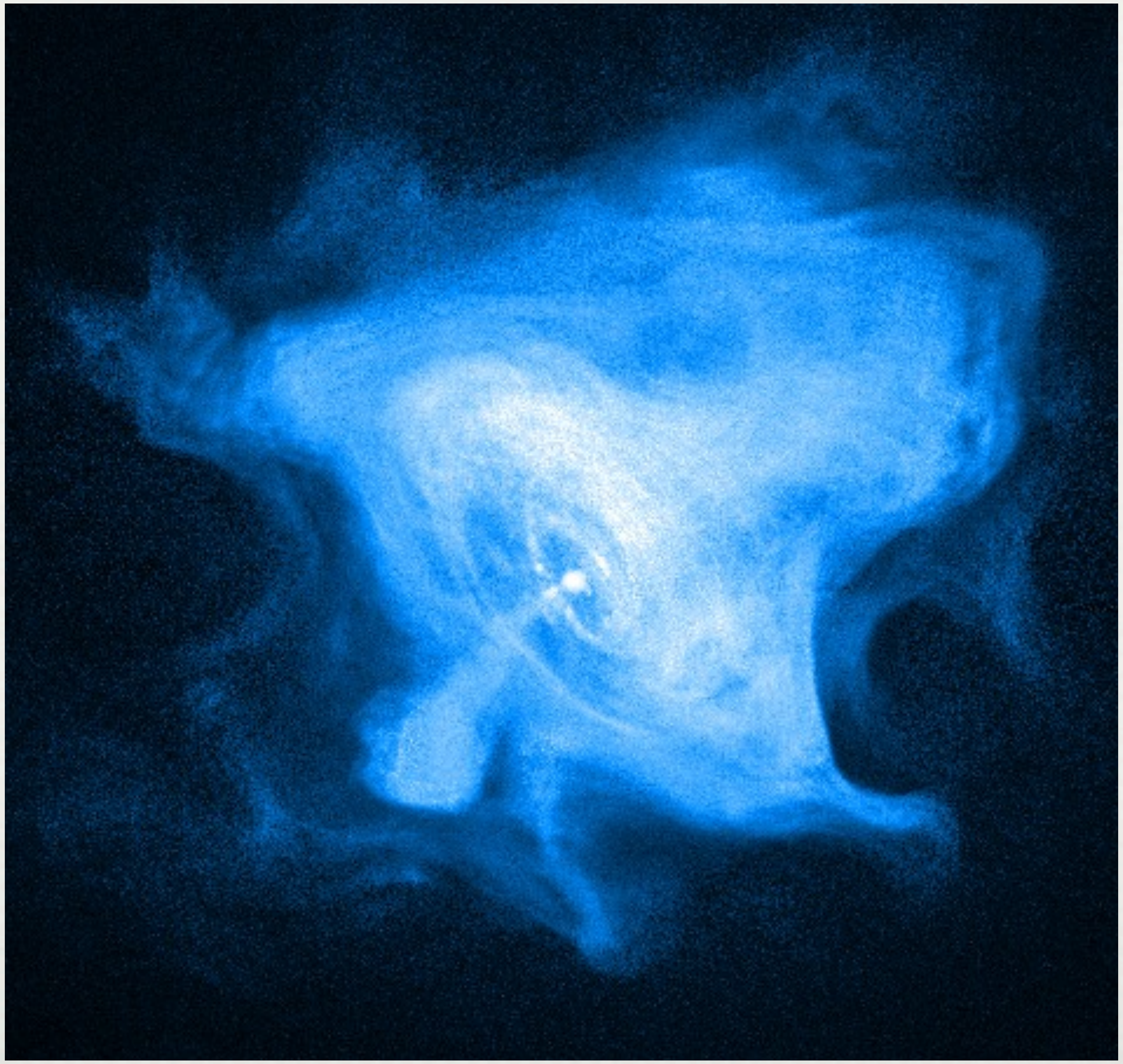
PULSARS

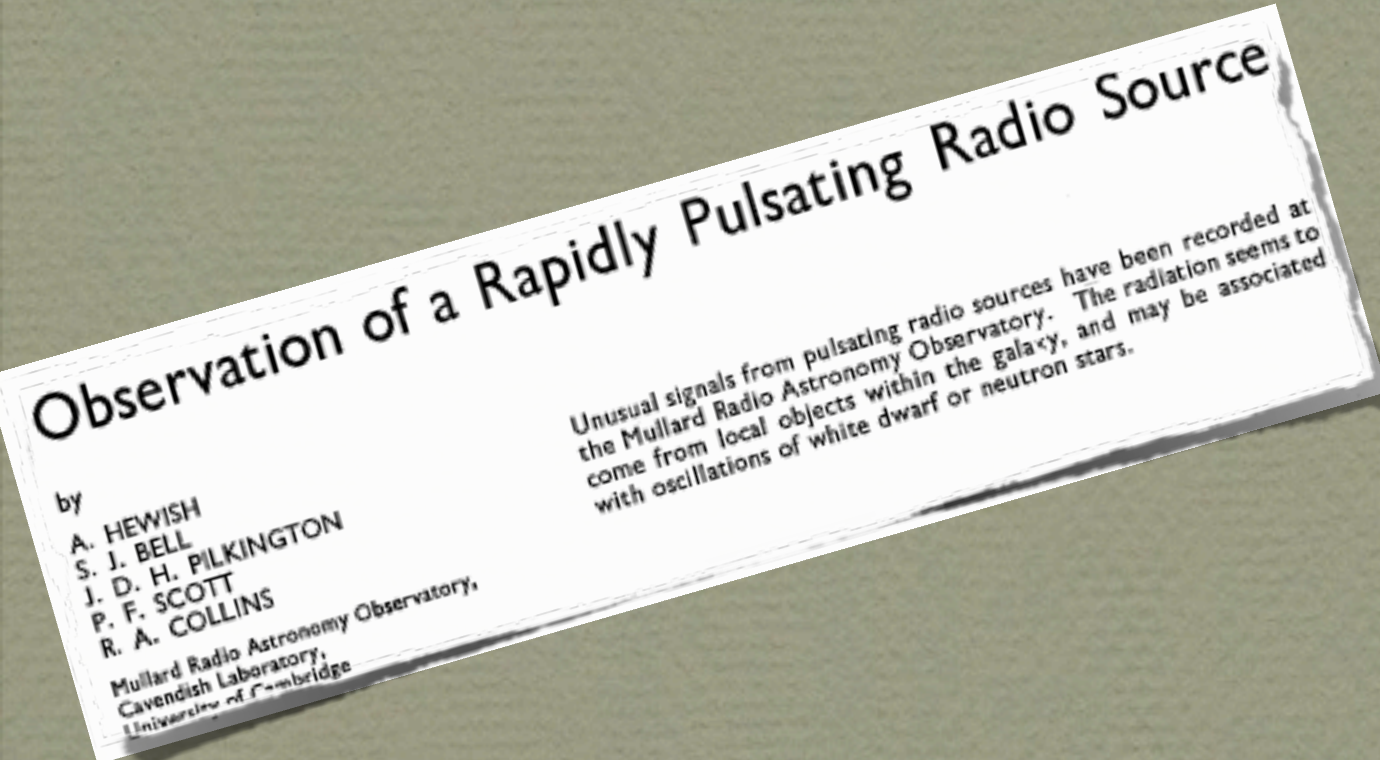


CHANDRA X-RAY IMAGE
OF THE CRAB NEBULA

KAI SCHWENZER

INTRODUCTION

History

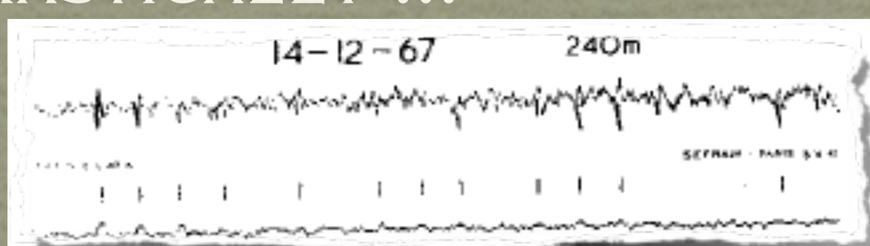

Observation of a Rapidly Pulsating Radio Source

by
A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
P. F. SCOTT
R. A. COLLINS

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

- First observed 1967 by Hewish, bell, et. al. in radio emission
- Localized source within the galaxy
- individual pulses vary drastically ...

