Course II: Compact Objects, the Dynamic Radio Sky, and 21st Century Radio Telescope Facilities

Jim Cordes
Professor of Astronomy
Cornell University

Five Lectures:

1. Astrophysics of neutron stars and other compact objects
2. Pulsar astrophysics (continued), plasma propagation effects on pulsar surveys and timing
3. Precision imaging and astrometry
4. The dynamic radio sky (transients and variability)
5. New radio telescope arrays for key science and discovery

Cornell University

9/13/11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   1

Pulsar Populations: P - Ṗ Diagram

- **Magnetars+high-field pulsars**
  - P ~ 5-12 s
  - B ~ $10^{14} - 10^{15}$ G
- **Canonical pulsars**
  - P~ 20ms – 5s
  - B ~ $10^{12\pm1}$ G
- **Recycled/Millisecond pulsars (NS-NS binaries, MSPs)**
  - P ~ 1.4 – 20ms
  - B ~ $10^8 - 10^9$ ms
- **Braking index n:**
  - Pdot $\propto P^{2-n}$, n=3 magnetic dipole radiation
- **Death line**
- **Strong selection effects**
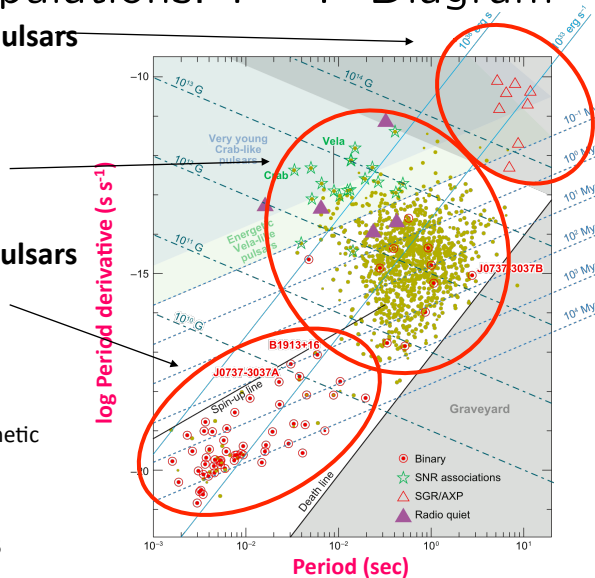
12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   2

Where is the action?

- Sub-hour NS-NS binaries, NS-BH binaries
- Sub-millisecond pulsars --- or not --- providing constraints on EoS, gravitational wave emission, mountains on NS
- Many NS mass measurements: constraints on EoS
- Extragalactic pulsars and magnetars
  - requires SKA sensitivity for periodic sources
  - Giant pulses: Arecibo to ~ 1-5 Mpc   SKA to Virgo cluster
- Better understanding of magnetospheric physics through combined Fermi detections of pulsars and radio beaming studies
- Discovery of many new, strange, fast transient sources
  - mostly neutron star variants or something else?
  - prompt radio bursts from GRBs (short bursts most likely)
- Pulsars orbiting Sgr A* + constraints of space time around a 4×10^6 $M_{\odot}$ black hole
- Strong constraints on/detection of nano-Hertz gravitational waves and constraints on massive-black hole astrophysics, cosmic strings
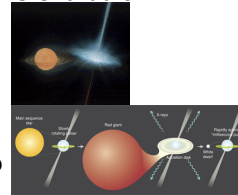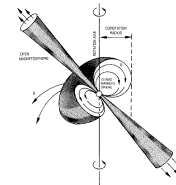
12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   3
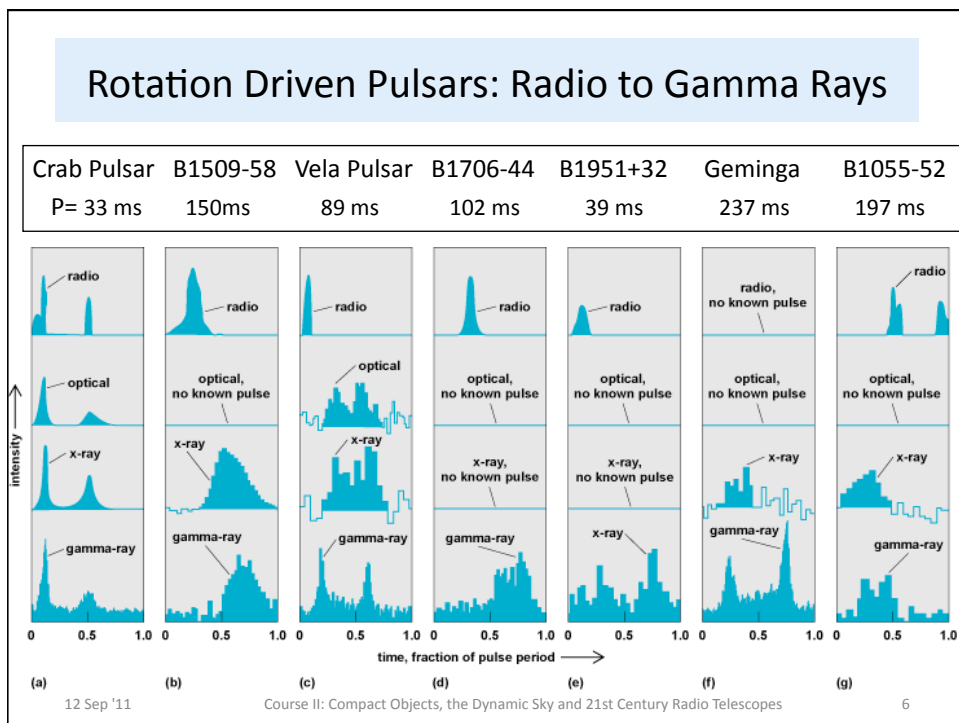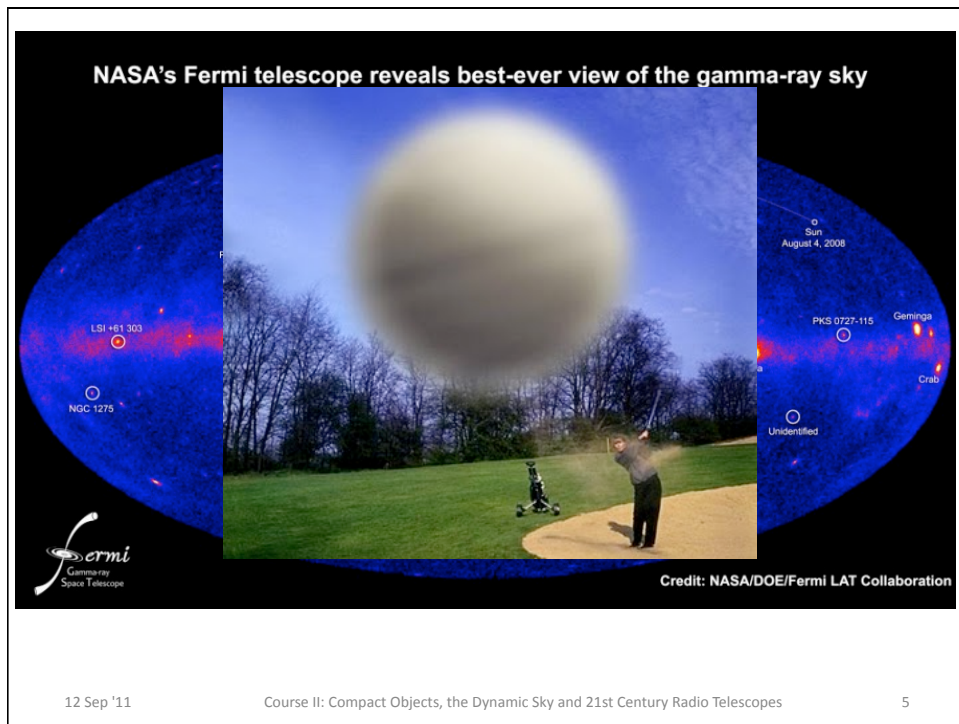
Manifestations of NS:

- Rotation driven:
  - "radio" pulsars (radio $\rightarrow \gamma$ rays)
  - magnetic torque $\dot{E} \propto I\Omega\dot{\Omega} \propto IB^2\Omega^4$
  - incoherent, nonthermal radiation (optical $\rightarrow$ gamma rays)
  - $\gamma\gamma \rightarrow e^+ e^-$ + plasma instability $\Rightarrow$ coherent radio

- Accretion driven:
  - X-rays $L_x = \varepsilon\dot{M}c^2$
  - LMXB, HMXB

- Magnetic driven: Crustquakes?
  - Magnetars (AXPs, SGRs) $L_x \gg \dot{E}$ $L_x \propto \frac{d}{dt}B^2$
  - Spindown from very high magnetic fields (> 10^{14} G)

- Gravitational catastrophes
  - Subclass of Gamma-ray bursts (NS-NS or NS-BH inspiral)?

