Goddard Pulsar Workshop, June 2016

Observing the Plasma-physical Processes Behind Pulsar Radiation

Joanna Rankin

Physics & Astronomy Department, University of Vermont

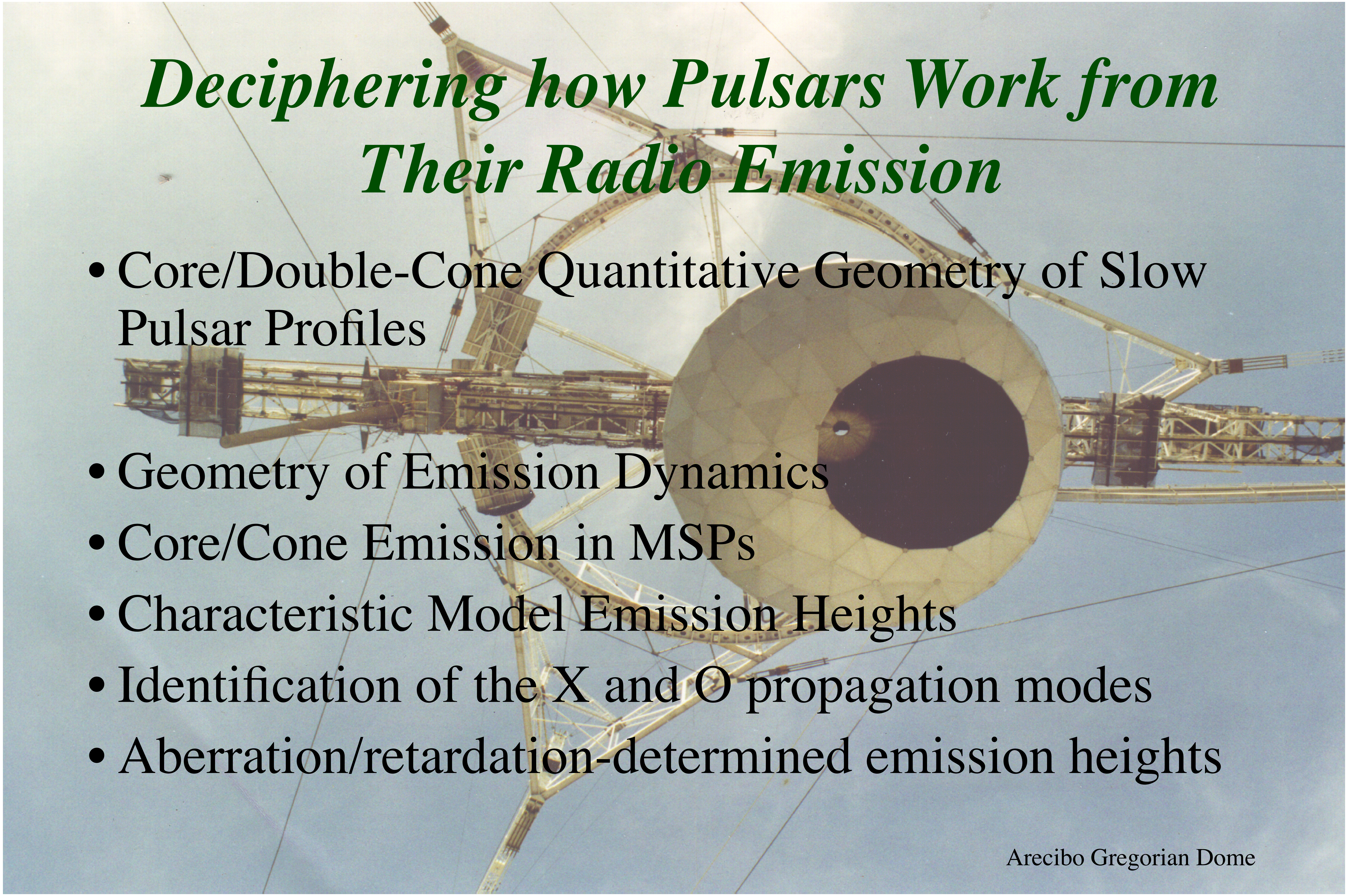
Arecibo Science Advocacy Partnership

Collaborators: *Dipanjan Mitra, Geoffrey Wright, Svetlana Suleymanova, Joeri van Leeuwen, Anne Archibald, Jason Hessels, Scott Ransom*

Deciphering how Pulsars Work from Their Radio Emission

- Core/Double-Cone Quantitative Geometry of Slow Pulsar Profiles

- Geometry of Emission Dynamics
- Core/Cone Emission in MSPs
- Characteristic Model Emission Heights
- Identification of the X and O propagation modes
- Aberration/retardation-determined emission heights

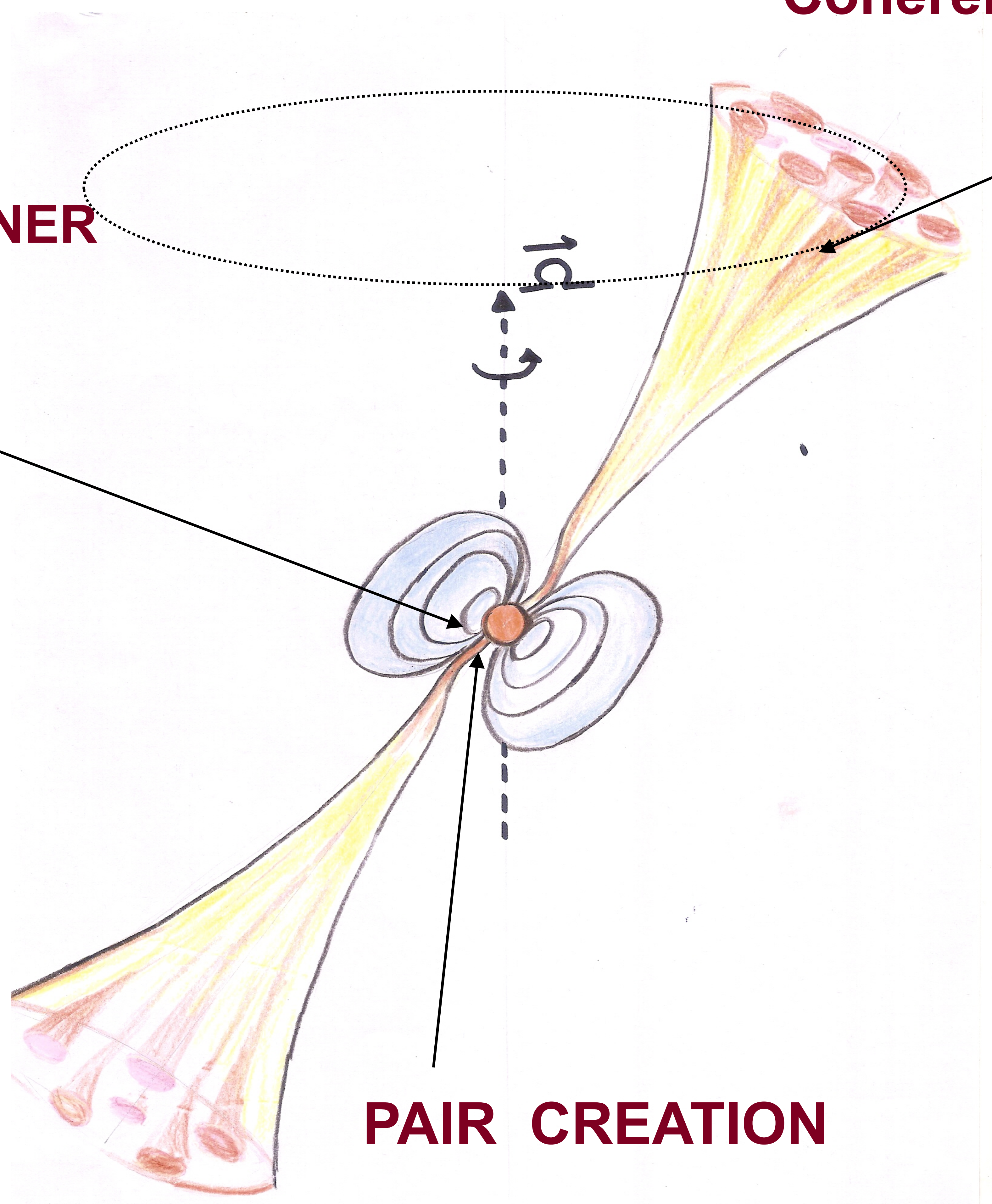


Arecibo Gregorian Dome

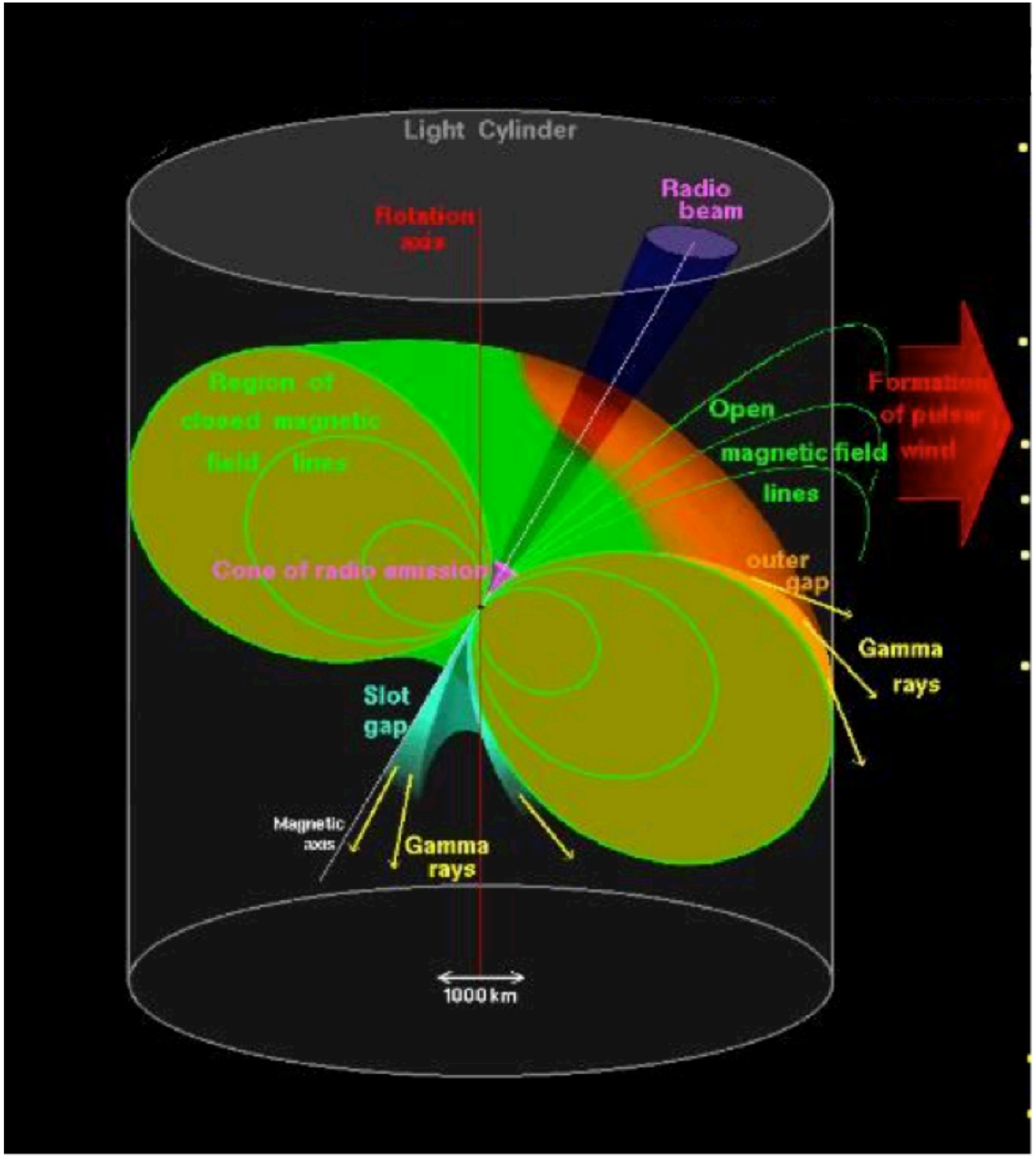
Inner Two Zones of the Polar Fluxtube

Coherent Radio Emission

FORMATION OF INNER VACUUM GAP



PAIR CREATION

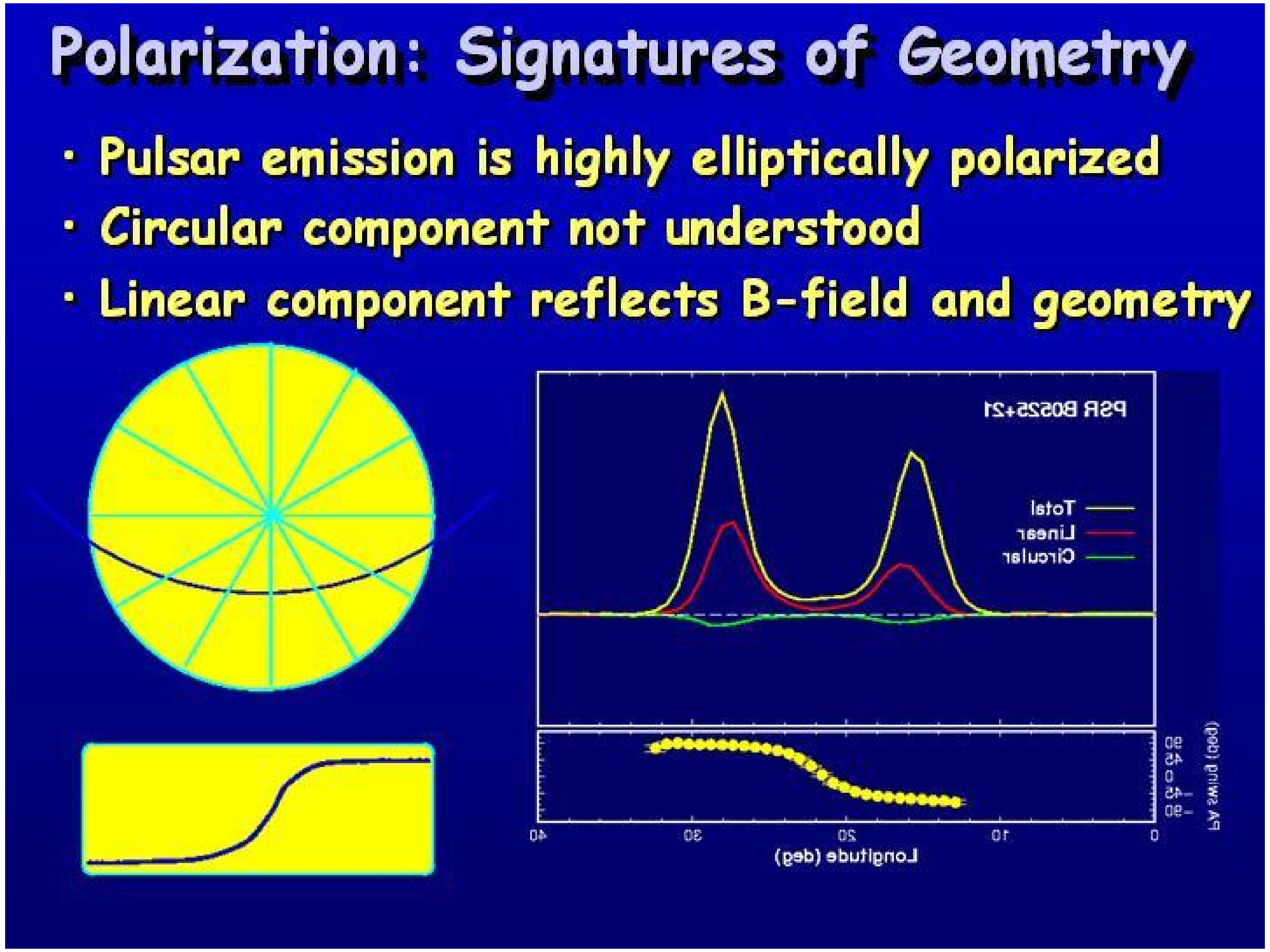


Three Polar Fluxtube Zones

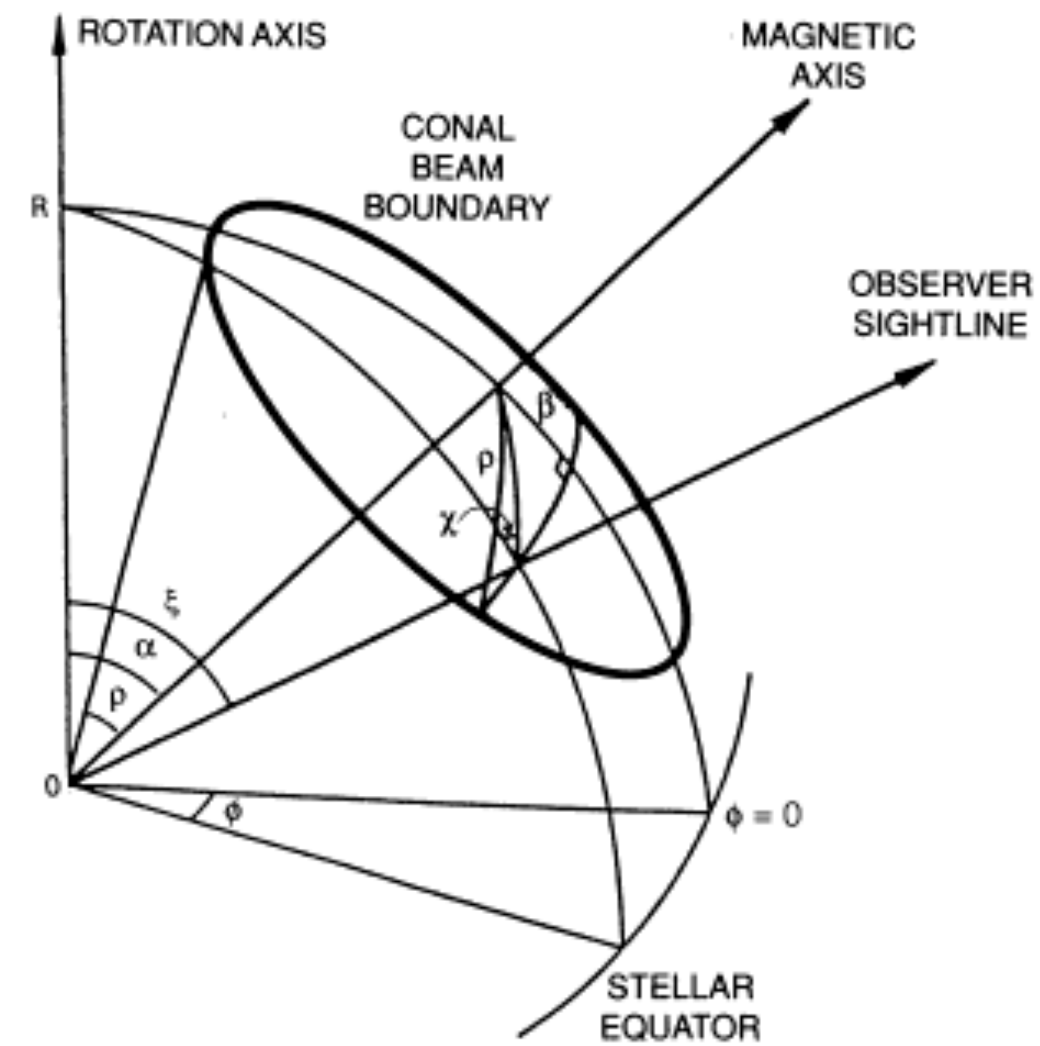
Multipolar Zone: polar cap out to a few stellar radii

Dipolar Zone: locus of most radio emission ~100-1000 km

Poloidal Zone: high altitude region where spindown currents alter the stellar dipolar B field



The Spherical Geometry of Pulsar Emission—
α, the magnetic latitude, and
β [=ζ– α], the sightline impact angle as a function of rotational phase or *longitude*, ϕ [°].

