Pulsars

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Purpose :

To outline

- Some interesting properties of pulsars
- Some of the current pulsar research topics at HartRAO

Outline

- Discovery of pulsars
- What is a pulsar
- Two interesting pulsars
  - Crab
  - Vela
- Some aspects of the HartRAO pulsar research

I : Discovery of pulsars

- 1932 : Discovery of neutron by Chadwick
  - News reaches Bohr, who was hosting Landau
  - Lev Landau spends day speculating on implications
  - Landau postulates existence of stars made completely of neutrons
  - Landau does not develop the theory

- 1934 : Baade & Zwicky propose existence of neutron stars. Propose
  - Rapid rotation
  - Ultra high density
  - Formation result of supernova explosion

- 1939 : Oppenheimer & Volkoff theoretically predict
    - Mass
    - Density
    - Diameter
- 1964 : Hoyle, Naarlikar & Wheeler argue for ultra strong magnetic field on a neutron star at the centre of Crab nebula
- 1967 : Pacini proposes that rapid rotation of highly magnetised neutron star is what powers Crab nebula

- 1968 : Hewish et. al. announce discovery of 1.377 s pulsating radio source at 81.5 MHz
- 1968 : Gold argues that the pulsating radio source is a rotating neutron star
- Identification not immediate :
  - white dwarf stars were thought better candidates
  - Pulsations were thought to be vibrations – possible
- 1968 : Vela & Crab pulsars discovered
  - Vela period : 89 ms
  - Crab period : 33ms
  - Debate settled – only neutron stars could vibrate or rotate 30 times per second

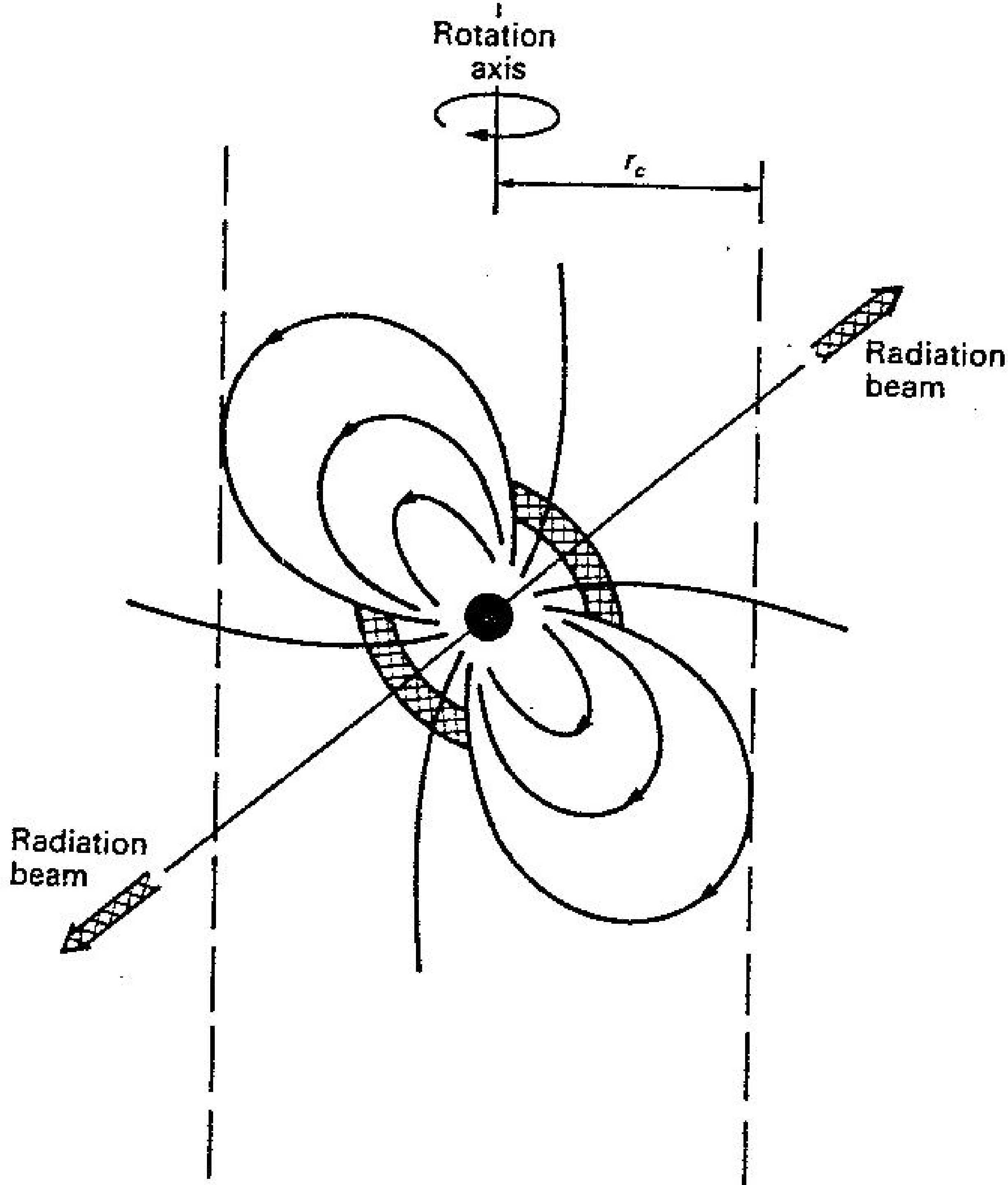
- 1969 : Rotation-vibration debate settled -
  - Rotation would slow down
  - Vibration can damp, but not slow
  - Spin-down measured for Vela and Crab
- Further confirmation : both Vela & Crab in supernova remnants

II : What is a pulsar ?

- Rapidly rotating neutron star
- Very dense
  - Mass : 1.2 to 1.4 solar masses
  - Radius : 10 – 15 km
- Huge magnetic field : 10^{12} gauss

Magnetic field

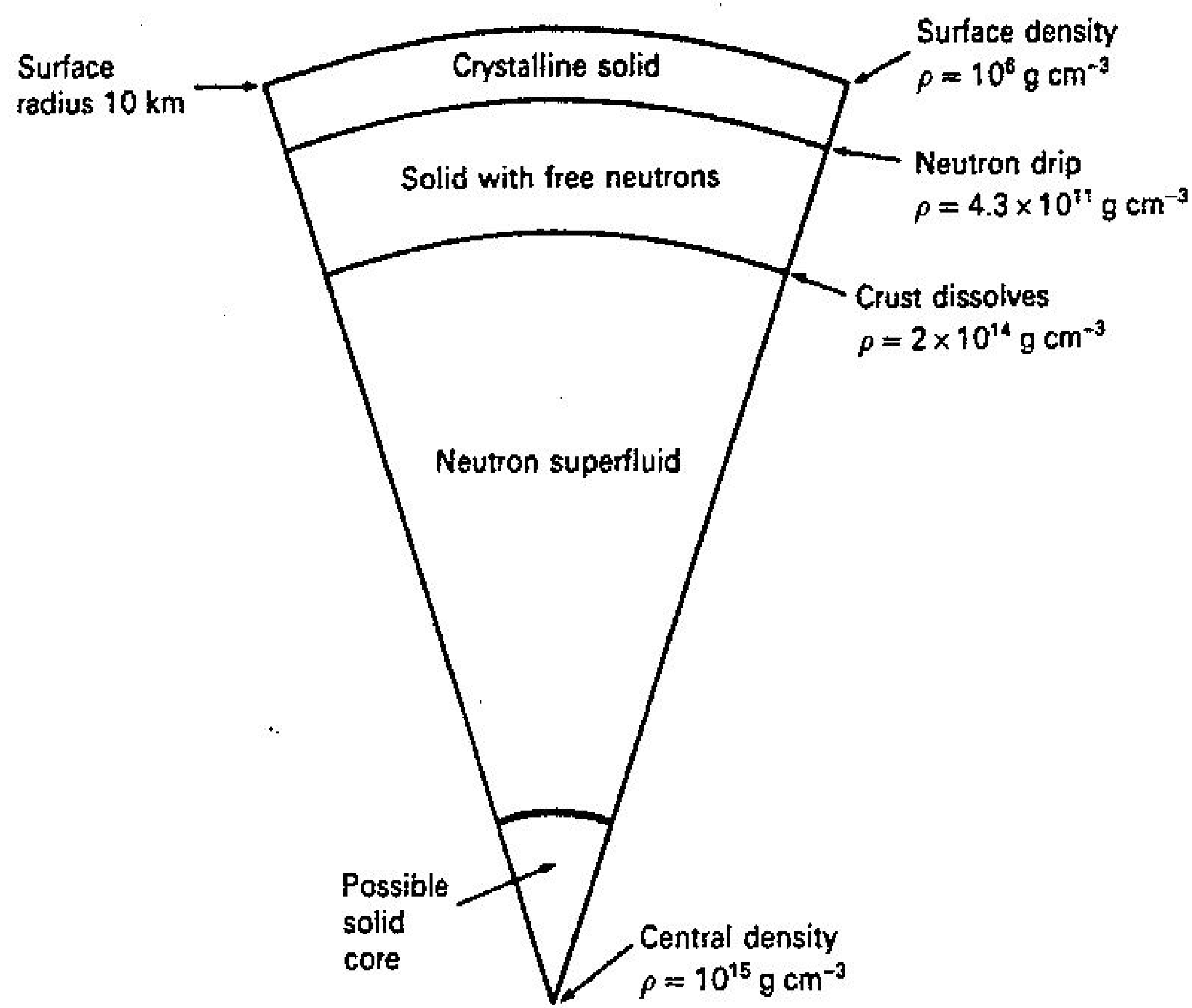
- Magnetic & rotation axes misaligned
- Magnetic field rotates
  - Magnetic dipole radiation
    - Energy loss
    - Gradual spin down
  - Huge induced electric field
    - Electrons dragged out of iron surface
    - Currents along field lines
    - Particle anti-particle cascades


Rotation
axis
r_c
Radiation
beam
Radiation
beam

Radiation

- 2 types of magnetic field lines
  - Open
  - Closed
- Particles accelerate along lines
  - Open field lines : particle beam
  - Closed field lines : particles trapped
- Accelerated particles radiate : curvature radiation
- Open field lines : beaming effect
- Closed field lines : cyclotron