12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   4

NASA's Fermi telescope reveals best-ever view of the gamma-ray sky

Credit: NASA/DOE/Fermi LAT Collaboration

12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   5

Rotation Driven Pulsars: Radio to Gamma Rays

Crab Pulsar	B1509-58	Vela Pulsar	B1706-44	B1951+32	Geminga	B1055-52
P= 33 ms	150ms	89 ms	102 ms	39 ms	237 ms	197 ms

12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   6

3

THEORY OF PULSARS: POLAR GAPS, SPARKS, AND COHERENT MICROWAVE RADIATION

M. A. RUDERMAN*
AND
P. G. SUTHERLAND†
Department of Physics, Columbia University
Received 1974 April 29; revised 1974 July 8

ABSTRACT

The huge magnetic fields characteristic of pulsars cause the nuclei (largely iron) of the stellar surface to form a tightly bound condensed state. Except for the very young Crab pulsar, theory and observation both support the view that the stellar surface is not hot enough to sustain an outflow of positive ions to balance the outflow of electrons as charge leaves the magnetosphere through the light cylinder along the open magnetic field lines. Adopting the conventional assumption that electrons do not return to the neutron star by coming back through the light cylinder along the open field lines, we are led to the following consequences for a neutron star whose magnetic moment tends to be antiparallel (as opposed to parallel) to its spin angular momentum: A polar magnetospheric gap is formed that spans the open field lines from the stellar surface up to an altitude of about 10^4 cm. In the gap $\mathbf{E} \cdot \mathbf{B} \neq 0$, although it vanishes essentially everywhere else in the near magnetosphere. The potential difference between the base and top of the gap is about 10^{12} volts. The gap continually breaks down (sparking) by forming electron-positron pairs on a time scale of a few microseconds. The gap positrons move out along the open field lines, and electrons flow to the stellar surface to close the pulsar's homopolar generator circuit as in the related Sturrock model.

We show how this can lead to injection into the near magnetosphere of ultrarelativistic positrons and the pairs subsequently produced by curvature radiation from the positrons leads to coherent microwave radiation in the frequency range and with remarkably many of the characteristics observed in pulsars. The properties and energetics of the sparking in the gap lead directly to (i) the maximum total luminosity of the pulsar and its dependence on period P: $L_{max} \sim 10^{31} P^{-15/7}$ ergs s^{-1}, (ii) the observed drifting of subpulses and quantitative expressions for P_2 and P_3 (assuming that the sparking is localized, rapidly fluctuating but only rarely self-quenching), (iii) microstructure of pulses, (iv) the turnoff of a pulsar as its period increases, and (v) apparent weakening of the magnetic field in older pulsars. The production of coherent microwave radiation in the near magnetosphere results in substantial qualitative agreement with observations in these areas: (i) shapes and widths of pulse envelopes, (ii) their period and frequency dependence, and (iii) the sweep of linear polarization through the pulse envelope.
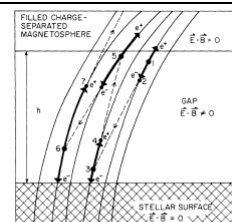
Subject heading: pulsars

Mind the Gaps

- Basics of magnetospheres
  - Goldreich & Julian (1969)
- Polar cap gaps for canonical pulsars
  - Sturrock (1970)
  - Ruderman & Sutherland (1975)
- Outer gaps for energetic young pulsars
  - Cheng and Ruderman
- Slot gaps
  - Arons et al. late 1970's
- basic explanation of P-Pdot diagram
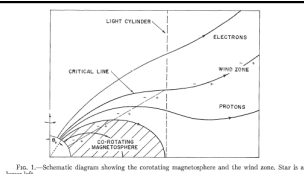- Some understanding of radio and high-energy beaming, energetics
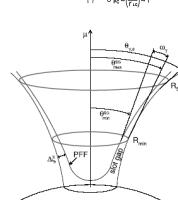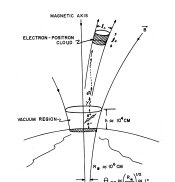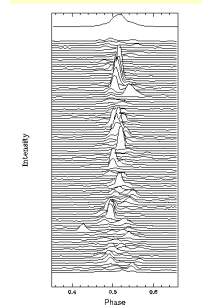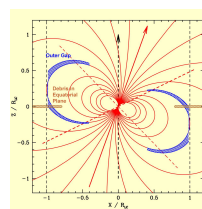
Binary Pulsars

- Most pulsars are <u>isolated</u> (not in binaries)
- Binary pulsars (about 1% of all pulsars):
  - White dwarf companions (~2/3 of millisecond pulsars)
  - Neutron star companions
  - Black hole companions (should exist, none known)
- Other companions:
  - planets (2 to 3 pulsars) (Note: first extrasolar planets detected !)
  - debris disks (not seen directly but inferred)
- **Importance:** testing theories of gravity, including General Relativity, precision masses of NS

12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   9
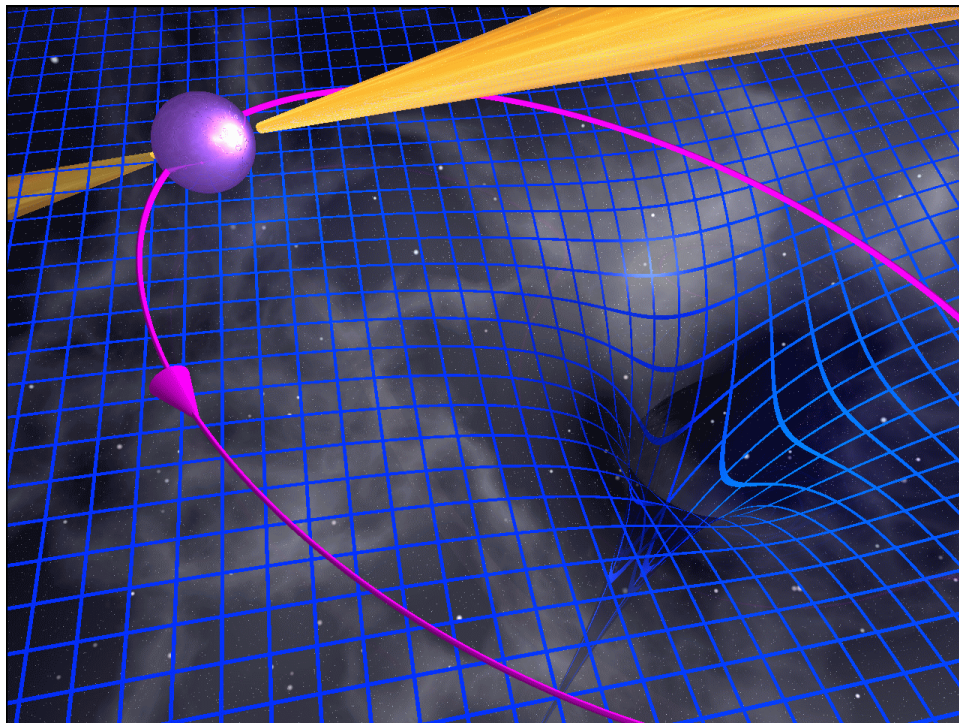
The Hulse-Taylor Binary Pulsar

Hulse & Taylor (1974)
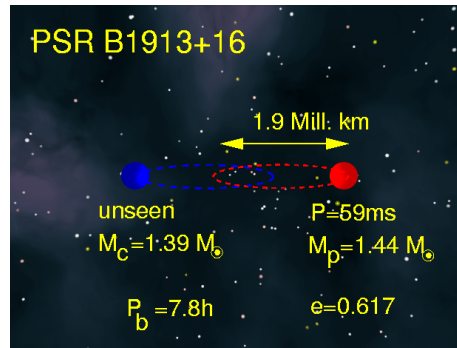
Weisberg & Taylor (priv. comm)