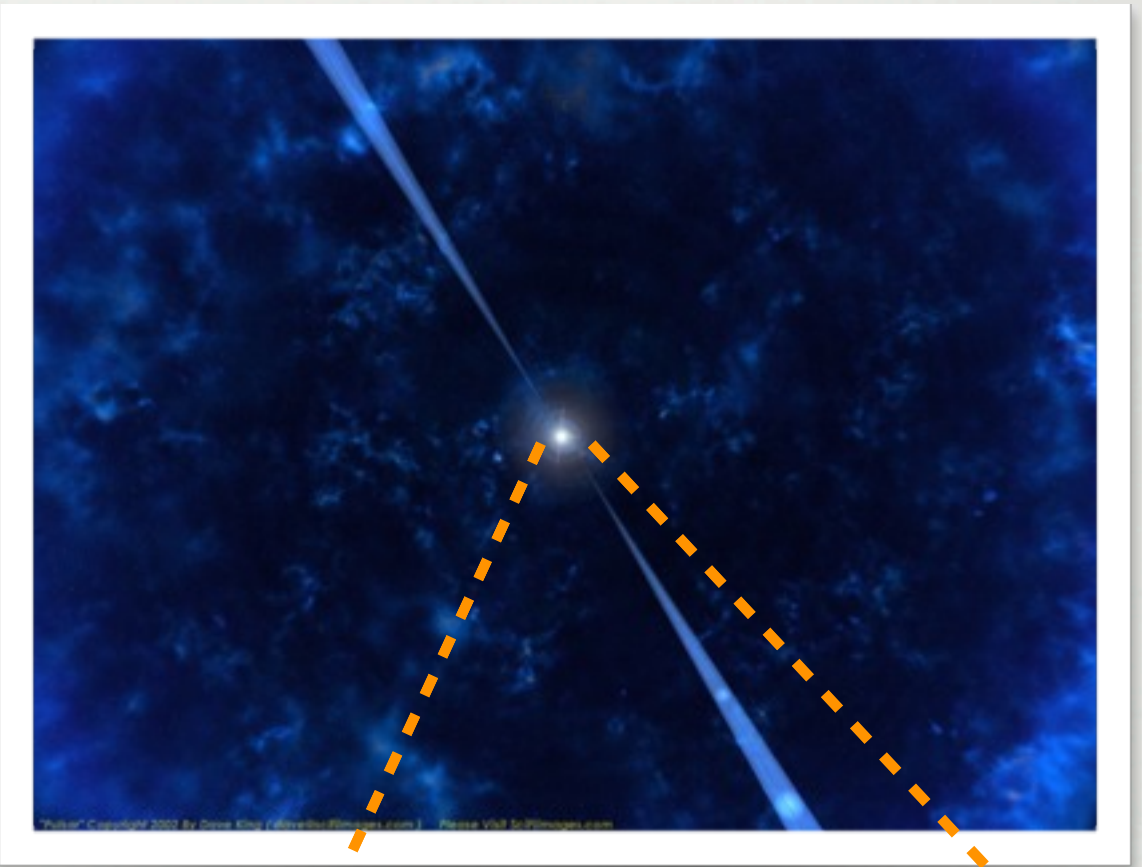


- ... but overall perfect periodicity

$$P_0 = 1{\cdot}3372795 \pm 0{\cdot}0000020 \text{ s}$$

WHAT ARE PULSARS?

- COHERENT EMISSION WITH PERIOD DOWN TO NEARLY 1 MS
- LIGHT TRAVELS ONLY 300 KM IN THIS TIME
- OBJECTS HAVE TO BE COMPACT!
  - EITHER ALIEN LIGHTHOUSES WARNING SPACESHIPS FROM FLOATING LUMPS OF DARK MATTER ...
  - RADIATED ENERGY: $10^{31}\mathrm{erg/s}$ (WORLD ENERGY CONSUMPTION: $10^{28}\mathrm{erg/y}$)



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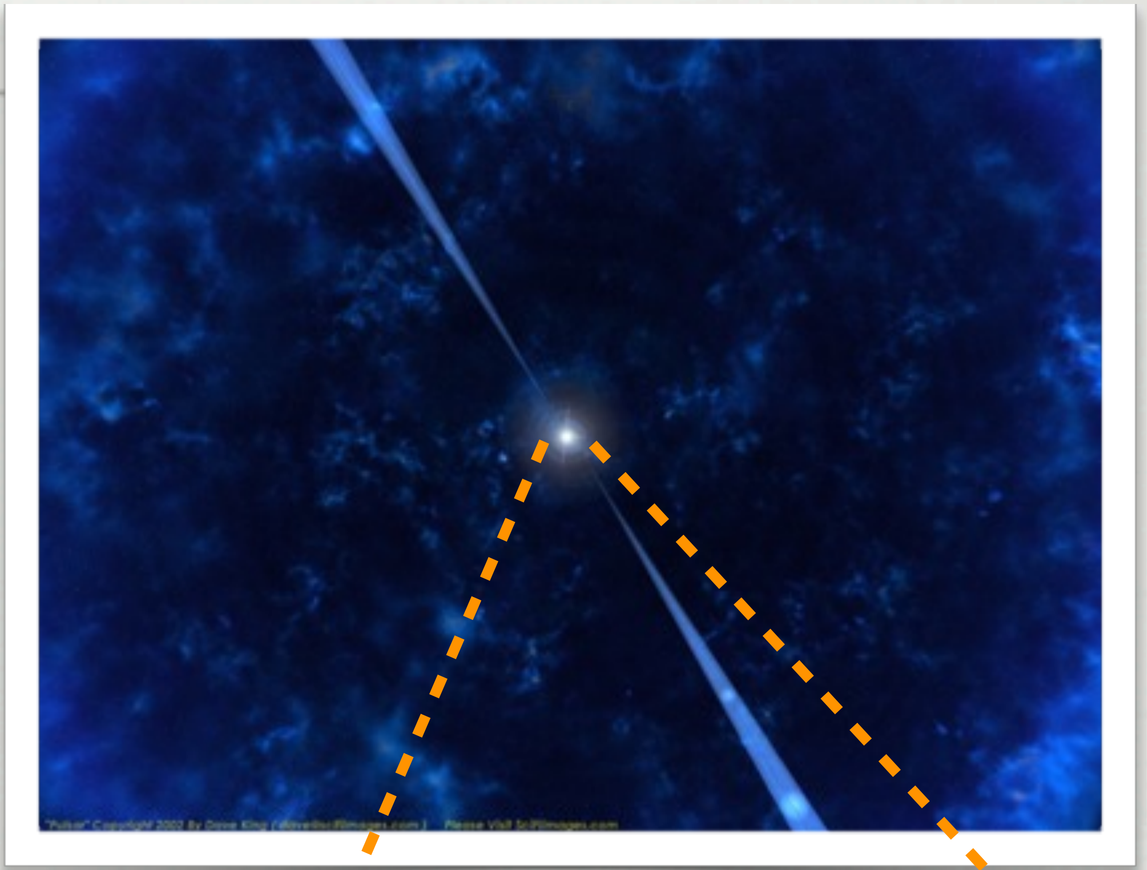
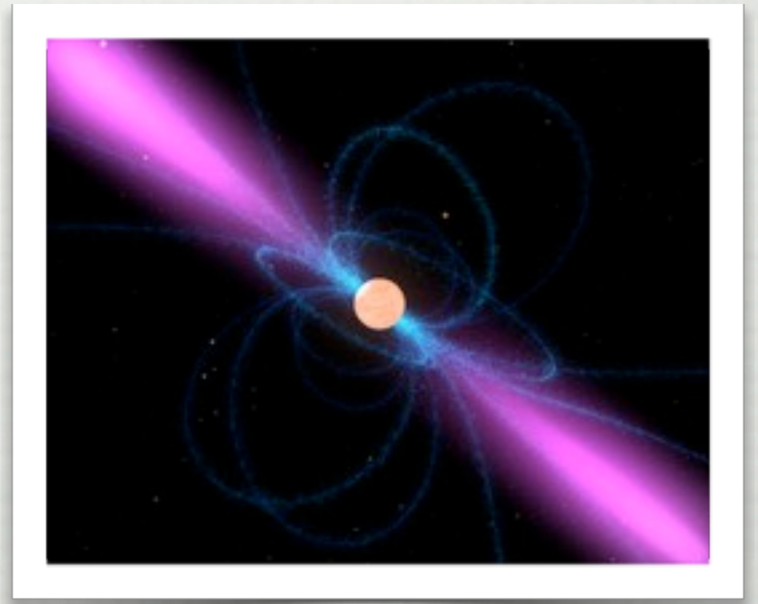
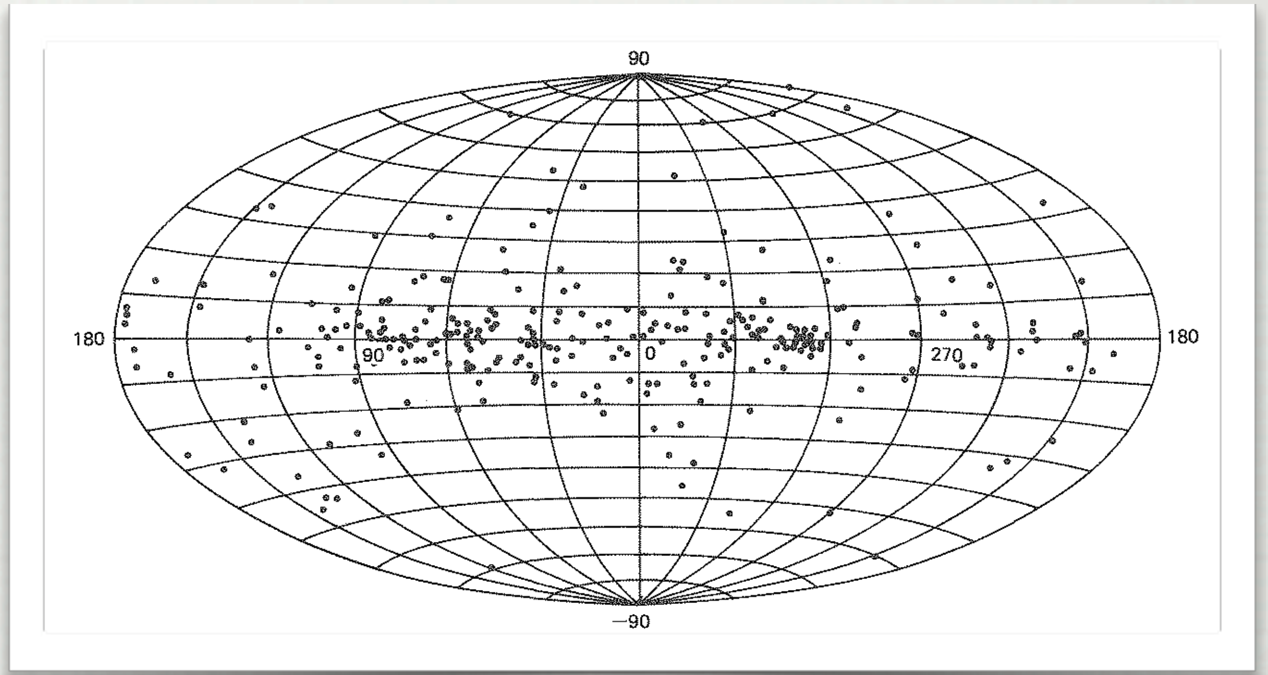
  - ... OR NEUTRON STARS





