Pulsar Timing and its Future Perspective

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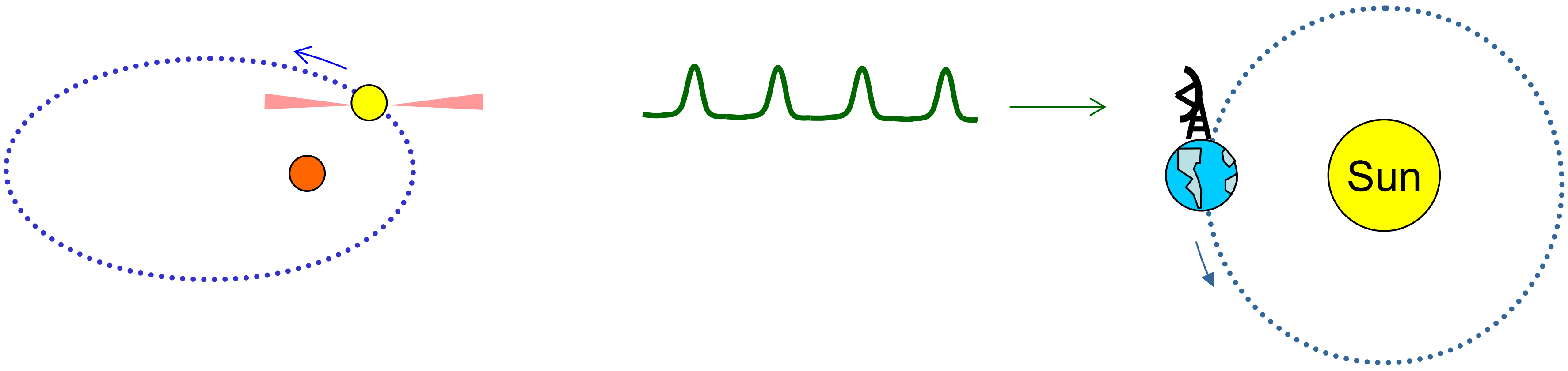
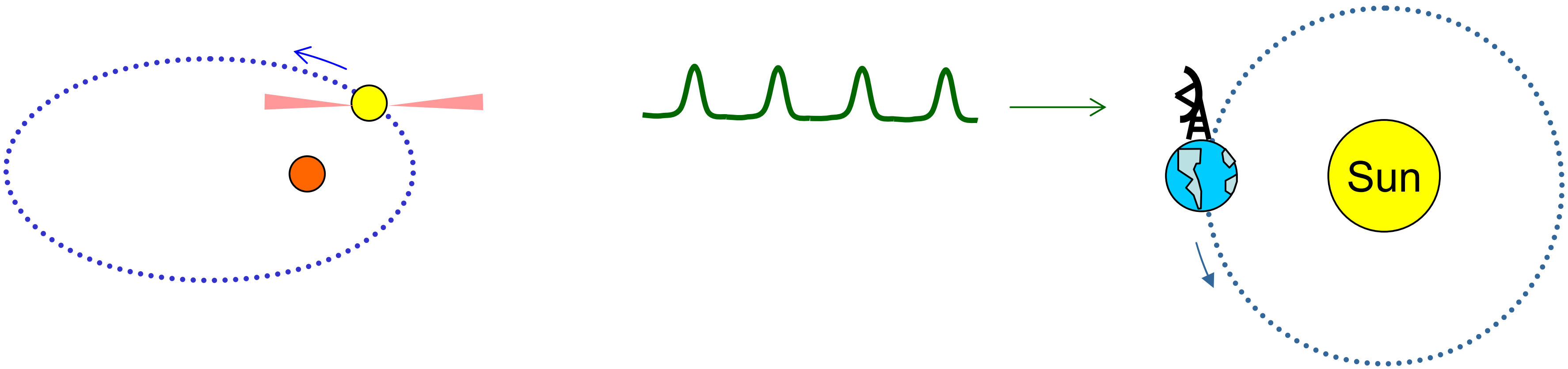
IAU XXVIth General Assembly, Prague
23 August 2006