PSR B1913+16

1.9 Mill. km

unseen
M_c=1.39 $M_\odot$

P=59ms
M_p=1.44 $M_\odot$

P_b =7.8h

e=0.617

General Relativity prediction

(y-axis: Cumulative shift of periastron time (s), from 0 to -40)

(x-axis: Year, 1975 1980 1985 1990 1995 2000 2005)
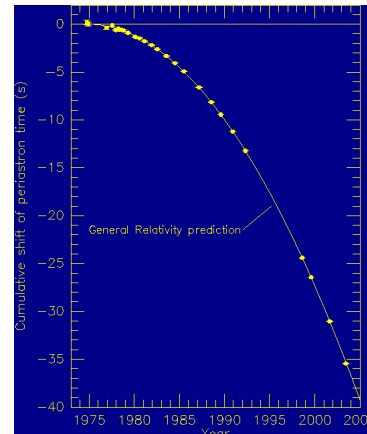
- **Orbit shrinks every day by 1cm**
- **Confirmation of existence of gravitational waves**

12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   11
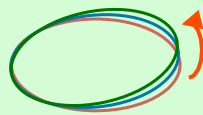
Precession

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3} \frac{1}{1-e^2} \left[\frac{G}{c^3}\left(m_1 + m_2\right)\right]^{2/3}$$
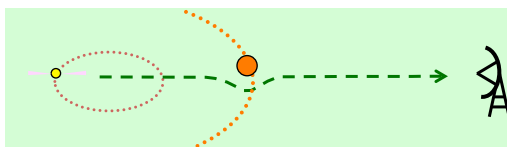
Shapiro Delay

$$\Delta t = 2\frac{G}{c^3} m_2 \ln\left[1 - \sin i \sin(\varphi - \varphi_0)\right]$$

v
r
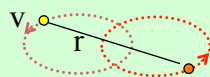
Grav Redshift/Time Dilation

$$\gamma = \frac{G^{2/3}}{c^2}\left(\frac{P_b}{2\pi}\right)^{1/3} e \frac{m_2(m_1 + 2m_2)}{(m_1 + m_2)^{4/3}}$$
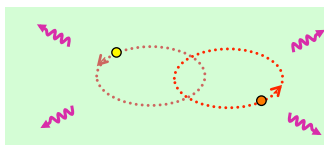
Gravitational Radiation

$$\dot{P}_b = -\left(\frac{192\pi}{5}\right)\frac{G^{5/3}}{c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)\frac{1}{(1-e^2)^{7/2}}\frac{m_1 m_2}{(m_1 + m_2)^{1/3}}$$

12 Sep '11   Course II: Compu...

Precession of Orbits

- Precession of Mercury's orbit was known by Einstein to not be fully accounted for by perturbations from other planets in the solar system
- The unexplained part of Mercury's advance of perihelion **(43 arc sec/ century)** was explained by Einstein, the first empirical triumph for GR.
- The periastron of PSR B1913+16 advances **4.2 degrees/year**. The daily periastron advance is the same as Mercury's perihelion advance in a century…
- The periastron advance of the double pulsar J0737-3039A,B is **16.9 degrees/ year**

12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   13

One of the best pulsars for timing
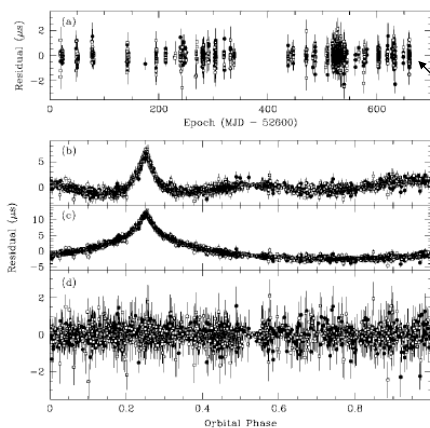
MSP J1909-3744 P=3 ms + WD

Jacoby et al. (2005)

Weighted σ_{TOA} = 74 ns

Shapiro delay

FIG. 1.—High-precision timing residuals for PSR J1909−3744. Filled circles represent TOAs from the 1341 MHz band, while open squares denote the 1405 MHz band. (a) Residuals vs. observation epoch for best-fit model taking Shapiro delay fully into account (Table 1). (b) Residuals vs. orbital phase for best-fit Keplerian model. Some of the Shapiro delay signal is absorbed in an anomalously large Roemer delay and eccentricity. (c) Residuals vs. orbital phase for the best-fit model, but with the companion mass set to zero (i.e., the correct Keplerian orbit, but neglecting Shapiro delay). (d) Residuals vs. orbital phase for the best-fit model taking Shapiro delay fully into account (Table 1).

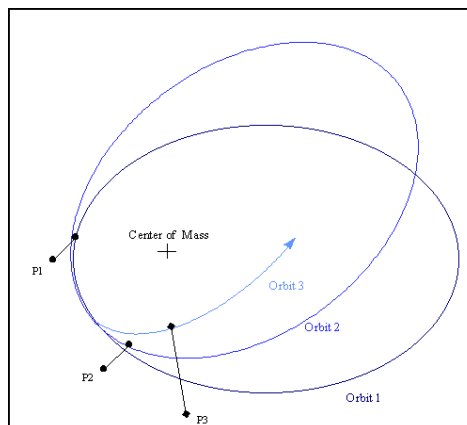12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   14

A Double-Pulsar System: A Rare Laboratory for Relativistic Gravity and Plasma Physics

A. G. Lyne,[1]* M. Burgay,[2] M. Kramer,[1] A. Possenti,[3,4]
R.N. Manchester,[5] F. Camilo,[6] M. A. McLaughlin,[1] D. R. Lorimer,[1]
N. D'Amico,[3,7] B. C. Joshi,[8] J. Reynolds,[9] P. C. C. Freire[10]

The clocklike properties of pulsars moving in the gravitational fields of their unseen neutron-star companions have allowed unique tests of general relativity and provided evidence for gravitational radiation. We report here the detection of the 2.8-second pulsar J0737−3039B as the companion to the 23-millisecond pulsar J0737−3039A in a highly relativistic double neutron star system, allowing unprecedented tests of fundamental gravitational physics. We observed a short eclipse of J0737−3039A by J0737−3039B and orbital modulation of the flux density and the pulse shape of J0737−3039B, probably because of the influence of J0737−3039A's energy flux on its magnetosphere. These effects will allow us to probe magneto-ionic properties of a pulsar magnetosphere.

Equations for Relativistic Orbits

Keplerian parameters:

Classical measurements of orbit give 5 parameters (P_b, x, e, ω, t_p) and the mass function. One additional GR measurement is needed to determine the masses M_1 and M_2 separately

$$f = \frac{(m_2 \sin i)^3}{M^2} = \left(\frac{2\pi}{P_b}\right)^2 x^3 T_\odot^{-1}$$

$$M = M_1 + M_2$$

$$x = a_1 \sin i / c$$

$$T_\odot = GM_\odot / c^3 = 4.925 \ \mu s$$

GR Effects on Orbit:

$$\dot{\omega} = 3 \left(\frac{P_b}{2\pi}\right)^{-5/3} (T_\odot M)^{2/3} \left(1 - e^2\right)^{-1}$$

Orbital precesssion rate

$$\dot{P}_b = -\frac{192\pi}{5} \left(\frac{P_b}{2\pi}\right)^{-5/3} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) \times$$
$$(1 - e^2)^{-7/2} T_\odot^{5/3} m_1 m_2 M^{-1/3},$$

Decay of orbital period (GW emission)

$$\gamma = e \left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_2 (m_1 + 2m_2),$$

Red shift + 2nd order Doppler effect

$$r = T_\odot m_2,$$

$$s = x \left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1}.$$

r,s = Shapiro delay parameters

Mass-Mass Diagram for J0737-3039A,B

System will merge in ~ 85 Myr

Distance ~ 500 pc

It will produce a spectacular gamma-ray burst, gravitational waves, and what else?

Will the Earth's biosphere be affected?

