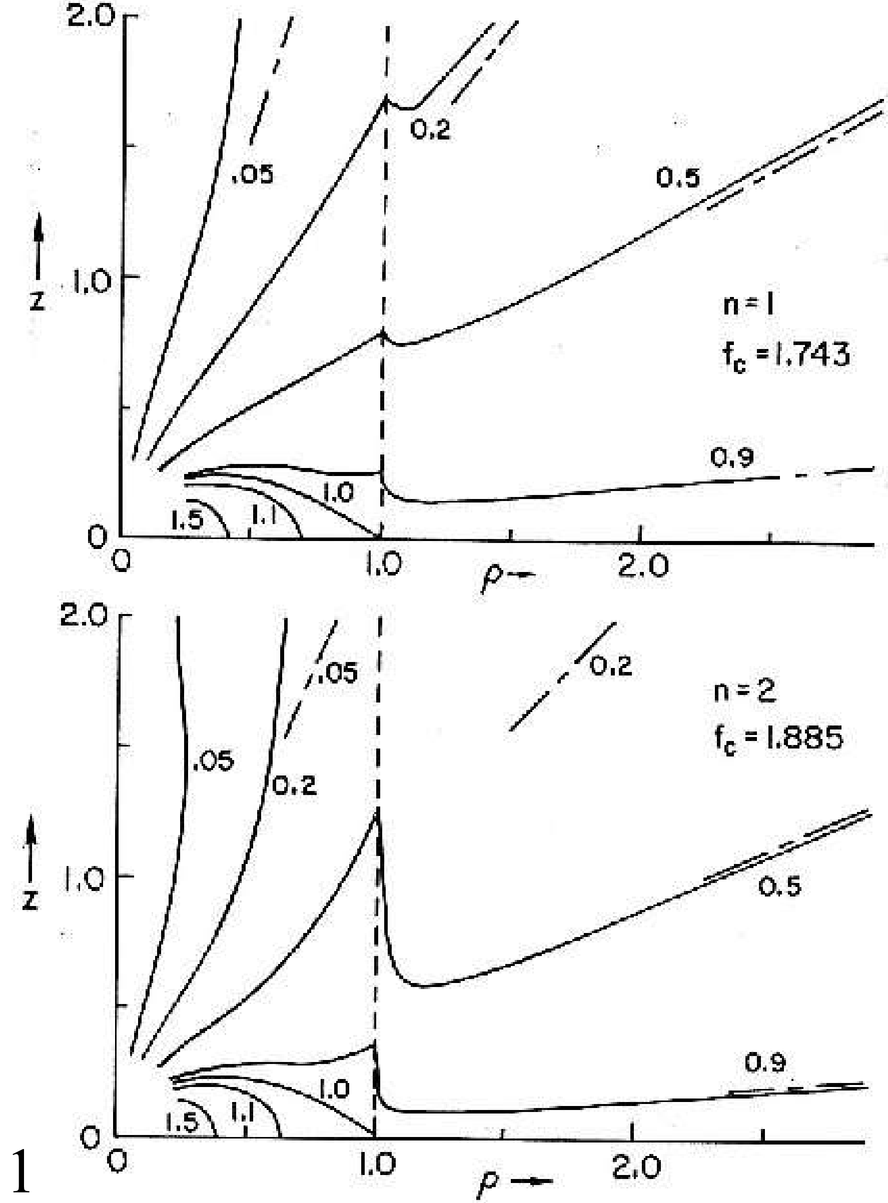
Pelizzari extensions

Assumed simple function

top figure close

computation too difficult (1976)

not important since model unphysical



See Michel, Rev. Mod Phys. 1982, **54**, 1

The Bunching Mechanism

THE ASTROPHYSICAL JOURNAL, 383:808–813, 1991 December 20

FORMATION OF DENSE CHARGED BUNCHES IN VACUUM GAPS

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Received 1990 May 21; accepted 1991 June 25

ABSTRACT

We point out that the pair-production discharge mechanism originally applied to pulsars by Sturrock automatically produces dense bunches that can produce coherence at radio frequencies with sufficient intensity to simulate pulsar action, about 10^{-5} of the total spindown energy. Such action requires cascading in vacuum gaps as suggested by Cheng, Ruderman, and Sutherland. The natural action of such discharging would be to eliminate such gaps, and we suggest that it is the inclination of the neutron star magnetic moment producing large-amplitude radiation fields that drive away plasma otherwise trapped at large distances from the neutron star. Other questions, such as heating of the surface, gamma-ray luminosities etc., need to be addressed if such a mechanism is to be incorporated into a pulsar model.