PROPERTIES OF PULSARS

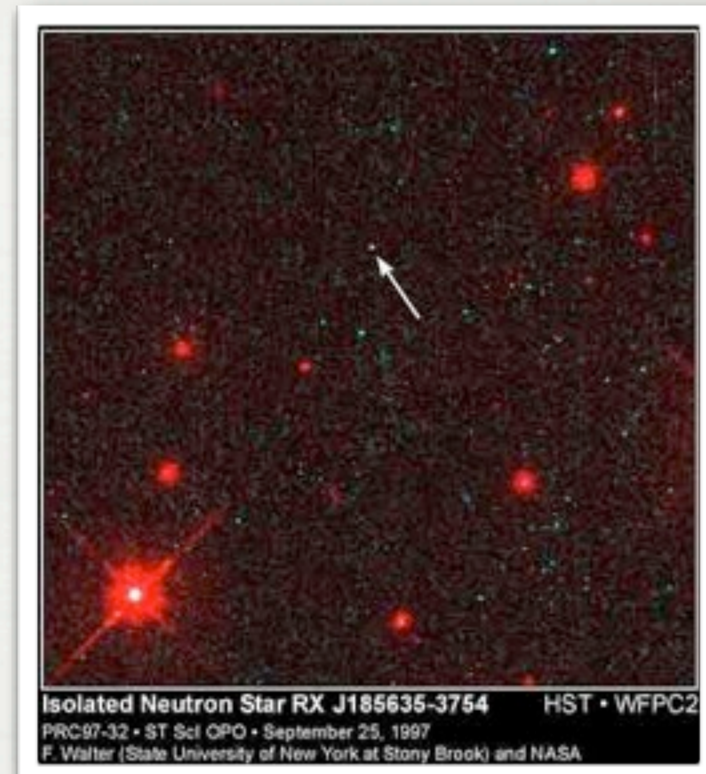
- CONTINUOUS EMISSION SPECTRUM RANGING FROM RADIO WAVES TO X-RAYS - BUT LUMINOSITIES AND PULSE FORMS DIFFERENT
- RADIO EMISSION CAN BE LINEARLY POLARIZED
- FREQUENCIES RANGING FROM BELOW 0.1HZ TO 716 HZ (PSR J1748-2446AD)
- PERIODS KNOWN TO 13 DIGITS
- GALACTIC ORIGIN
- SOME ARE ASSOCIATED WITH SUPERNOVA REMNANTS
- CAN FEATURE LARGE LINEAR VELOCITIES $> 500 \mathrm{km/s}$ - 10 TIMES LARGER THAN PROGENITORS



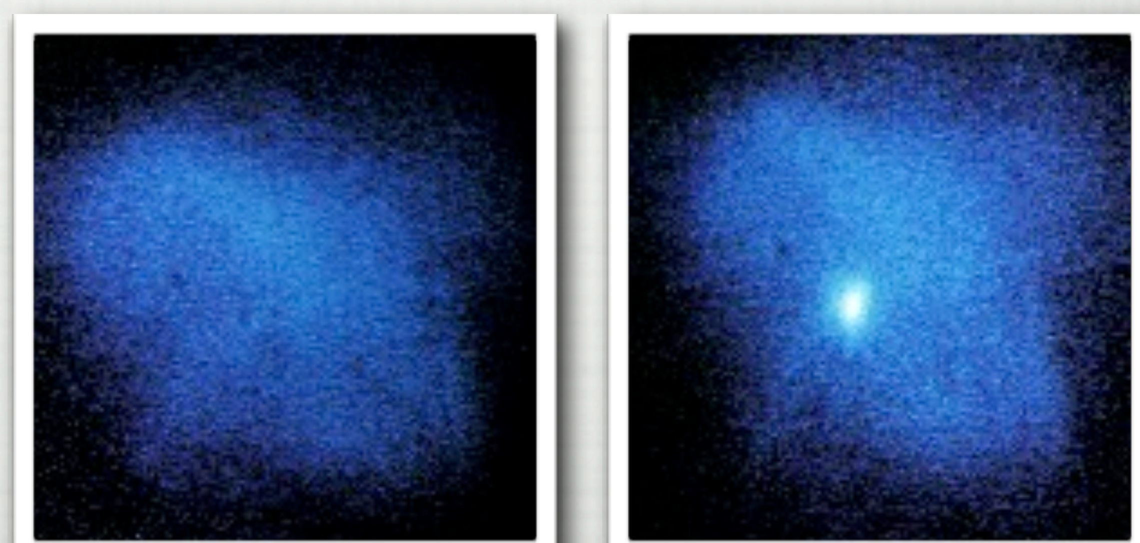
WHY ARE PULSARS INTERESTING?

(FOR NUCLEAR AND PARTICLE PHYSICS)

- ONLY WAY TO SEE ROTATION
- PROVIDE PRECISE(!) RESULTS:
  - SPIN FREQUENCIES & THEIR TIME DERIVATIVES
  - MASSES (SHAPIRO DELAY)
  - DISTANCES (DISPERSION MEASURE)
  - AGE (SPIN-DOWN AGE)
- TEACH US ABOUT THE DENSE MATTER IN THE INTERIOR!
- PROPERTIES OF MATTER (VISCOSITY, SUPERFLUIDITY, ...)



ISOLATED COMPACT STAR



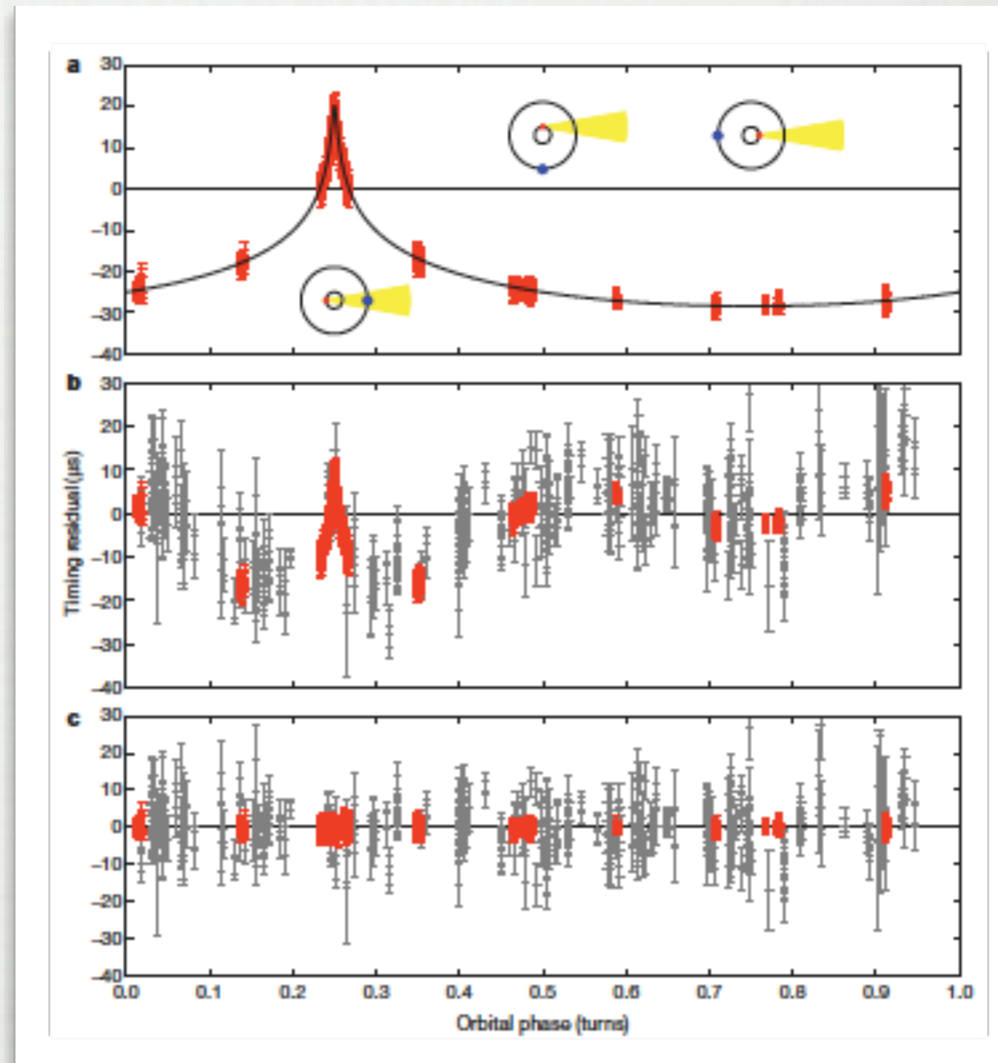
X-RAY EMISSION FROM CRAB PULSAR(*1054 A.D)