...tury Radio Telescopes   17

Precision NS Masses
PSR J1614-2230 (P=3.15ms) (Demorest et al. 2010)

Shapiro Delay

12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   18

NS Masses

NS masses determined from Keplerian orbital elements + GR orbital effects (Shapiro delay, orbital decay)

Millisecond pulsars accrete ~ 0.1 $M_\odot$ more mass than NS-NS binaries that accrete for shorter times

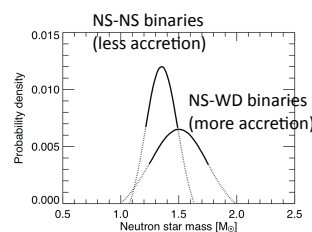NS-NS binaries (less accretion)

NS-WD binaries (more accretion)
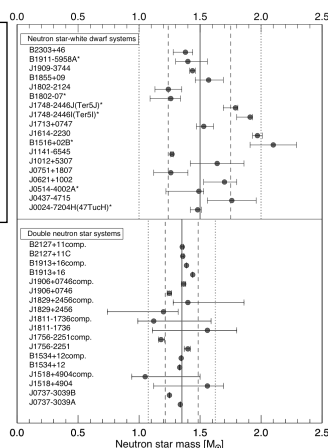
Figure 2. Posterior predictive density estimates for the neutron star mass distribution. DNS and NS-WD systems have respective peaks at 1.35 $M_\odot$ and 1.50 $M_\odot$. Probability densities are normalized to show the 95% posterior probability range. The solid parts of the curves show the central 68% probability range which correspond to 1.35 ± 0.13 $M_\odot$ and 1.50 ± 0.25 $M_\odot$ for the DNS and NS-WD system, respectively.
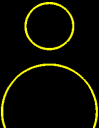
Kiziltan et al. 2010

Double Neutron Star Binaries

P_{orb}	e	
2.46 hr	0.09	J0737−3039A
3.98 hr	0.09	J1906+0746
7.67 hr	0.18	J1756−2251
7.75 hr	0.62	B1913+16
8.05 hr	0.68	B2127+11C
10.10 hr	0.27	B1534+12
28.22 hr	0.14	J1829+2456

Nine known NS-NS binaries

These objects will merge in ~ 100 Myr

Mergers produce:

- Gamma-ray bursts
- Chirped gravitational wave signature
- Particle blast waves

Mergers of Compact Objects

NS-NS binary

NS-BH binary

Merger rate of NS-NS binaries: R ~ $10^{-5 \pm 0.5}$ yr^{-1}

Based on 7 binaries discovered in last 34 years!

Shortest expected orbital period in Milky Way: ~ 5 to 10 min with a lifetime ~ 10^5 years

12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   21

Birth Rates and Population Numbers

$$N_{\text{detectable}} = f_b \times R \times T_{\text{radio}}$$

f_b = beaming fraction
R = birth rate
T_{radio} = radio emitting lifetime

$\sim 0.2 \times 10^{-2}\,\text{yr}^{-1} \times 10^7\,\text{yr}$	$= 2 \times 10^4$	canonical pulsars
$\sim 0.2 \times 10^{-4}\,\text{yr}^{-1} \times 10^9\,\text{yr}$	$= 2 \times 10^4$	MSPs
$\sim 0.2 \times 10^{-4.5 \pm 0.5}\,\text{yr}^{-1} \times 10^8\,\text{yr}$	$= 200 - 2000$	NS − NS binaries
$> 10\% \times \text{NS} - \text{NS binaries}$		NS − BH binaries

The SKA has high detection probabilities for most of these objects

⇒ "full Galactic census" of these NS sub- populations

12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21   22

Radio Emission from Pulsars

- Totally unexpected
- Radio emission is weak (for most pulsars) in terms of detectability
- But given the size of the neutron star and its magnetosphere, it is remarkable that we can detect them at all.
- Why can such small volumes produce detectable radiation?
- Answer: radio emission is <u>coherent</u> (from plasma bunching or plasma maser)
  - two-stream instability
  - langmuir collapse, solitons

N = number of particles
Intensity $\sim N^2$ coherent
$\sim N$ incoherent

Kinds of Astrophysical Radio Emission

Continuum:

incoherent
- Thermal emission from ionized gas (bremsstrahlung, free-free emission); blackbody radiation
- Synchrotron radiation (e⁻ spiraling in interstellar B)

coherent
- Solar bursts: swept-frequency, narrowband radiation
- Pulsar radiation
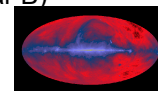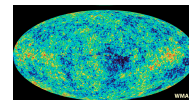
Spectral line:

incoherent
- Recombination lines (H, He, C)
- 21 cm hyperfine emission from H

coherent
- Molecular maser emission (OH, H_2O, methanol, SiO…)

Coherent Astrophysical Signals

- Most radiation produced by astrophysical sources is *temporally incoherent* and *partly spatially coherent*:
    - blackbody radiation from stars: temporally incoherent, but compact (partial coherence)
    - cosmic microwave background: temporally incoherent and spatially incoherent (isotropic)
    - masers (microwave amplification by stimulated emission of radiation): temporally incoherent, high spatial coherence
    - pulsars: very high spatial coherence, sometimes highly temporally coherent

Spatial Coherence

Coherent radiation has all of its sinusoidal components *in phase*

- Spatial coherence: two-slit diffraction pattern

The wavefronts have constant phase transverse to the slit mask
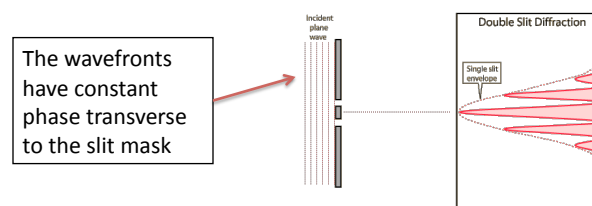
- Spatial coherence is required to see the pattern of constructive and destructive interference in the diffraction pattern
- Spatial coherence is connected to the source size and to how different components of a source radiate

Temporal Coherence

- <u>Temporal</u> coherence: describes the relationship of different Fourier components that make up a signal vs. time:

| Coherent: a delta function! | Incoherent: white noise |
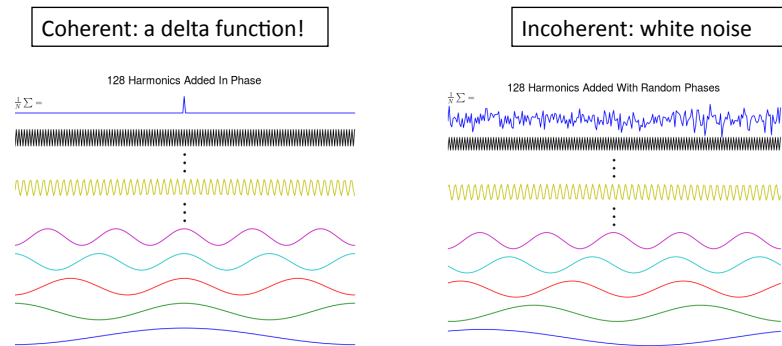
Radiation Temperatures

- The radiation temperature of <u>incoherent processes</u> is limited by the mean particle energy:

  - Thermal: $kT_b < kT_{\text{particles}}$
  - Non-thermal: $kT_b < \langle \gamma m c^2 \rangle$ $\gamma = \text{Lorentz factor}$

- Incoherent synchrotron radiation: T_b is limited by inverse Compton radiation (ICR) to ~ 10^{12} K because larger energies per particle cool rapidly from ICR.