Subject headings: hydromagnetics — particle acceleration — pulsars — radiation mechanisms — stars: neutron

Simple Calculation

- Charge on neutron star $Q = \frac{4\pi\epsilon_0 \Omega a^3 B_0 \cos\xi}{3}$

$$\rho_c = (rR_{\rm LC})^{1/2}$$

- Curvature of B field

$$E = \frac{\Omega B_0 a^3}{3r^2}$$

$$\dot{W} = \frac{e^2\gamma^4 c}{6\pi\epsilon_0 \rho_c^2}$$

- Electric field from Charge

$$W_{\rm photon} = \frac{3\gamma^3 \hbar c}{2\rho_c}$$

- Synchrotron Radiation rate

Remaining Calculations

- Condition for pair production

$$B\gamma_p = B_{\text{pair}} \equiv 4 \times 10^{12}\ \text{G}$$

$$\gamma_p \equiv \frac{W_{\text{photon}}}{m_e c^2}$$

- Photon energy scaled to electron rest mass

$$\sin\theta \approx \frac{(r_1 - r)}{\rho_c}$$

$$B\gamma_p \sin\theta = B_{\text{pair}}$$

- Gamma ray angle to B field

$$s_n \approx \frac{(r_n - r_{n+1})^2}{4\rho_c}$$

$$\gamma_{\text{coh}} \approx \left(\frac{\rho_c}{s}\right)^{1/3}$$

- Gammas pair produce:

$$f_{\text{coh}} \approx N_{\text{total}}\left(\frac{\gamma_{\text{coh}}}{\gamma}\right)^4 = \frac{1}{6\pi\gamma_{\text{coh}}^2}$$

- Bunch size

Cascade Process

1) Lorentz contracted electron E field

2) Curved “pulse” are the gamma rays

3) Same approx. for Bremmstrahlung

4) Might be underestimated in rates!