Internal structure

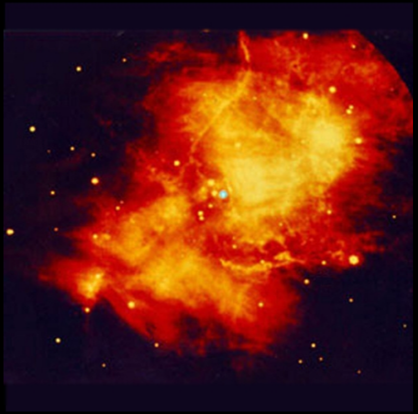


III : 2 Interesting Pulsars

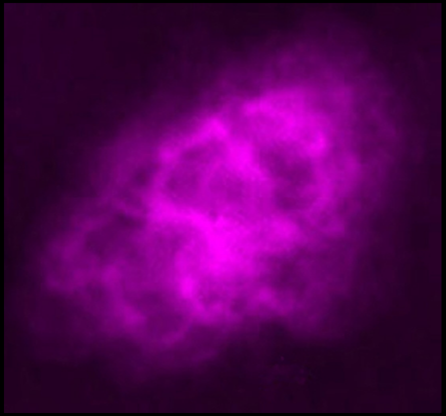
- Crab
- Vela

Crab pulsar

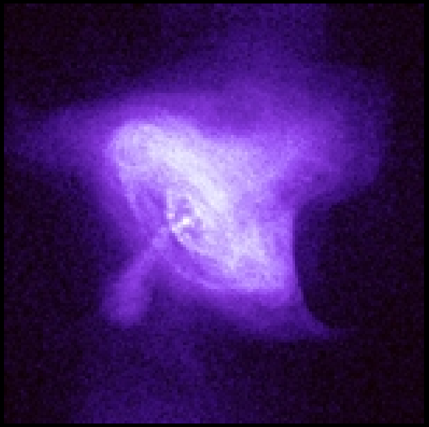
Optical



Infrared



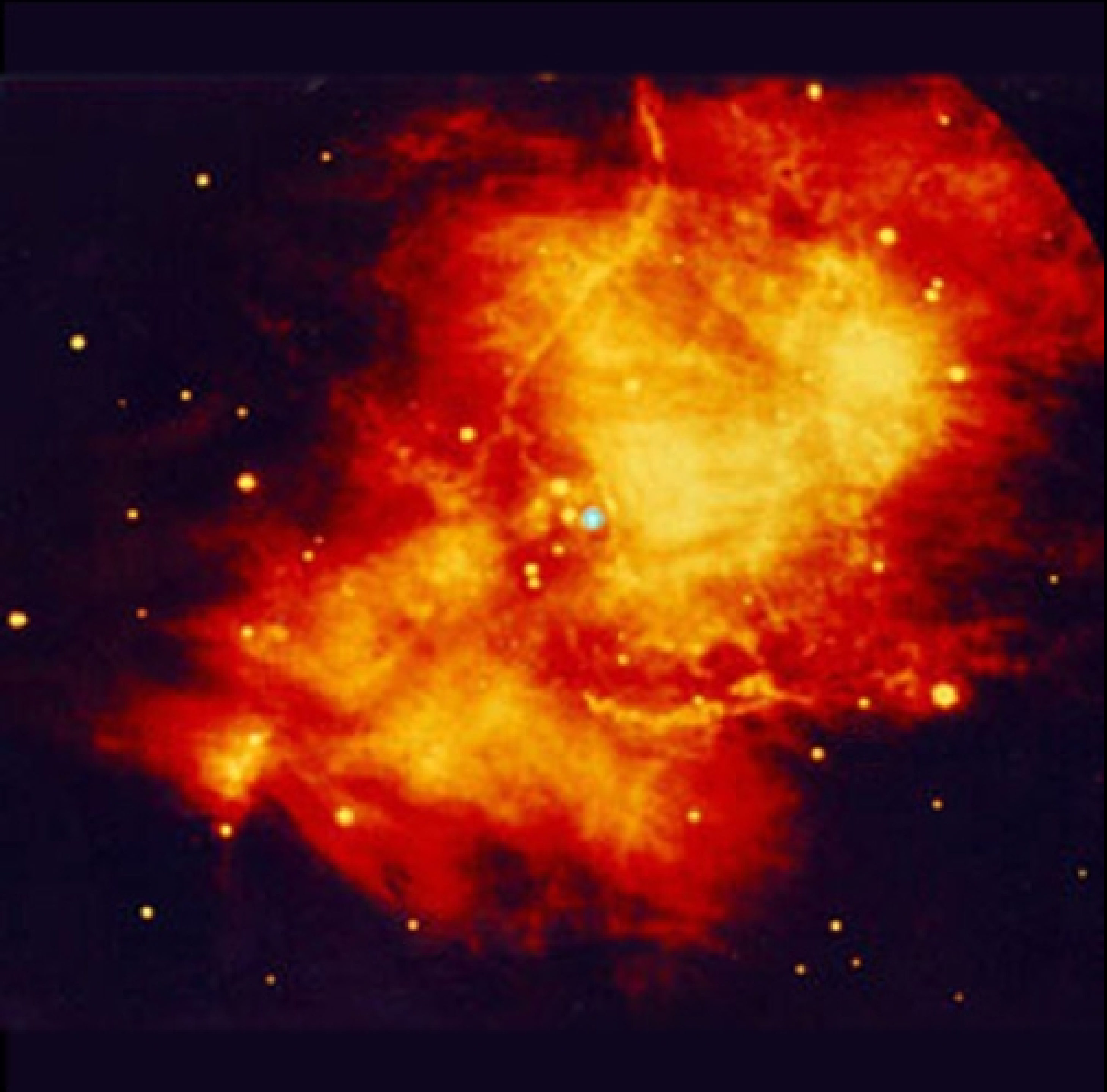
Radio



X-ray

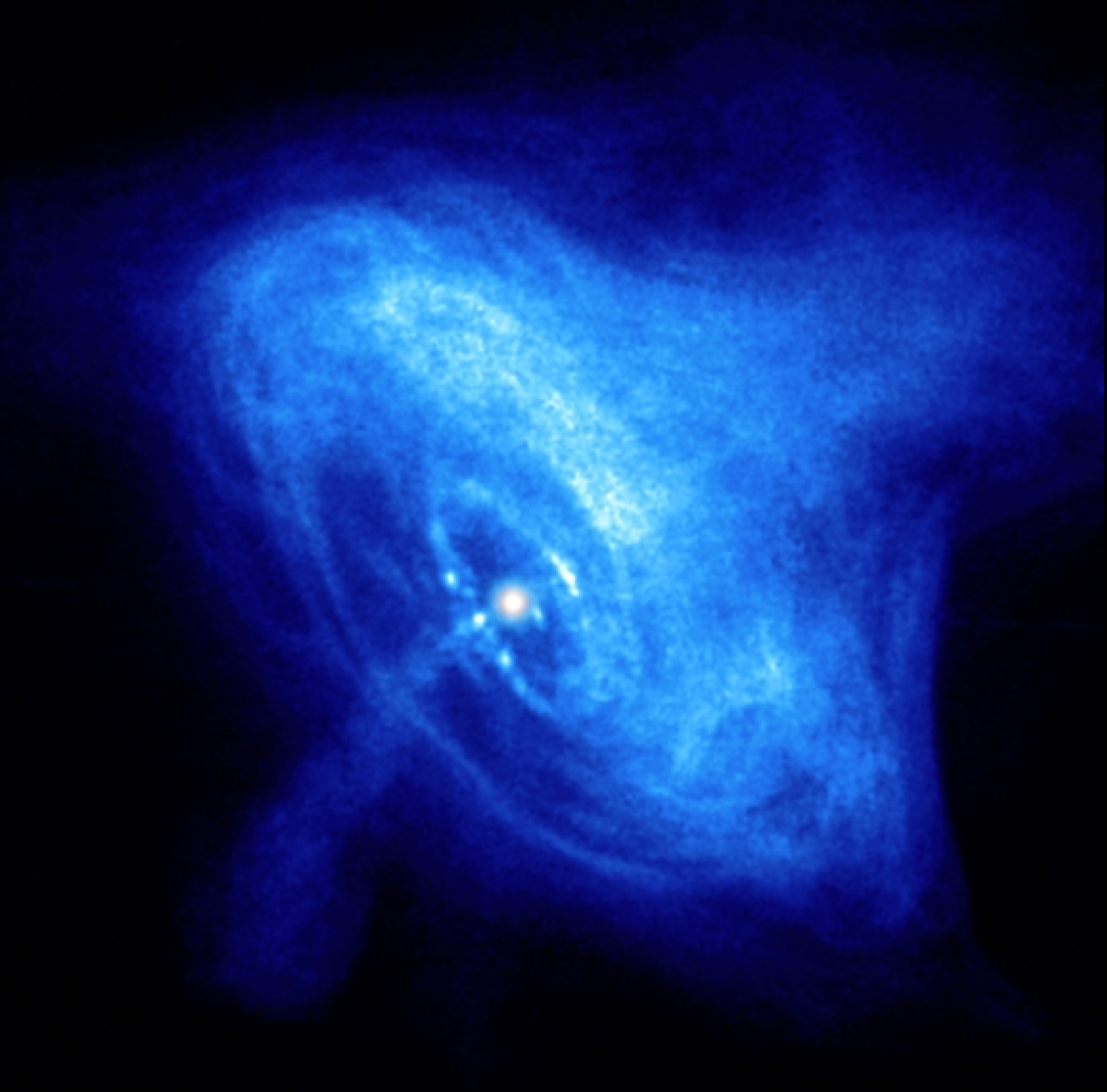
Composite

optical



Infrared

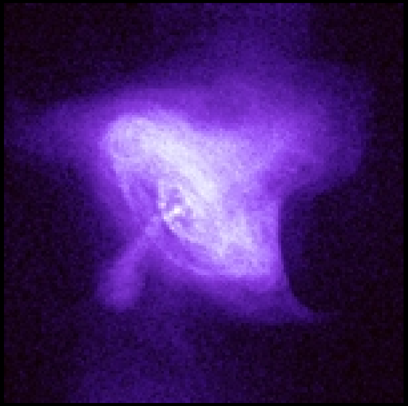
Radio



X-ray

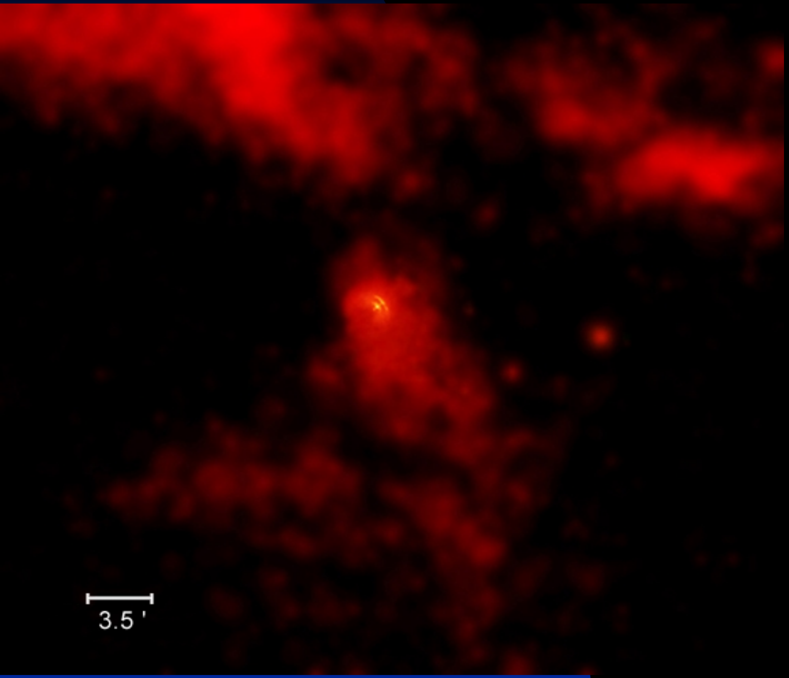
Composite

Crab pulsar - Chandra



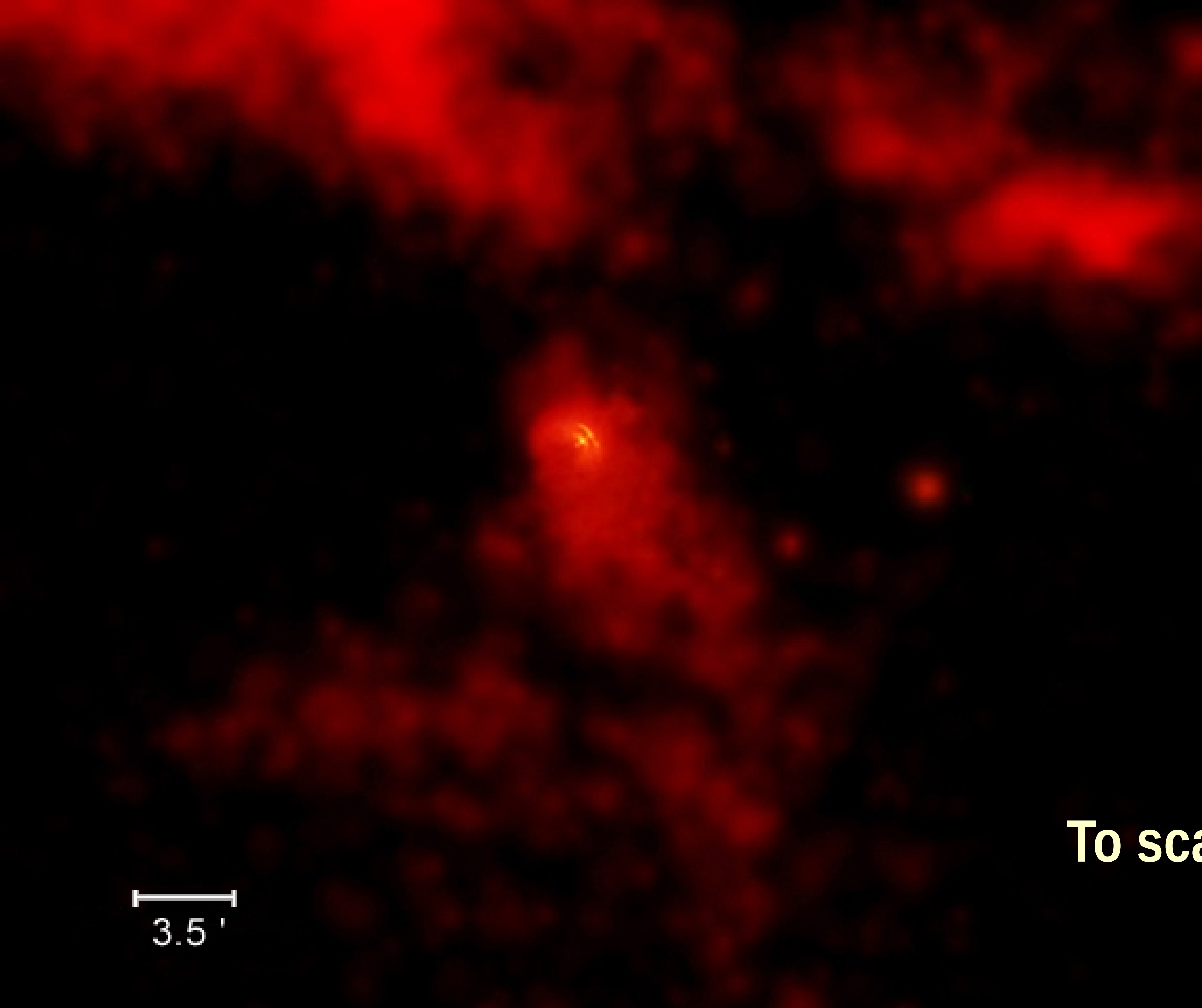
- dynamic rings
- wisps and jets of matter and antimatter
- inner ring about one light year across.