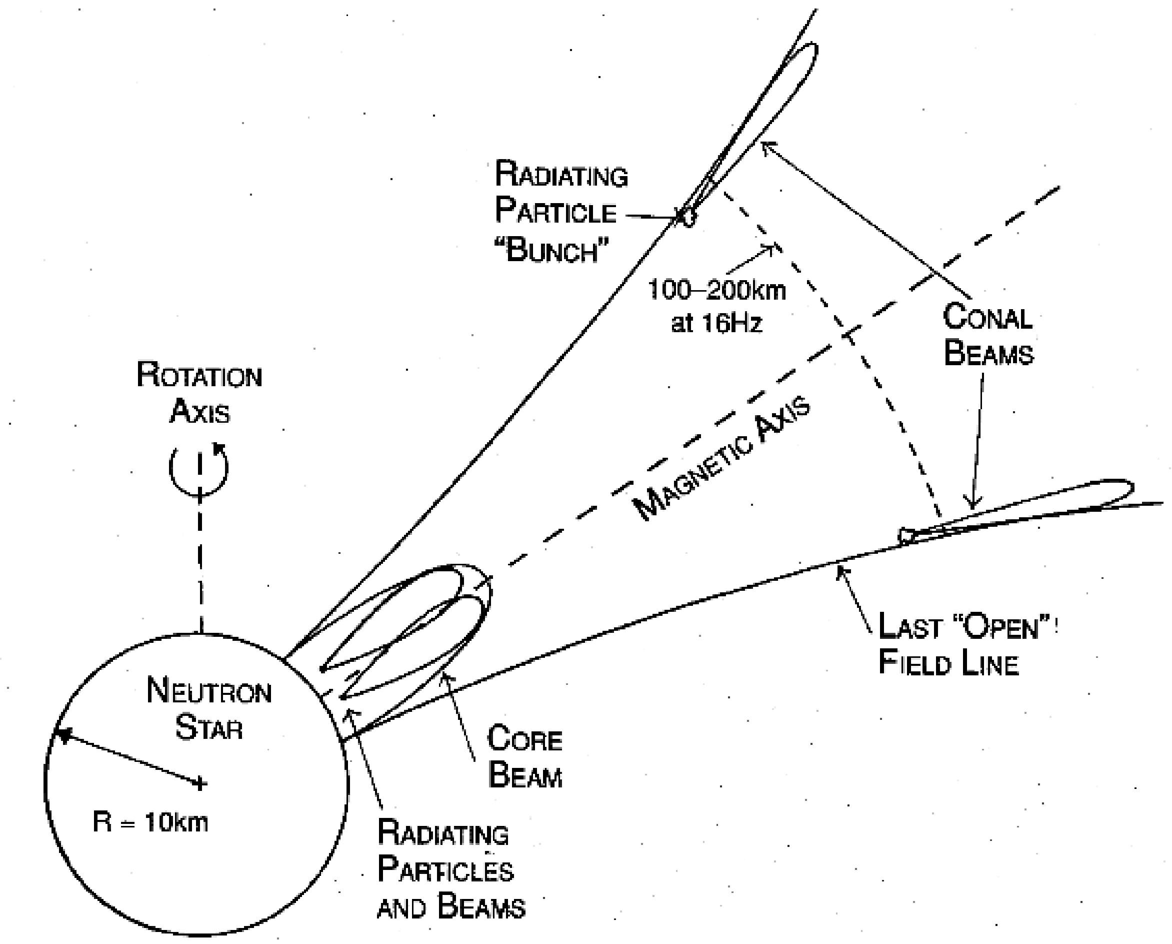


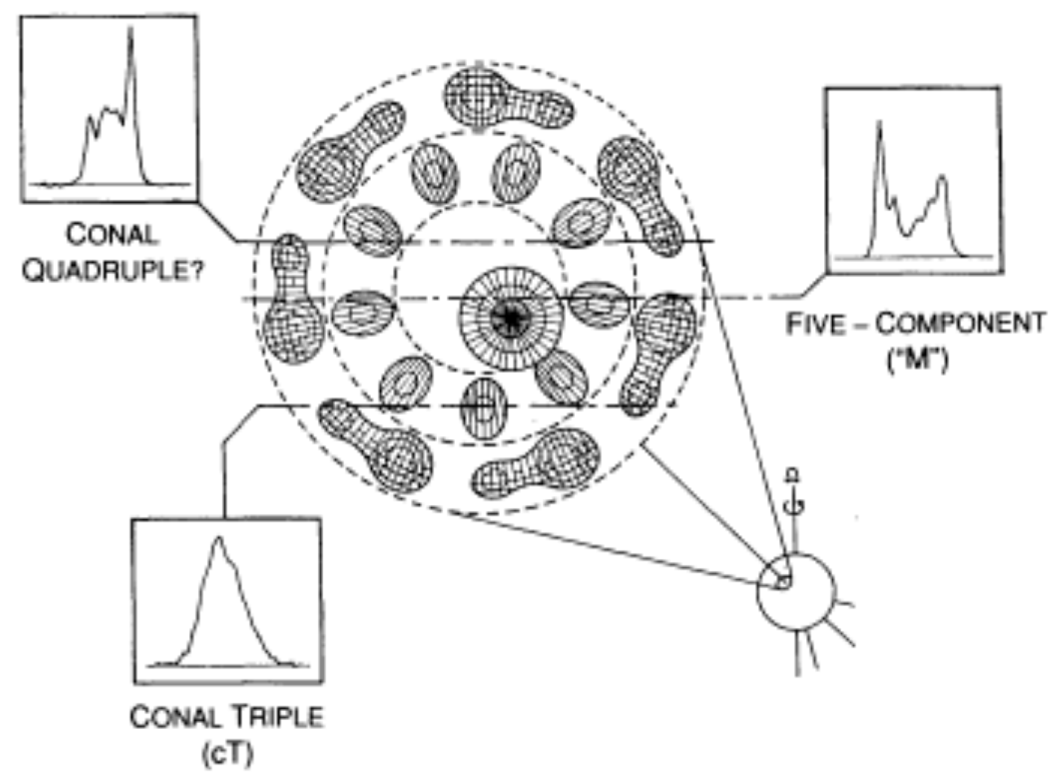
Such PA behavior is known as "RVM" (Rotating Vector Model).
In addition there are two "OPMs" (Orthogonal Polarization Modes)

Slide credit: Michael Kramer

Core/Double Cone Beams and their Geometrical Properties

- Two concentric Conal Beams around a central Core beam—note this implies roughly symmetrical profile forms
- All three beams reflect the angular size of the polar flux tube at some height
- Polar-cap angular size is—
  $2.45° P^{-1/2}$
  where P is the rotational period
- Core beam is emitted close to the surface
- Conal beams have half-power dimensions $5.75° P^{-1/2}$ and $4.33° P^{-1/2}$ at 1-GHz
- Cones, outer and inner, are emitted at some 220 and 130 km in slow pulsars
- A little spherical geometry allows us to match polarized profiles to the model
- Can then determine the basic geometry: magnetic latitude α and impact angle β



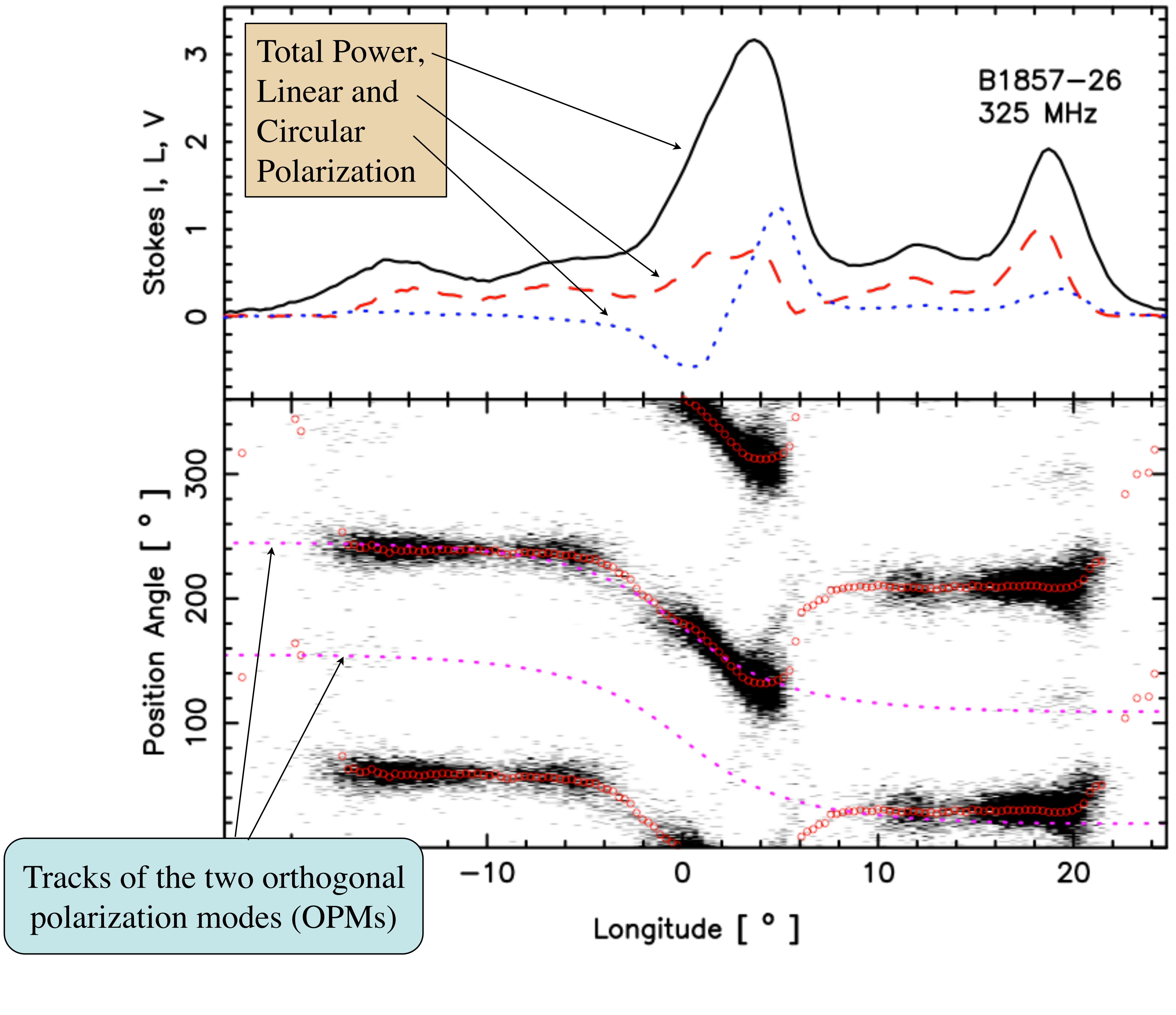


Backer (1980), Rankin (1983, 1993)

This is Remarkable!!

- Core Components seem to maintain the angular dimension of the polar cap although they seem to be emitted at a height of some 100-300 km
- Cones come in two flavors, inner and outer. Some pulsars show one, others the other and a few both.
- When drift or stationary modulations occur in one cone, the same is seen in the other, phase locked!!

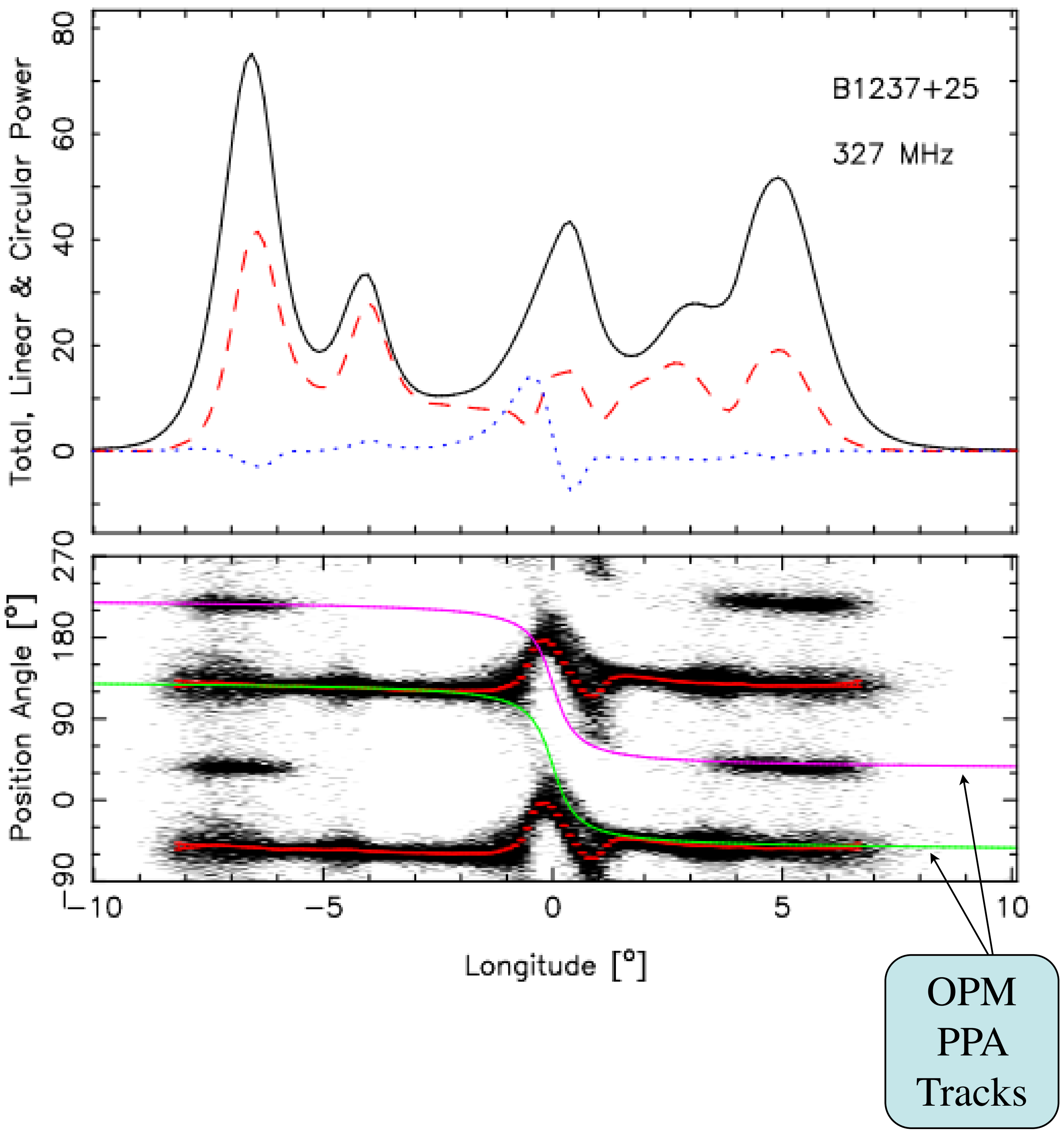
An Example of a Core/Double Cone Profile