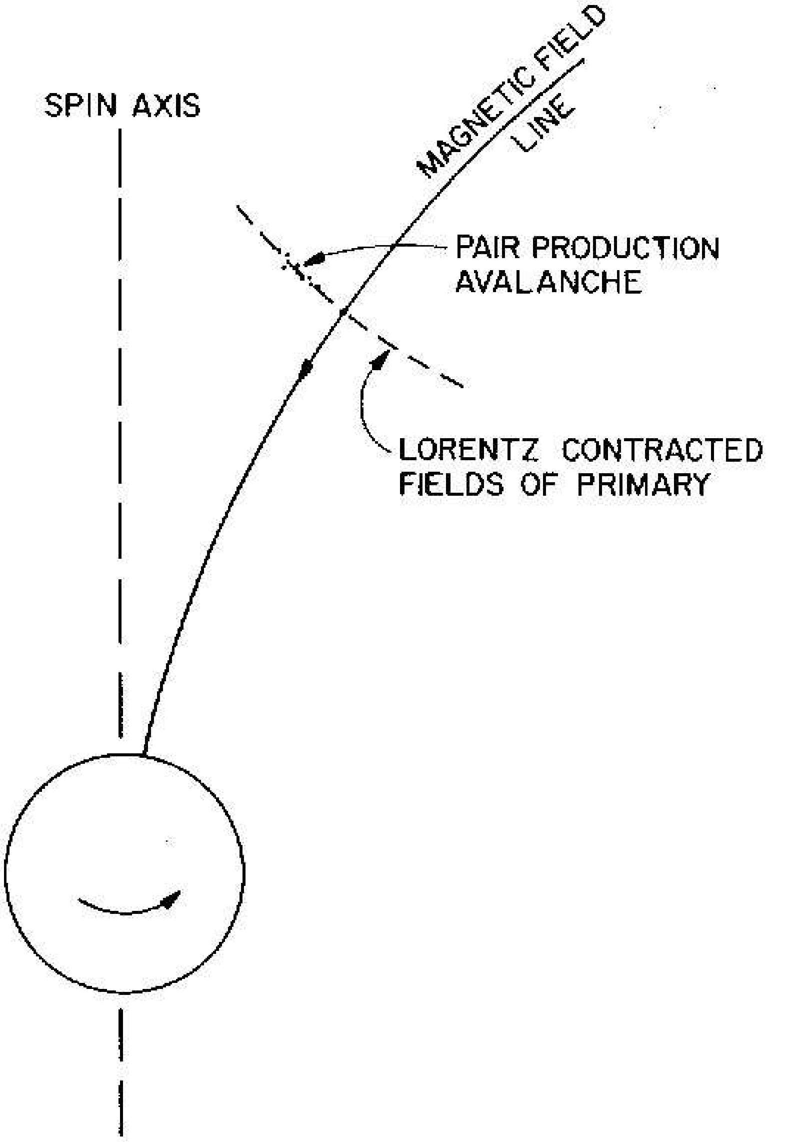


Table listing bunch properties

TABLE 1

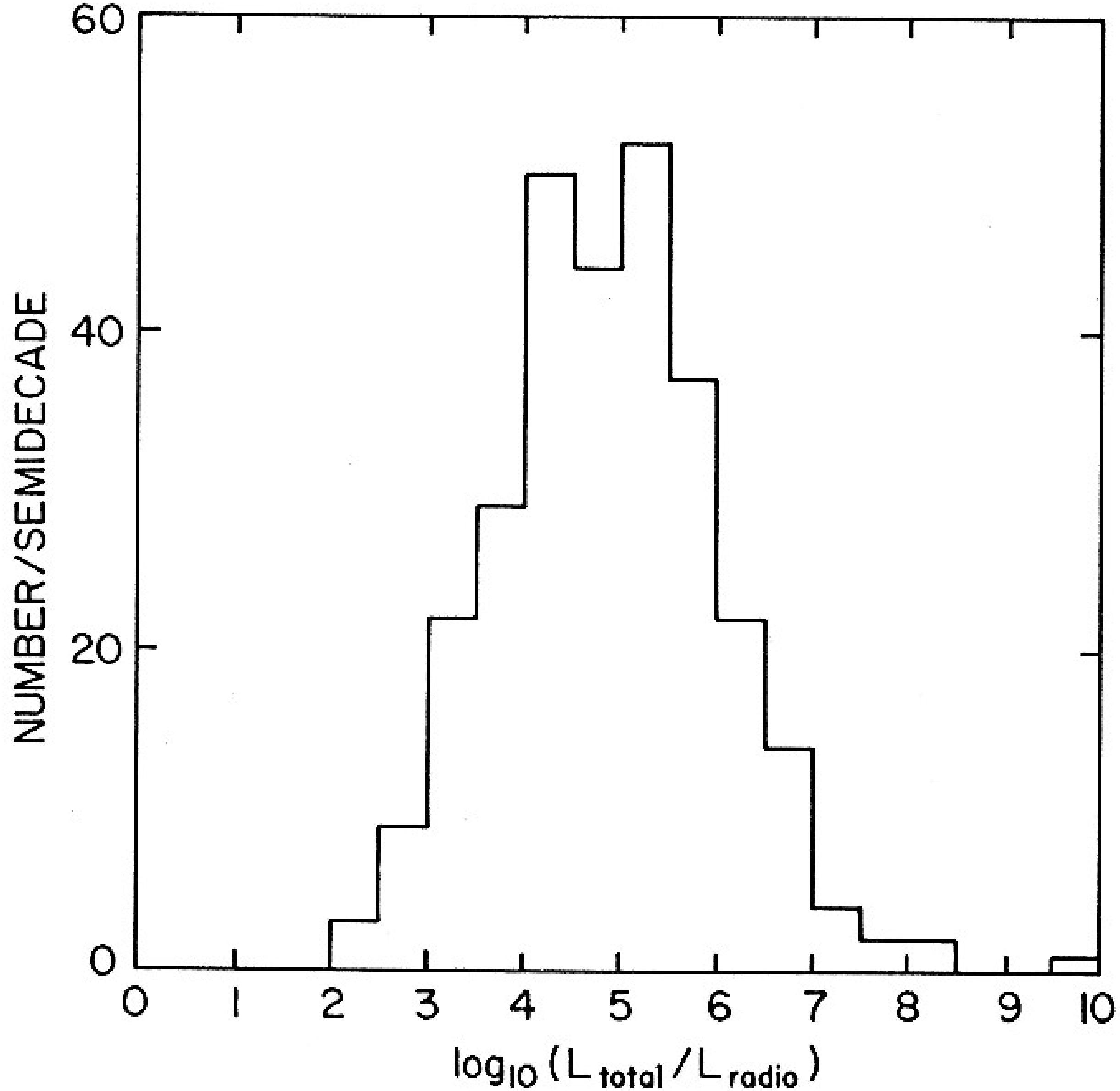
CRITICAL ALTITUDES CALCULATED FOR TYPICAL PULSAR PARAMETERS (UNSHIELDED)