SHAPIRO-DELAY ... AND THE HEAVIEST NEUTRON STAR

- IN BINARY SYSTEMS THE LIGHT FROM THE BEAM OF A PULSAR PASSING CLOSE TO THE COMPANION IS DELAYED DUE TO ITS LARGE MASS
    - SPACE IS CURVED - PATH IS LONGER
- RECENT VERY PRECISE MEASUREMENT OF THE MASS OF THE NEUTRON STAR PSR J1614-2230:

$$(1.97 \pm 0.04) M_\odot$$

- SEVERE RESTRICTION FOR THE DENSE MATTER EOS



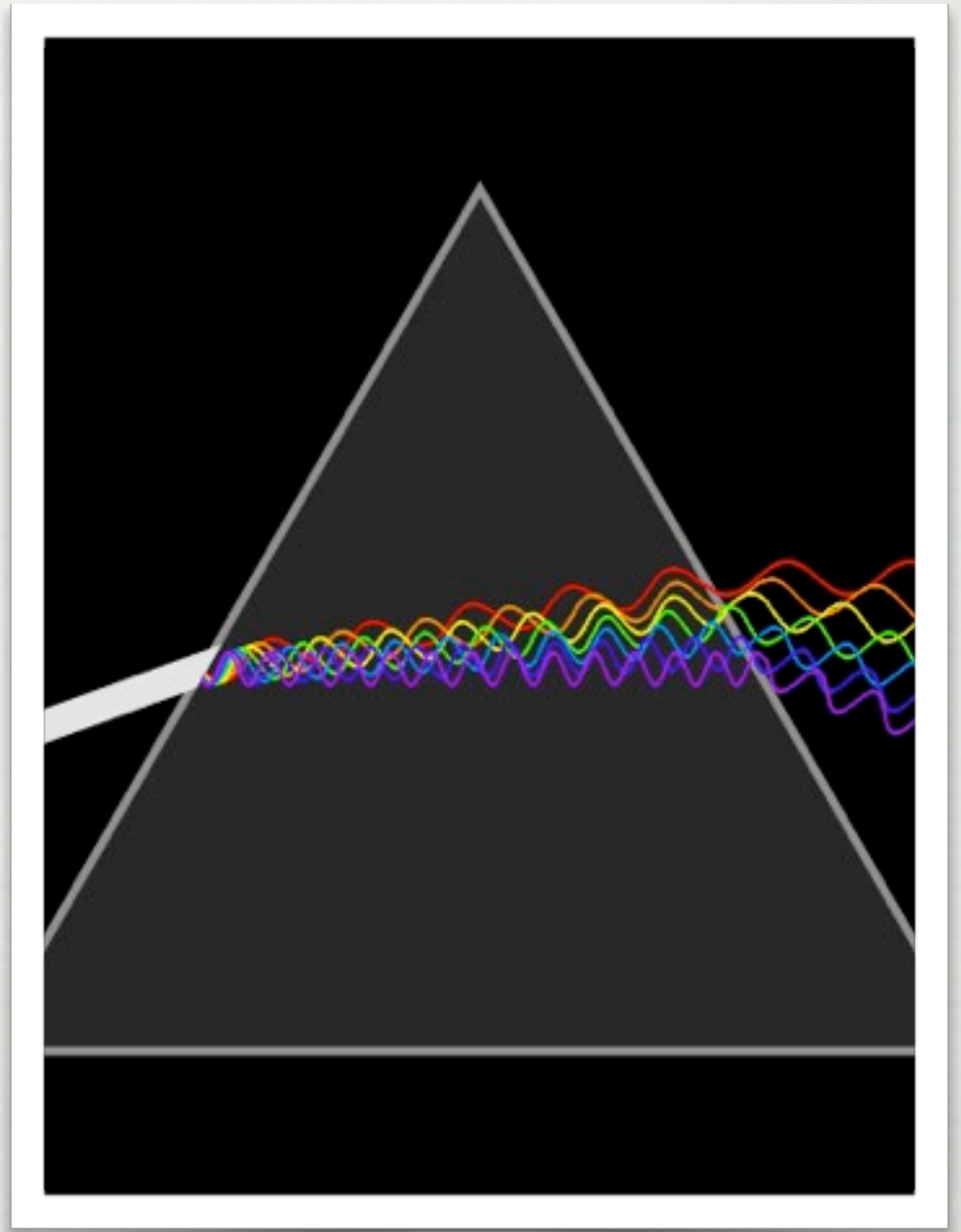
P. B. DEMOREST, ET. AL., NATURE 467 (2010) 1081

DISPERSION MEASURE

- INTERSTELLAR MEDIUM DISPERSES INDIVIDUAL PULSES
- MEASURED TIME DELAY OF DIFFERENT COMPONENTS

$$\frac{\Delta t_a}{\Delta \omega} = -\frac{4\pi e^2}{mc\omega^3} \langle n_e \rangle L$$

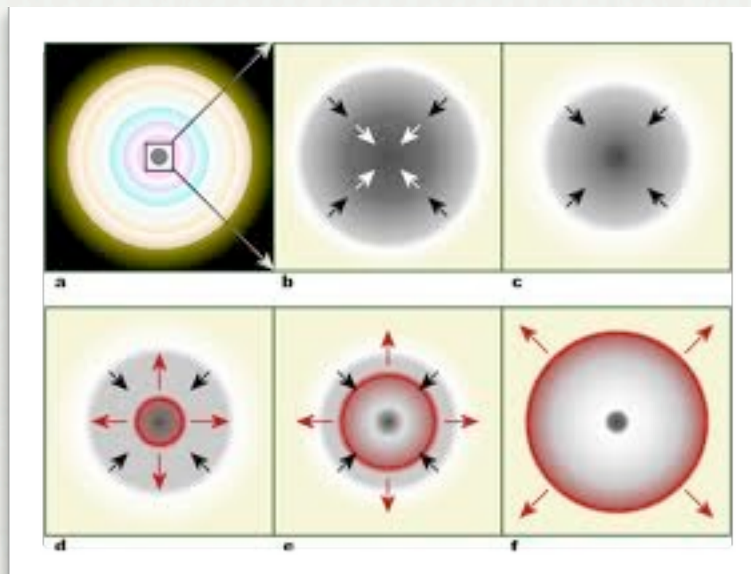
- YIELDS THE DISTANCE GIVEN AN ESTIMATE FOR THE AVERAGE ELECTRON DENSITY



ROTATION

PULSAR FREQUENCIES

- CREATION IN CORE-COLLAPSE SUPERNOVA



- REMNANT SHRINKS STRONGLY

- ANGULAR MOMENTUM
  $$J = I\Omega = \tilde{I} M R^2 \Omega$$
  IS CONSERVED => SPIN UP

- FOR INSTANCE FOR THE SUN:

$$R_\odot \approx 7 \cdot 10^5 \mathrm{km} \quad , \quad R_{NS} \approx 14 \mathrm{km}$$

$$T_\odot = 25\mathrm{d} \approx 2 \cdot 10^6 \mathrm{s} \;\Rightarrow\; T_{NS} = T_\odot \frac{R_{NS}^2}{R_\odot^2} \approx 1 \mathrm{ms}$$

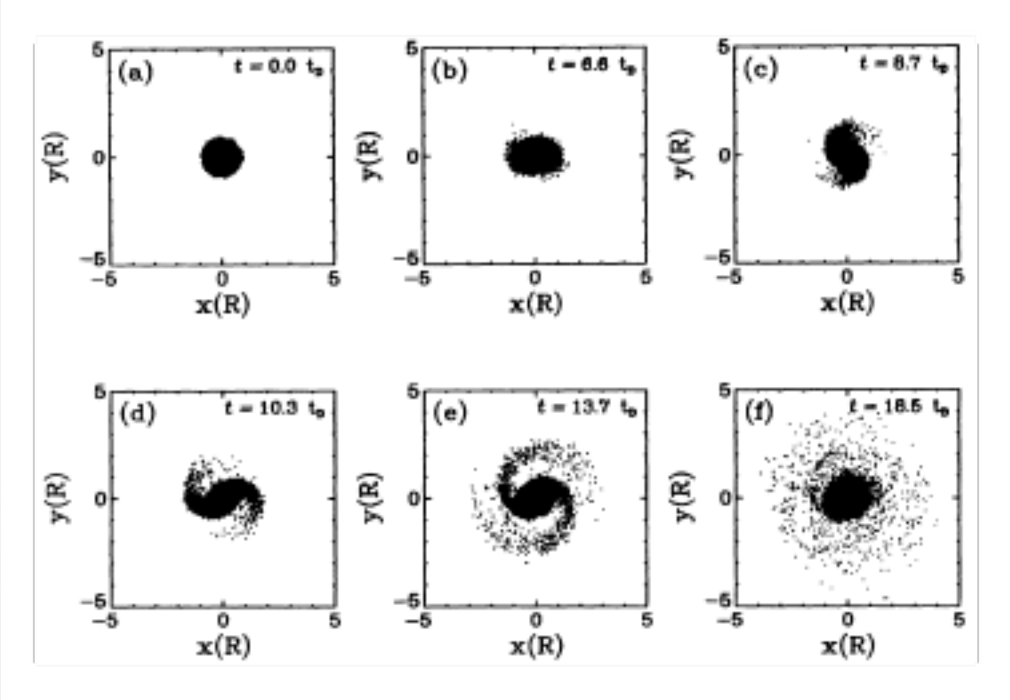
KEPLER FREQUENCY

- IF A STAR ROTATES TOO FAST, GRAVITY CANNOT OVERCOME THE CENTRIFUGAL FORCES AND MATTER IS SHED AT THE SURFACE
- THE MAXIMUM STABLE "KEPLER FREQUENCY" IS

$$\Omega_K \approx \frac{4}{9}\sqrt{2\pi G\bar{\rho}}$$

	$M\ [M_\odot]$	$M_{core}\ [M_\odot]$	$R\ [km]$	$n_c\ [n_0]$	$\langle n \rangle\ [n_0]$	$\Omega_K\ [kHz]$
NS	1.4	(1.39)	11.5	3.43	1.58	6.02
	2.0	(1.99)	11.0	4.91	2.46	7.68
	2.21	0.85	10.0	7.17	3.37	9.31
SS	1.4	–	11.3	2.62	1.91	6.17
	2.0	–	11.6	4.95	2.43	7.09
HS	1.4 (S)	0.38*	10.8	5.89	1.85	6.61
	1.4(M)	0.66*	10.3	6.66	2.09	7.06
	1.4(L)	1.06	12.7	2.32	1.17	5.16
	2.0	1.81	12.2	4.89	1.84	6.62