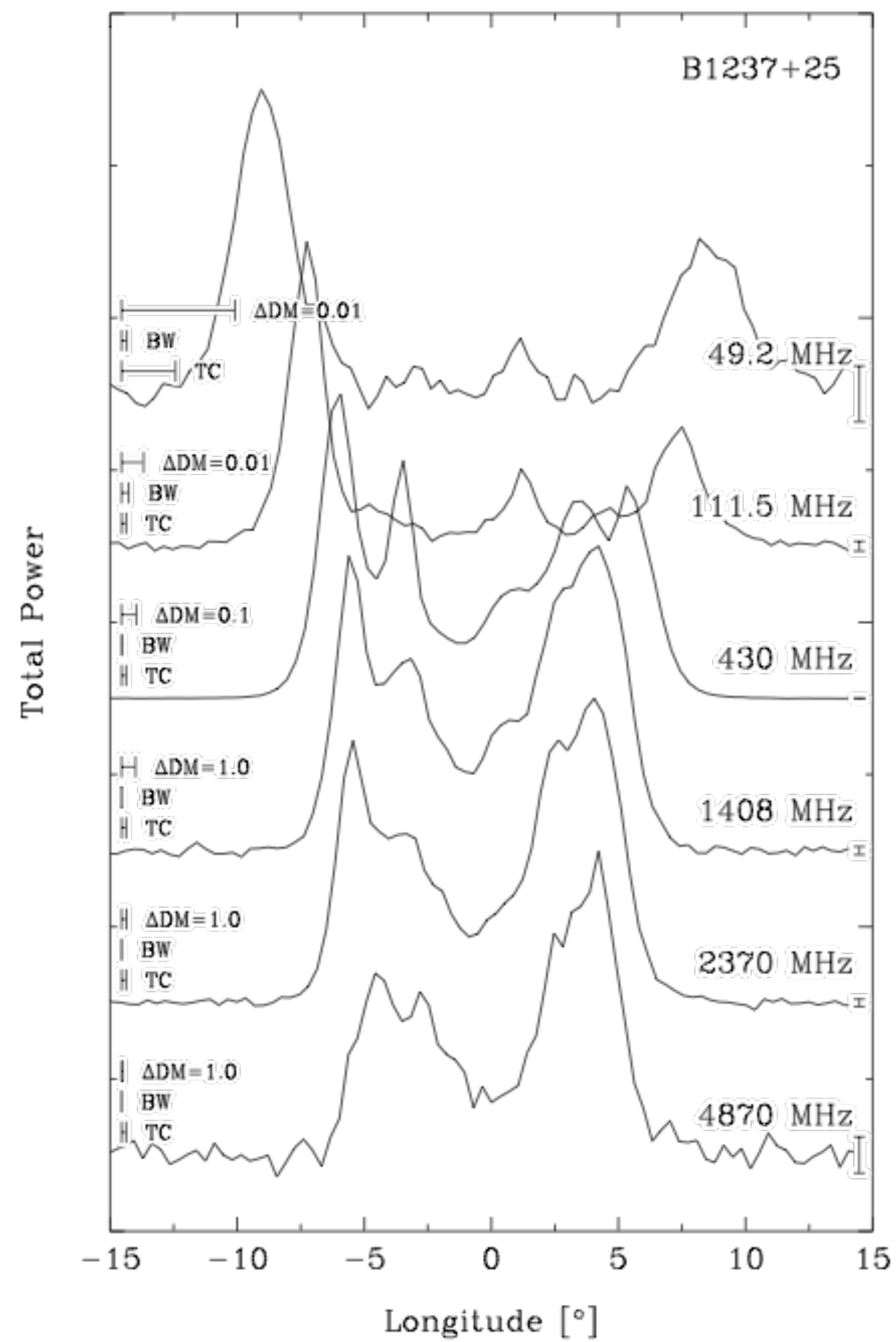
Five components
-double cone
-core
-all dimensions scale to size of polar cap
-core beam gives us knowledge of magnetic latitude, cones the sightline impact angle

Another Core/Double Cone Profile Example

Most other cores occur by themselves, or with only one of the cones



Frequency Evolution



Core Emission Has Distinct Properties

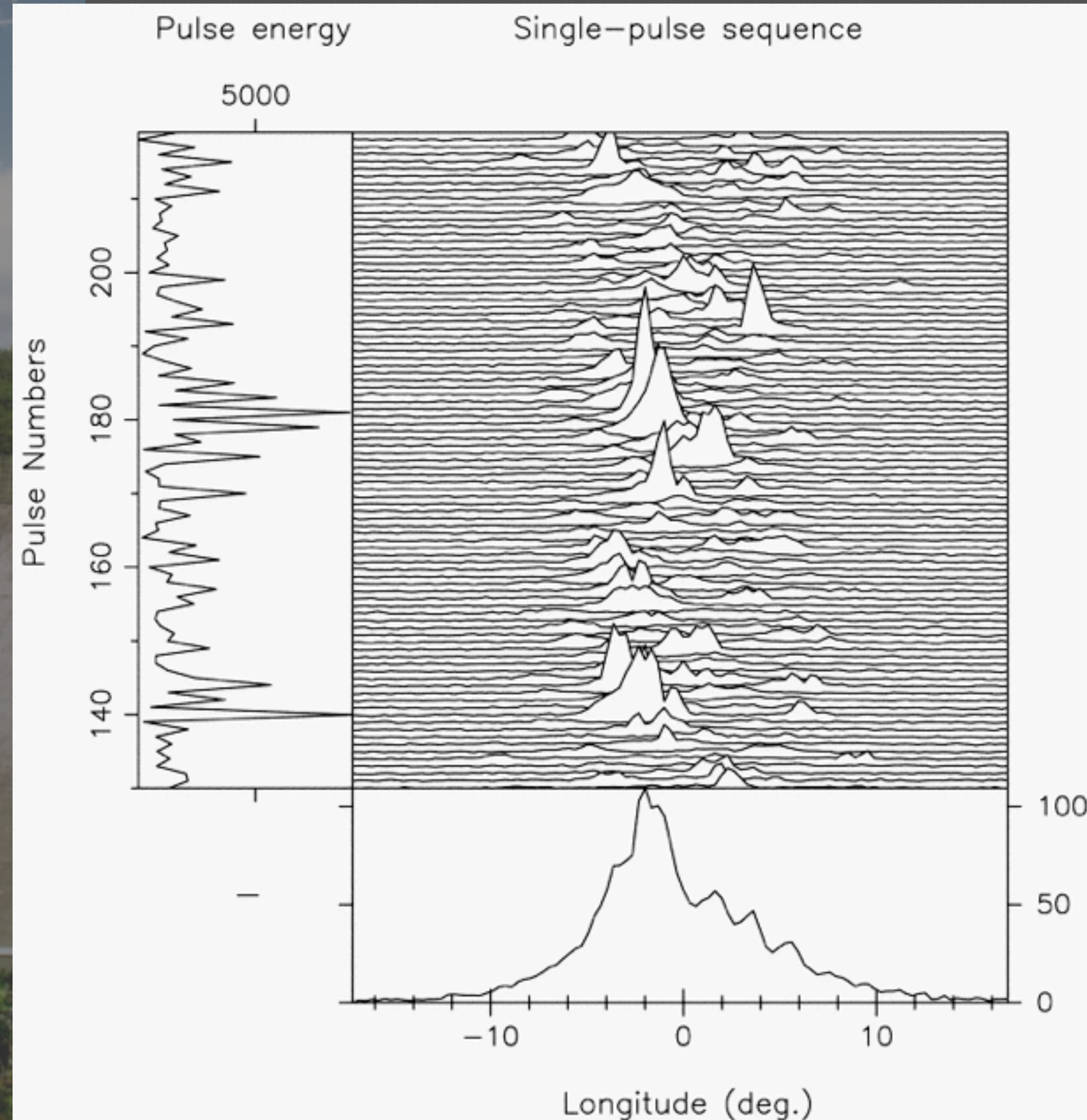
- Dominant in higher energy slow (P ~ 300 msec) pulsars
- Such stars are seen at great distance across the Galaxy
- Widths go as $2.45°P^{-1/2}$ polar-cap size at the NS surface
- Centered on/close to the magnetic axis
- No “drifting” is observed
- Often marked by antisymmetric Stokes V
- Usually have a steeper RF spectrum than conal emission
- Often highly linearly depolarized by OPMs

.... *as opposed to Conal Emission Properties*

- Dominant in slow, low energy (P ~ 1 sec) pulsars
- Such stars are local and seen all around the sky
- Discrete inner and outer cones with radii $4.33°P^{-1/2}$ and $5.75°P^{-1/2}$ along the polar fluxtube boundary
- Produced by a rotating carousel "beamlet" system,
  ... thus "drifting" or periodic modulation
- Some conal pulsars show cessations or "nulls"
- Cones have complex subbeam systems in both of the two polarization modes (OPMs)
- Little circular polarization (Stokes V)

PSR B0943+10: Remarkable Drifting and Moding

- Notice the prominent drifting subpulses
- —and that the weaker ones are just above the noise level
- This pulsar drifts so regularly that we could confirm that the drift is produced by a subbeam "carousel"

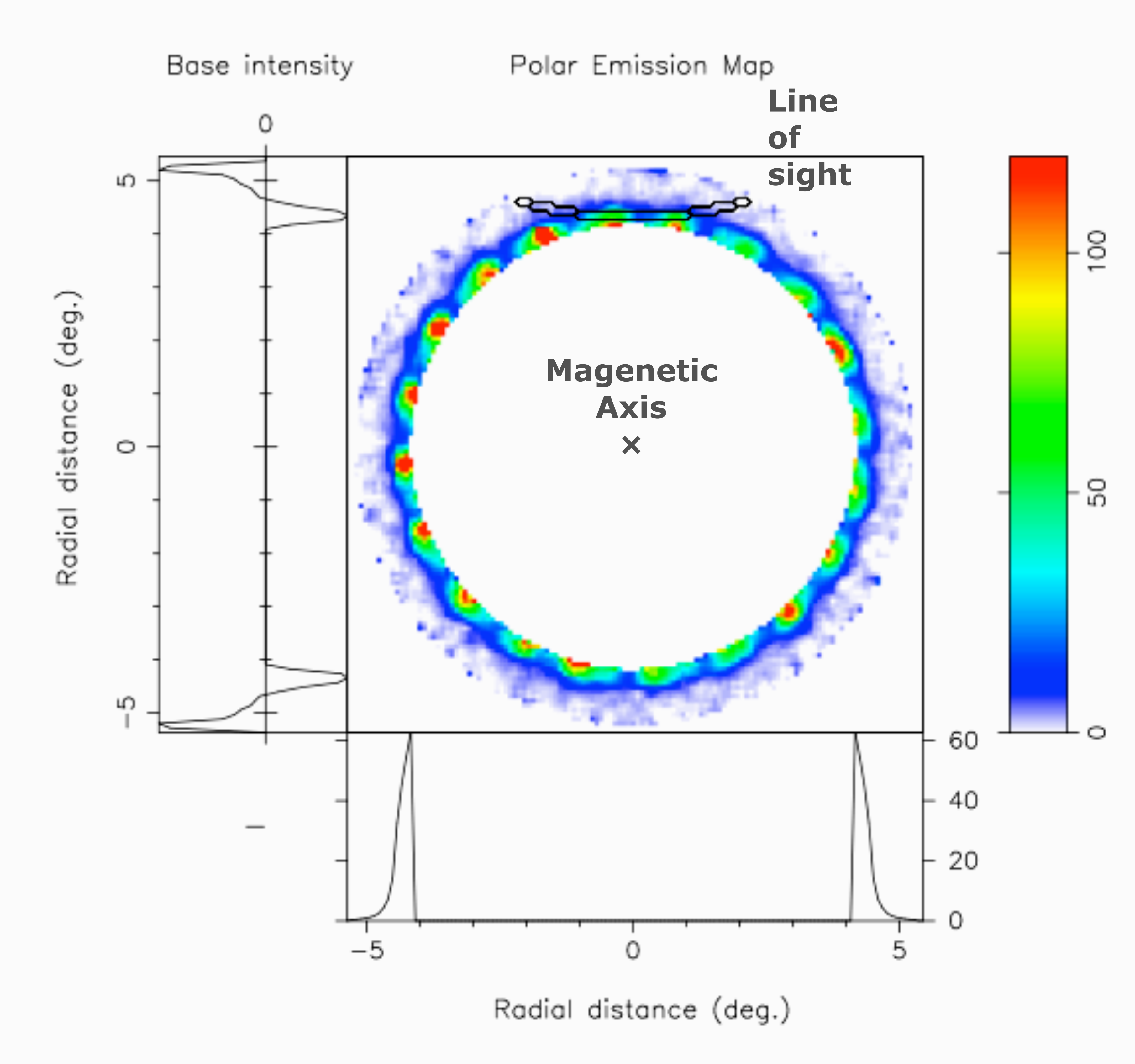


Deshpande & Rankin, 2001 *MNRAS*, **322**, 438

The University of Vermont

The Rotating Subbeam "Carousel" of PSR B0943+10

- 20 subbeams within the emission cone
  - Rotates in about 37 stellar-rotation periods or 41 seconds
  - Spin axis at top, magnetic axis at center
  - Carousel rotation through sightline produces drifting!
  - Strong support for vacuum gap models