Vela Pulsar

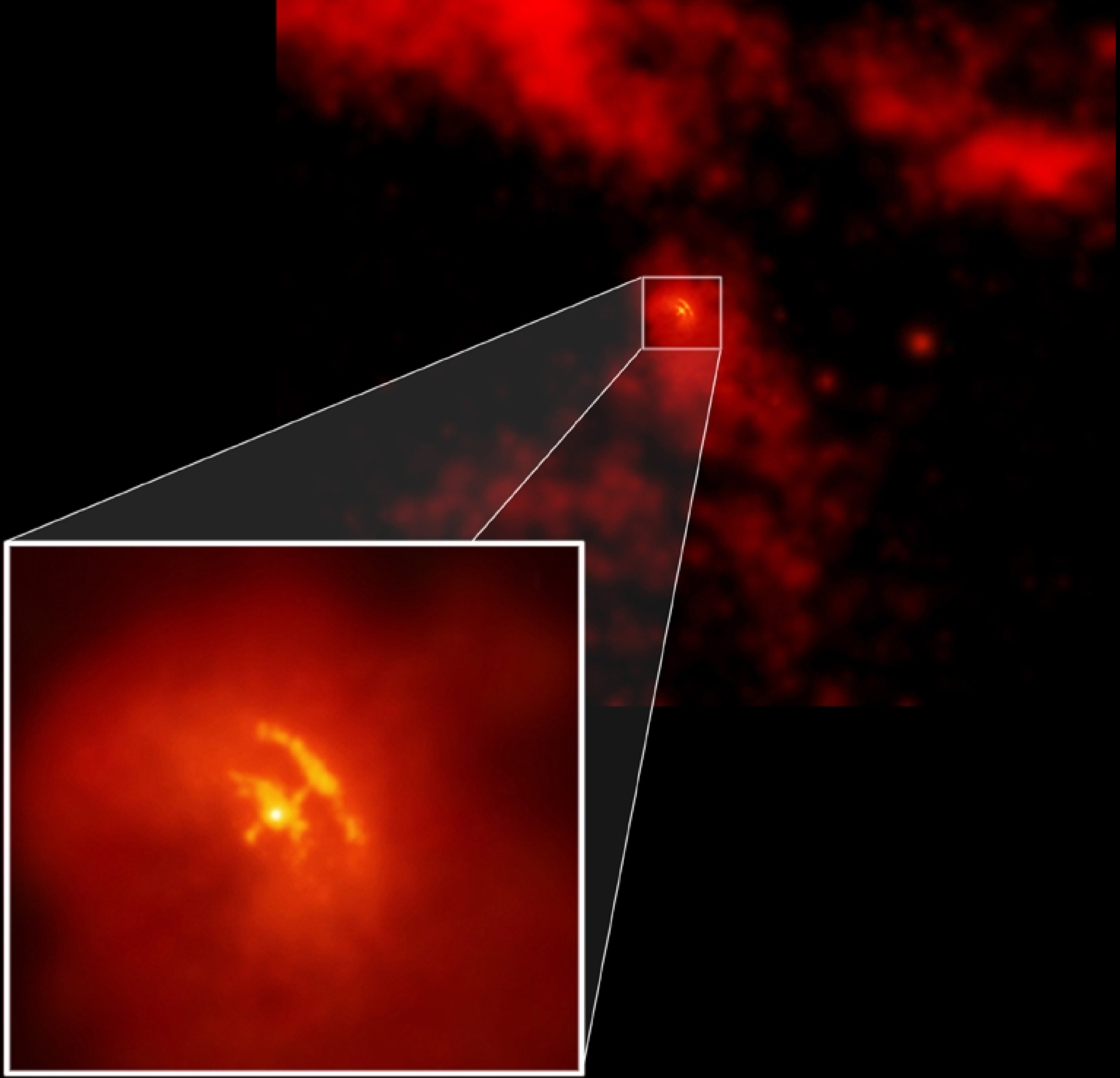


Displays characteristics similar those of Crab pulsar

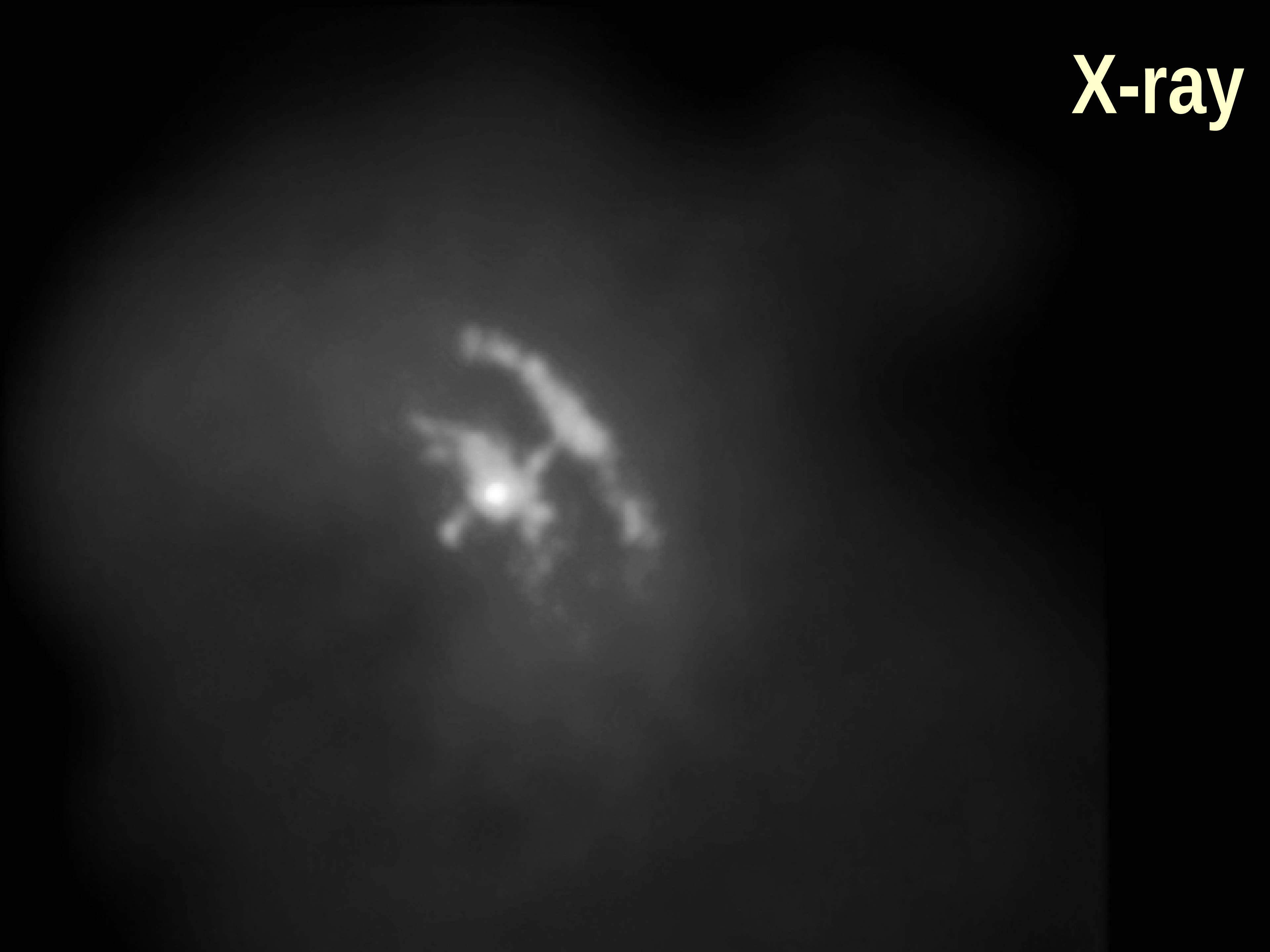
- Supernova remnant
- Rapid motion
- Bow shock wave
- Characteristic rings
- Particle jets