- DEPENDS ON THE PARTICULAR STAR MODEL AND ALLOWS PERIODS $O(\mathrm{ms})$
- HEAVIER AND MORE COMPACT STARS HAVE LARGER Ω_K
- AT FREQUENCIES ABOVE Ω_K MATTER IS SHED VIA UNSTABLE COMPRESSIONAL OSCILLATION MODES ("BAR-MODE")



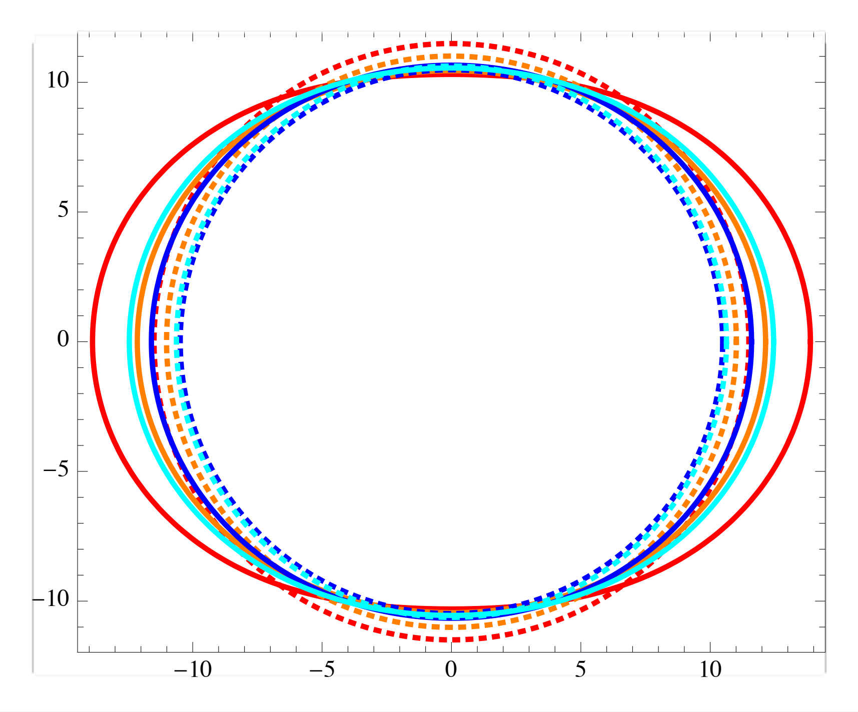
AGE DEPENDENCE

- PULSAR FREQUENCIES AND SPIN-DOWN RATES PRESENT IMPORTANT OBSERVABLES AND SHOW A STRIKING AGE-DEPENDENCE
- SPIN FREQUENCIES SEEM TO EXPERIENCE AN EVOLUTION DURING THE PULSARS LIFE
- ALL OBSERVED FREQUENCIES ARE BELOW THE THEORETICAL KEPLER LIMIT (FACTOR OF 2)

MANCHESTER, ET. AL. ASTRO-PH/0412641

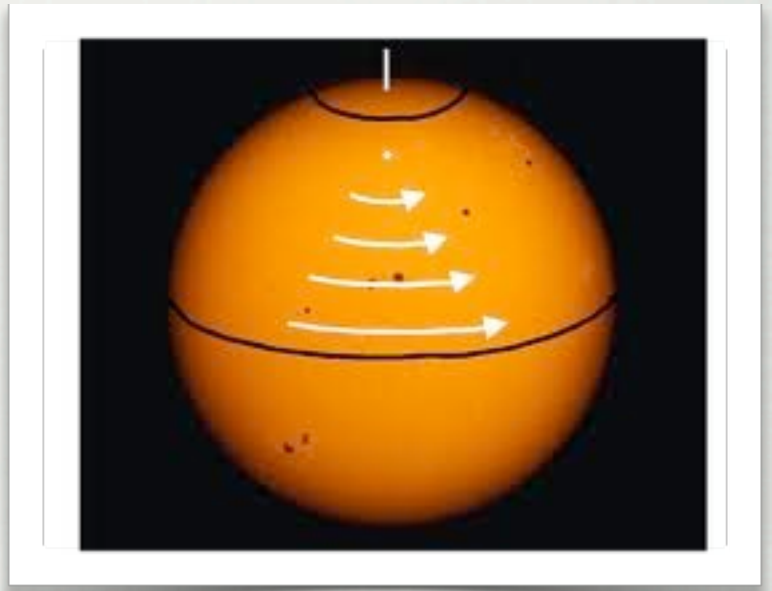
ROTATION AND STRUCTURE

- ☐ ROTATION LEADS TO CENTRIFUGAL FORCES THAT DEFORM THE STAR
- ☐ ROTATING STAR MODELS CAN BE OBTAINED IN A LINEAR PERTURBATION ANALYSIS FROM THE SOLUTIONS OF THE STATIC TOLMAN-OPPENHEIMER-VOLKOV EQUATIONS
- ☐ ROTATION GENERALLY INCREASES THE POSSIBLE MASSES SINCE THE CENTRIFUGAL FORCES COUNTERACT GRAVITY



RED: NEUTRON STAR
BLUE: STRANGE STAR
DOTTED: STATIC MODEL
SOLID: ROTATING AT LIMITING FREQUENCY

DIFFERENTIAL ROTATION



- INITIALLY DIFFERENTIAL ROTATION
  IS POSSIBLE
- BUT IT IS DAMPED BY
  SHEAR VISCOSITY
- AFTER LESS THAN A YEAR THE STAR ROTATES
  UNIFORMLY
- CRUST FORMS
  AND THE STAR ROTATES AS A RIGID BODY

SPIN-UP & SPIN-DOWN

FREQUENCY CHANGES

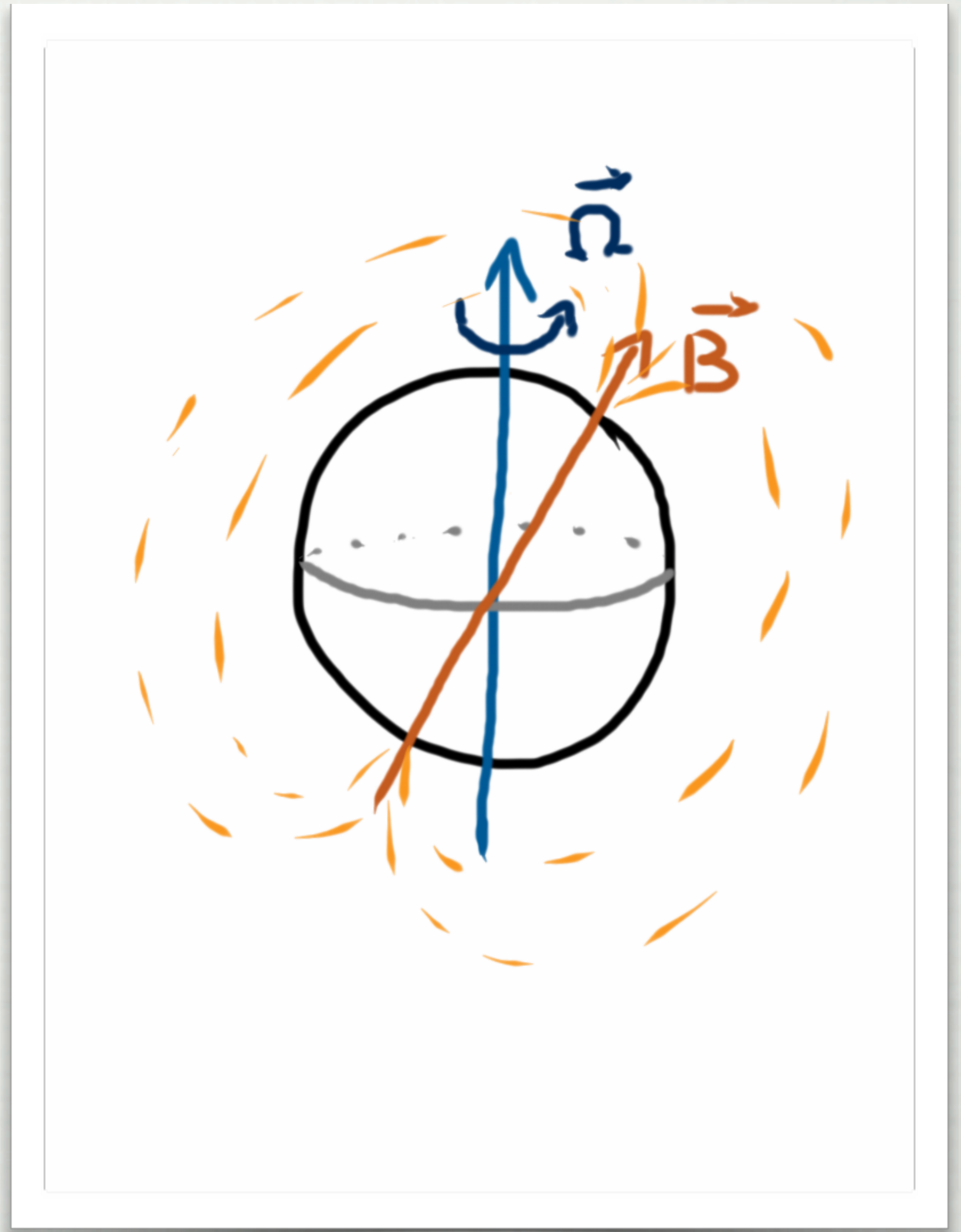
- A SPHERICAL UNIFORMLY ROTATING BODY (MAGNETIC MOMENT ALIGNED WITH AXIS) DOES NOT RADIATE ...
- ... BUT PULSARS FREQUENCIES CHANGE WITH TIME
  - PRECISE MEASUREMENTS OF 1. AND 2. DERIVATIVES
  - MOST SHOW A FREQUENCY DECREASE (SPIN-DOWN) BUT SOME SHOW A FREQUENCY INCREASE (SPIN-UP)
- SPIN-DOWN MECHANISMS: RADIATION (γ, e, p OR g, ν)
- SPIN-UP MECHANISMS: ACCRETION, "GLITCHES"

