Modeling of Pulsar Magnetospheres

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Outline

- Pulsar magnetosphere: open questions
- Pulsar theory: status update
- Pulsar models: pros, cons and fails.
- High energy emission models: emerging role of reconnection
- Conclusions and outlook
Pulsars: observationally driven

Pulsar theory:
Open questions:

☆ What is the structure of pulsar magnetosphere and how do pulsars spin down?

☆ What are the properties of the wind near pulsar? In the nebula?

☆ What causes pulsed emission?

☆ How are observed spectra generated? (how particles are accelerated?)
Open questions:

- The structure of the magnetosphere is the primary question, as all emission physics must be done in the context of proper magnetospheric geometry.

- Related question is the nature of the spin-down: most energetic, but mostly invisible, process in normal pulsars.
Magnetospheric cartoon

- Open & closed (corotating) zones.
- Minimal (Goldreich-Julian) charge density
- Light cylinder
- Sweepback
- Plasma is born in discharges
Pulsars: energy loss

- Corotation electric field
- Sweepback of B field due to poloidal current
- ExB -> Poynting flux
- Electromagnetic energy loss

Only gamma-ray output of pulsars is an interesting (<10%) fraction of the main spin-down energy flux.

\[ \rho_{\text{GJ}} = -\frac{\vec{\Omega} \cdot \vec{B}}{2\pi c} \]

Goldreich & Julian 1969
Magnetospheric shape

Several ways of modeling, depending on charge supply:

- Vacuum rotator
- Ab-initio particle
- Full RMHD
- Force-free variants
- “Pulsar equation”
Magnetospheric shape

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Analytic field line shape and spin down power formula
Magnetospheric shape

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AS & Arons 02; Michel et al 84, 01

Is the charge-separated solution dead?
Non-axisymmetric instabilities

Disk-Torus Electrosphere
Michel et al `84-01

Diocotron instability
AS & Arons 02;
Petri et al 02-

Possibility of radial current
Electrospheres are a curiosity
Add pairs?

Belyaev & AS, in prep

Petri et al 02
Magnetospheric shape

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Not spinning down?

Yuki & Shibata 12
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Space-charge limited flow + pairs + gaps. Curvature radiation from radiation reaction limited acceleration.
Gaps in understanding of gaps...

- Acceleration due to charge starvation
- Gaps imply space-charge separated background flow, even though pairs are created.
- PWNe require pair densities $>>$ minimum charge separated density.

Gap models are best developed but are not self-consistent.
Magnetospheric shape

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High magnetization near the star is difficult to simulate with MHD. Require simplification: force-free
Magnetospheric shape

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- Force-free:
- “Pulsar equation”

NS is immersed in massless conducting fluid with no inertia.

\[ \rho E + \left(\frac{1}{c}\right) j \times B = 0 \]

\[ \frac{1}{c} \frac{\partial E}{\partial t} = \nabla \times B - \frac{4\pi}{c} j, \quad \frac{1}{c} \frac{\partial B}{\partial t} = -\nabla \times E, \]

\[ j = \frac{c}{4\pi} \nabla \cdot E \frac{E \times B}{B^2} + \frac{c}{4\pi} \frac{(B \cdot \nabla \times B - E \cdot \nabla \times E)B}{B^2} \]

Gruzinov 99, Blandford 02

Time-independent version -- pulsar equation (Scharleman & Wagoner 73, Michel 73)

\[ \frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} \frac{(\Psi)''(\Psi)}{2\ell(1-x^2)} \]

Contopoulos, Kazanas & Fendt 1999
Properties: current sheet, split-monpolar asymptotics; closed-open lines; Y-point; null charge surface is not very interesting. Now at least 5 groups can do this (recently, Yu 11, Parfrey 11, Petri 12, in addition to AS 06, McKinney 06, Kalapotharakis 09)
Oblique rotator: force-free
Spin-down of oblique rotator

\[ \dot{E} = \frac{\mu^2 \Omega^4}{c^3} (1 + \sin^2 \theta) \]

\[ \dot{E}_{\text{vac}} = \frac{2}{3} \frac{\mu^2 \Omega^4}{c^3} \sin^2 \theta \]

NB: this is a fit!