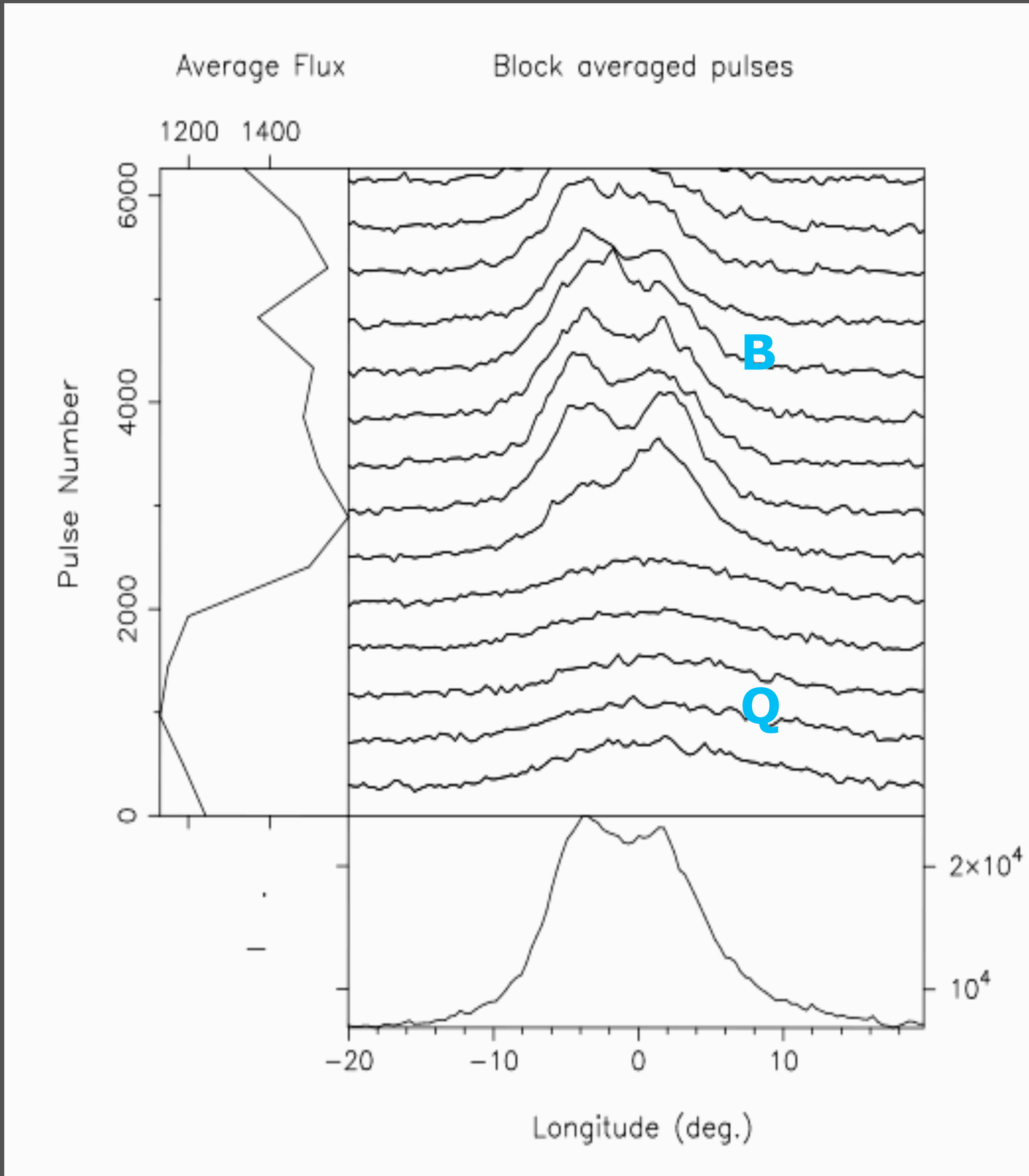


Deshpande & Rankin, 2001 *MNRAS*, **322**, 438

The University of Vermont

Q-to-B-Mode Transitions in B0943+10

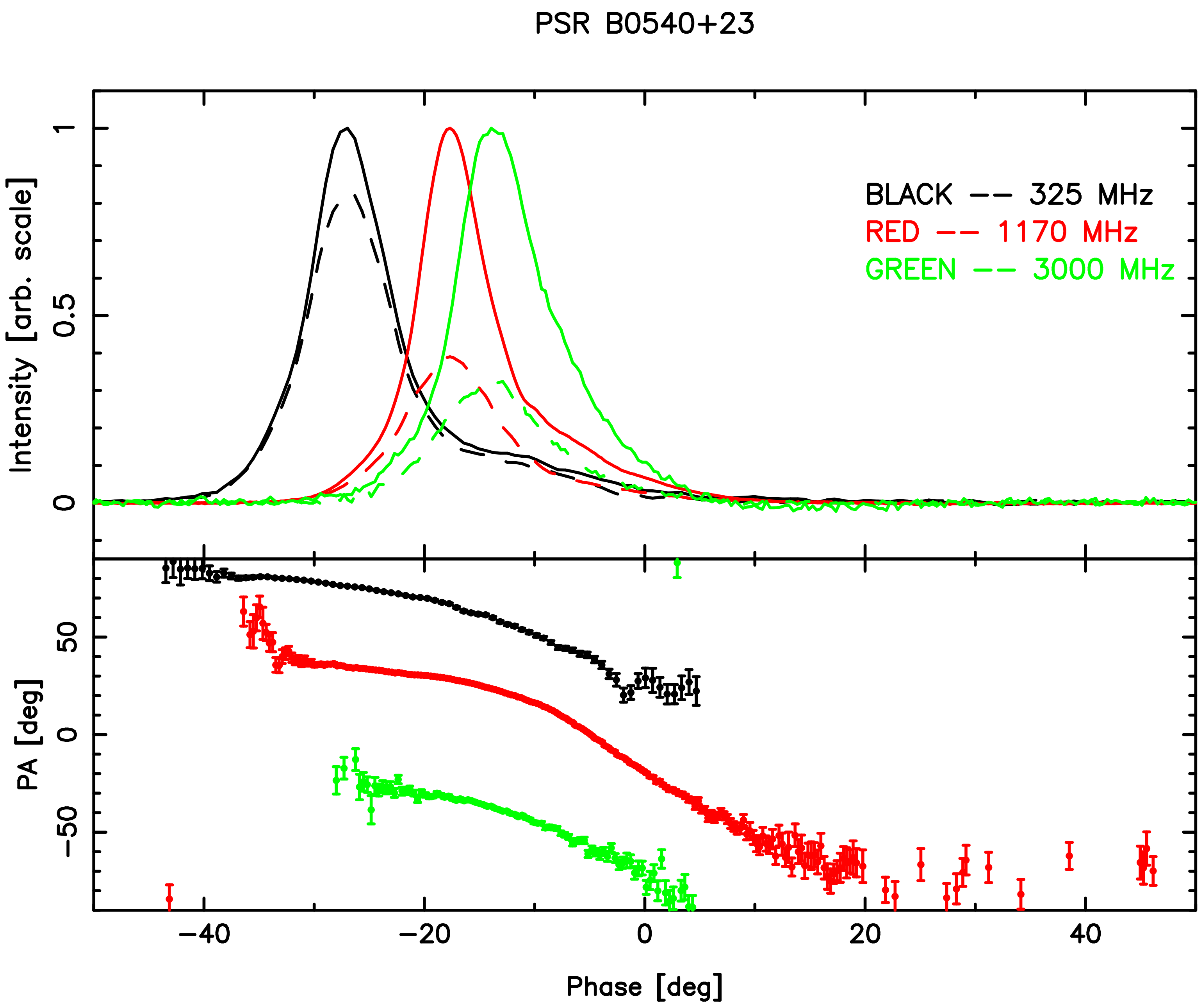
Arecibo 327-MHz observations in 2003



Profiles are 480-pulse averages

- First 5 are broad, single, non-drifting Q mode
- B mode begins at pulse 2540 and is clearly brighter
- Profile evolution identical after each mode switch (memory)
- Modal profiles differ in intensity form and polarization

What of Faster Pulsars??



Profiles aligned at PPA steepest gradient points

Aberration/Retardation becomes ever more important for faster pulsars

Many faster pulsars have only one component and a far trailing center of their PPA traverse

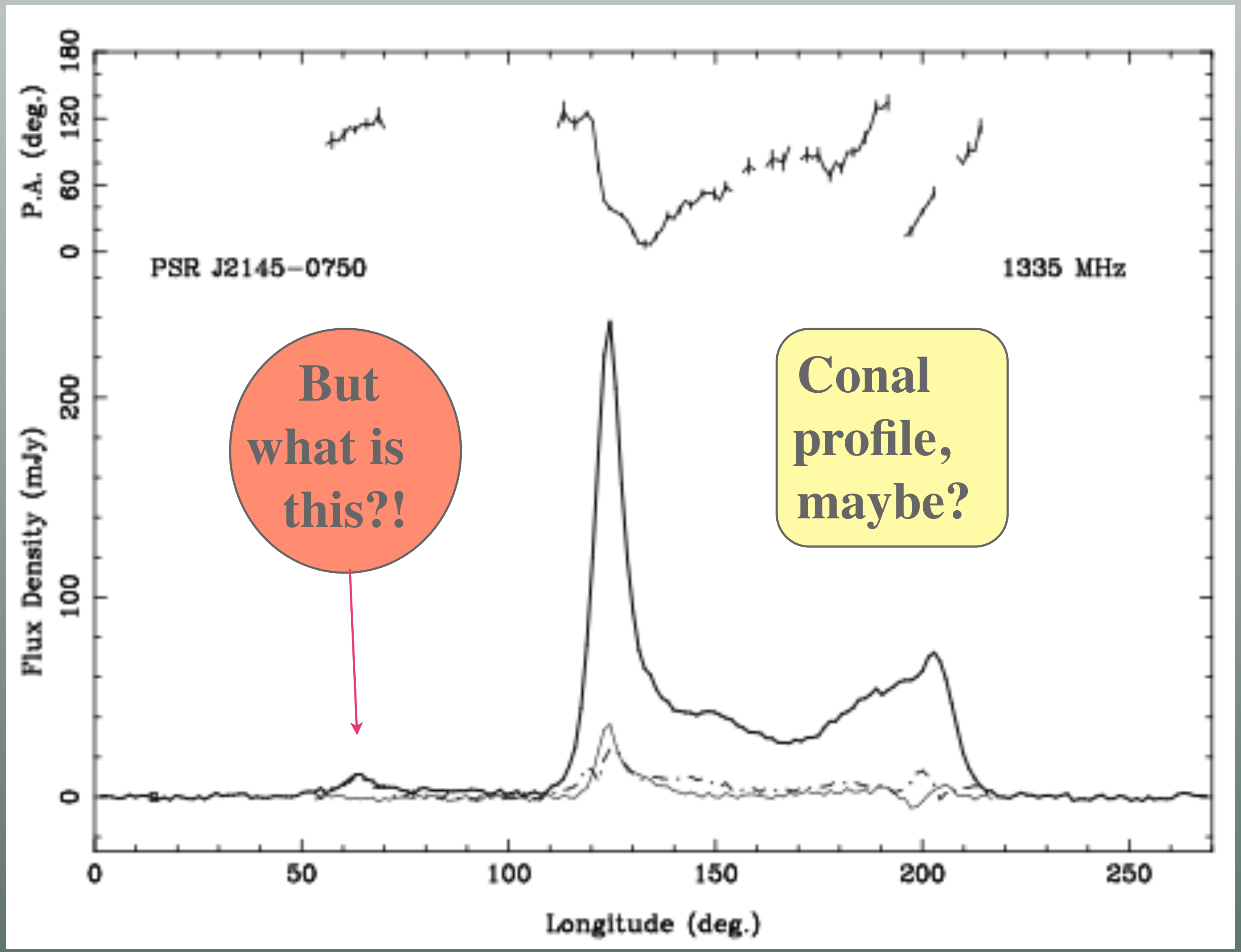
A/R may distort core/cone emission of faster pulsars beyond easy recognition

But What About Core/Cone Structure in Millisecond Pulsars?? This is a Crucial Question for Many Reasons

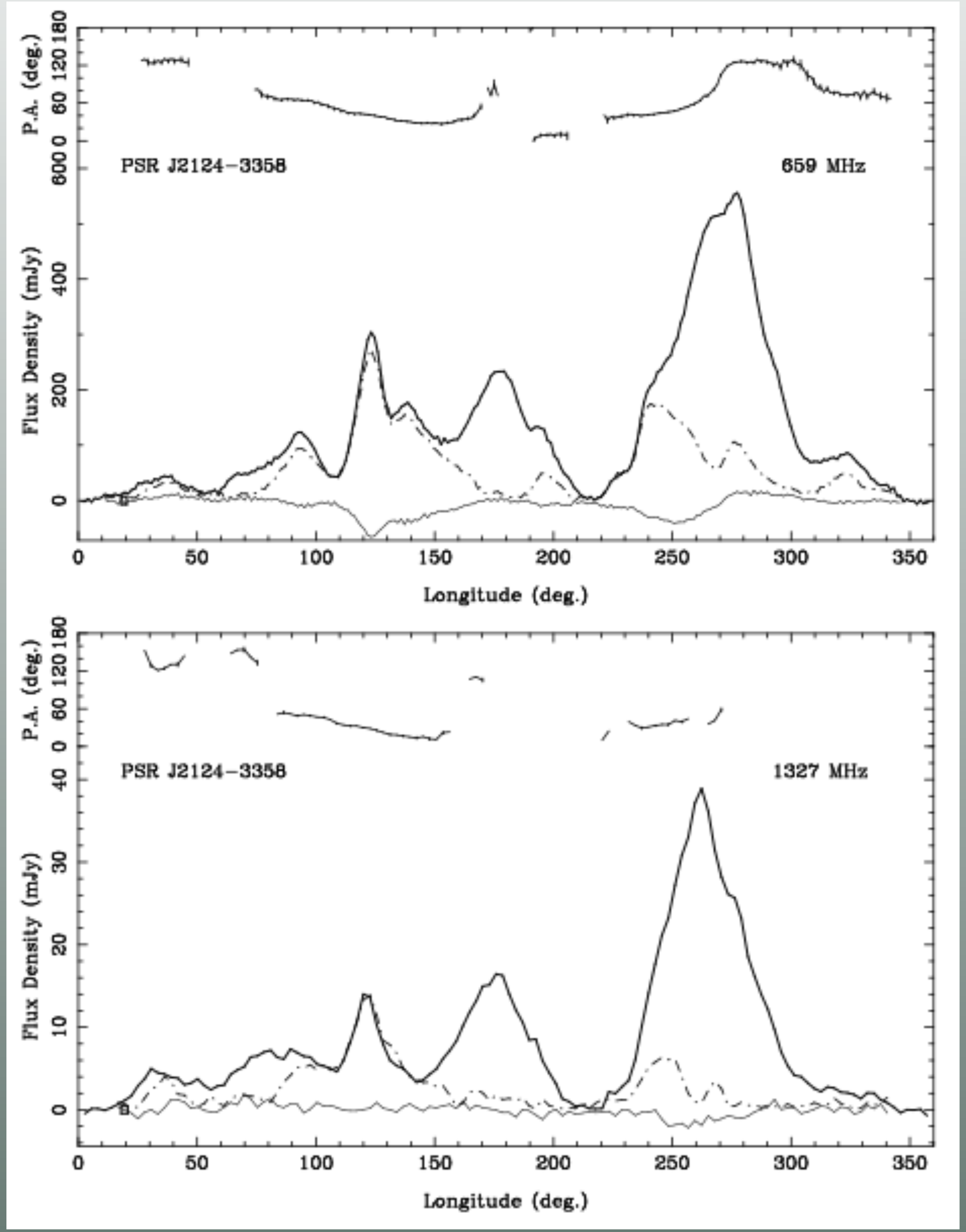
One might expect core emission to be dominant in MSPs. Among the slow pulsar population, core emission tends to become more prominent in faster pulsars.

But one encounters lots of discouraging profiles when trying to identify core/cone beaming configurations in MSPs.

The multipole and dipoles zones of slow pulsars overlap in millisecond pulsars, so most profile may be unrecognizable.

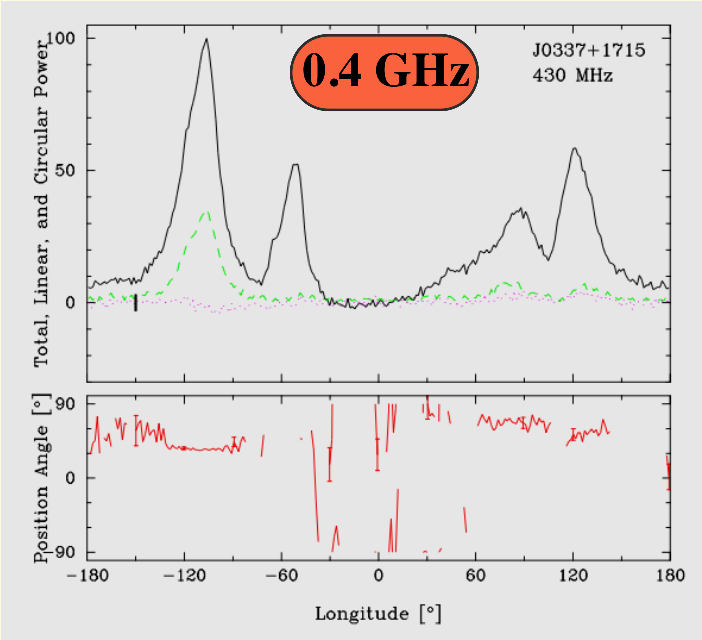


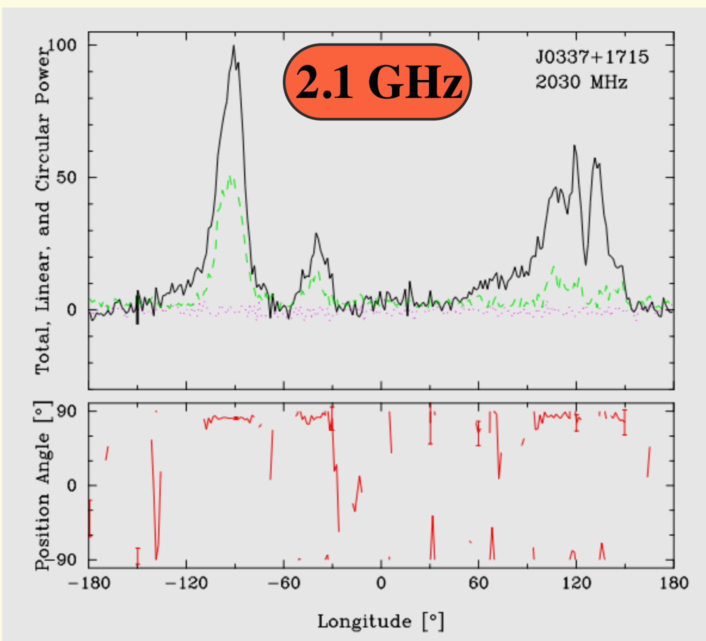
Horrid case in point!

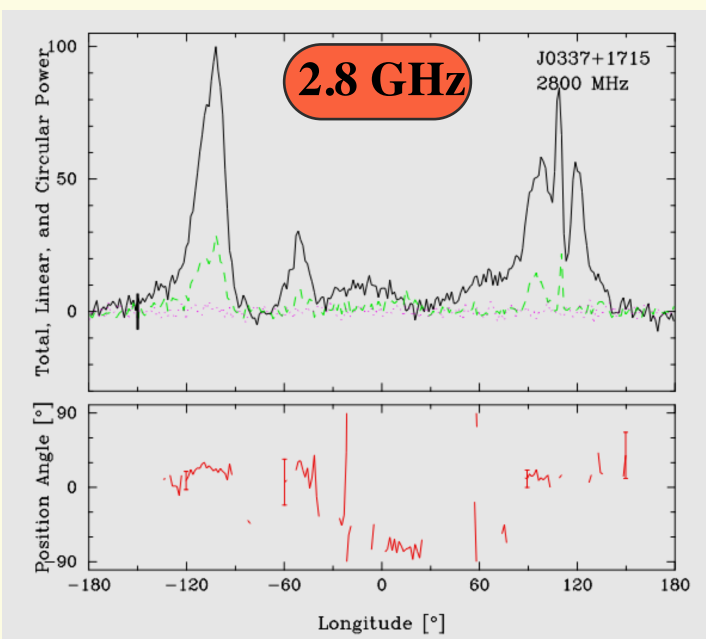


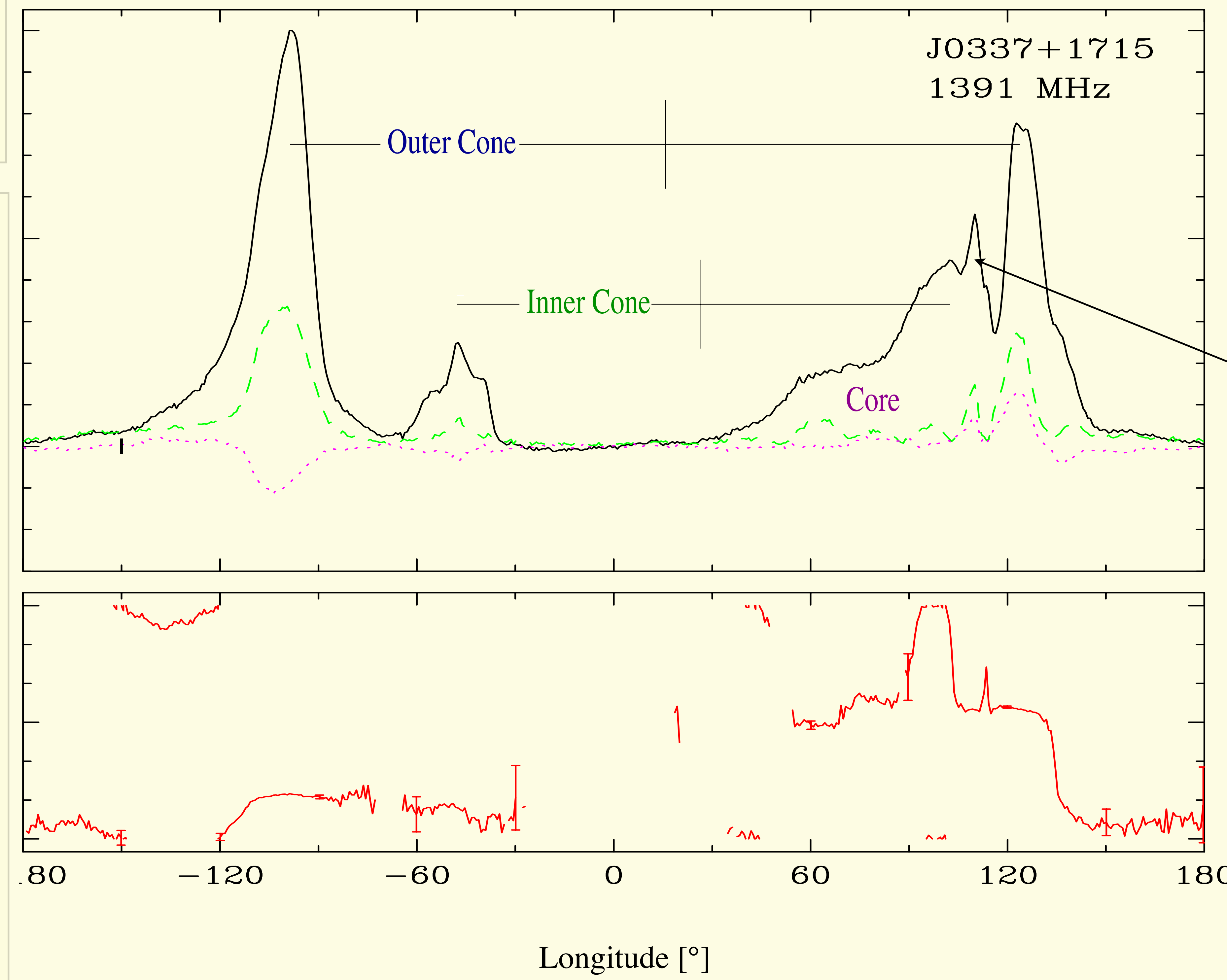
Polarimetry: Manchester & Han 2006, *MNRAS*, **370**, 673.