MAGNETIC DIPOLE MODEL

- MAGNETIC DIPOLE FIELD THAT IS TILTED COMPARED TO THE ROTATION AXIS (EARTH)
- GENERATES A FLUCTUATING ELECTRIC DIPOLE FIELD WHICH RADIATES OFF ENERGY

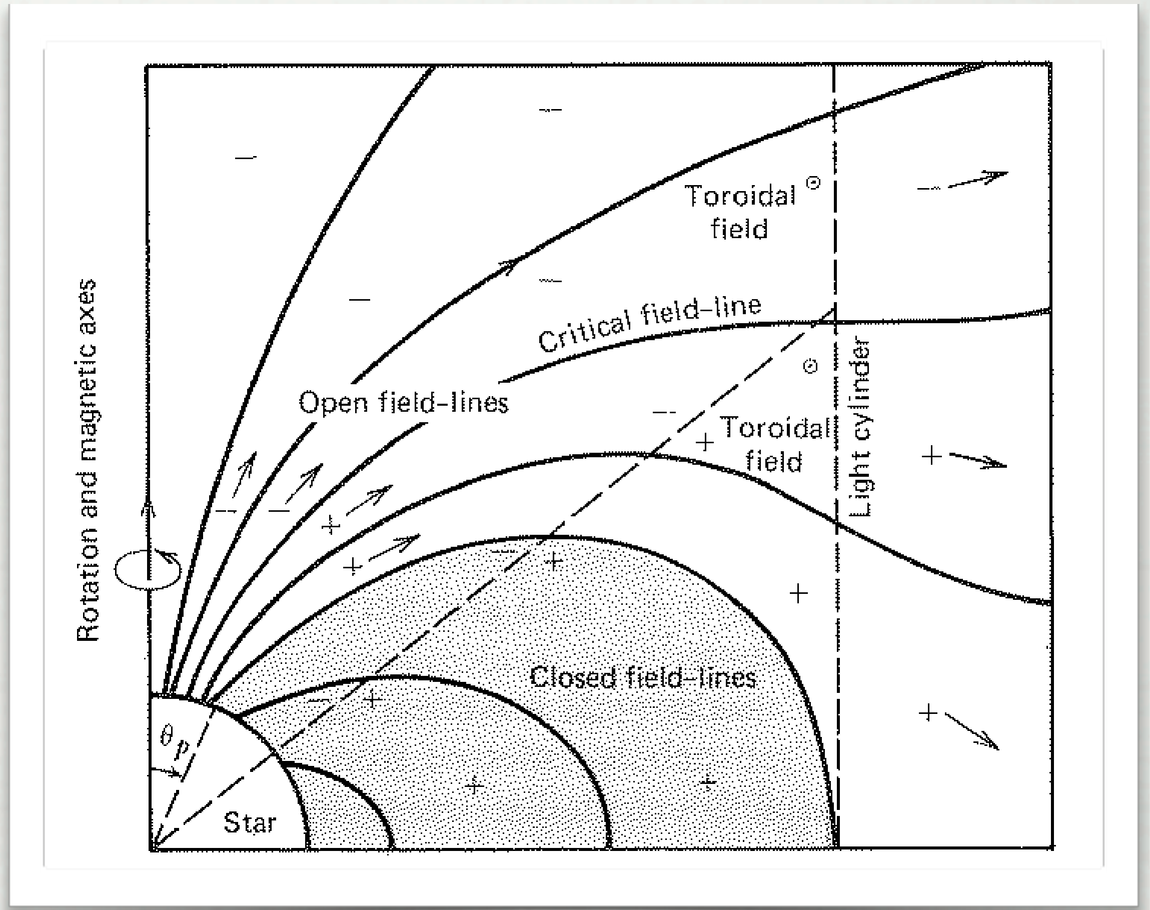
$$\dot{E} = -\frac{B_p^2 R^6 \Omega^4 \sin^2 \alpha}{6c^3}$$

- STAR LOSES ROTATIONAL ENERGY AND SPINS DOWN - "MAGNETIC BRAKING"



MAGNETOSPHERE (& JETS)

- FIELD LINES WITHIN LIGHT-CYLINDER CO-ROTATE WITH PULSAR
- LARGE ELECTRIC FIELDS CAN PULL OUT CHARGED PARTICLES OFF THE SURFACE OF THE STAR
- THEY SPIRAL ALONG THE FIELD LINES AND RADIATE
- JET GENERATION IS A NON-LINEAR MAGNETO-HYDRODYNAMICAL PROBLEM



$$\rho \frac{d\vec{v}}{dt} = -\vec{\nabla} p - \rho \vec{\nabla} \phi + \frac{1}{c} \vec{J} \times \vec{B}$$

R-MODE OSCILLATIONS

- R-MODE: EIGENMODE OF A ROTATING STAR WHICH IS UNSTABLE AGAINST GRAV. WAVE EMISSION

  N. ANDERSSON, ASTROPHYS. J. 502 (1998) 708

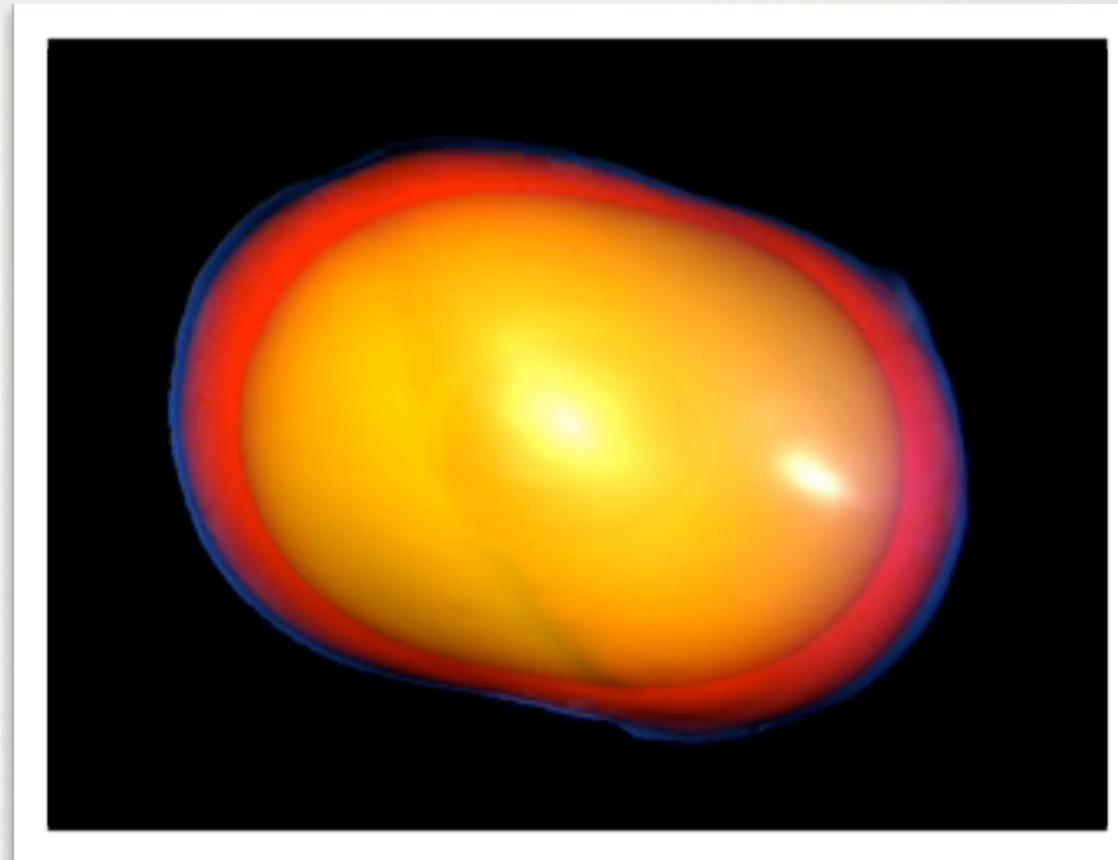
- LARGE AMPLITUDE R-MODE OSCILLATIONS COULD QUICKLY SPIN DOWN A STAR

  B. J. OWEN, ET. AL., PHYS. REV. D 58 (1998) 084020

- BUT R-MODE GROWTH HAS TO BE STOPPED BY SOME NON-LINEAR DAMPING MECHANISM - PREVIOUSLY SIMPLY ASSUMED!