A.S.’06; also confirmed by Kalapotharakos & Contopoulous 09
IN COROTATING FRAME

60 degree inclination

Force-free

Force-free current density
3D force-free magnetosphere: 60 degrees inclination

Similar to heliospheric current sheet

60 degrees force-free current
IN COROTATING FRAME

90 degree inclination

Force-free

Force-free current density
There is a continuum of solutions that depend on plasma supply. These can be characterized by the presence of accelerating E field, or resistivity. See Jason Li’s talk.
Recent advances:

- Better understanding of the cascades and driving of current (see Timokhin’s talk)

- Polar cascades can supply current both $>$ and $<$ than GJ current. Implies time-dependence.
  Interestingly, current $<\text{GJ}$ does not pair produce.
Recent advances:

- Full RMHD is now in 3D!
- Oblique rotator can now be studied in ideal MHD (Tchekhovskoy & AS, in prep)
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- Spherical grid which allows non-axisymmetric solutions. Magnetization > 100. Fixed magnetization inside 0.7 LC
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Spin down luminosity

\[ L/L_{\text{aligned}} = 1 + 1.15 \sin^2 \alpha \]

Obliqueness

Variation with angle is similar to force-free
Recent advances:

- Full RMHD is now in 3D!
- Big uncertainty: velocity along the field lines is not self-consistent (depends on cascades). We are working on various

Current sheet is formed and has gas pressure in it
Recent advances:

- Full particle modeling with PIC (particle-in-cell) in 3D (AS in prep).
- Idea: supply enough neutral plasma and “let it figure it out.”
- $E = E_{\text{plasma}} + E_{\text{Deutsch}}$;
  $B = B_{\text{plasma}} + B_{\text{Deutsch}}$

Step 1: Test electrons & ions become distributed in different locations -- no clear sheet.
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Recent advances:

- Vacuum field + plasma

- Full particle modeling with PIC (particle-in-cell) in 3D.

- Turn on plasma back reaction:
  - Electrons & ions now are together and form a current sheet. Approaches force-free.
Recent advances:

- In principle, such a solution has everything: acceleration, plasma velocity, reconnection.
- In practice the resolution will always be limited.
- Also, the aligned rotator part depends on good BCs on the star -- still in progress.

Vacuum field + plasma
Where does emission come from?

- With force-free shape of the magnetosphere at hand, emission physics can be studied again.

- Most progress so far is on the geometry of the emission so far (gamma-rays).

- Does the emission come from gap regions? Inside or outside LC?
Where does emission come from?

- Select flux tubes that map into rings on the polar caps. The rings are congruent to the edge of the polar cap.
- While ad-hoc, the point is to study the geometry of the possible emission zone.
- Emission is along field lines, with aberration and time delay added.
Emission from different flux tubes

Emission from two poles merges on some flux tubes: what’s special about them?

Bai & A. S. 2010
Association with the current sheet

Field lines that produce best force-free caustics seem to “hug” the current sheet at and beyond the LC.

Significant fraction of emission comes from beyond the light cylinder.

Best place to put a resistor in the circuit!
Relativistic magnetospheres

Anatoly Spitkovsky (Princeton)

Force-free light curves

"Separatrix Layer" model is a real contender. It's not just outer gap vs slot gap anymore!

Inclination angle

Most of the emission in FF model accumulates beyond 0.9 RLc

Double peak profiles very common.

Bai & AS, 2010
Source of emission

- Emission is geometrically associated with the current sheet
- What is the acceleration and radiation mechanism in current sheet?
  
  Most likely culprit -- relativistic reconnection. This is different from conventional picture of accelerating gaps starved of plasma and curvature emission

- Boosted synchrotron from heated plasma can work
Better ideas of flow direction in the current sheet needed.

In PIC simulations get outflows near $\sqrt{\sigma}$.

Minijets?

Since beaming along extrapolated B field in the current sheet makes double peaks, it’s a contender.
Conclusions

- Magnetospheric shape is now known and confirmed in the limit of abundant plasma in 3D.
- Geometrically these models are being contrasted with gamma-ray observations (Separatrix Layer vs Gaps).
- More realistic models with 3D RMHD, cascade physics and full PIC are advancing -- expect cool results in the next few years. Benefit a lot from Moore’s law.
- Reconnection may play an important and under-appreciated role in both emission and determining the magnetospheric shape.
- The origin of long time scale variability is likely not magnetospheric.