- <u>Coherent processes</u>: the radiation temperature is essentially unbounded

Radiation Temperatures

Rayleigh Jeans regime for blackbody radiation:

$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{1-e^{-h\nu/kT}} \approx \frac{2kT}{\lambda^2}$$

Flux density:

$$F_\nu = \int d\Omega I_\nu(\Omega) \approx \Omega_s I_\nu(max)$$

Time variable source:

$$l_s \sim c\Delta t$$
$$\Omega_s \sim \left(\frac{c\Delta t}{D}\right)^2$$

$$\Rightarrow T_{\text{eff}} \sim \frac{\lambda^2 F_\nu}{2k}\left(\frac{D}{c\Delta t}\right)^2$$
$$\approx 3.5 \times 10^{17}\,\text{K}\, F_\nu(\text{Jy})\left(\frac{D_{\text{kpc}}}{\nu_{\text{GHz}}\Delta t_{\text{s}}}\right)^2$$

Unit of flux density: 1 Jansky = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1} = 10^{-26} watts m^{-2} Hz^{-1}

Nanoshots from the Crab Pulsar
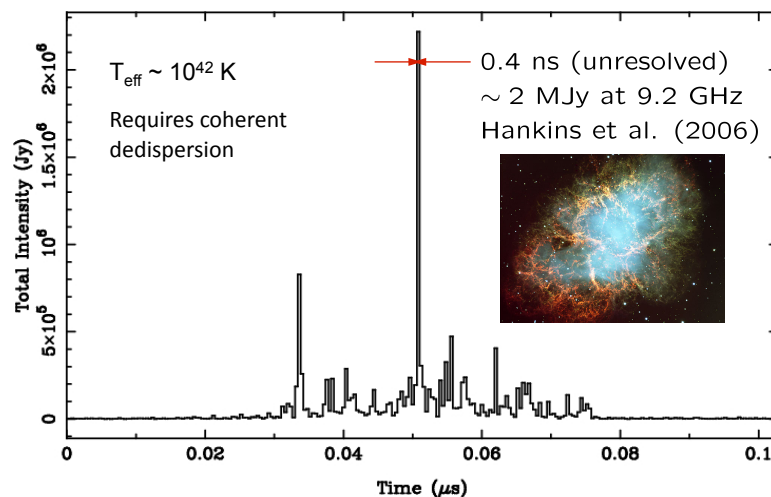
$T_{\text{eff}} \sim 10^{42}$ K

Requires coherent dedispersion

0.4 ns (unresolved)
$\sim$ 2 MJy at 9.2 GHz
Hankins et al. (2006)

How do we "measure" Brightness Temperatures from Pulsars?

- <u>We don't</u> because we cannot measure the angular size of an emission region (too small)
- We can <u>infer</u> their size as follows:
  - For a source of size 2R, the minimum duration of its emission is Δt=2R/c with c = speed of light.
  - We can estimate its angular size as θ_s = 2R/D where D = distance
- The brightness temperature is then

$$T_b = \frac{\lambda^2 S}{2k\Omega_s} \approx \frac{S}{2k}\left(\frac{D}{\nu\Delta t}\right)^2 \approx 10^{20.5}\,\mathrm{K} S_{\mathrm{mJy}}\left(\frac{D_{\mathrm{kpc}}}{\nu_{\mathrm{GHz}}\Delta t_{\mathrm{ms}}}\right)^2$$

12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   31

pulse is actually spread out over time (ms-sec) by interstellar dispersion
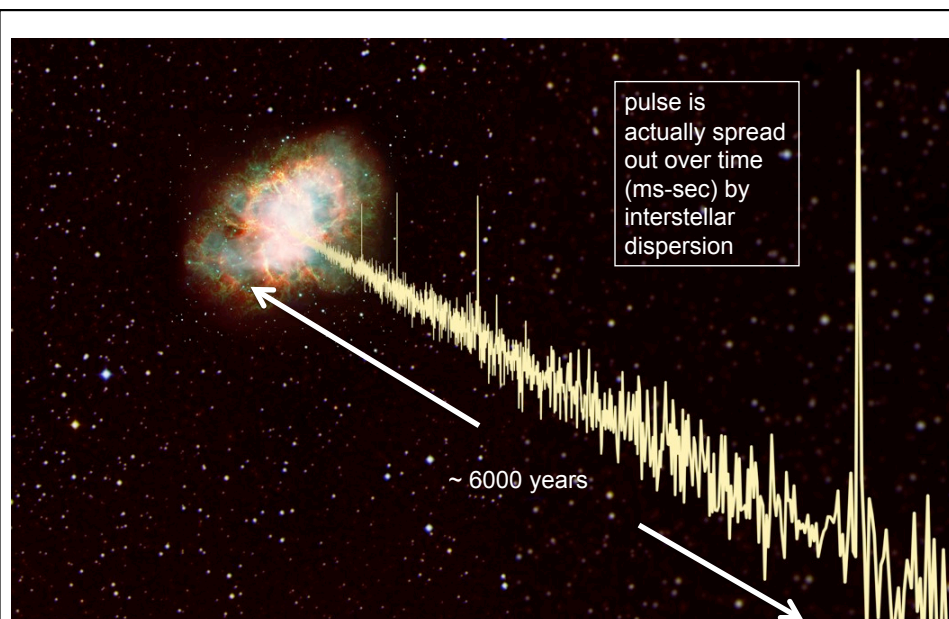
~ 6000 years

Image courtesy of NRAO/AUI and Joeri van Leeuwen (UC Berkeley) / ESO / AURA

12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   32

Plasma Propagation Effects

- Radio propagation phenomena (many)
- Dedispersion methods
- Kolmogorov-like microstructure in the ionized ISM
- Astronomical impacts:
  - Pulsar surveys
  - Precision pulsar timing to detect gravitational waves
  - Pulsars orbiting Sgr A* (GR tests, dark matter)
  - Scattering in the intergalactic medium

10 Dec 2010   NYU   33

Starting Point: Index of Refraction

- Dispersion relation in free space:
  - ω = kc
  - phase velocity = group velocity = ω/k = c
- Cold plasma (collisions not important):
  - No magnetic field:
    $$\omega = kc/n_r(\omega) \qquad n_r(\omega) = \left(1 - \omega_p^2/\omega^2\right)^{1/2}$$
    $$\omega_p^2 = \text{plasma frequency} = \frac{4\pi n_e e^2}{m}$$
    - phase velocity = $c/n_r(\omega) > c$ (speed of phase fronts)
    - group velocity = dω/dk = $cn_r(\omega) < c$ (speed of a wave packet)
  - With magnetic field: birefringent (left, right)

  $$n_{l,r} \approx 1 - \omega_p^2/2\omega^2 \mp \omega_p^2 \omega_{B_\parallel}/2\omega^3$$

  - cyclotron frequency $\omega_{B_\parallel} = \frac{eB\cos\theta}{m_e c}$

9/13/11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   34

Propagation through the interstellar plasma

Refractive indices for cold, magnetized plasma

$$n_{\ell,r} \sim 1 - \nu_p^2/2\nu^2 \mp \nu_p^2\nu_{B_\parallel}/2\nu^3$$
$$\nu \gg \nu_p \sim 2\,\text{kHz} \qquad \nu \gg \nu_{B_\parallel} \sim 3\,\text{Hz}$$

Propagation velocities are frequency dependent:
Phase velocity: $v_p = \frac{\omega}{k} = \frac{c}{n_{\ell,r}}$

birefringence

Group velocity: $v_g = \frac{\partial\omega}{\partial k} = \frac{\partial}{\partial k}\left(\frac{kc}{n_{\ell,r}}\right)$

Group delay $= \Delta$(Time of Arrival)

$$
\begin{aligned}
t &= t_{\text{DM}} \pm t_{\text{RM}} \\
t_{\text{DM}} &= 4.15\,\text{ms}\,\text{DM}\,\nu^{-2} \\
t_{\text{RM}} &= 0.18\,\text{ns}\,\text{RM}\,\nu^{-3}
\end{aligned}
$$

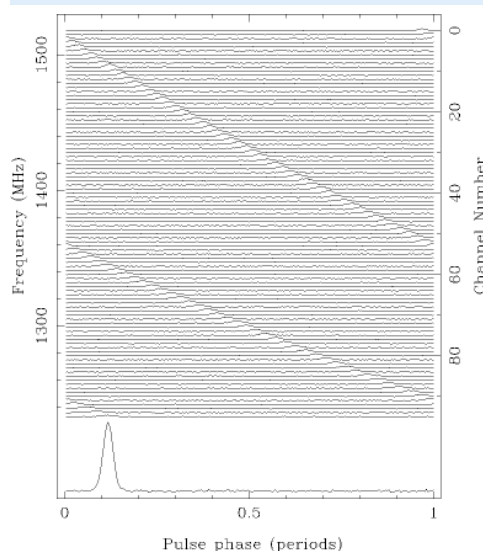Dispersion Measure DM $= \int ds\, n_e$ units: pc cm^{-3}
Rotation Measure RM $= 0.81 \int ds\, n_e B_\parallel$ units: rad m^{-2}

Dispersion

$$t_{\text{DM}}(\nu) = \frac{4.15 \times \text{DM}\ \text{ms}}{\nu_{\text{GHz}}^2}$$