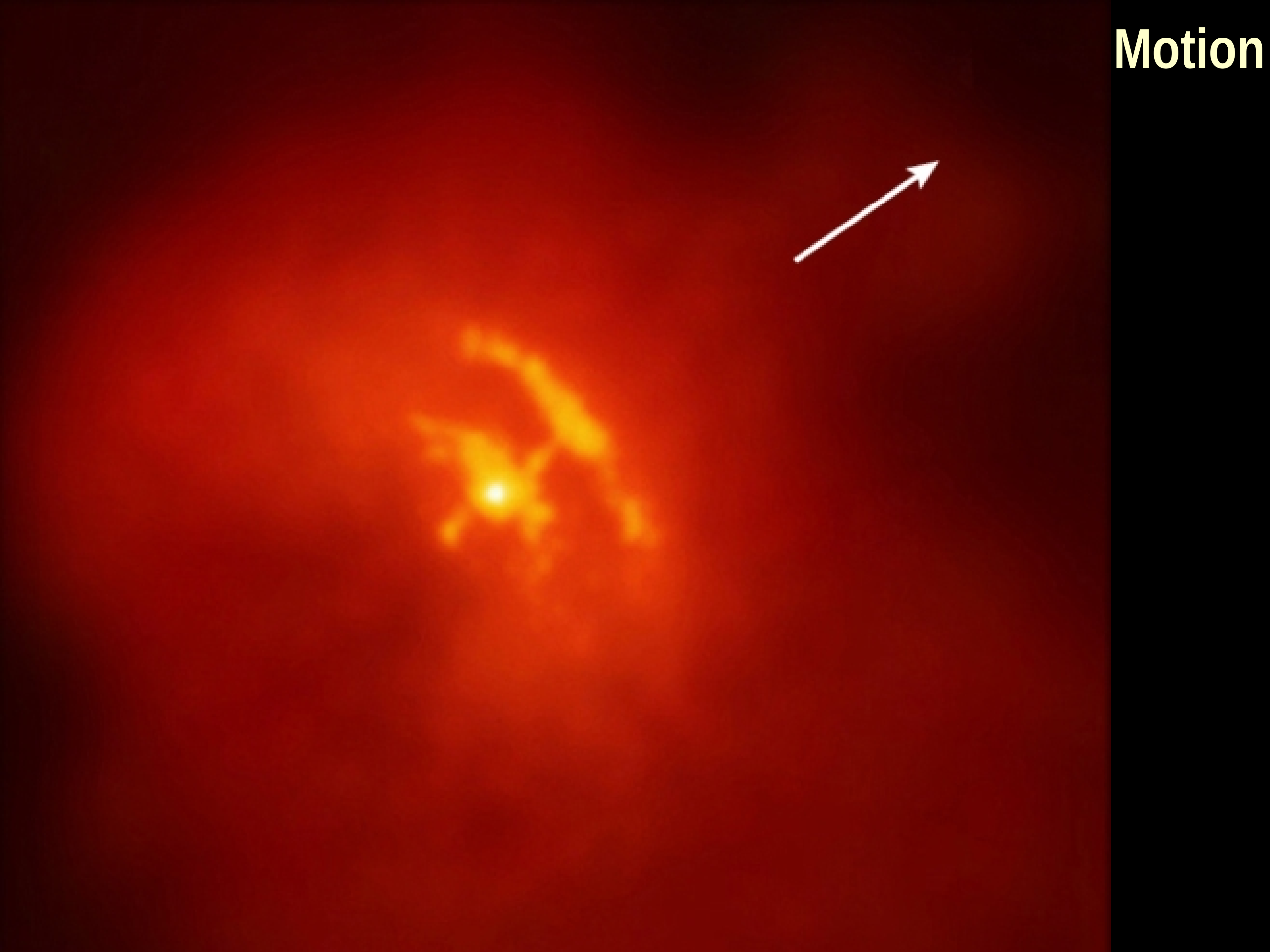


To scale




X-ray

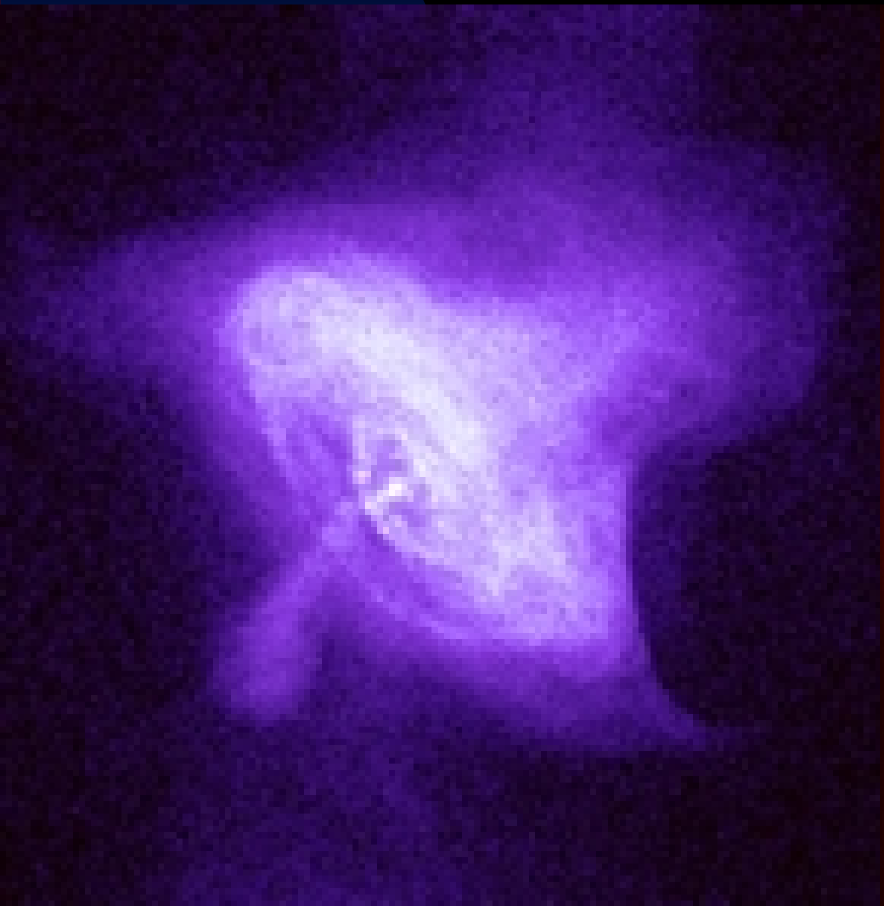

X-ray


Motion

Similarity of structure

Crab

Vela



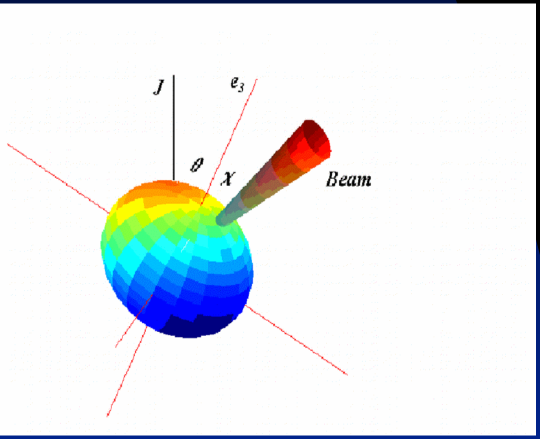
HartRAO Pulsar Research

The Programme

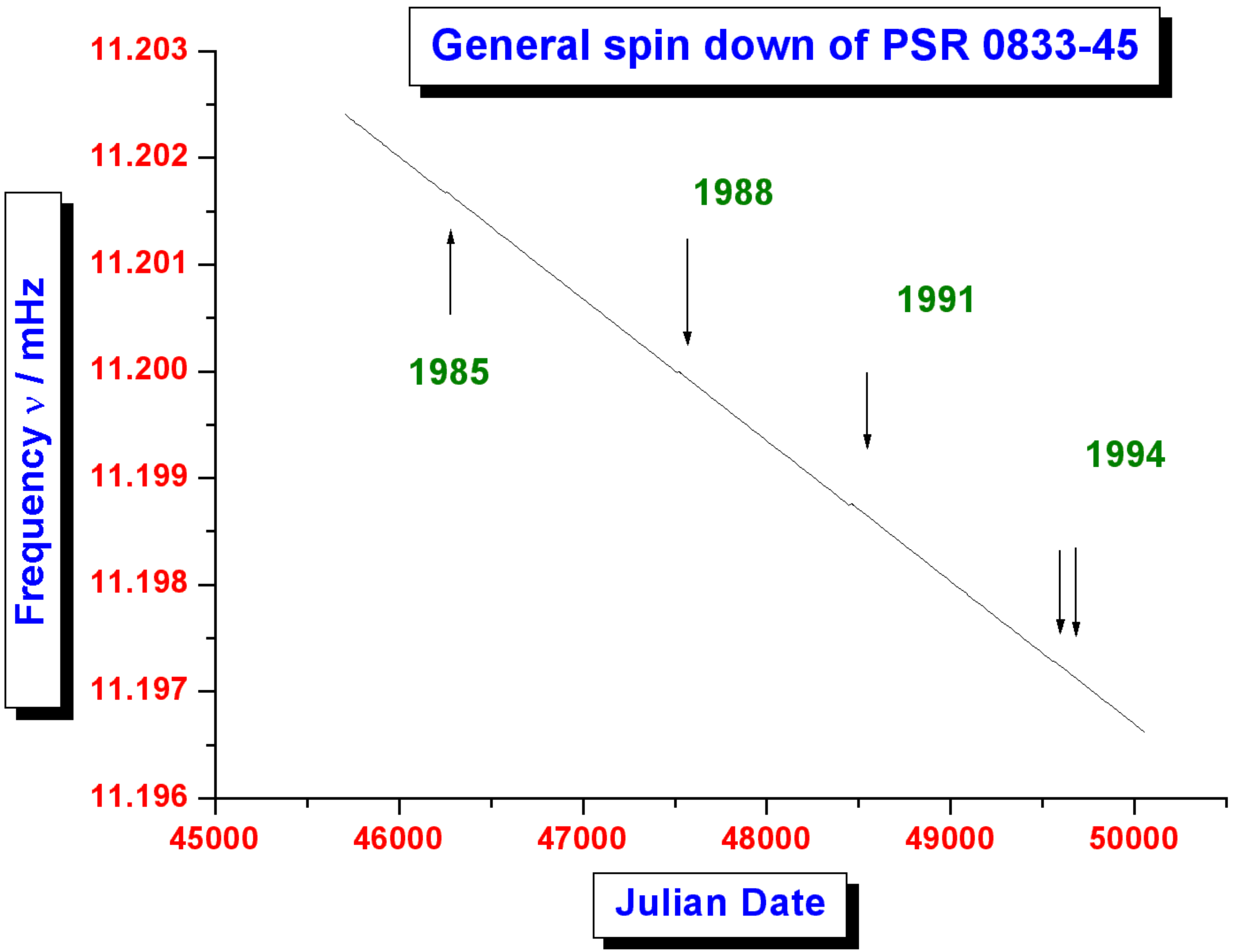
- Began 1984
- Person responsible 1984 – 1996

  Claire Flanagan
- Monitors 27 pulsars
  - Each once every 2 weeks
  - Vela, daily, if no VLBI
  - 15-18 yrs data on each
  - Most complete and extensive data spans in world on this sample

Observations : Pulse arrival times



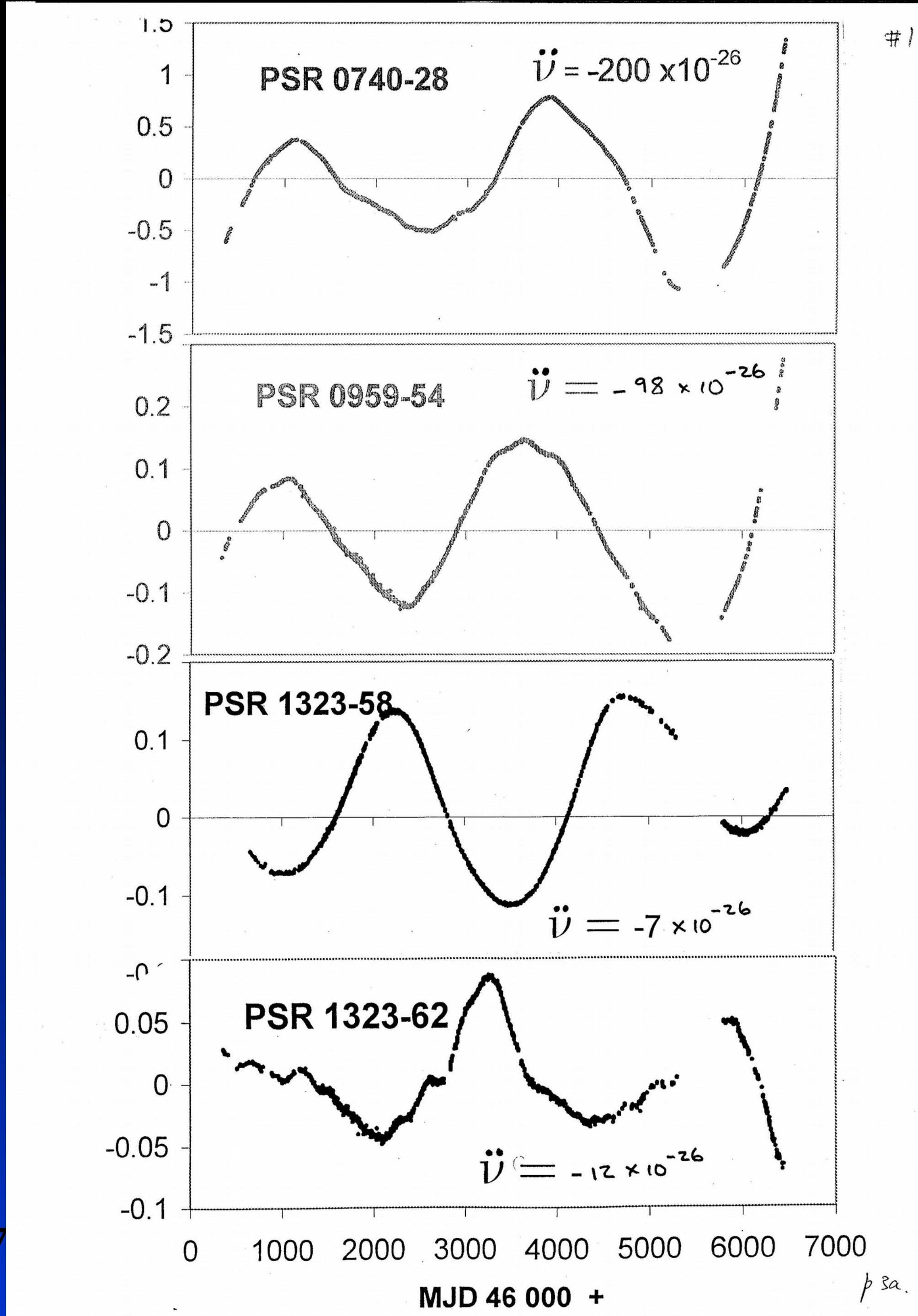
- EM beam is locked onto solid crust
- Each revolution, 1 pulse
- Measure pulse arrival times
- Convert to arrival time at barycentre of solar system
- Analysis of arrival times reveals what the crust is doing


General spin down of PSR 0833-45
Frequency ν / mHz
Julian Date
11.203
11.202
11.201
11.200
11.199
11.198
11.197
11.196
45000
46000
47000
48000
49000
50000
1985
1988
1991
1994

Analysis

- Rotation frequency vs. arrival times is approximately straight
- Slope almost, but not quite, zero
- Small slope reveals gradual spin down due to radiation effects
- Spin down expected to be non-linear in long term (10^3 yrs)

- Fit data with polynomial, quadratic or cubic, etc.
- Read basic parameters from fit
- Subtract fit from point : residuals
- Residuals reveal fine details of rotation behaviour
- Residual structure of two types:
  - Systematic variation
  - Random fluctuations, or rotation noise
- Residuals give information about physical processes in and around pulsar



Timing residuals of 4 pulsars

Systematic oscillations

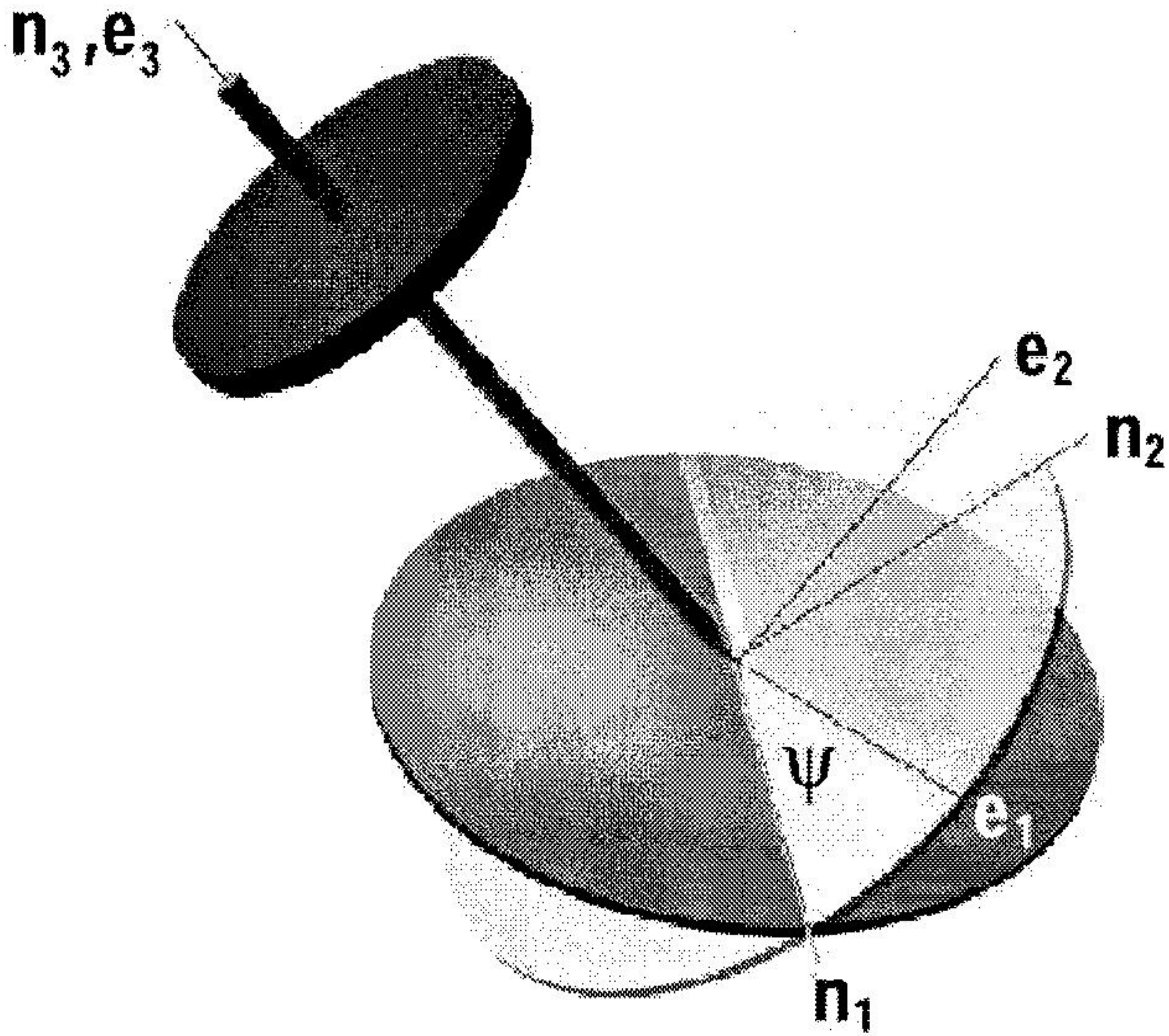
- Possible mechanisms
  - Binary companion
  - Precession
  - Oscillation of superfluid interior
  - Noise
  - Others?
- Postulate, model, predict, compare