Event	Altitude[a]	eQ/rmc^2	γ	γ_p	N	s_n(m)	Coherence[b]
r_1.........	27.2	1.5E + 09	7.9E + 07	7.8E + 04	0.0	...	0.0
r_2.........	13.6	3.0E + 09	9.4E + 07	1.9E + 05	1.6E + 04	1.8E + 03	3.4E − 24
r_3.........	10.2	4.0E + 09	1.0E + 08	2.7E + 05	3.4E + 06	1.4E + 02	1.4E − 20
r_4.........	8.54	4.8E + 09	1.1E + 08	3.3E + 05	9.3E + 09	3.2E + 01	1.9E − 16
r_5.........	7.66	5.4E + 09	1.1E + 08	3.8E + 05	2.0E + 13	1.0E + 01	1.6E − 12
r_6.........	7.03	5.8E + 09	1.1E + 08	4.3E + 05	3.9E + 16	5.5	6.1E − 09
r_7.........	6.58	6.2E + 09	1.1E + 08	4.6E + 05	6.1E + 19	2.8	2.1E − 05

[a] In stellar radii assuming $a = 10^4$ m.

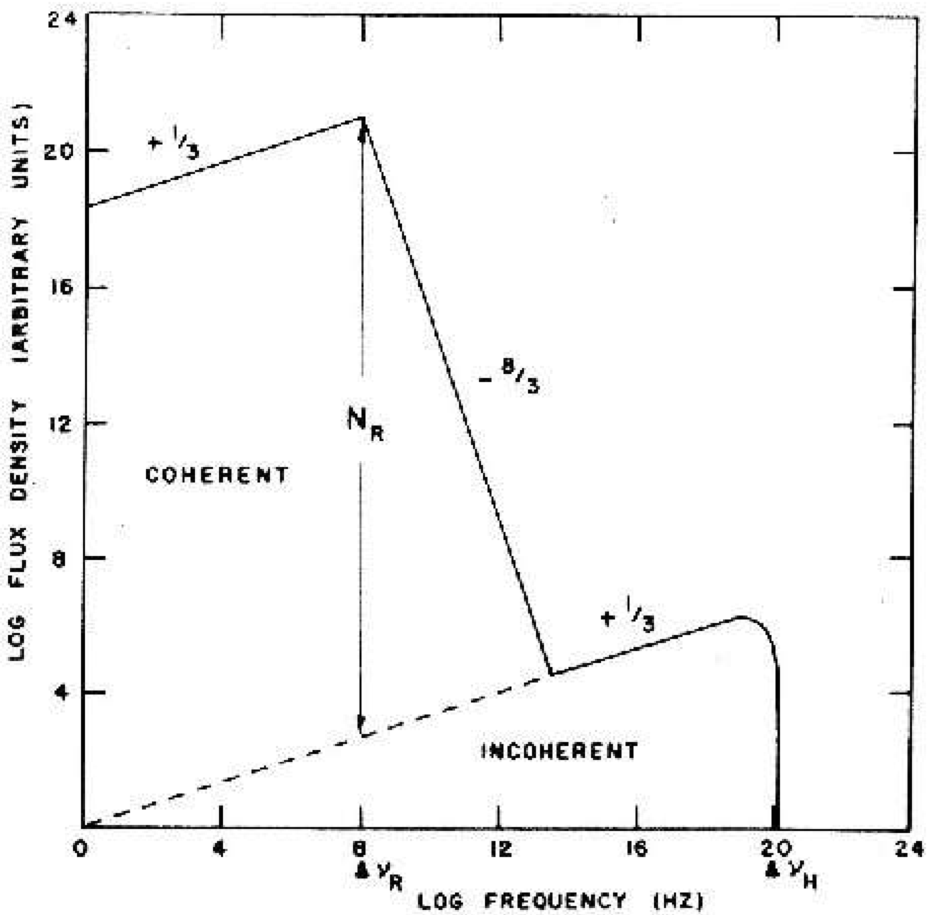
[b] Notation here is 1.5E + 09 ≡ 1.5×10^9, etc.