High frequencies arrive earlier than low frequencies

DM is unique to each pulsar

DM changes with time due to motion of the pulsar and turbulence in the interstellar medium

Dedispersion
Two methods:

Coherent:

- operates on the voltage proportional to the electric field accepted by the antenna, feed and receiver
- computationally intensive because it requires sampling at the rate of the total bandwidth
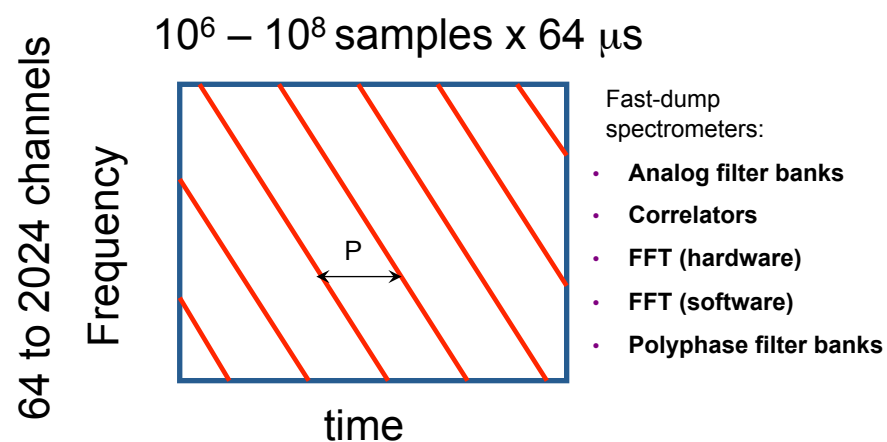- "exact"

Post-detection:

- operates on intensity = $|voltage|^2$
- computationally less demanding
- an approximation

9 June 2011   IPTA Morgantown   37

Basic data unit = a dynamic spectrum

$10^6 - 10^8$ samples x 64 μs

64 to 2024 channels

Frequency

P

time

Fast-dump spectrometers:

- **Analog filter banks**
- **Correlators**
- **FFT (hardware)**
- **FFT (software)**
- **Polyphase filter banks**

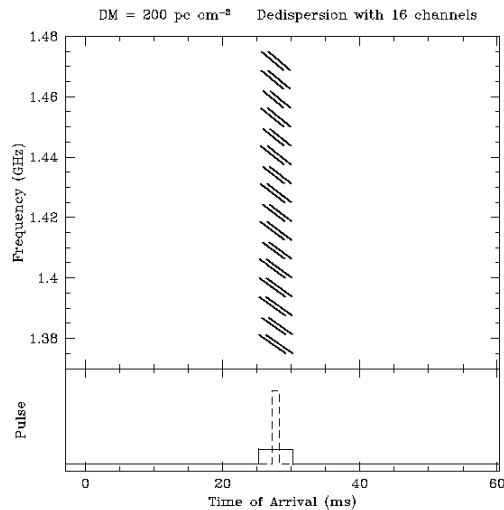9 June 2011   IPTA Morgantown   38

Post-detection Dedispersion:
Sum intensity over frequency after correcting for dispersion delay

DM = 200 pc cm⁻³   Dedispersion with 16 channels

Residual time smearing:

$$\Delta t = \left[\Delta t_{DM}^2 + (1/\Delta\nu)^2\right]^{1/2}$$
$$= \left[(a\Delta\nu)^2 + (\Delta\nu)^{-2}\right]^{-1/2}$$
$$\implies \text{minimum smearing time across a channel when}$$
$$\Delta\nu = \left[8.3\ \mu s\,DM\nu^{-3}\right]^{-1/2}$$

A consequence of the uncertainty principle for Fourier transforms:
Δ𝜈Δt ~ 1

9 June 2011   IPTA Morgantown   39

Dispersed Pulse   **Coherently dedispersed pulse**

DM = 200 pc cm⁻³   No Dedispersion

DM = 200 pc cm⁻³   Coherent Dedispersion

Δt = 8.3 µs DM ν⁻³ Δν
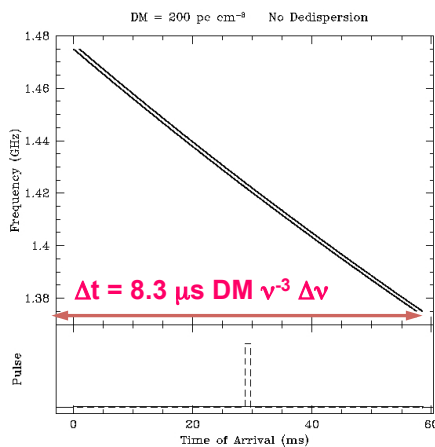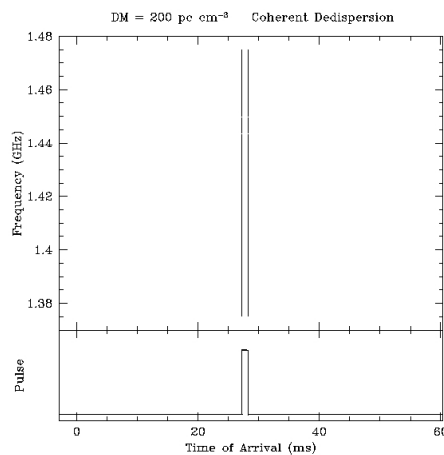
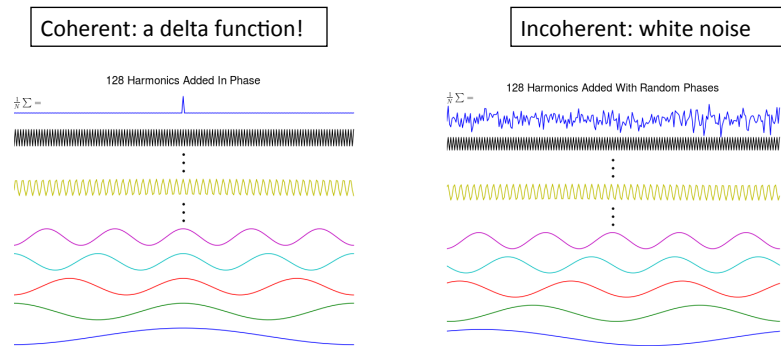9 June 2011   IPTA Morgantown   40

Temporal Coherence

- <u>Temporal</u> coherence: describes the relationship of different Fourier components that make up a signal vs. time:

Coherent: a delta function!	Incoherent: white noise

128 Harmonics Added In Phase

$\frac{1}{N}\Sigma =$

128 Harmonics Added With Random Phases

$\frac{1}{N}\Sigma =$

12 Sep '11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   41

Coherent Dedispersion
pioneered by Tim Hankins (1971)

Dispersion delays in the time domain represent a phase perturbation of the electric field in the Fourier domain:

$$\vec{E}_{measured}(\omega) = \vec{E}_{emitted}(\omega)e^{ik(\omega)z}$$

Coherent dedispersion involves multiplication of Fourier amplitudes by the inverse function,

$$e^{-ik(\omega)z}$$

An example of matched filtering

For the non-uniform ISM, we have

$$k(\omega)z \rightarrow \int dz\, k(\omega) \propto \omega^2 DM + constant$$

which is known to high precision for known pulsars.

One parameter: DM

The algorithm consists of

$$IFFT\{FFT\,[E_{measured}(t)]\times e^{-ik(\omega)z}\} \approx E_{emitted}(t)$$
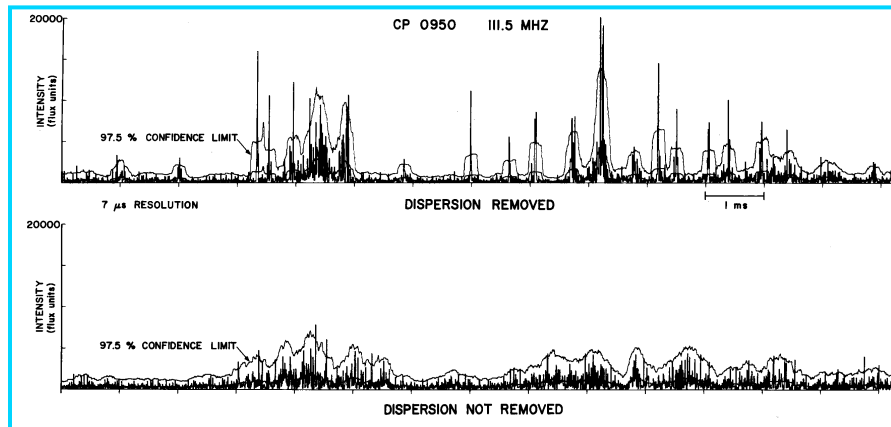
Application requires very fast sampling to achieve usable bandwidths.