Precession

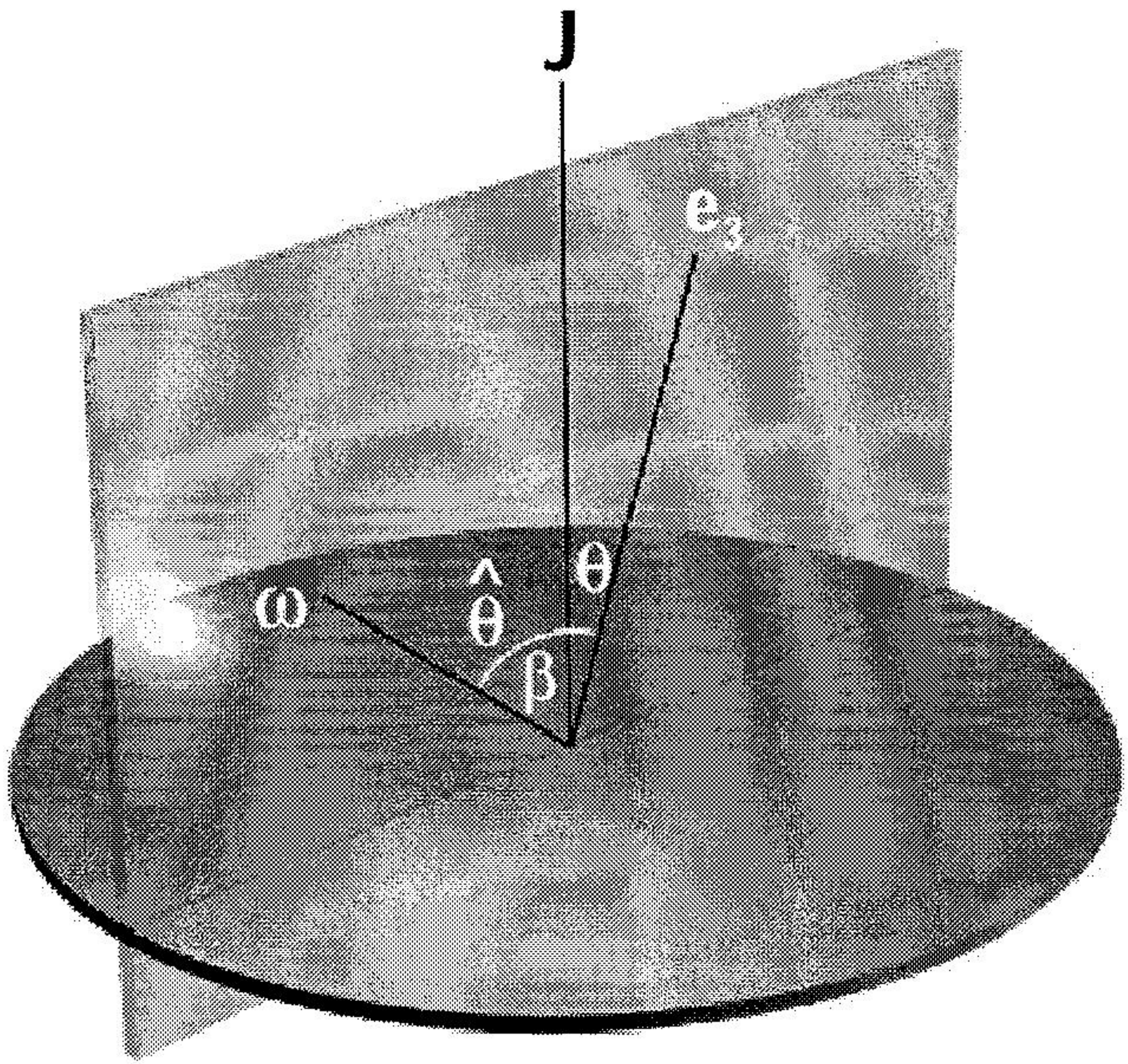
- Asymmetric mass distribution : 2 possibilities :
  - Axisymmetric : oblate spheroid
  - Non-axisymmetric : most general shape
- Most natural motion : precession
- Two types of motion :
  - Torqued
  - Not torqued, or free
- For pulsars, weakly torqued
- 1st approximation : free, axisymmetric

What is precession?

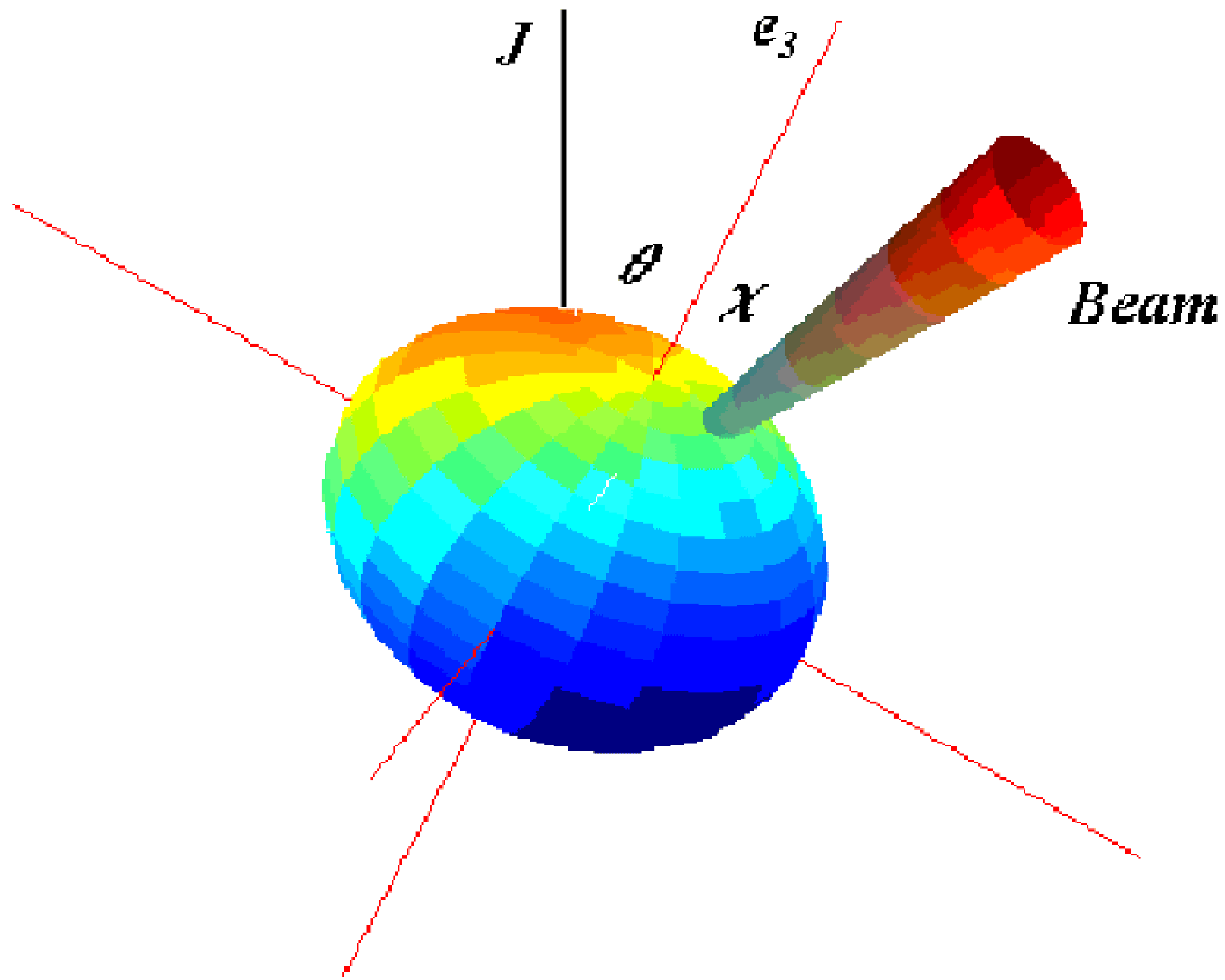
- Zero torque = constant angular momentum : defines fixed axis in space
- Axis of symmetry inclined at constant angle to fixed angular momentum direction : wobble angle
- Axis of symmetry spins rapidly around fixed angular momentum axis – wobble, or space precession : determines pulse arrival time frequency
- Body of pulsar spins slowly around symmetry axis : modulates pulse arrival time with long period oscillation, precession frequency



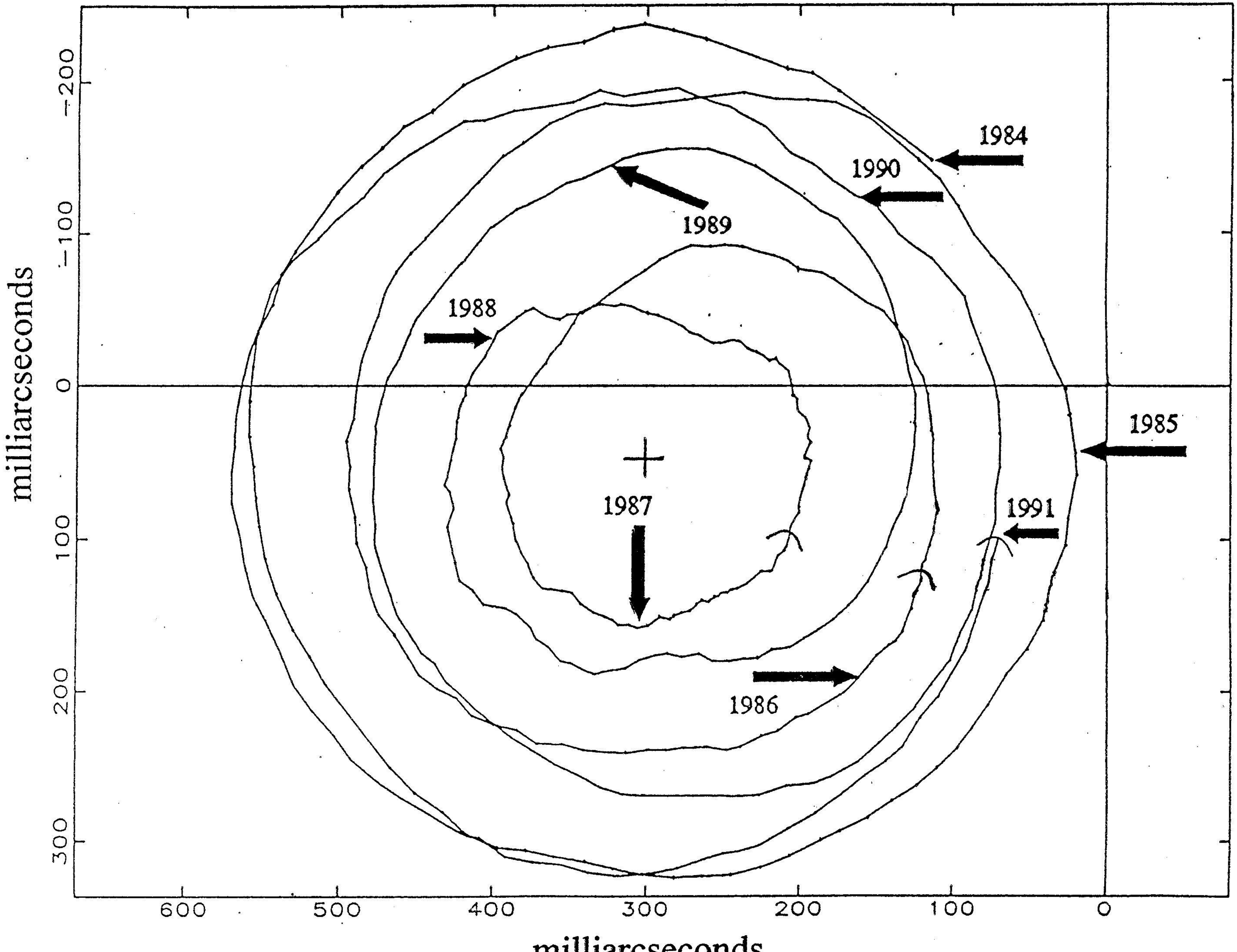
The *body* and *nodal* frames.



The reference plane and the "merry-go-round".