Double-Cone/Core-Component Profile Structure in 2.7-msec Triple-System MSP J0337+1715









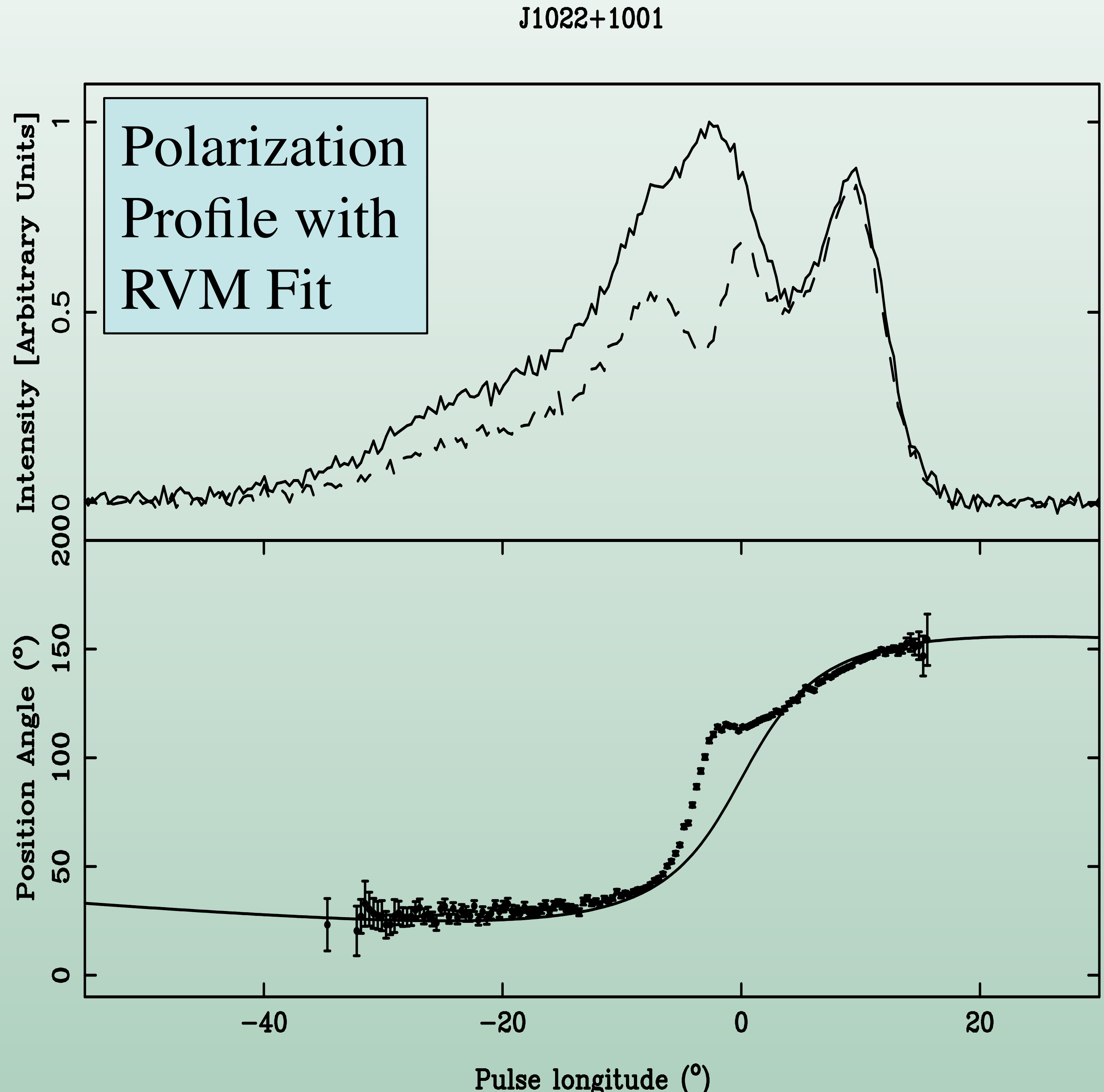
Quantitative Geometry suggests a 30-40 km emission height within a light-cylinder of radius is 130 km.

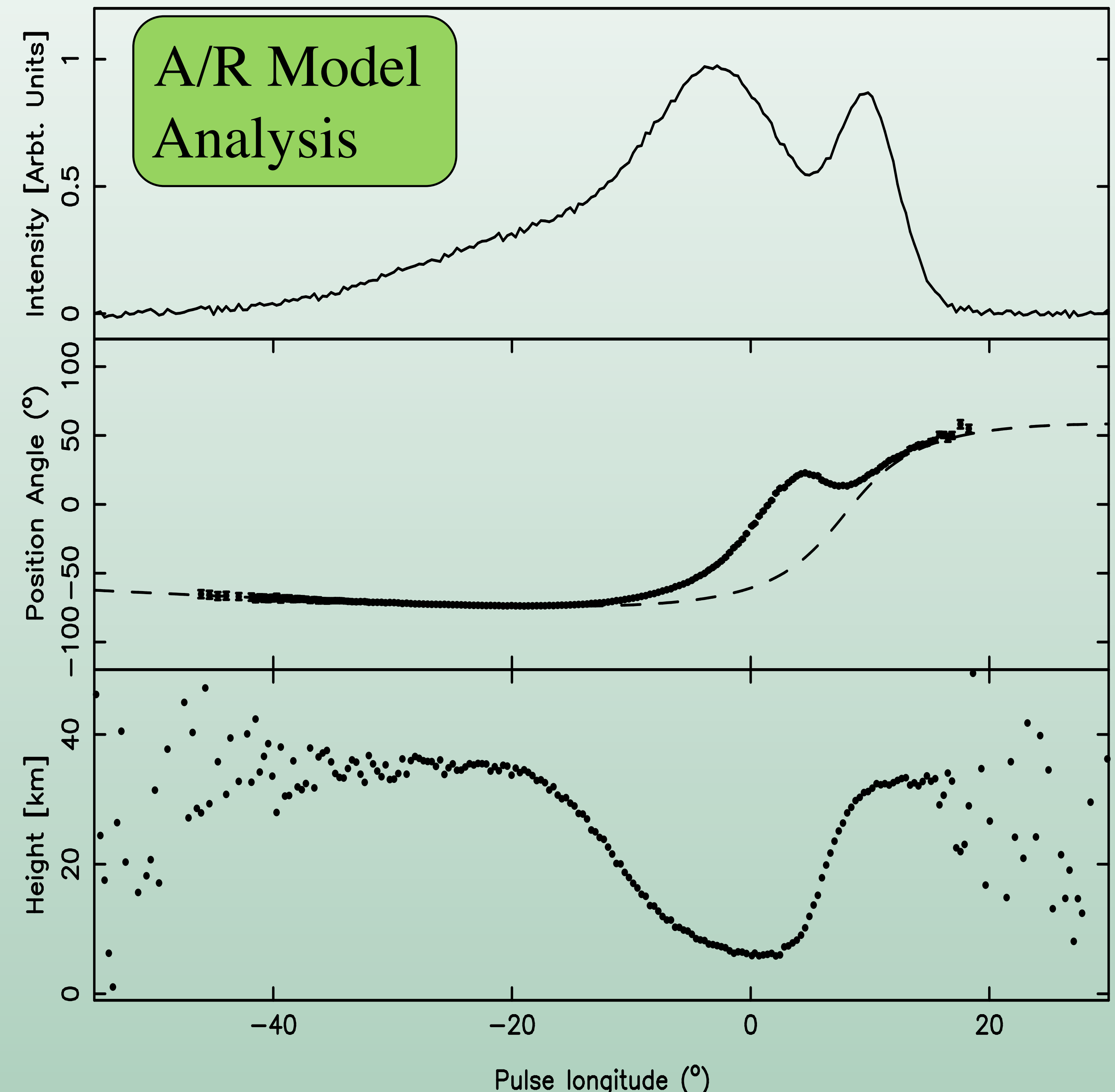
Caustic emission feature?

Aberration/Retardation analysis gives a 50-km emission height within the light-cylinder radius of 130 km.

Collaborators: ***Anne Archibald, Jason Hessels, Joeri Van Leeuwen, Scott Ransom***

A Somewhat Similar Analysis for the 16-ms MSP J1022+1001

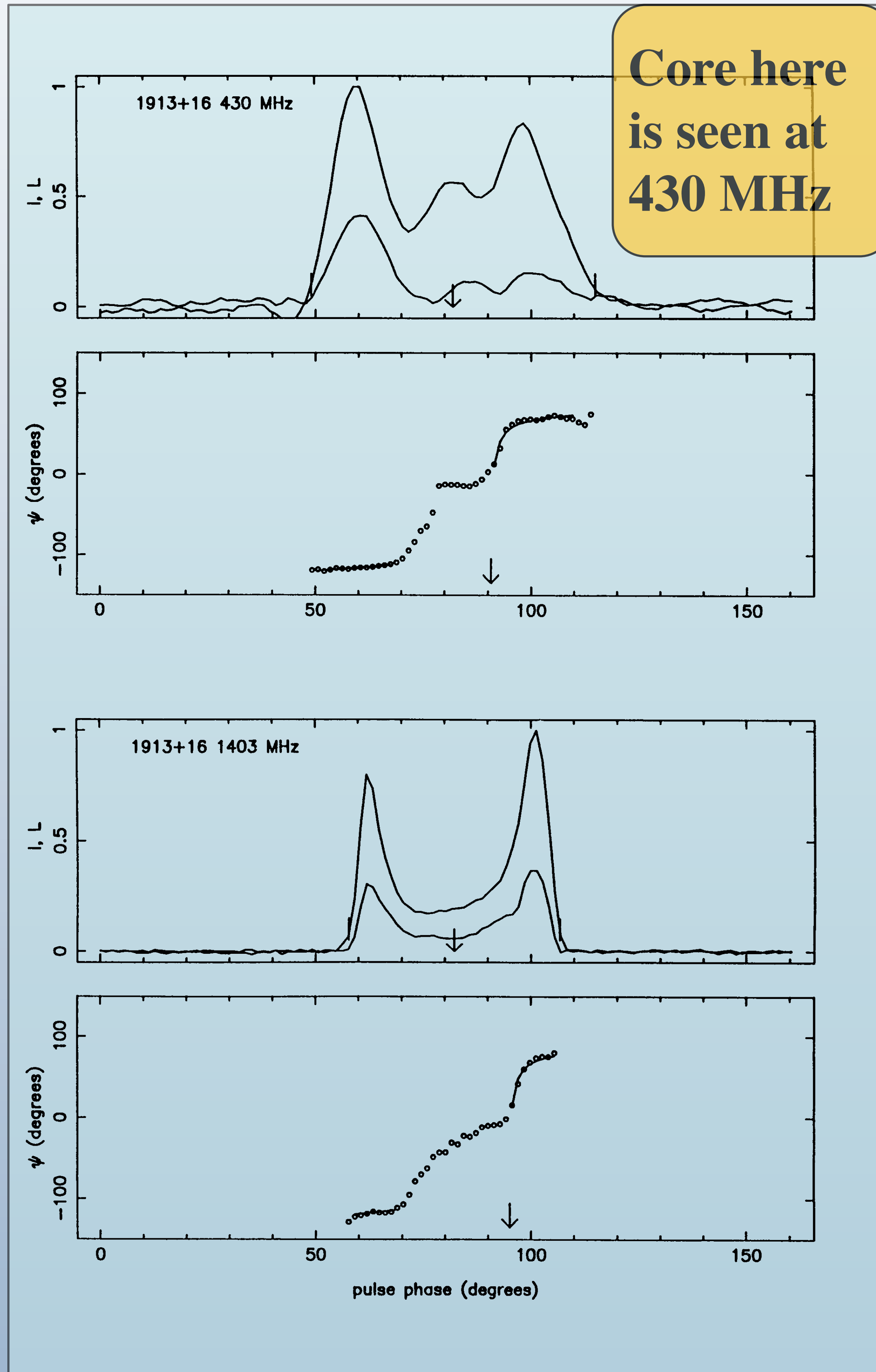




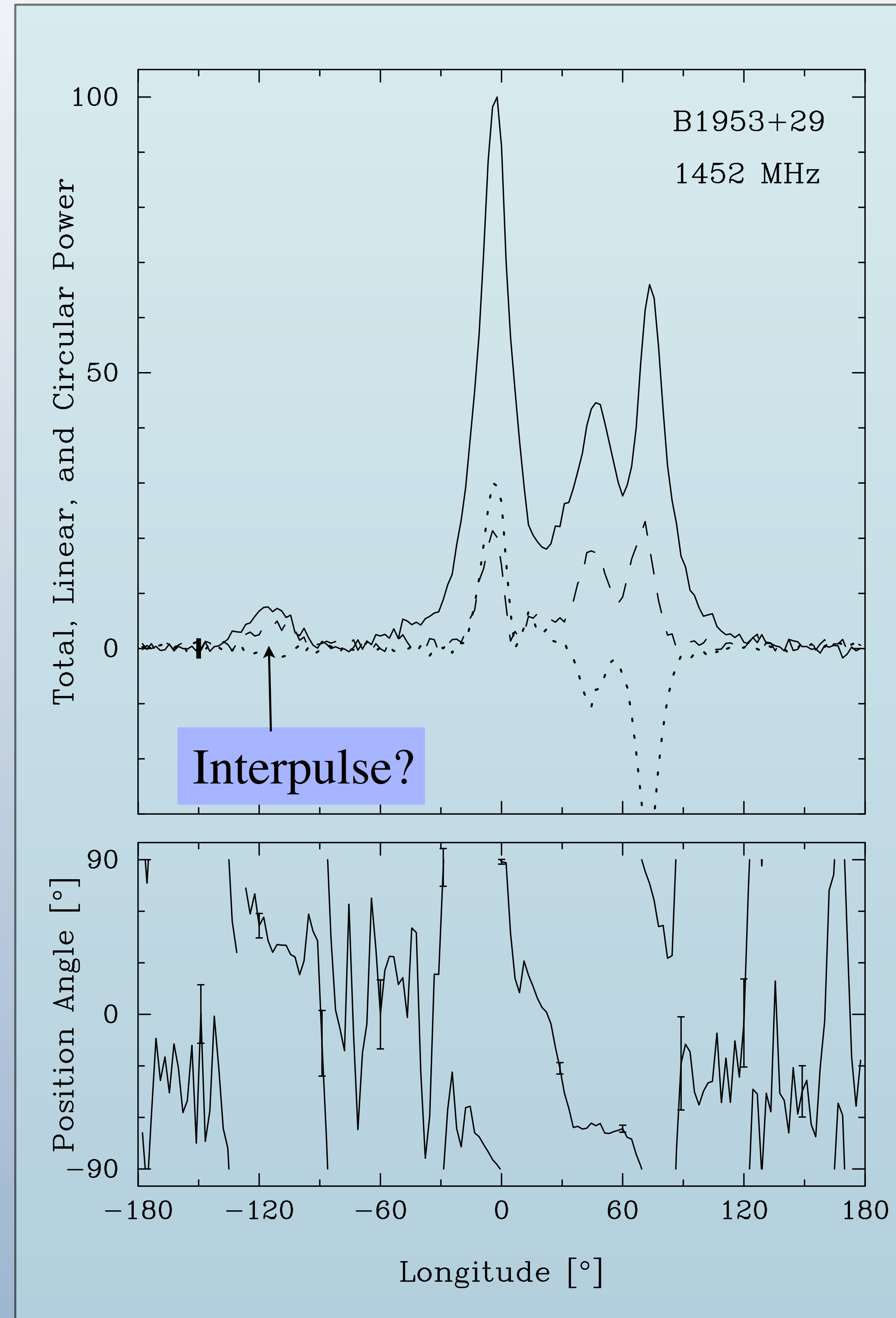
Mitra & Seiradakis 2004 *astro-PH*

Two Old MSPs with Core/Cone Profile Structure and comprehensible quanitative geometry