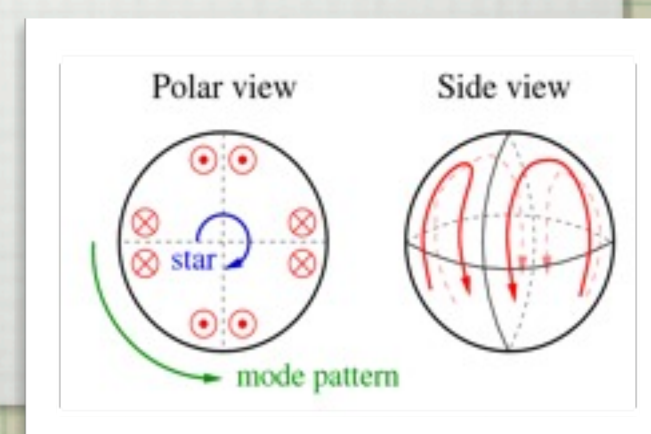
- OTHERWISE, LARGE AMPLITUDE R-MODES COULD BE DESTROYED BY DECAY INTO OTHER MODES

  L.M. LIN AND W.M. SUEN, MON. NOT. ROY. ASTRON. SOC. 370 (2006) 1295



SIMULATION BY L. LINDBLOM

$$\left|\frac{\delta\rho}{\rho}\right| \approx \sqrt{\frac{4\pi 5!}{7}}\frac{\partial\rho}{\partial p}R^2\Omega^2\alpha\left(\frac{r}{R}\right)^3 Y_3^2\left(\theta,\phi\right)$$



VISCOUS DAMPING

- VISCOSITIES DESCRIBE THE DISSIPATION DUE TO MICROSCOPIC INTERACTIONS:

$$\left.\frac{d\epsilon}{dt}\right|_{visc} = -\eta \left(\nabla_a v_b + \nabla_b v_a - \frac{2}{3}\delta_{ab}\nabla_c v_c \right)^2 - \zeta \left(\vec{\nabla} \cdot \vec{v} \right)^2$$

SHEAR BULK

- A LOCAL DENSITY OSCILLATION

$$n(\vec{r}, t) = \bar{n} + \Delta n(\vec{r}) \sin\left(\frac{2\pi t}{\tau}\right)$$

... LEADS TO AN EXPRESSION FOR THE BULK VISCOSITY OF THE FORM

$$\zeta \approx -\frac{2}{\omega^2} \left\langle \frac{d\epsilon}{dt} \right\rangle \frac{\bar{n}^2}{(\Delta n)^2}$$

- A DRIVING DENSITY FLUCTUATION INDUCES A CORRESPONDING CHEMICAL POTENTIAL OSCILLATION

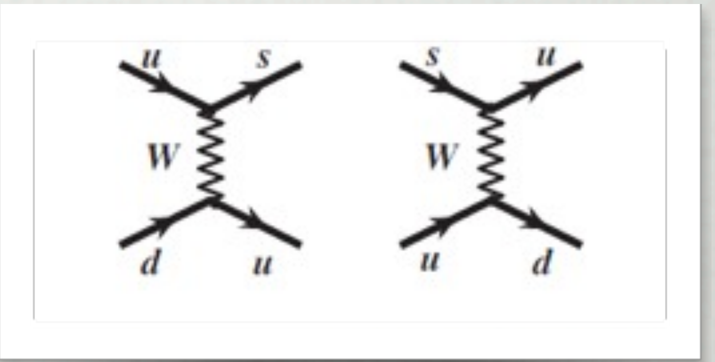
$$\mu_\Delta = C\frac{\delta n}{\bar{n}} + B\bar{n}\delta x$$

WITH SUSCEPTIBILITIES THAT CHARACTERIZE THE MATTER

$$C \equiv \bar{n}\frac{\partial \mu_\Delta}{\partial n} \quad \text{AND} \quad B \equiv \frac{1}{\bar{n}}\frac{\partial \mu_\Delta}{\partial x}$$

DAMPING PROCESSES

- HADRONIC MATTER:
  - SHEAR VISCOSITY FROM LEPTONIC SCATTERING
  - BULK VISCOSITY FROM WEAKURCA PROCESSES BOTH DIRECT $n \rightarrow p + e + \bar{\nu}_e$, $p + e \rightarrow n + \nu_e$ AND MODIFIED WITH BYSTANDER NUCLEON FOR MOMENTUM CONSERVATION
- STRANGE QUARK MATTER:
  - SHEAR VISCOSITY FROM QUARK SCATTERING
  - BULK VISCOISTY FROM NON-LEPTONIC WEAK PROCESSES $s + u \leftrightarrow d + u$

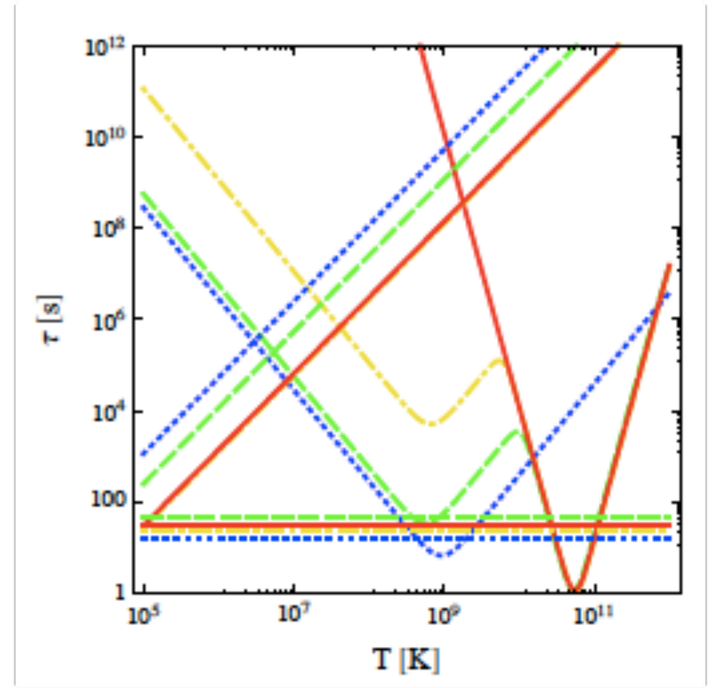


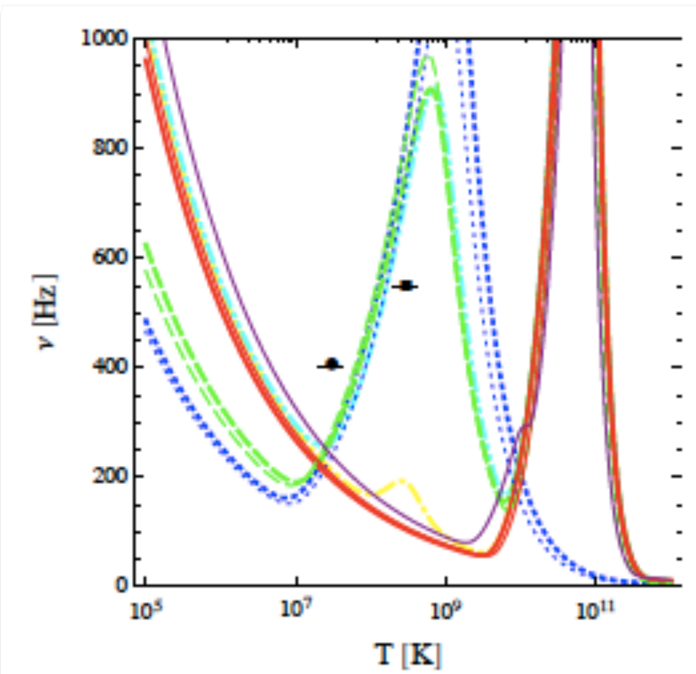
DAMPING TIME SCALES

- DAMPING TIMES

$$\frac{1}{\tau_i} \equiv -\frac{1}{2E}\left(\frac{dE}{dt}\right)_i$$

- SHEAR VISCOSITY DOMINATES AT LOW TEMPERATURES - BULK VISCOSITY AT HIGH TEMPERATURES





(CORE TEMPERATURE)

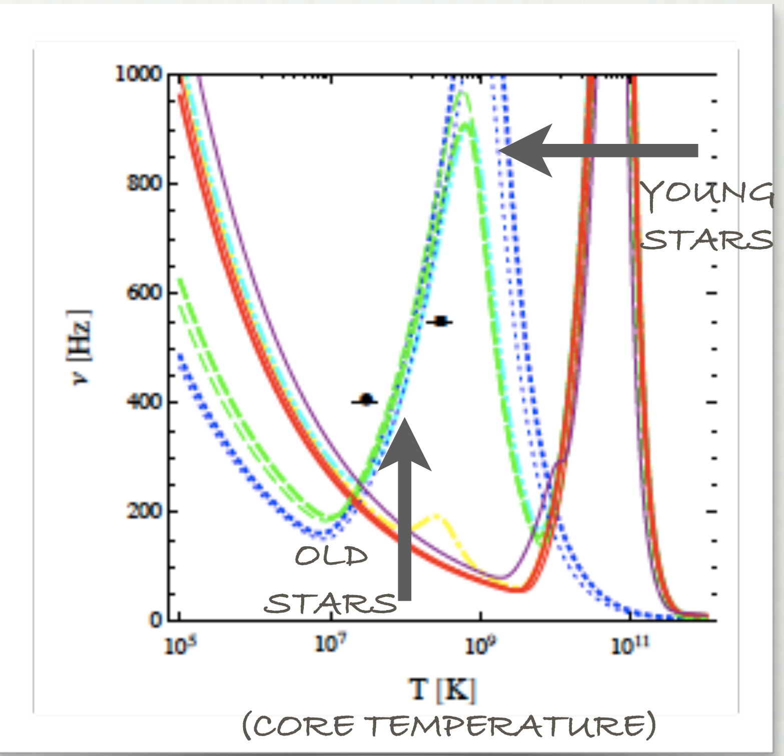
- THERE ARE INSTABILITY REGIONS WHERE THE R-MODE BECOMES LARGE

R-MODE SATURATION

- R-MODE HAS TO BE SATURATE AT SOME LARGE AMPLITUDE
- POSSIBLE MECHANISM:
  - COUPLING BETWEEN DIFFERENT OSCILLATION MODES
  - LARGE AMPLITUDE INCREASE OF THE BULK VISCOSITY
  - NON-LINEAR HYDRODYNAMIC EFFECTS
- THE SATURATION AMPLITUDE DETERMINES HOW FAST R-MODES CAN SPIN-DOWN A PULSAR