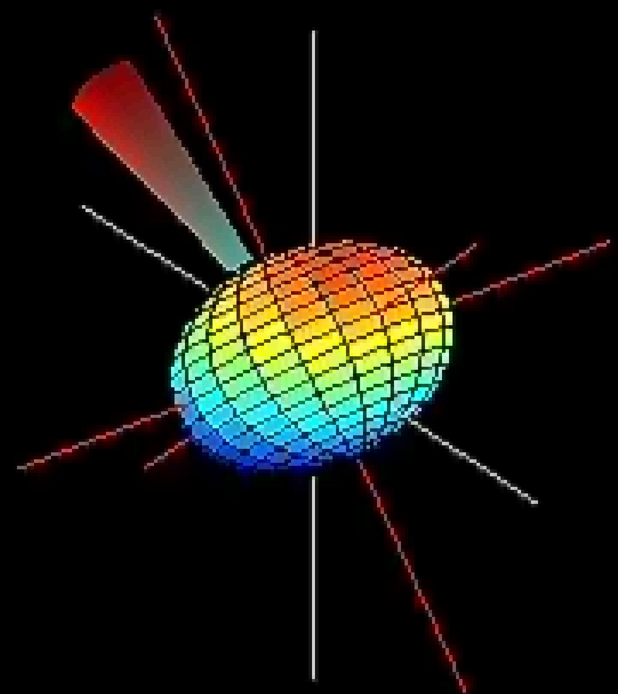

J
e3
θ
χ
Beam

- Rotation axis not coincident with either angular momentum axis, or axis of symmetry : seen from pulsar,
  - moves slowly around symmetry axis
  - at precession frequency
  - in forward precessional motion
  - like motion of earth : Chandler wobble



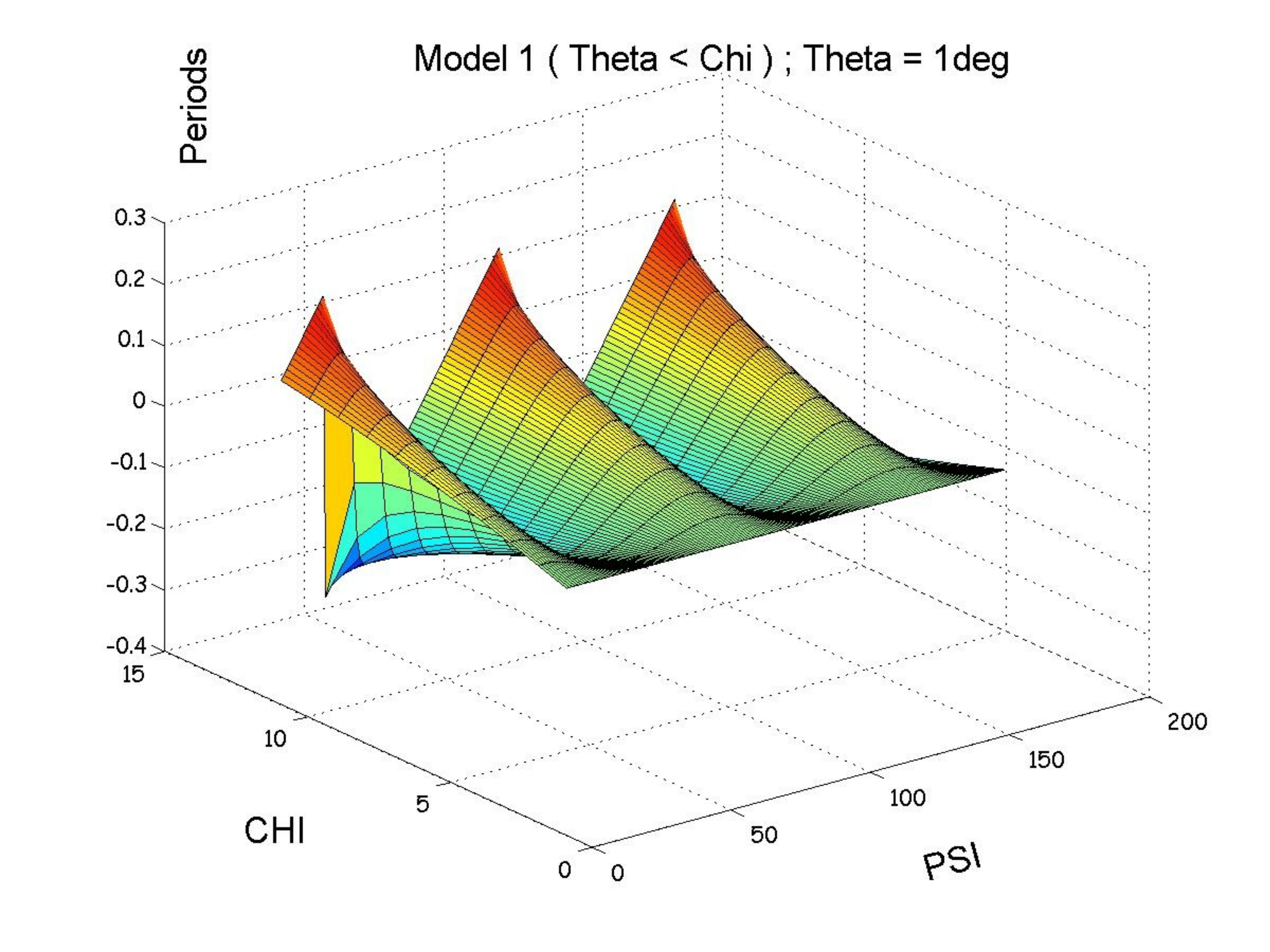
1984
1990
1989
1988
1985
1987
1991
1986
milliarcseconds
-200
-100
0
100
200
300
600
500
400
300
200
100
0
milliarcseconds

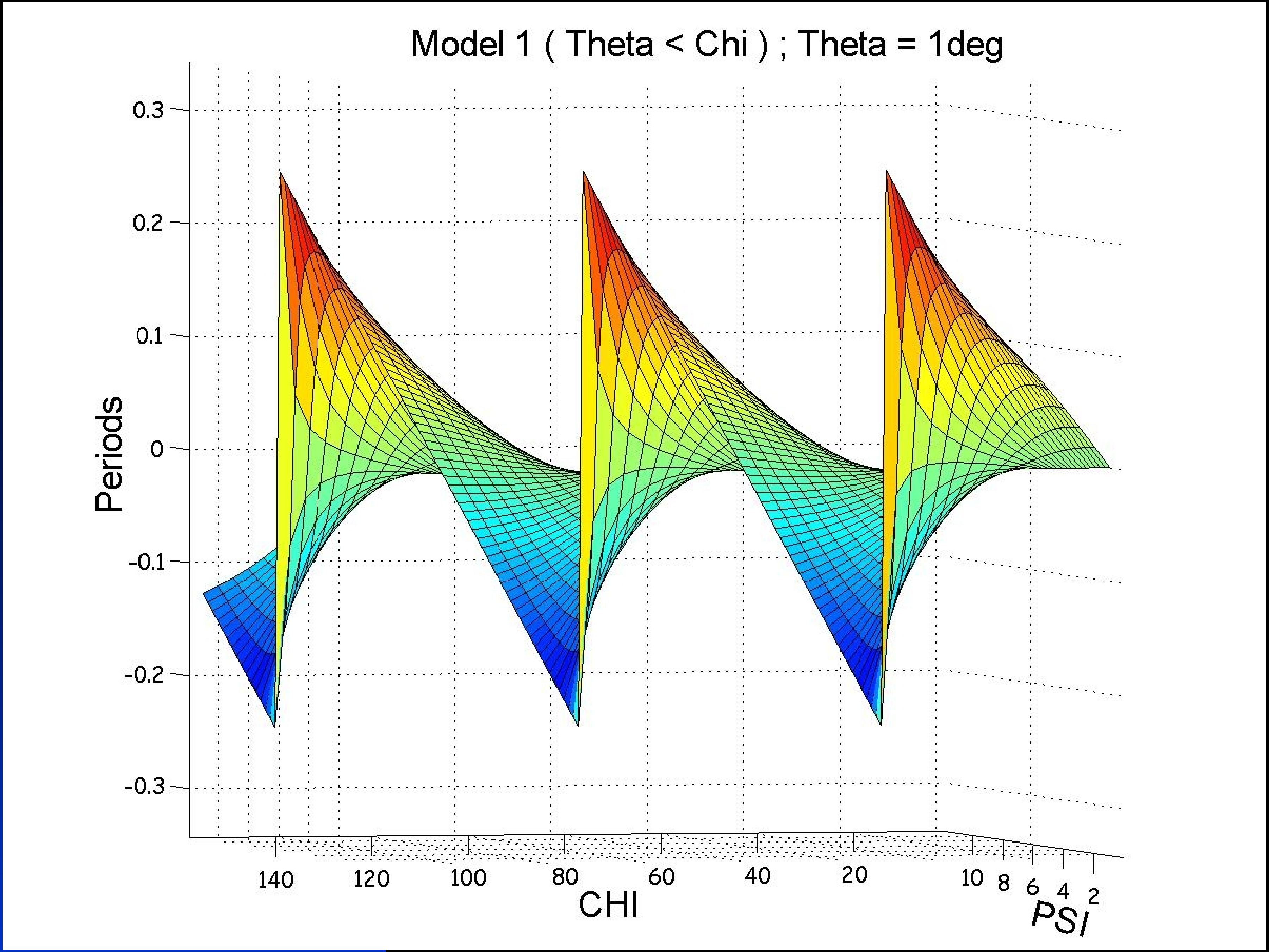
Animation of precessing pulsar with offset beam