Binary Pulsar



Core here is seen at 430 MHz

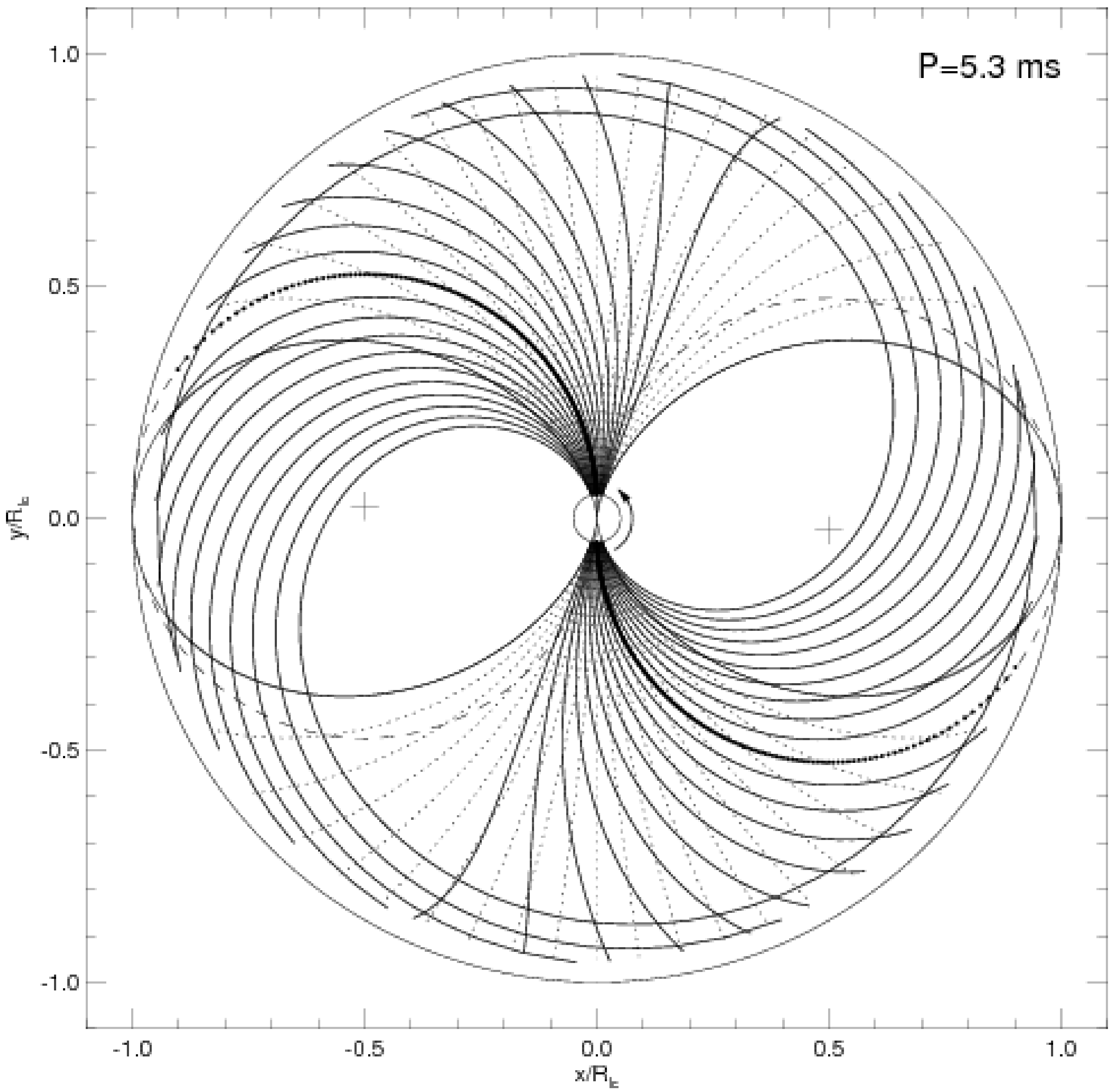


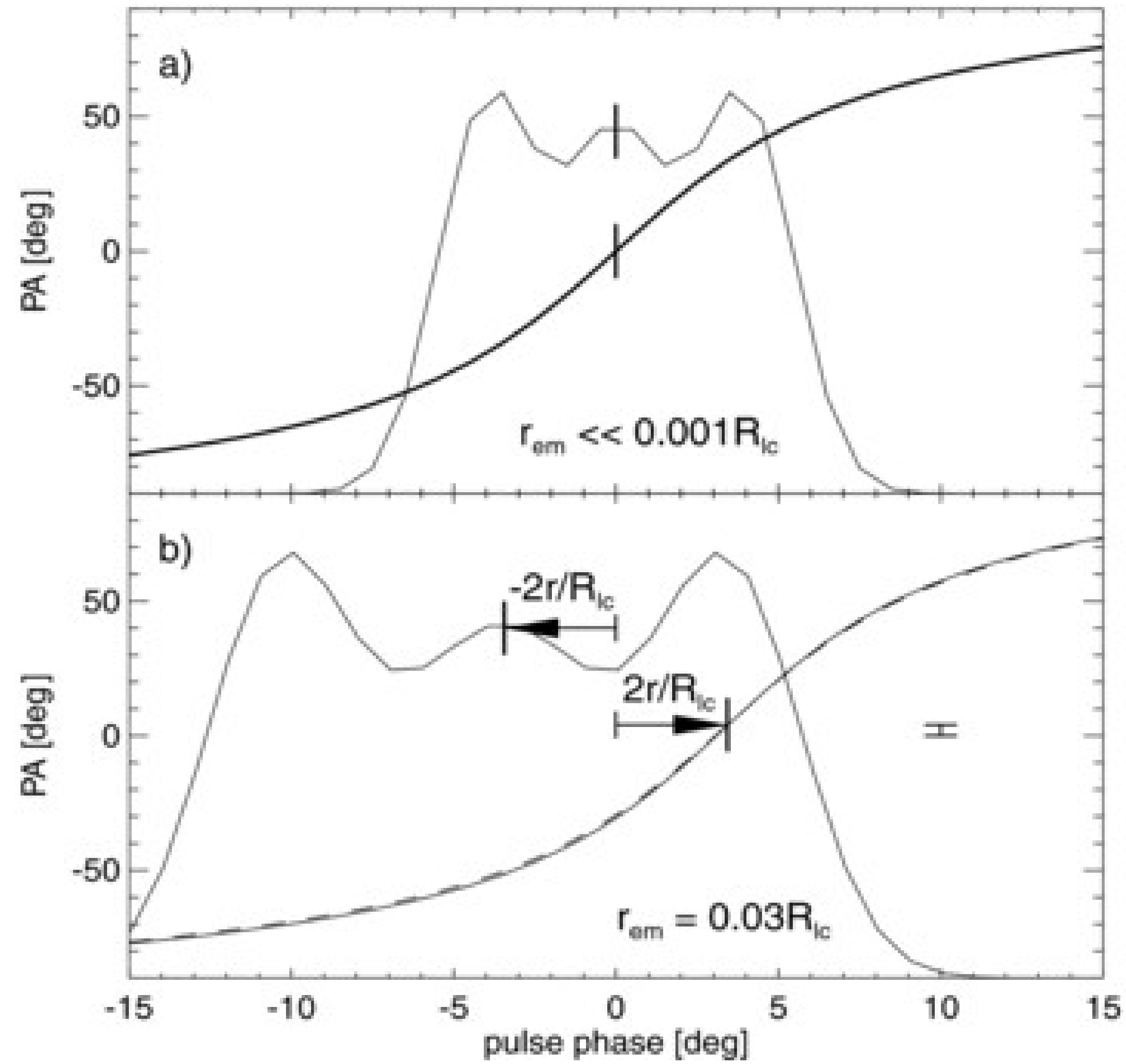
Second MSP

Where Does the Radio Emission Come From?

- Core/Double Cone Model gives 1-GHz emission heights along fluxtube boundary of 100-200 km, underestimating height by a factor of about 2.5
- A/R measurements provide accurate physical emission heights typically around 500 km (Blaskiewicz et al. 1991)
- A variety of average profile and pulse-sequence analyses provide compatible numbers.

A/R effect: Influence of increased emission altitude on the observed PA curve.

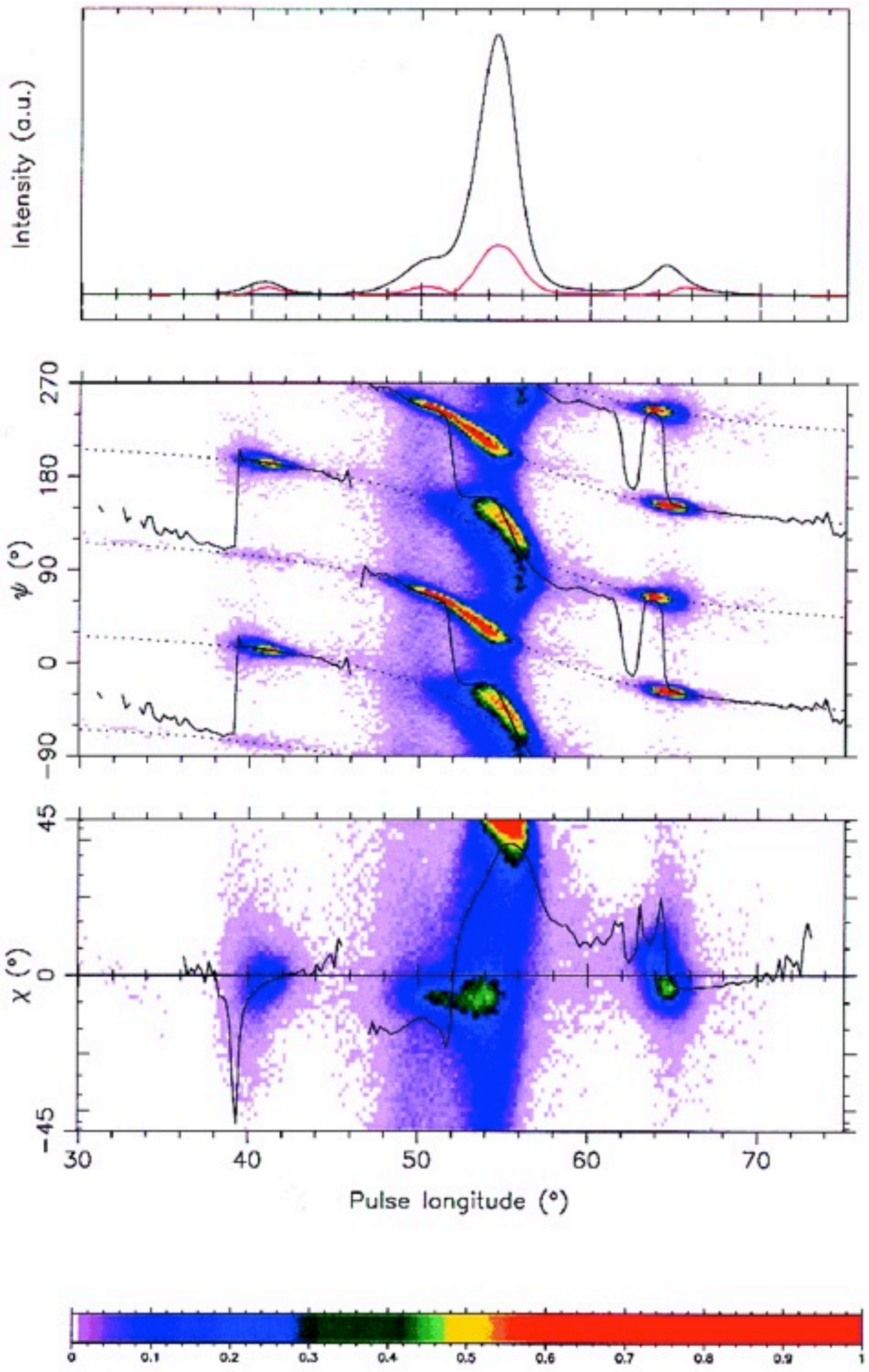




$$Shift: \quad \Delta\phi = \frac{4r}{R_{LC}}$$

Dyks J MNRAS 2008;391:859-868
Dyks J MNRAS 2010

MONTHLY NOTICES
of the Royal Astronomical Society



B0329+54 Core Emission

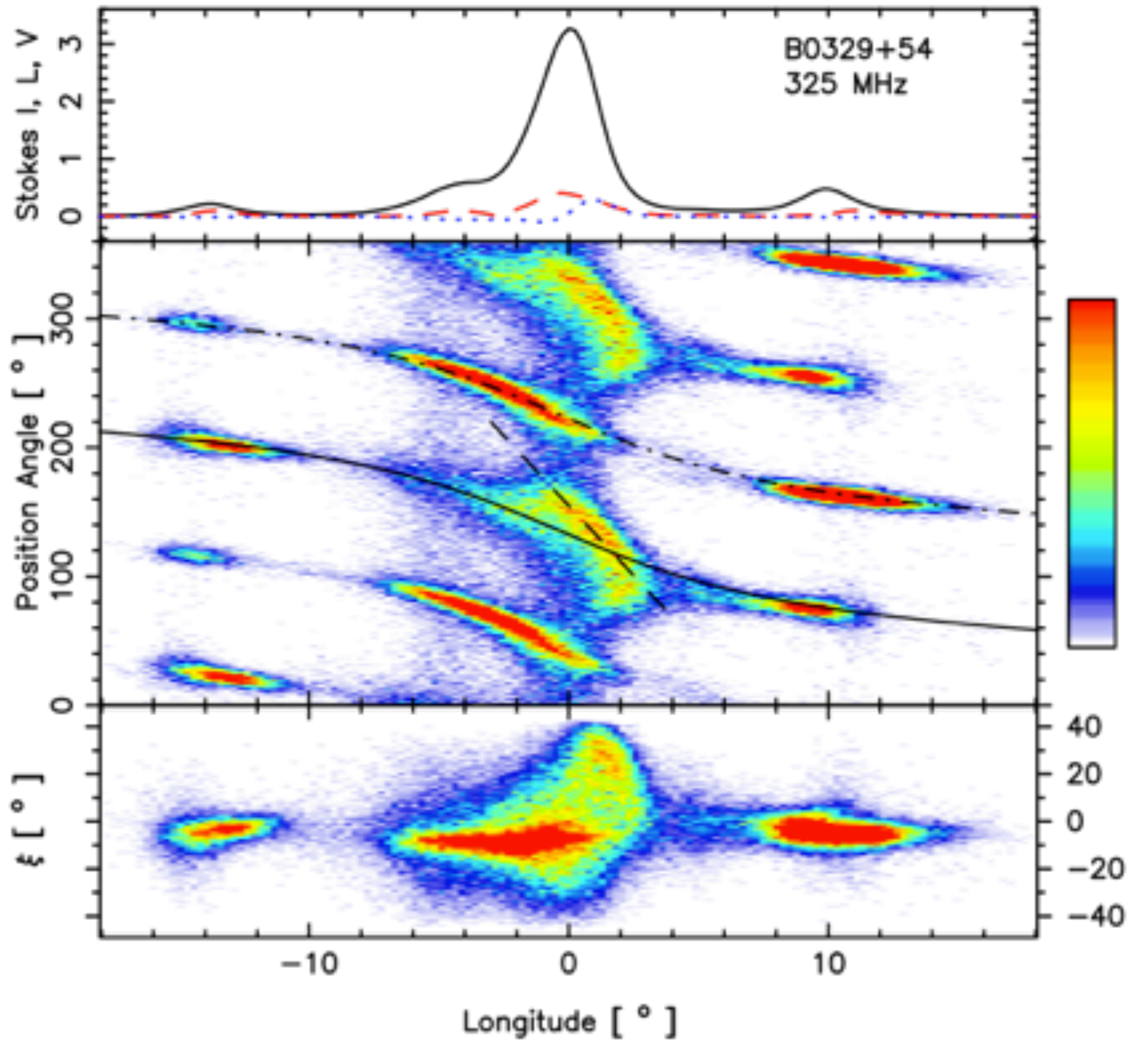
Similar Effects in Other Stars

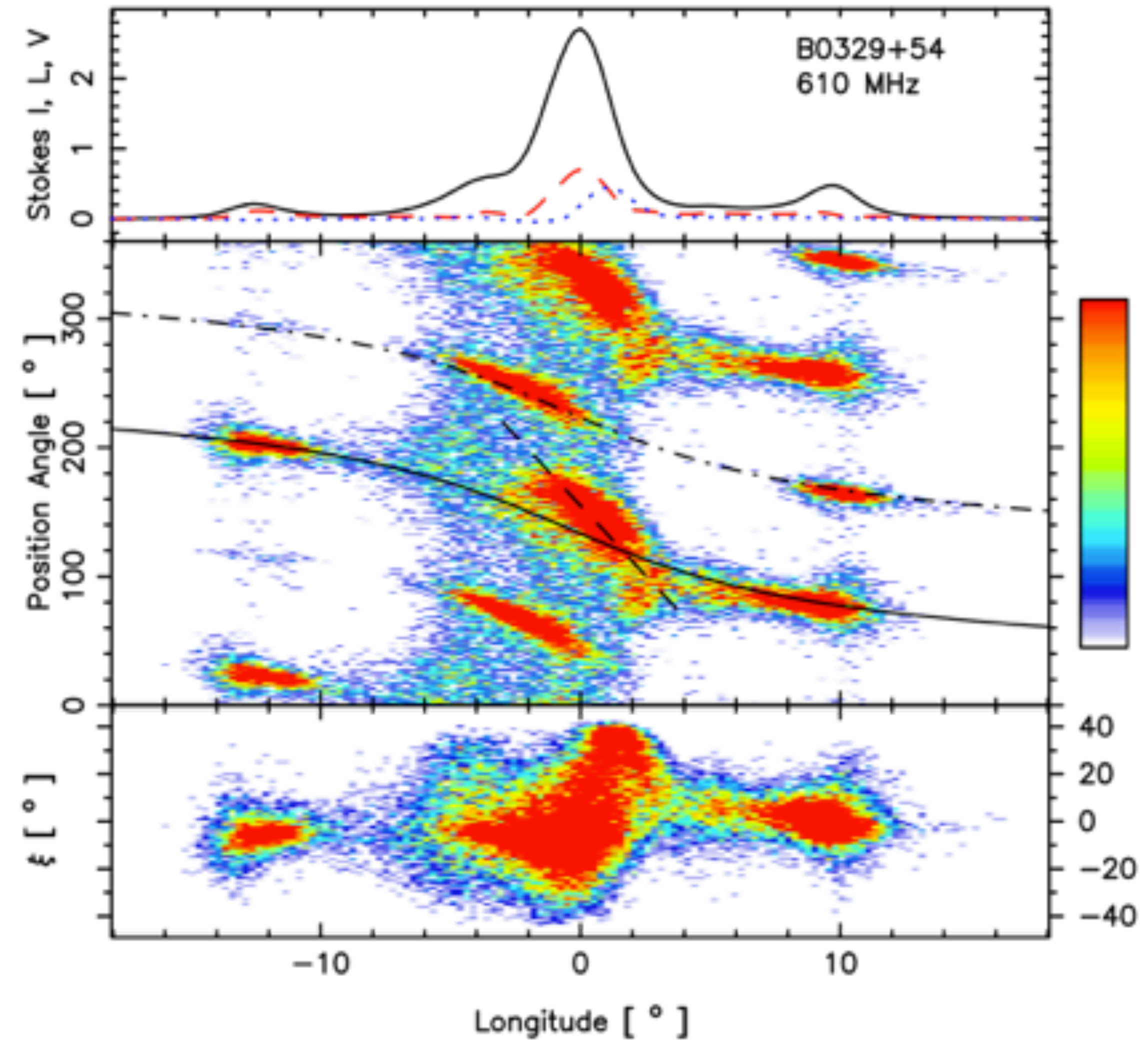
A string of papers have drawn attention to the prominent non-RVM polarization under its central CORE component.