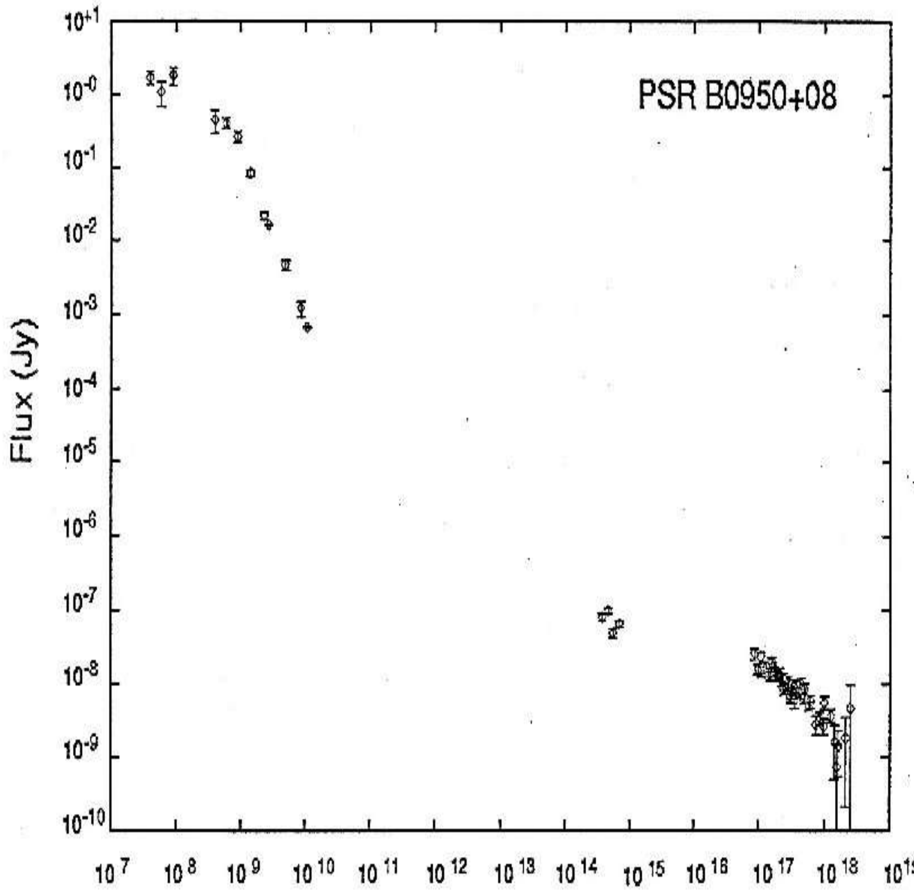
Radio Pulsar Efficiencies



Note: radio luminosity only rough estimate

Idealized spectrum from spherical bunches vs Measured spectrum for B0950





What's the point?