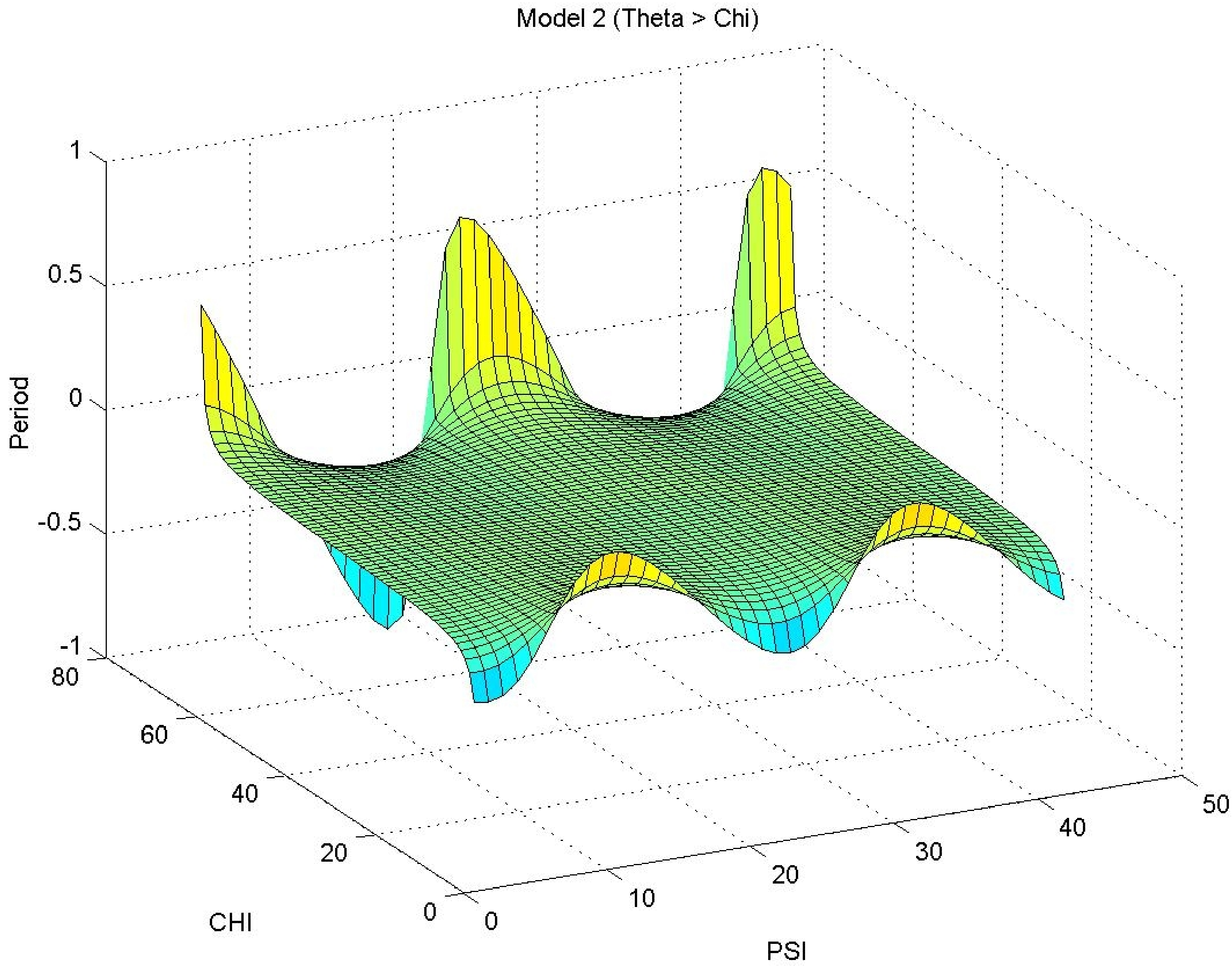
Body Frame
Space Frame

Effect on residuals

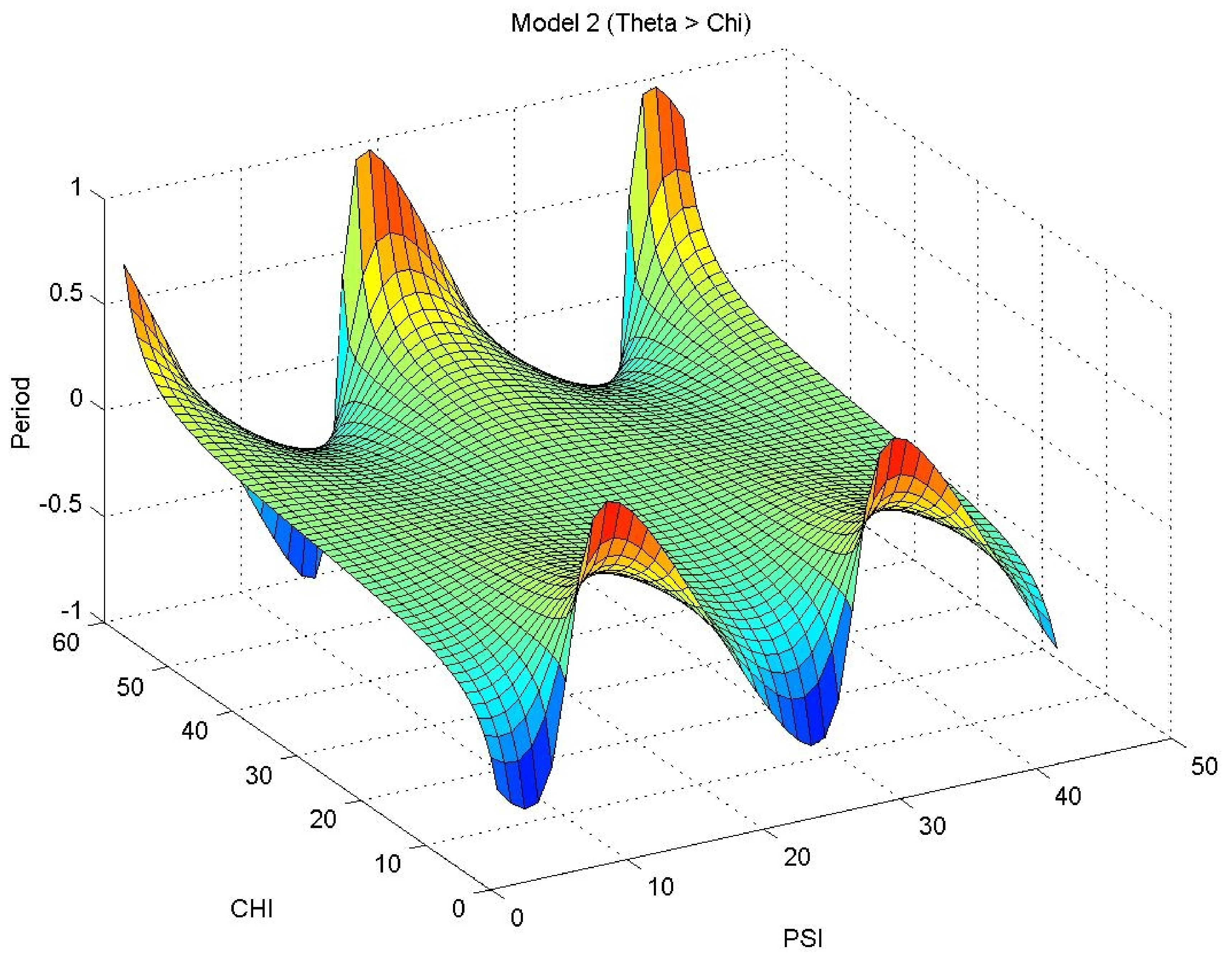


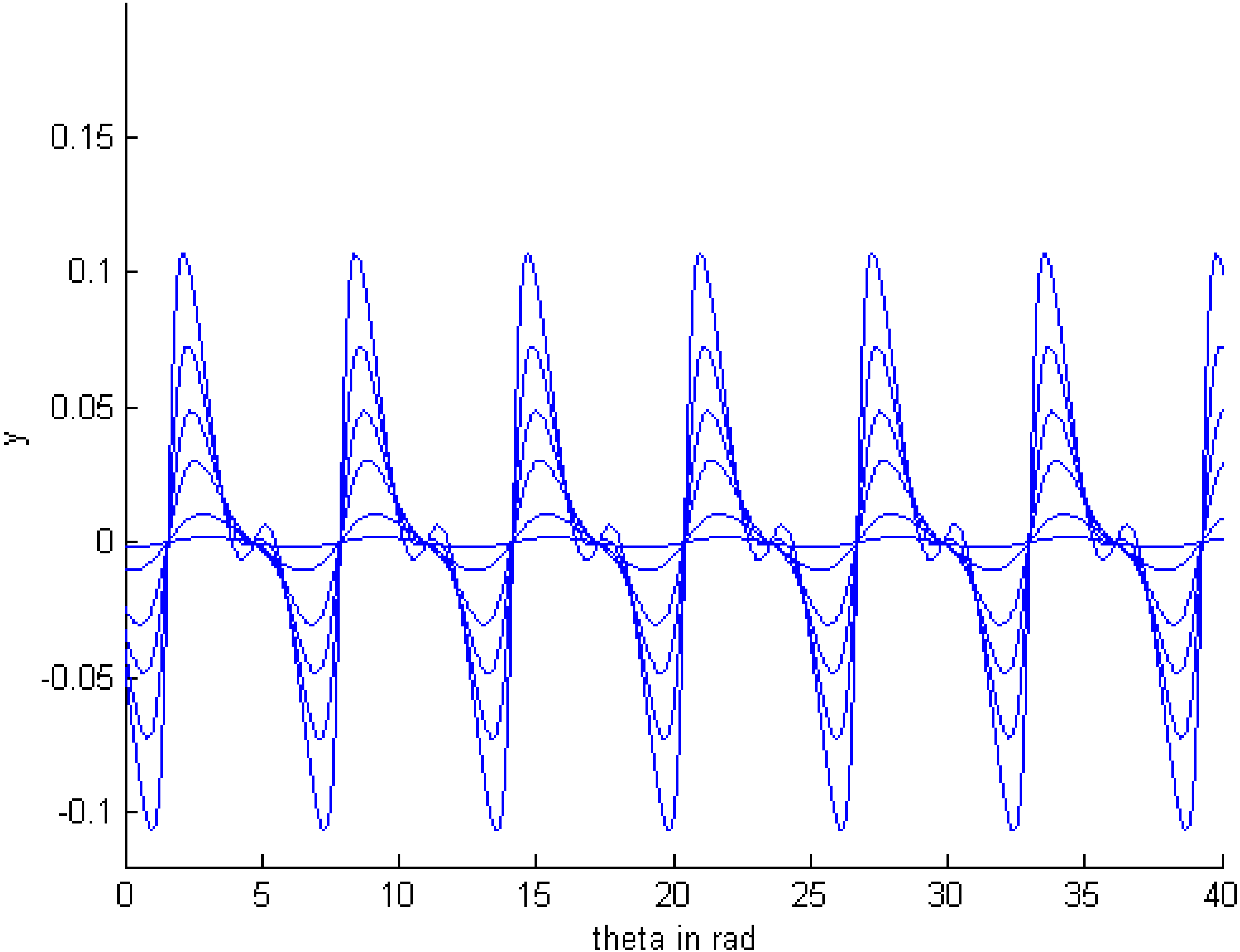


Model 1 (Theta < Chi) ; Theta = 1deg
Periods
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
CHI
140
120
100
80
60
40
20
PSI
10
8
6
4
2



Model 2 (Theta > Chi)
Period
1
0.5
0
-0.5
-1
CHI
80
60
40
20
0
PSI
0
10
20
30
40
50


Model 2 (Theta > Chi)
Period
1
0.5
0
-0.5
-1
CHI
60
50
40
30
20
10
0
PSI
0
10
20
30
40
50

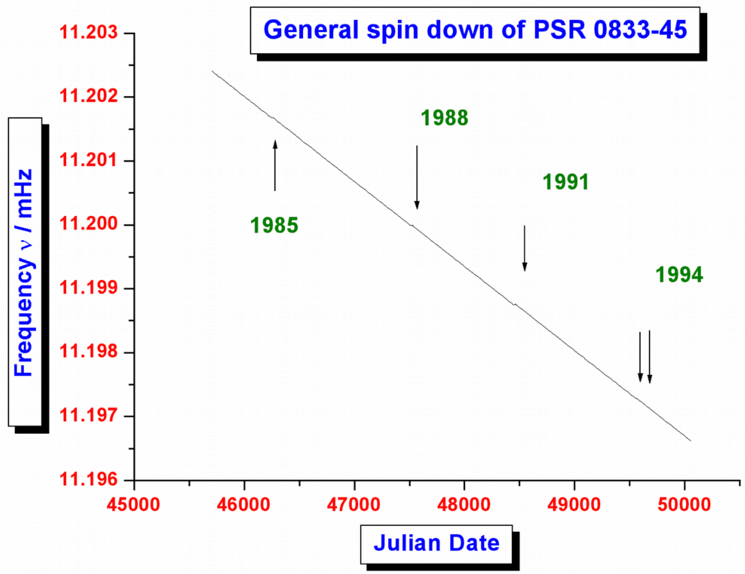


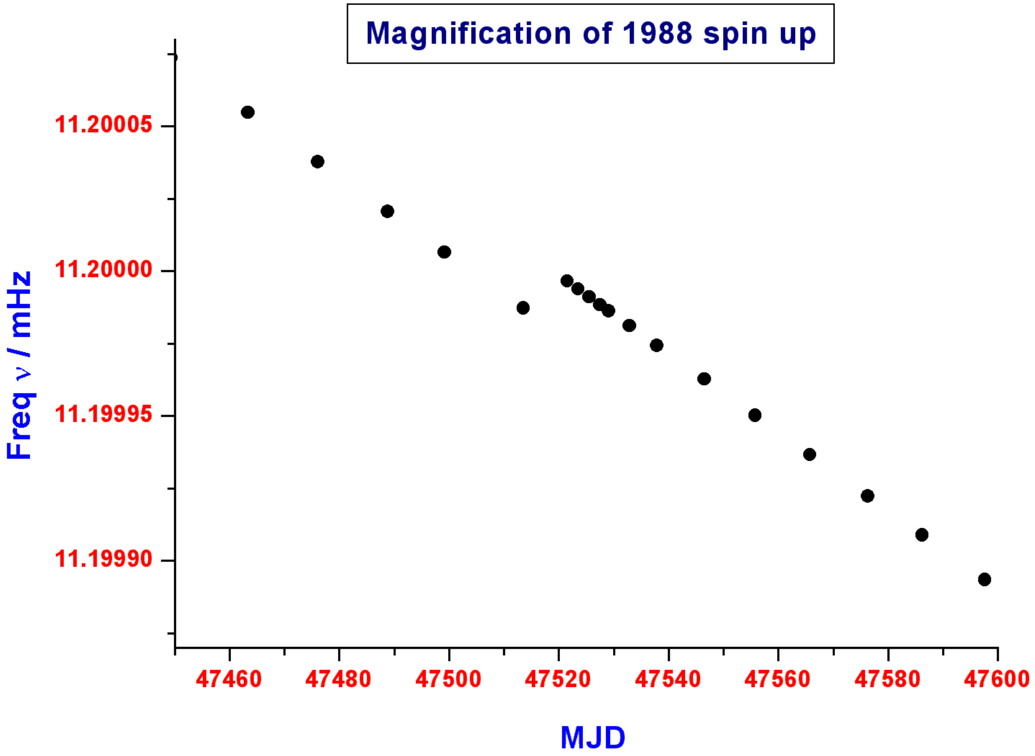
0.15
0.1
0.05
0
-0.05
-0.1
y
0
5
10
15
20
25
30
35
40
theta in rad