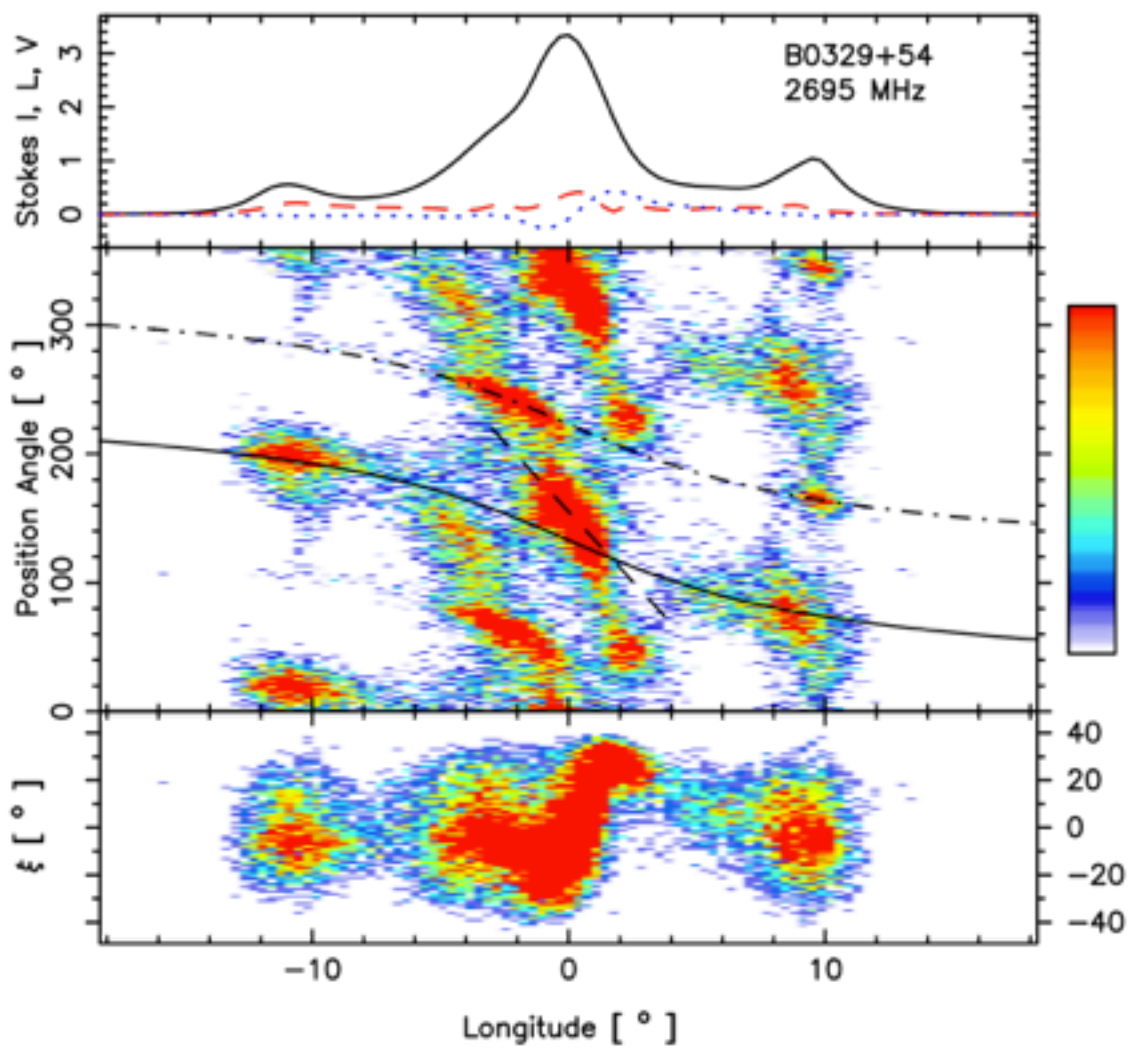
Edwards & Stappers' (2004) analysis of a carefully calibrated 328-MHz WSRT observation exhibited this emission with great clarity.

They attributed the effect to refraction in the pulsar magnetosphere.

Unfortunately, they had only a single frequency observation available.







Multi-Frequency Polarization Behavior

-Triple core/cone profile with "pedestal"

-Note the two polarization modes

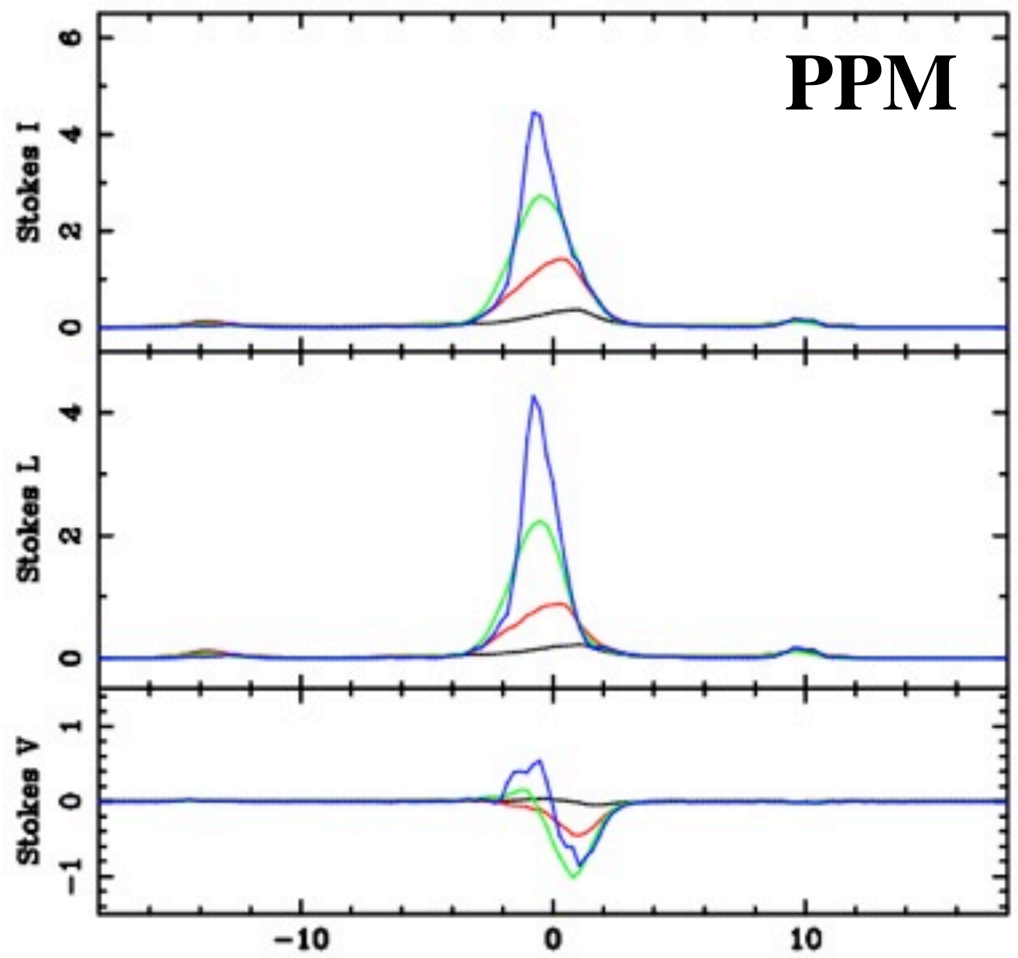
-Rotating-Vector-Model (RVM) fits to each of the two modes (PPM & SPM)

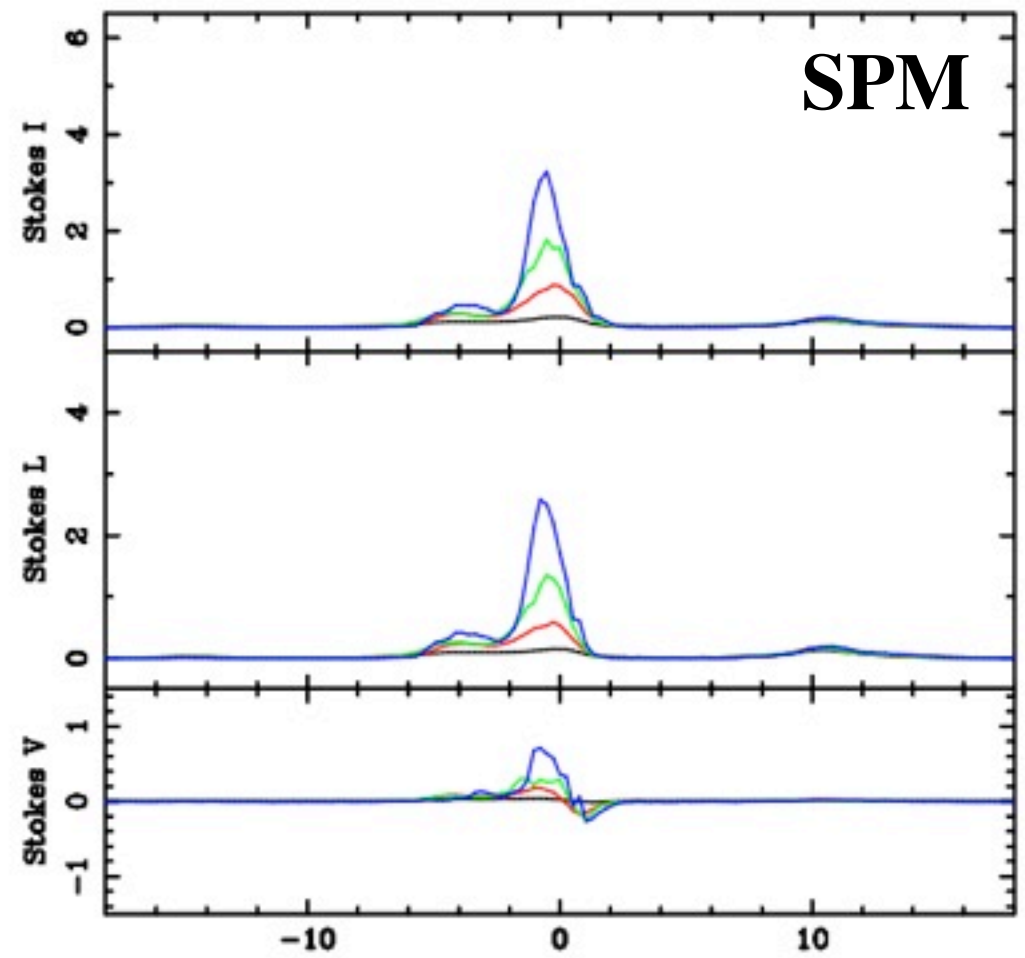
-Clear regions of non-RVM polarization associated with the PPM

What can it indicate?

Mitra, Rankin &Gupta 2007 *MNRAS*, **379,** 932.

Primary- (PPM), Secondary (SPM) and Depolarized (unPOL) Behaviour



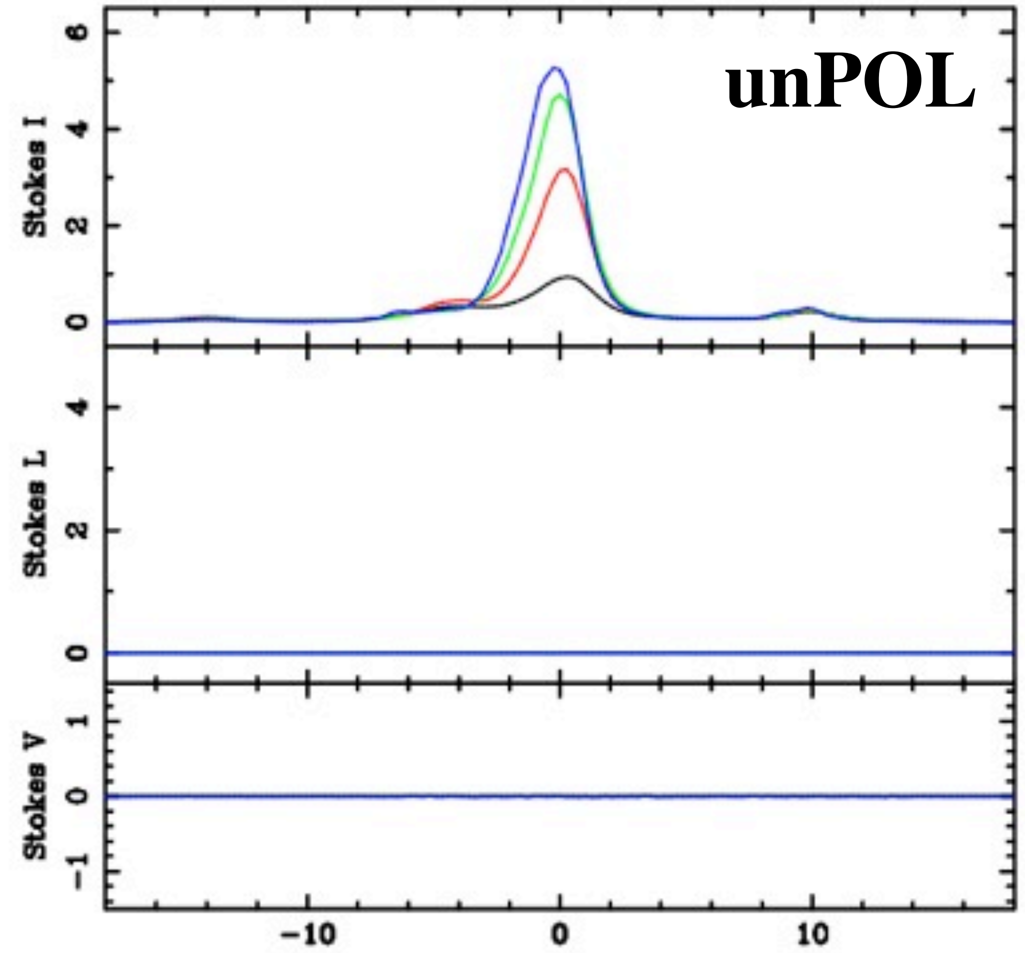


Mode- and Intensity Segregation

Four intensity levels are shown.

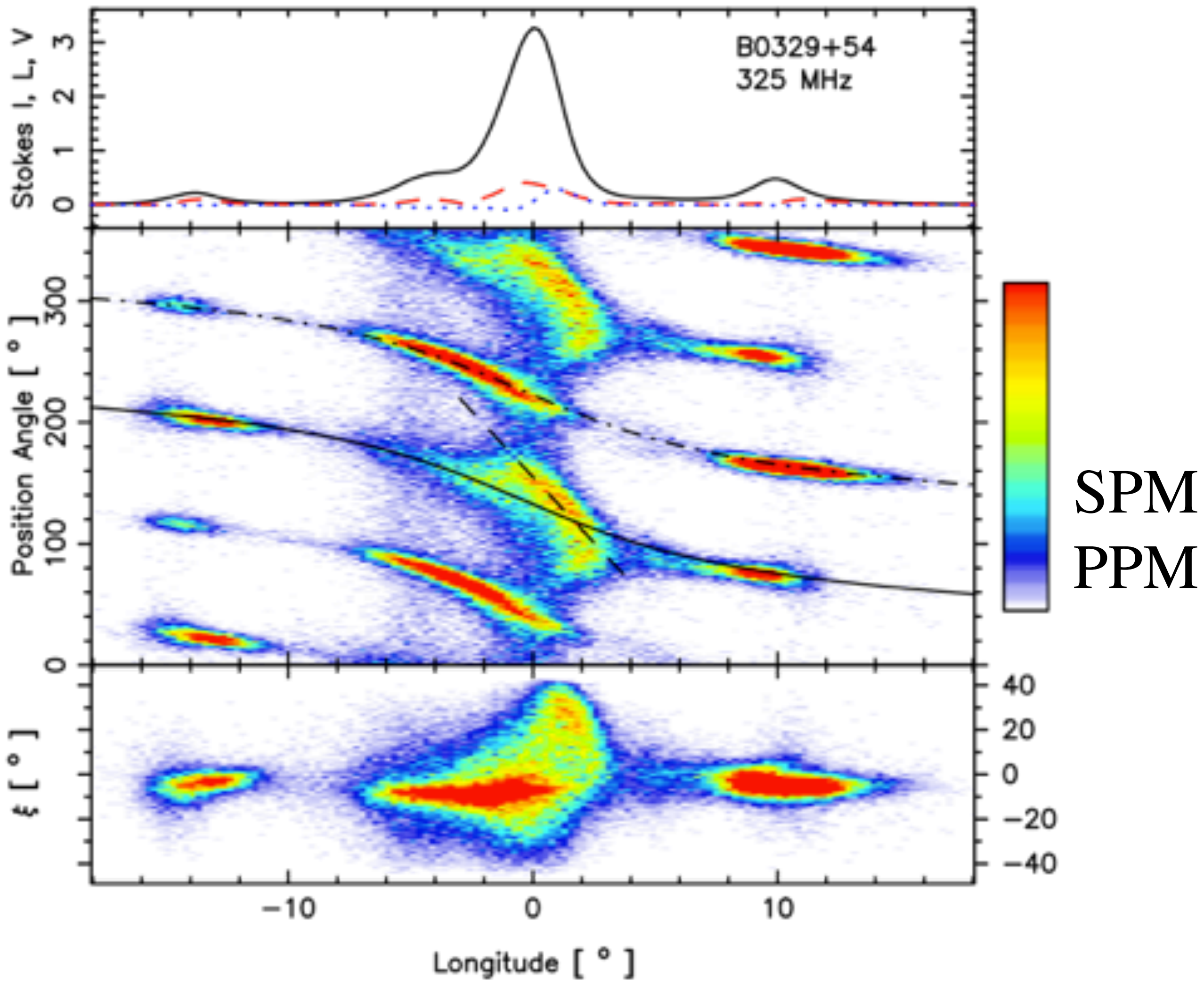
Note how the emission moves earlier (retarded) with higher intensity

And how the circular polarization changes from negative to antisymmetric.