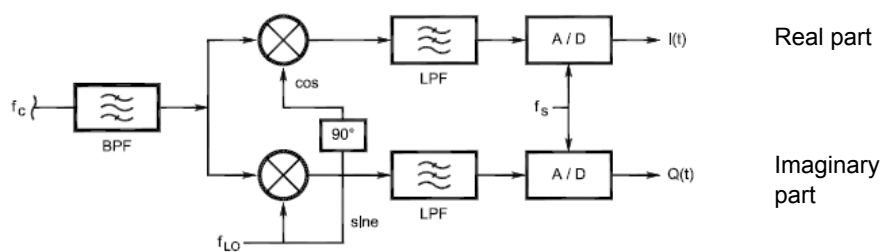10 July 2007   Single Dish Summer School 2007

Micropulses coherently dedispersed
(Hankins1971)

10 July 2007   Single Dish Summer School 2007

Backend stage of mixing: quadrature baseband mixing

Real part

Imaginary part

$\epsilon(t) = I(t) + iQ(t) = $ complex baseband signal

voltage at intermediate frequency in heterodyned system:
$v(t) = \mathcal{R}e\left\{\epsilon(t)e^{2\pi i f_0 t}\right\} = $ real

9/16/09   A6520   44

Coherent Dedispersion
pioneered by Tim Hankins (1971)

Coherent dedispersion works by explicit deconvolution:

$$E_{measured}(t) = E_{emitted}(t) * FFT\{e^{ik(\omega)z}\}$$
$$\Rightarrow E_{emitted}(t) \approx E_{measured}(t) * FFT\{e^{-ik(\omega)z}\}$$

Comments and Caveats:

• Software implementation with FFTs to accomplish deconvolution (Hankins 1971)

• Hardware implementations: real-time FIR filters (e.g. Backer et al. 1990s-present)

• Resulting time resolution: 1 / (total bandwidth)

• Requires sampling at Nyquist rate of 2 samples × bandwidth

  ⇒ Computationally demanding

• Actual time resolution often determined by <u>interstellar scattering</u> (multipath)

• **Most useful for low-DM pulsars and/or high-frequency observations**

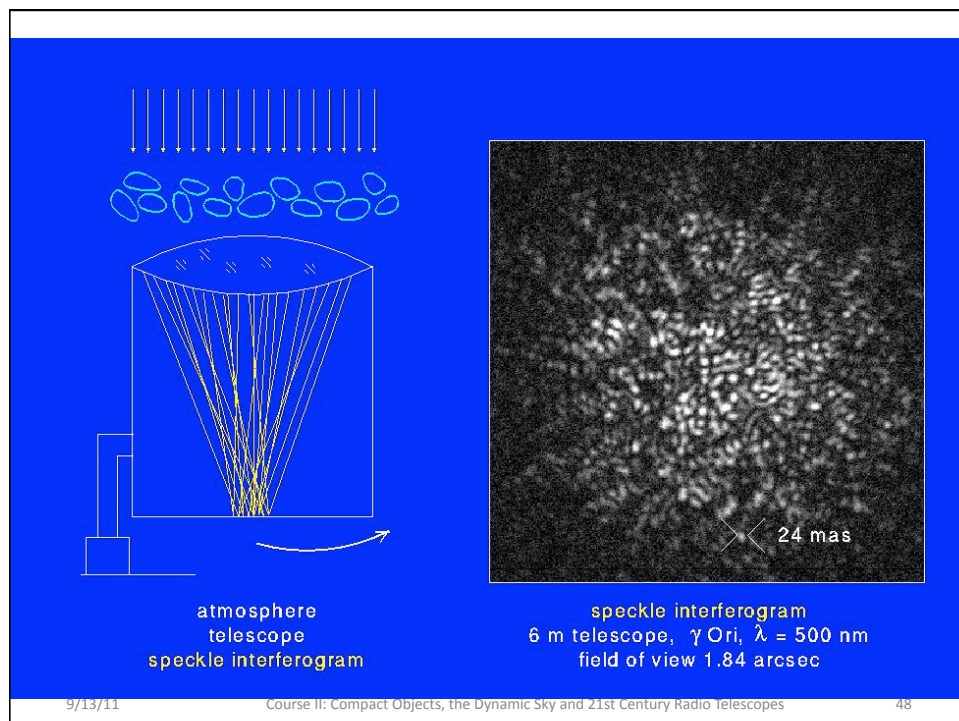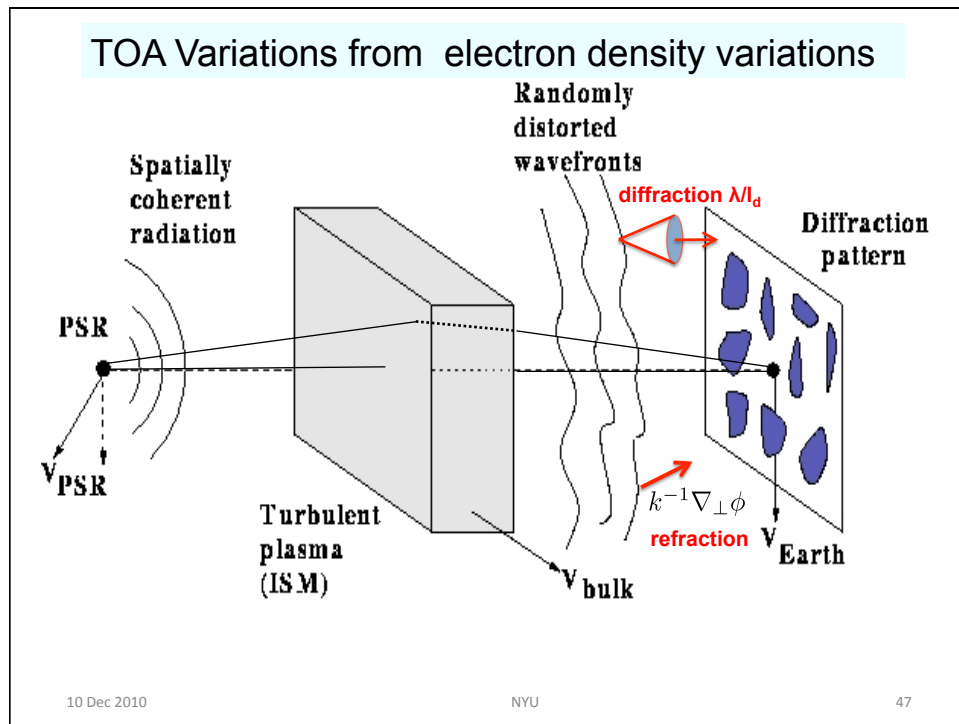10 July 2007   Single Dish Summer School 2007

Interstellar Radio Scattering

- Discovered as angular broadening ("seeing") of interstellar OH masers (1.6 GHz) (1967)
- Also discovered as scintillations ("twinkling") of pulsar intensities (1968)
- Both are diffraction effects:
  - Angular: $\theta_d \approx \lambda / l \approx 1$ mas for $l \approx 10^4$ km
  - Temporal broadening: $\tau_d \sim D\theta_d^2 / 2c \sim 1$ ms for $D = 1$ kpc
  - Correlation bandwidth for scintillations $\sim 1 / \tau_d$
- Why pulsars are especially useful:
  - Require source size $\leq \lambda / D\theta_d \sim 1$ μas to see twinkling (the "stars twinkle, planets do not" effect)
  - Much smaller than an active galactic nucleus
  - Pulsar magnetosphere: $\theta \sim cP/2\pi D \sim 0.1$μas
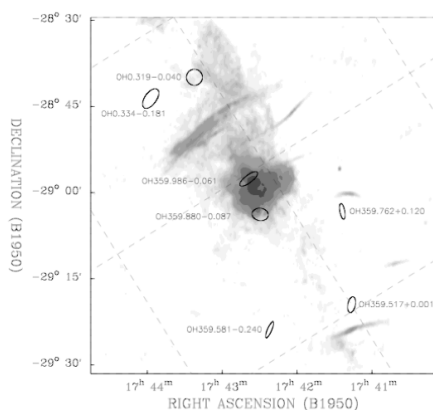 - Pulsars emit coherent radio emission (AGNs: incoherent)
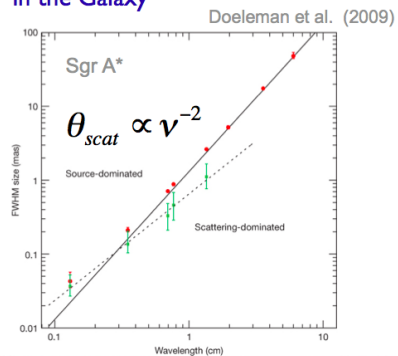
10 Dec 2010   NYU   46