STAR EVOLUTION

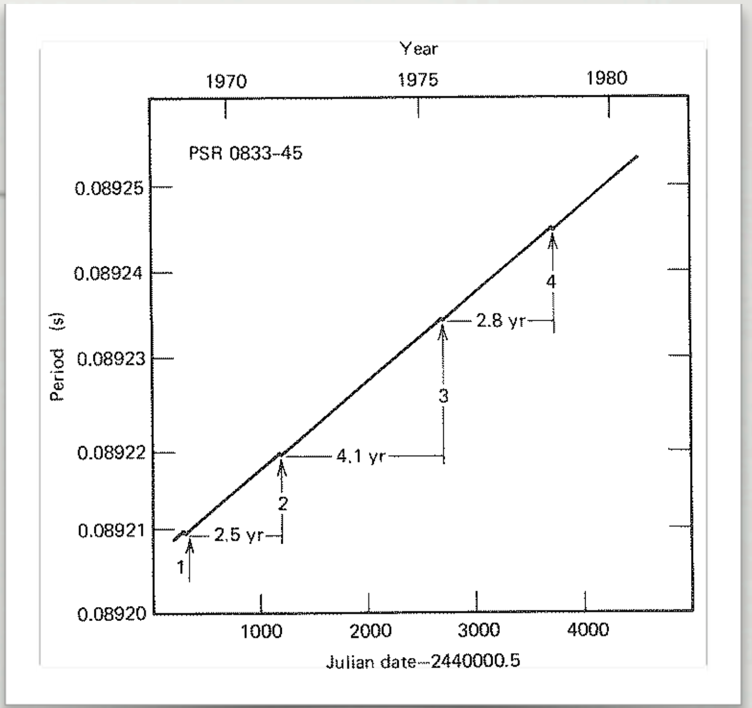
- FAST YOUNG STARS ENTER INSTABILITY REGION FROM THE RIGHT
  - R-MODE INSTABILITY DEVELOPS AND STAR SPINS DOWN
  - EXPLAINS THE ABSENCE OF FAST YOUNG STARS



- ACCRETING OLD STARS IN BINARIES ("LMXBS") ENTER THE INSTABILITY REGIONS FROM BELOW
  - INSTABILITY REGION LIMITS THEIR SPIN FREQUENCY
  - DOES EXPLAIN WHY THEY DO NOT SPIN AT KEPLER FREQUENCY
- DEPENDS STRONGLY ON MICROPHYSICS, COOLING, ...

GLITCHES

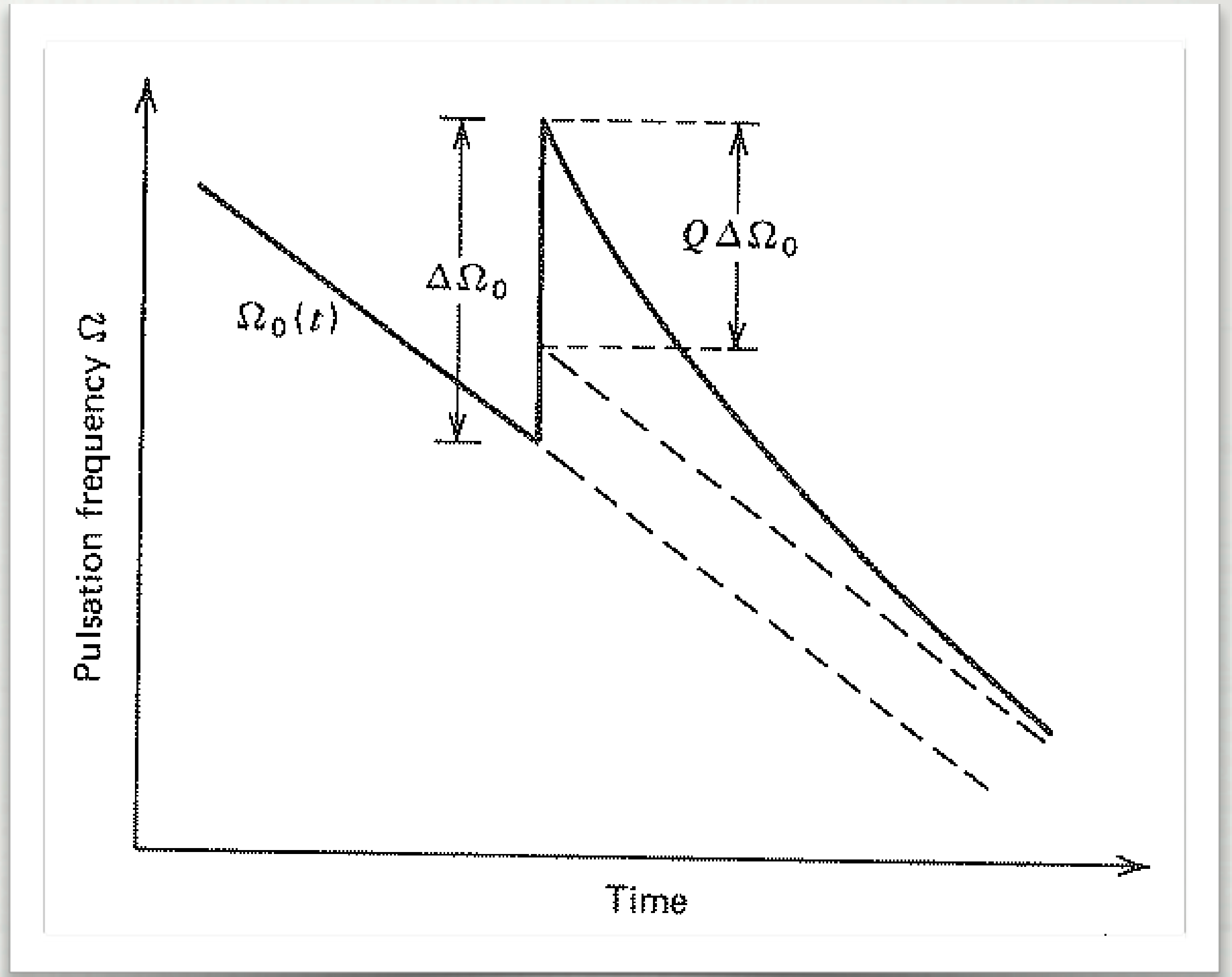
MECHANISM



- “GLITCHES” ARE OBSERVED SUDDEN (UNPREDICTIBLE) PULSAR SPIN-UPS
- POSSIBLE EXPLANATIONS:
  - “STARQUAKE”: SUDDEN DEFORMATION IN THE SOLID CRUST DUE TO TENSIONS ARISING WHEN THE ROTATION FREQUENCY DECREASES (STAR BECOMING MORE SPHERICAL)
  - SUDDEN RELOCATION OF SUPERFLUID VORTEX LINES “PINNED” TO THE SOLID CRUST
  - MAGNETOSPHERIC INSTABILITIES: CLOSED FIELD LINES TRAP PARTICLES CARRYING ANGULAR MOMENTUM AND SUDDENLY RELEASE THEM

GLITCH RELAXATION

- PULSAR SPIN-UP OVERSHOOTS
  - FAST BIG SPIN-UP IN SECONDS ...
  - ... AND SUBSEQUENT SLOW RELAXATION TO AN ONLY MODERATELY SHIFTED SPIN-DOWN CURVE WITHIN YEARS



- THE CHANGE IN THE RATE $\Delta\dot{\Omega}/\dot{\Omega} = O(10^{-2})$ IS MUCH BIGGER THAN THE CHANGE IN THE FREQUENCY $\Delta\Omega/\Omega = O(10^{-6})$

TWO COMPONENT MODEL

- SIMPLE MODEL: CHARGED FLUID COMPONENT IN THE CORE IS COUPLED TO THE CHARGES IN THE CRUST VIA MAGNETIC FIELDS
  - CHARGE FLUID COMPONENT CO-ROTATES AND IMMEDIATELY FOLLOWS SPIN INCREASE
- NEUTRON SUPERFLUID IN THE BULK IS ONLY COUPLED BY WEAKLY FRICTIONAL FORCES BETWEEN NORMAL AND SUPERFLUID COMPONENT WITH RELAXATION TIME τ
- ANGULAR MOMENTUM CONSERVATION IN COUPLED SYSTEM AFTER THE GLITCH: $I_c\dot{\Omega} = -\alpha - \frac{I_c(\Omega - \Omega_c)}{\tau} \quad , \quad I_n\dot{\Omega}_n = \frac{I_c(\Omega - \Omega_c)}{\tau}$
- WITH SOLUTION: $\Omega(t) = \Omega_0(t) + \Delta\Omega_0(Q\mathrm{e}^{-t/\tau} + 1 - Q)$

CONNECTION TO EOS

- MODEL PARAMETERS ARE OBTAINED FROM SPIN DOWN OBSERVABLES $$\tau = -\frac{\dot{\Omega}(t=0)}{\Delta\ddot{\Omega}(t=0)} \qquad Q = -\frac{\Delta\dot{\Omega}(t=0)}{\Delta\Omega_0}\tau$$
- OBSERVED Q VALUES VARY STRONGLY FOR DIFFERENT PULSARS CRAB PULSAR: $Q \approx 0.95$; VELA PULSAR: $Q \approx 0.05$
- ASSUMING THAT τ AND α ARE CONSTANT AND THE INDIVIDUAL ANGULAR MOMENTA ARE INDIVIDUALLY CONSERVED DURING THE INITIAL STAR-QUAKE ALLOWS TO CONNECT Q TO THE MOMENTS OF INERTIA $$Q \approx \frac{I_n}{I_c + I_n}$$
- MOMENTS OF INERTIA DEPEND ON THE EQUATION OF STATE AND THE MASS OF THE STAR $$I = \frac{8\pi}{3}\int_0^R \rho(r) r^4 dr$$

CONCLUSION

- PULSARS ALLOW THE MOST PRECISE OBSERVATIONS OF NEUTRON STAR PROPERTIES
- VERY COMPLEX SYSTEMS WITH A DYNAMIC MAGNETOSPHERE AND STRONGLY COLLIMATED JETS
- ROTATION INFLUENCES MANY ASPECTS (FORM, MASS, STABILITY, COOLING, ...)
- CAN PROVIDE INFORMATION ABOUT DETAILED PROPERTIES OF THE STAR INTERIOR (TRANSPORT, SUPERFLUIDITY, ...)
- PRECISION DATA COULD ALLOW TO DISTINGUISH BETWEEN DIFFERENT FORMS OF DENSE MATTER