Mitra, Rankin & Gupta 2007 *MNRAS*, **379,** 932.

How Is the non-RVM "Kink" to be Understood Physically??



Please keep in mind—

--High intensity core emission is seen at earlier longitudes

--Higher intensity core emission is associated with the delayed PPM "kink"

--Stronger emission moves up/earlier along the "kink"

--This cannot be a propagation effect; it must be geometric

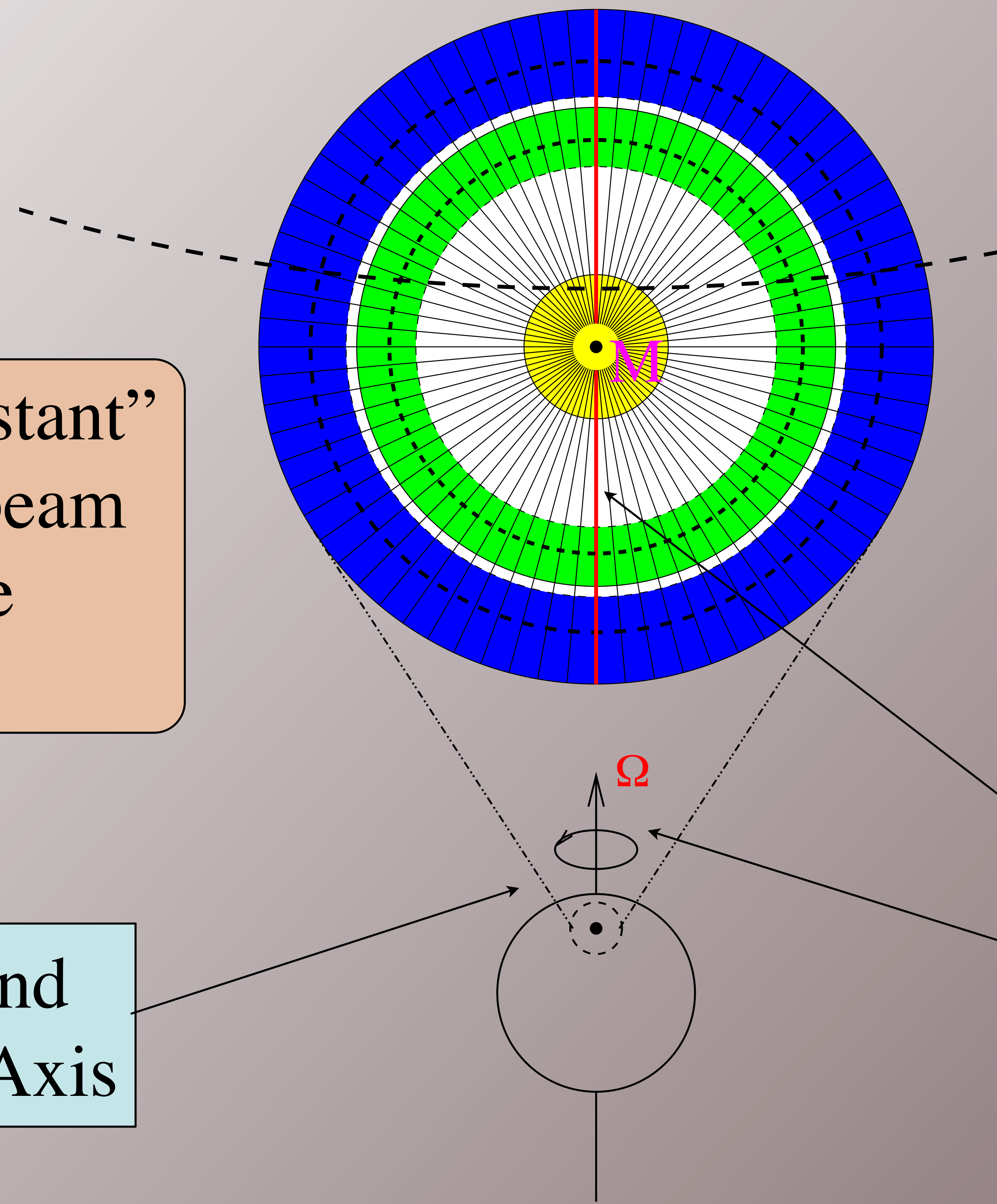
--This is just the signature of A/R, aberration/retardation

Apparently, we are here seeing evidence of the primary core radiation process—that is a height-dependent amplification or cascade along the **B** axis with $\Delta t/4c$ indicating some 300-400 km.

Mitra, Rankin &Gupta 2007 *MNRAS*, **379,** 932.

Core "Fiducial" Polarimetry Reveals the Emission Physics

Sightline



The "Fiducial Instant" when a pulsar's beam squarely faces the Earth

Note the outer & inner conal beams, and core (yellow) around the magnetic axis M.
Note that the fiducial field lines (red vertical) are || to the rotation Ω

Pulsar and Rotation Axis

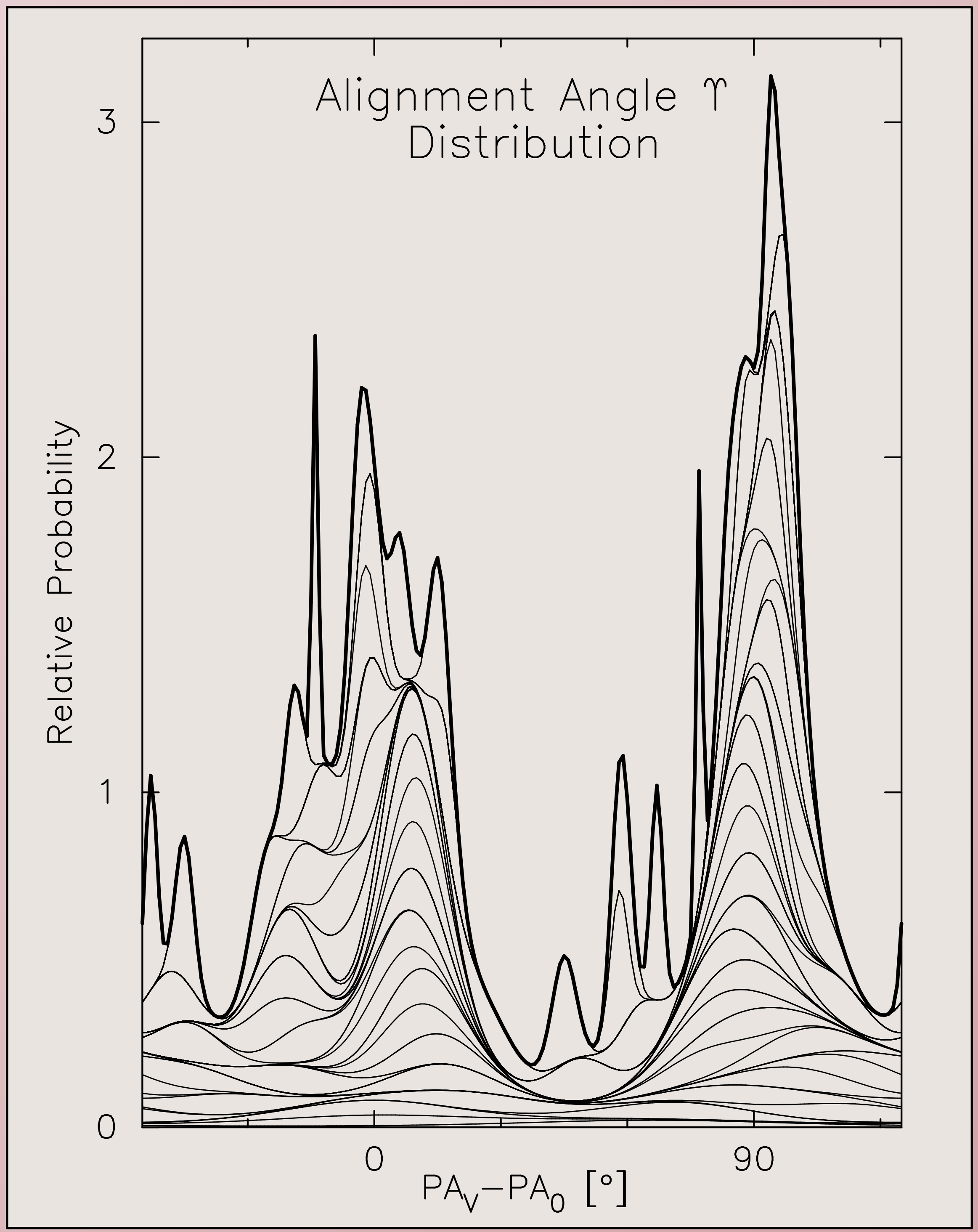
Rankin 2015 *in press.*

Absolute "Fiducial" Polarimetry Entails—

- Accurate absolute polarimetry (ccw from North)
- Polarization angle (PPA) measurement at the "fiducial" (magnetic axis) longitude
- Reference to infinite frequency by unwrapping Faraday rotation

Fiducial PA_0s then represent proxies for the unseen rotation axis orientation on the sky Ω

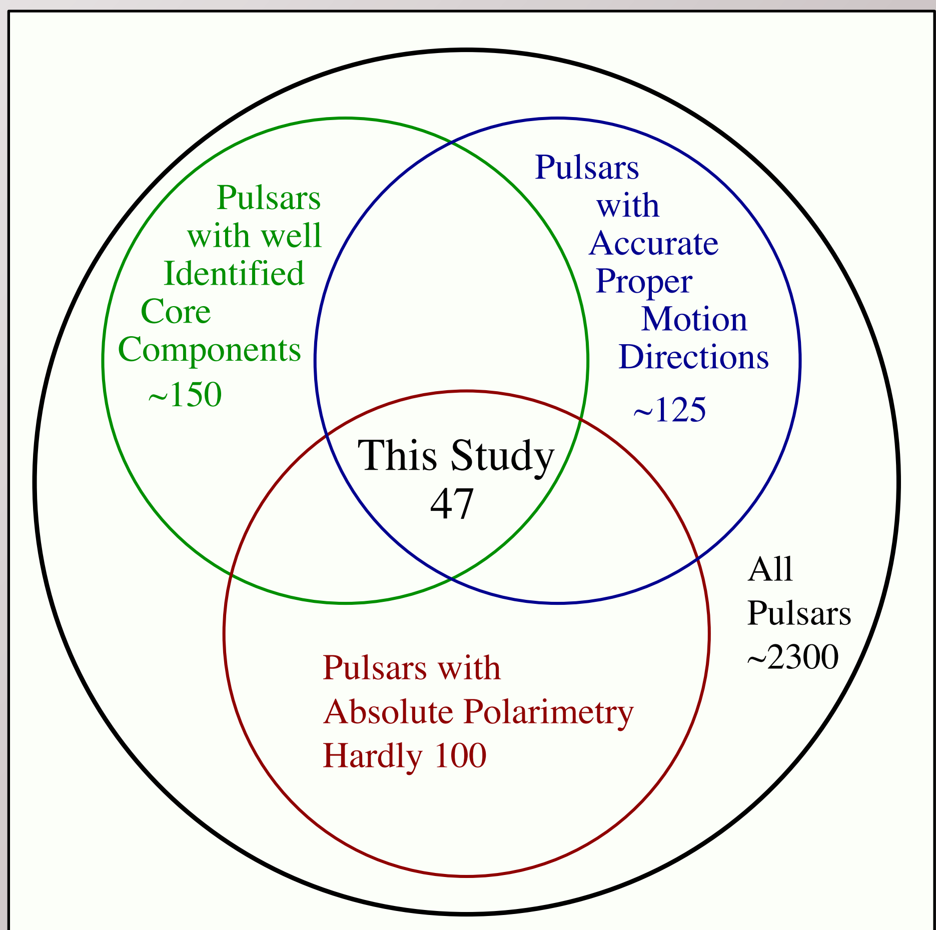
Difference angles between the fiducial and proper-motion directions tend to both 0° and 90° because of OPM confusion, thwarting physical interpretation.



Restricting Consideration to Core Components .....

Some 50 Pulsars Qualify in Three Ways for this Analysis—

- Core Components
- Absolute Polarimetry
- Accurate Proper Motions

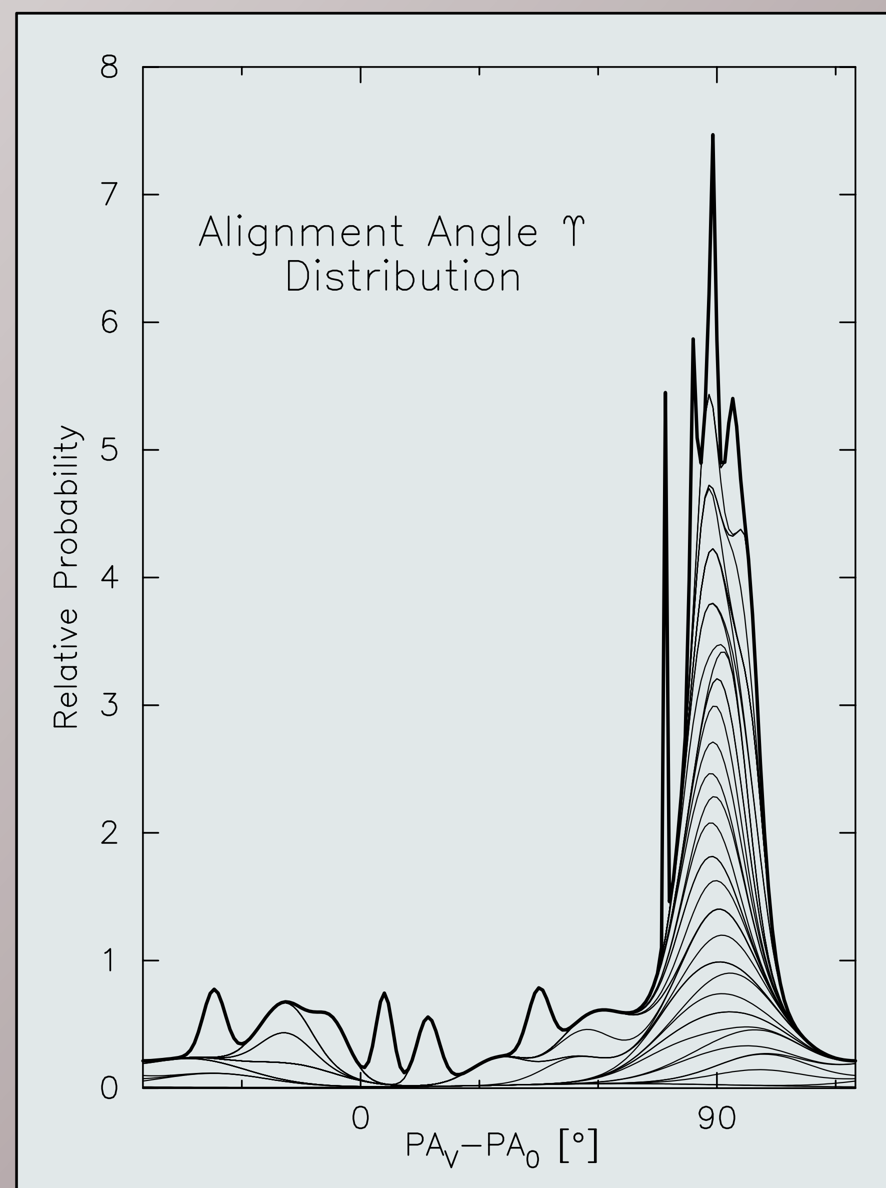


Rankin 2015 *in press.*

Alignment angle

$$\Psi = PA_{PM} - PA_{FID}$$

between the proper-motion direction and the fiducial PPA on the sky



Ψ Distribution for "Parent" Core Emission

Conclusions

✴ *Pulsar velocities are mostly polarized ⊥ to the "parent" core radiation*

✴ *This core radiation is polarized ⊥ to the local magnetic field*

✴ *SN "kicks" are thus || to the pulsar spin axis Ω*

✴ ***Most pulsar radiation highly plasma processed***

Take Aways:

- *Radio pulsar phenomena occur within the dipolar zone of the polar fluxtube*
- *Core/Double Cone Geometry works well for slow pulsars and probably for some MSPs*
- *Provide a key foundation for interpreting single pulse phenomena*
- *Pulsar radio emission occurs at a height of about 500 km. Key result later talks will interpret further*
- *Core radiation polarized $\perp$ to B and represents the X propagation mode*