TOA Variations from electron density variations

Randomly distorted wavefronts

Spatially coherent radiation

diffraction λ/l_d

Diffraction pattern

PSR

V_{PSR}

Turbulent plasma (ISM)

$k^{-1}\nabla_\perp \phi$

refraction

V_{Earth}

V_{bulk}

10 Dec 2010   NYU   47

24 mas

atmosphere
telescope
speckle interferogram

speckle interferogram
6 m telescope, γ Ori, λ = 500 nm
field of view 1.84 arcsec

Scattering of Sgr A* and GC Pulsars

- Temporal and angular broadening by turbulent ionized gas
- The most scattered line of sight in the Galaxy

Doeleman et al. (2009)

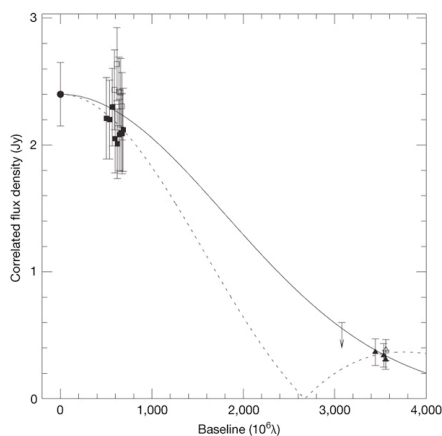Sgr A*

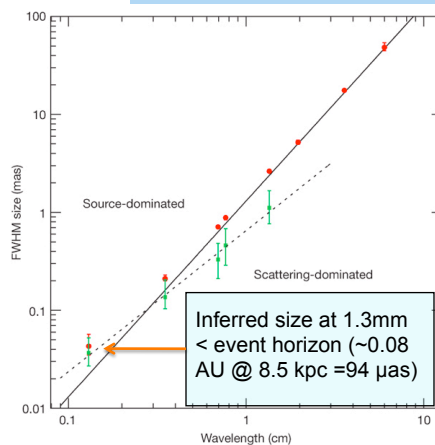$$\theta_{scat} \propto \nu^{-2}$$

Frail et al. (1994)

10 Dec 2010   NYU   49

Size of Sgr A* (4 x 10^6 M$_\odot$)
Doeleman et al. 2008

Visibility Function at 1.3mm

Angular size vs λ

Source-dominated

Scattering-dominated

Inferred size at 1.3mm < event horizon (~0.08 AU @ 8.5 kpc =94 µas)

9/13/11   Course II: Compact Objects, the Dynamic Sky and 21st Century Radio Telescopes   50
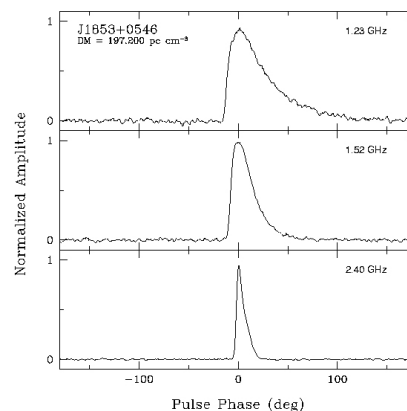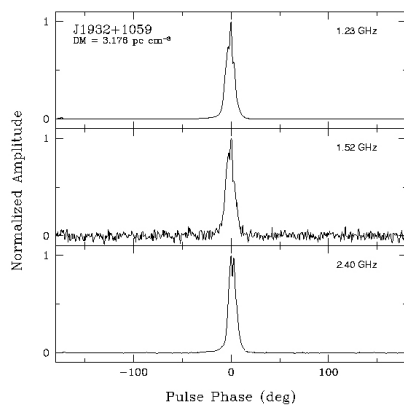
Pulse broadening from interstellar scattering:

$$\tau_{\mathsf{d}} \sim \frac{\text{rms excess path length}}{c} \sim \frac{D\theta_d^2}{2c} \propto \nu^{-4}$$

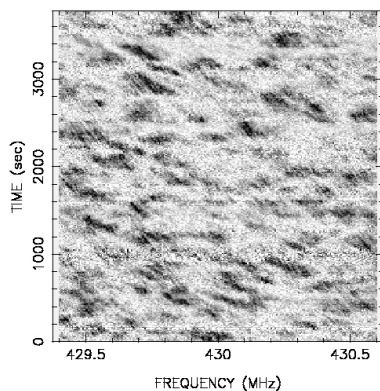Low-DM pulsar: $\tau_d \ll$ pulse width   High-DM pulsar: $\tau_d \sim$ pulse width

Arecibo WAPP data, Bhat et al 2004

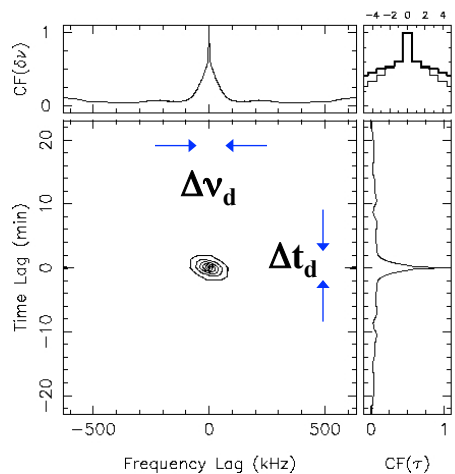10 July 2007   Single Dish Summer School 2007

Dynamic Spectrum
Diffractive Interstellar Scintillations

2D Autocorrelation Function
⇒ **Characteristic DISS frequency and time scales**

$\Delta\nu_d$

Δt_d

10 Dec 2010   NYU   52

Turbulence in Ionized ISM

- Extends to scales ~100-1000 km
- Similar to Kolmogorov turbulence in a neutral, incompressible fluid
  - ISM is ionized
  - ISM is compressible
  - no worries: the electron density is a "passive tracer" of the true turbulence in the velocity field and magnetic field in the ISM
  - the turbulence appears to be anisotropic: small scale fluctuations are oriented relative to the interstellar magnetic field
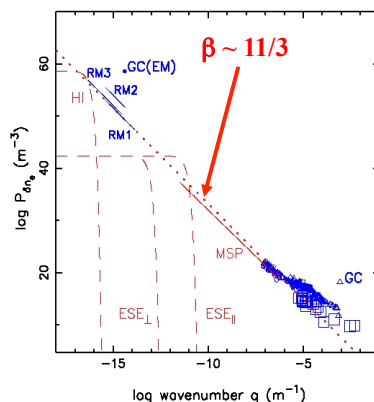
10 Dec 2010   NYU   53

Estimated Wavenumber Spectrum for δn_e

$$\text{Spectrum} = C_n^2 q^{-\beta}$$
$$\langle n_e^2 \rangle = \int d^3 q \, C_n^2 q^{-\beta}$$
$$\text{SM} = \int_{\text{LOS}} ds \, C_n^2(s)$$

$\beta \sim 11/3$

Constraints on spectrum:

Small scales: (100s km to 1000 AU)
  - Scaling of DISS parameters with ν
    - angle, frequency, time
  - Scintillation arcs
  - DM(t) on months to years
  - DM(θ) in globular clusters
  - RISS parameters

Large scales: (0.01 pc to 100 pc)
  - RM vs $\delta\theta$
  - EM, DM, SM on same LOS
  - Bow shock contours (Guitar Neb)

All scales:
  - Cosmic ray scattering on δB and linkage $\delta n_e/n_e \sim \delta B/B$

Anisotropies seen on heavily scattered LOS: connection to B

see also Armstrong, Rickett, Spangler 1995

10 Dec 2010   NYU   54