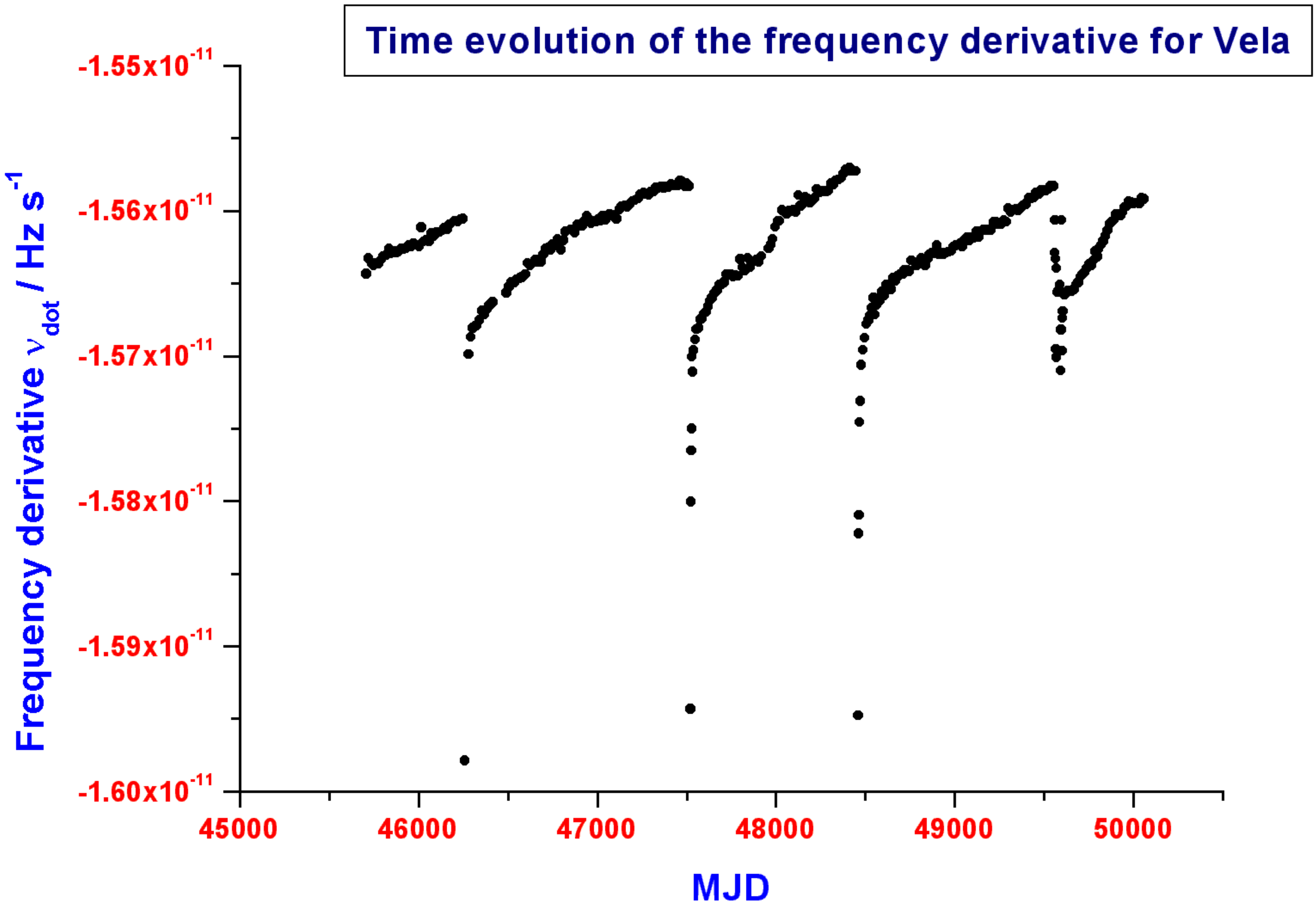
Timing irregularities

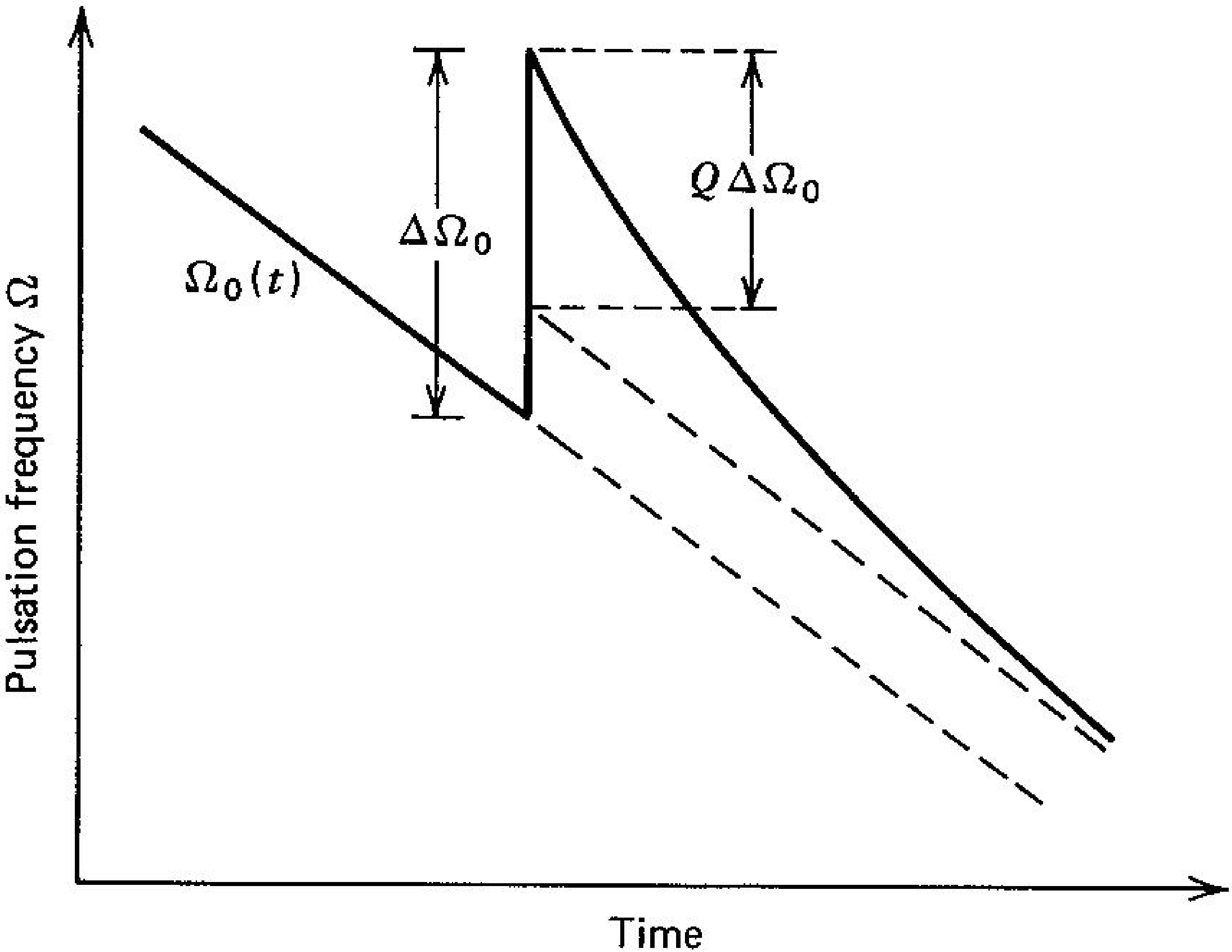
- Huge moment of inertia makes pulsars stable time keepers, but period of rotation not constant :
  - Radiative slow-down
  - Systematic oscillation of rotation rate
  - Stochastic, or random, variations of rotation rate : i.e. timing irregularities

- 2 types of timing irregularities :
  - Timing noise
  - Glitches : sudden increases of rotation rate
- Typically, glitches are increases of rotation rate of 1 part in a million
- Believed that all pulsars glitch
- Glitching believed to be a function of age
- New pulsars are active : glitching is generally frequent and weak
- Old pulsars are more stable : glitching infrequent and large

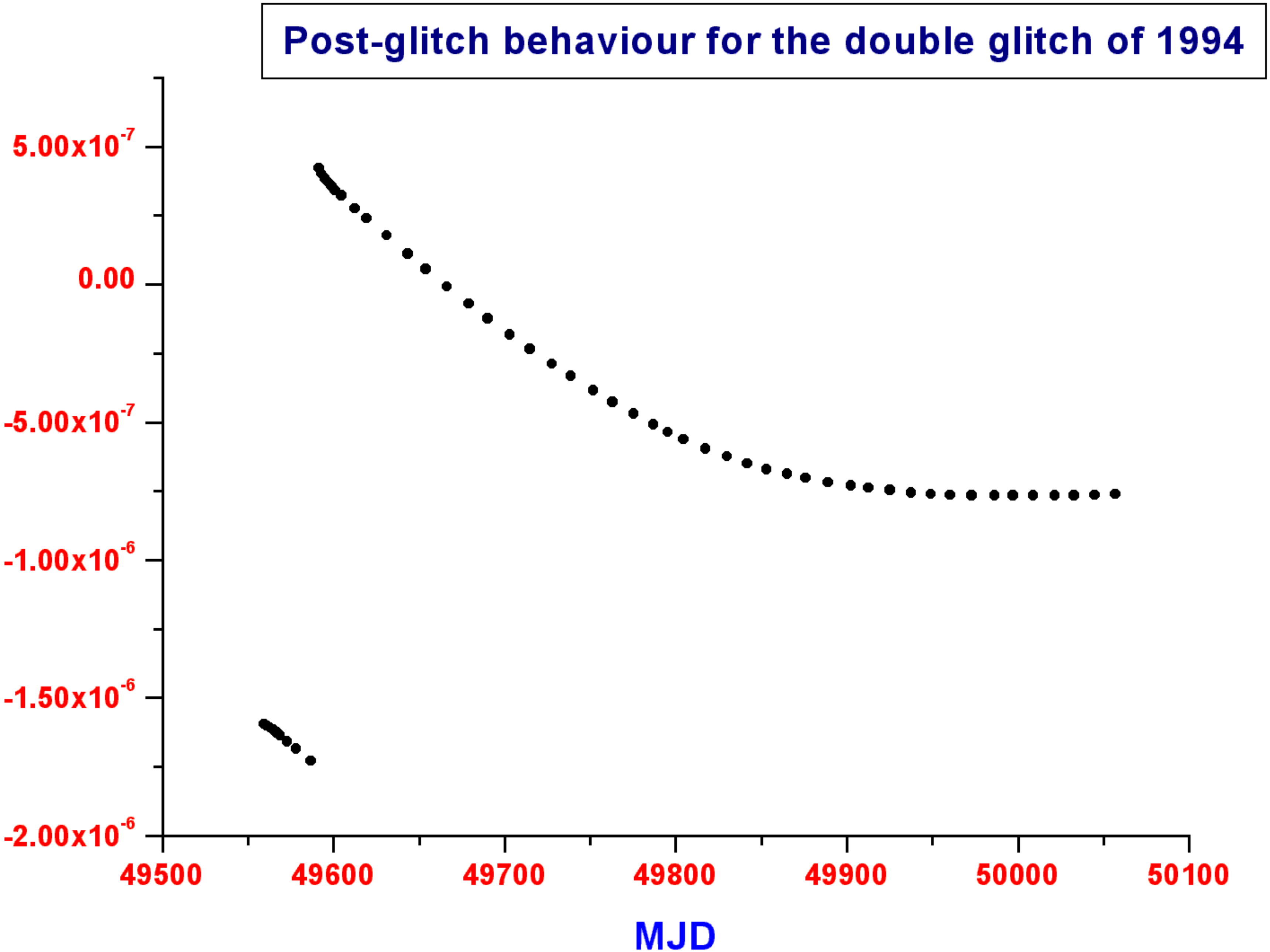

General spin down of PSR 0833-45
Frequency ν / mHz
11.203
11.202
11.201
11.200
11.199
11.198
11.197
11.196
1985
1988
1991
1994
45000
46000
47000
48000
49000
50000
Julian Date


Magnification of 1988 spin up
Freq ν / mHz
11.20005
11.20000
11.19995
11.19990
47460
47480
47500
47520
47540
47560
47580
47600
MJD


Time evolution of the frequency derivative for Vela
Frequency derivative ν_{dot} / Hz s^{-1}
$-1.55x10^{-11}$
$-1.56x10^{-11}$
$-1.57x10^{-11}$
$-1.58x10^{-11}$
$-1.59x10^{-11}$
$-1.60x10^{-11}$
45000
46000
47000
48000
49000
50000
MJD



$\Delta\Omega_0$
$Q\,\Delta\Omega_0$
$\Omega_0(t)$
Pulsation frequency Ω
Time


Post-glitch behaviour for the double glitch of 1994
5.00x10^-7
0.00
-5.00x10^-7
-1.00x10^-6
-1.50x10^-6
-2.00x10^-6
49500
49600
49700
49800
49900
50000
50100
MJD

Summary

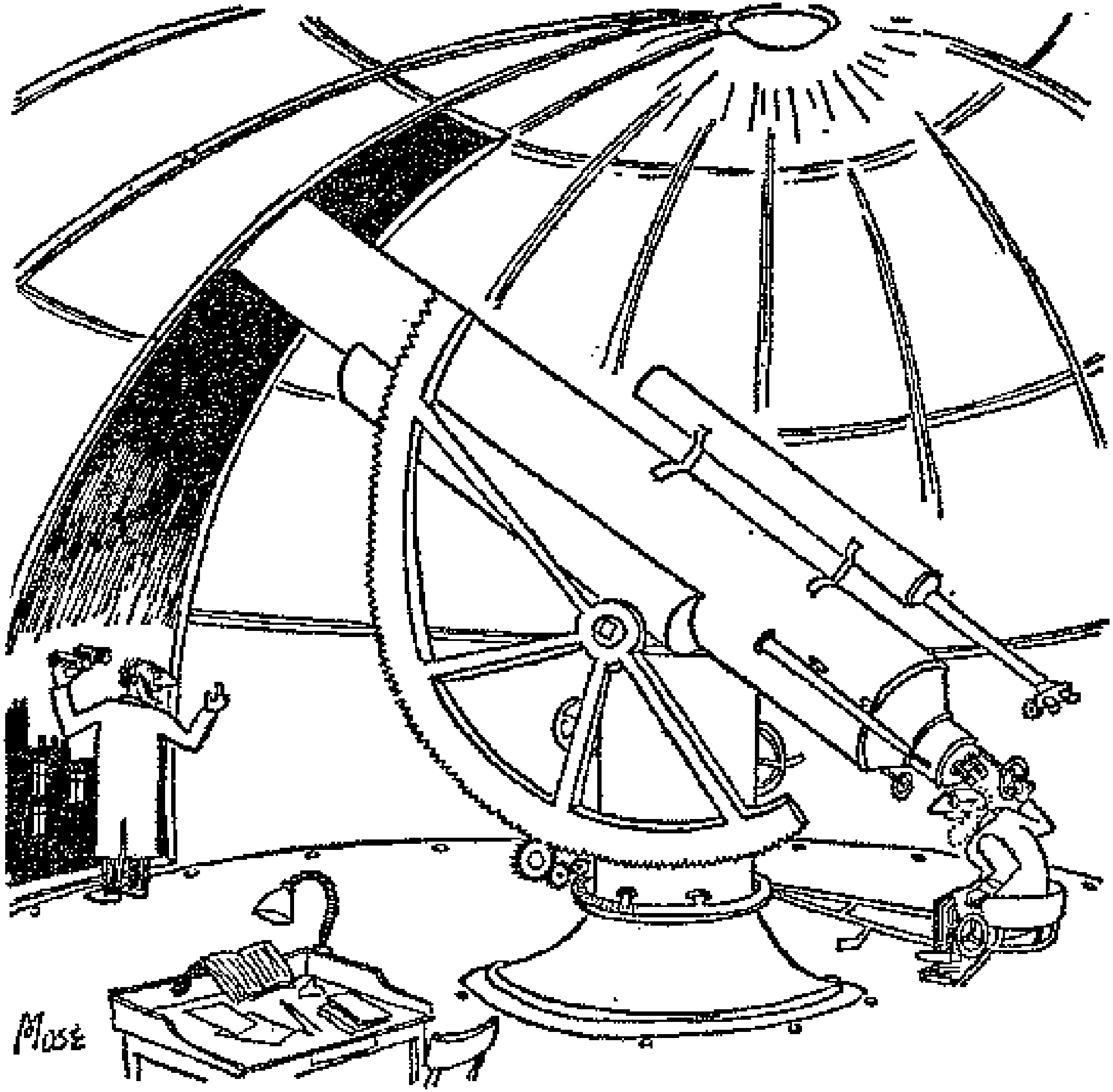
- Regular timing behaviour reveals rotational behaviour of crust
- Oscillatory timing behaviour reveals underlying dynamics of rotation
- Timing noise reveals nature of stochastic processes in pulsar interior, surface and magnetosphere
- Glitches reveals nature and dynamics of pulsar superfluid interior

What radio astronomers do :

- Work all day
- Work all night
- Work when sun shines
- Work for moonshine
- Work when cloudy
- Work when dry

In contrast,

What optical astronomers do ….


Mose