- Standard well-known equations
- No “tooth-fairies” required
- Coherence due to bunching
- Not “simple” but is direct

Criticisms

Might be too bright in X-rays (bunches hitting poles)
poles covered by domes, acceleration vanishes

New considerations

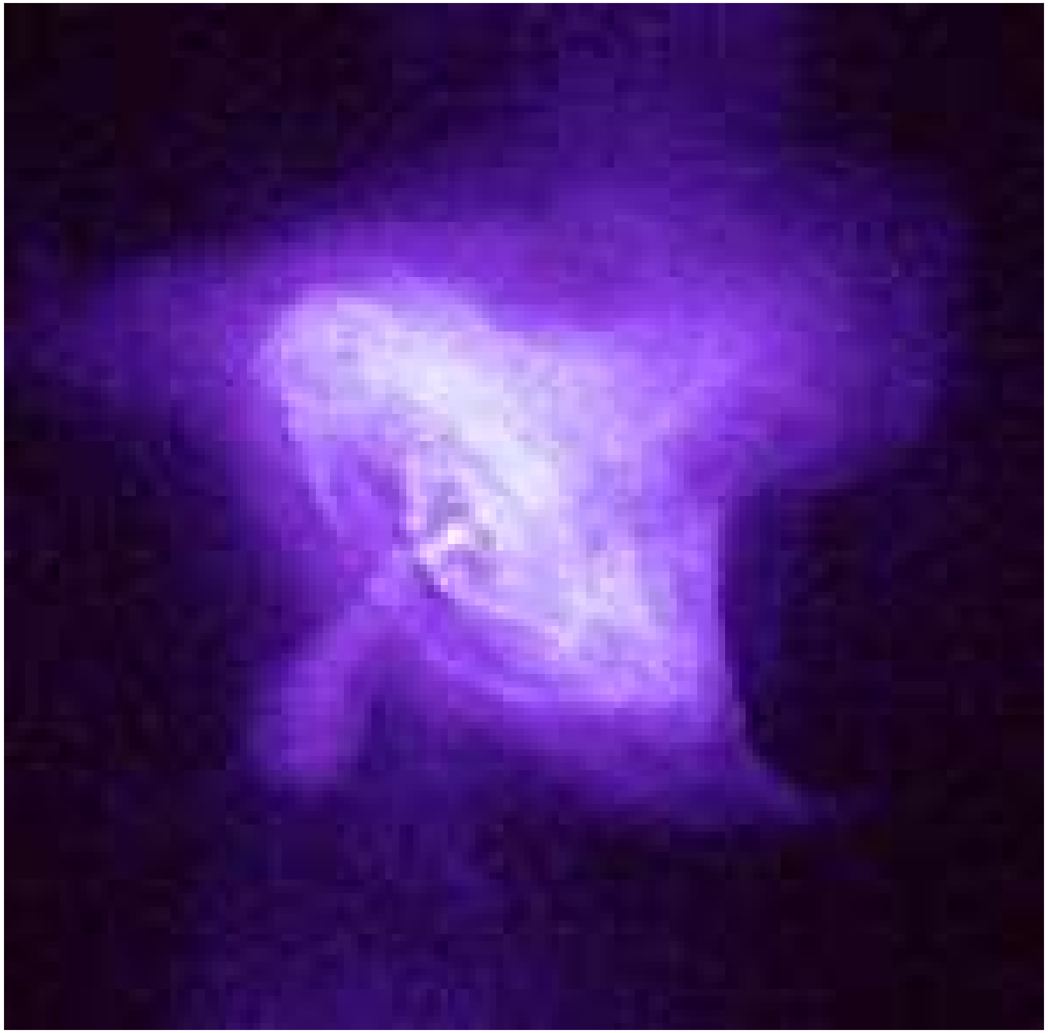
Jet formation (acceleration of upper parts of domes by the waves)

Positron maintained discharge (from opposite polar caps)

Inclined dipole essential for pulsar action (not just to sweep the "lighthouse" beam about)

Crab Movie in X-rays

Crab Nebula in X-rays



Things to notice from Movie:

Clear Jet at about 7 O'Clock

Clear equatorial outflow

Inclination of spin axis about 30 deg to LOS

Completely consistent with Dome/Torus

Truth Table

- Open cascade model
- System "empty"
- Coherence: bunching
- Radio emission "downwards"
- NOT aligned
- JETS and equatorial outflow

- Filled MHD model
- System "filled"
- No known mechanism
- Radio emission "upwards"
- Alignment "unimportant"
- 4pi?

Encyclopedia of the Future

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