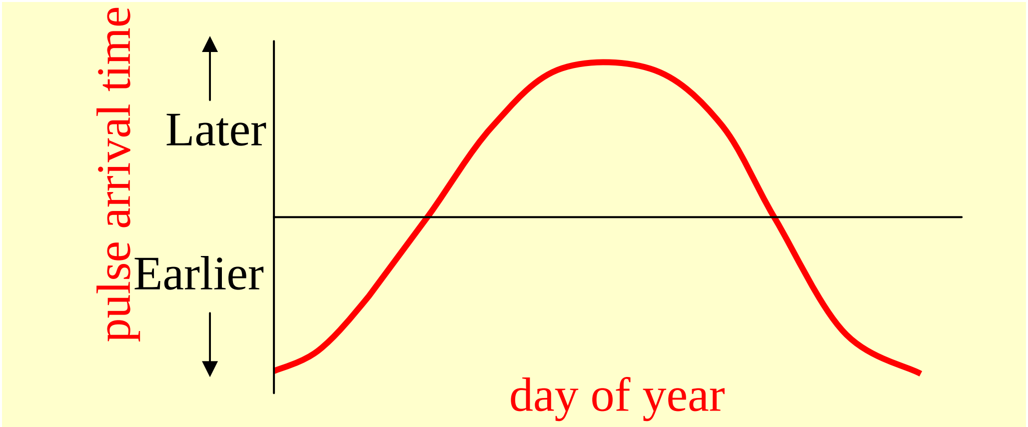
I. Motivation

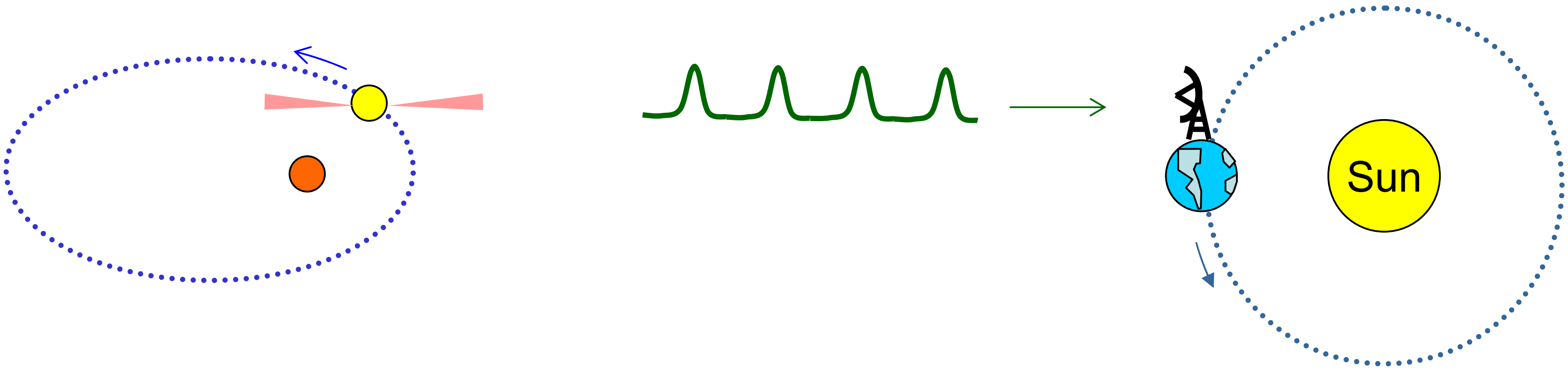
II. How has progress been made in pulsar timing?

III. Long-term observations of recycled pulsars: some time series


Sun


Sun


pulse arrival time
Later
Earlier
day of year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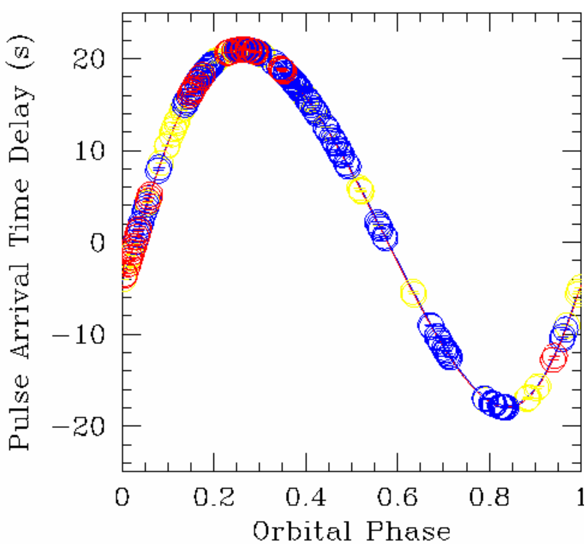
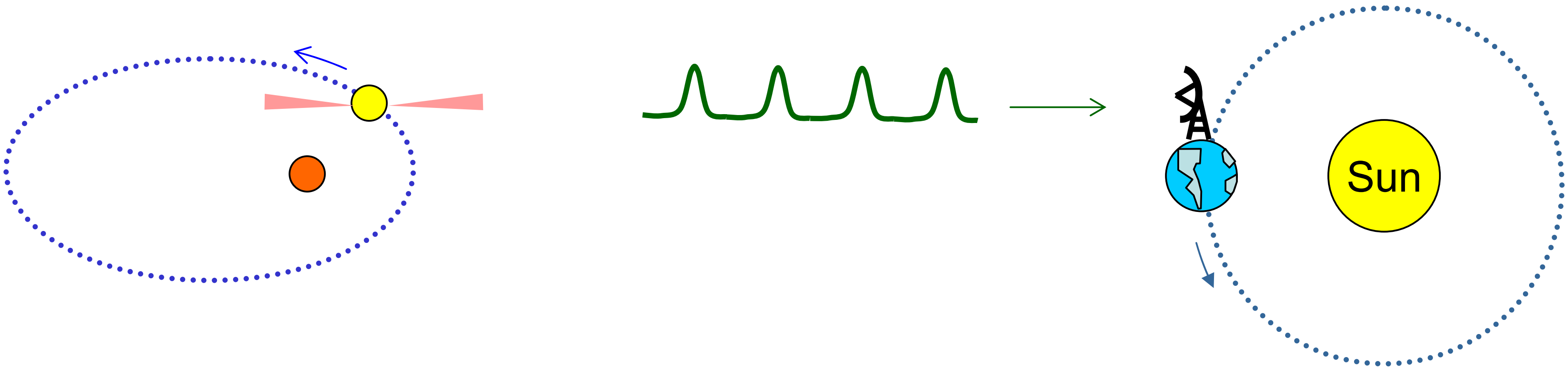
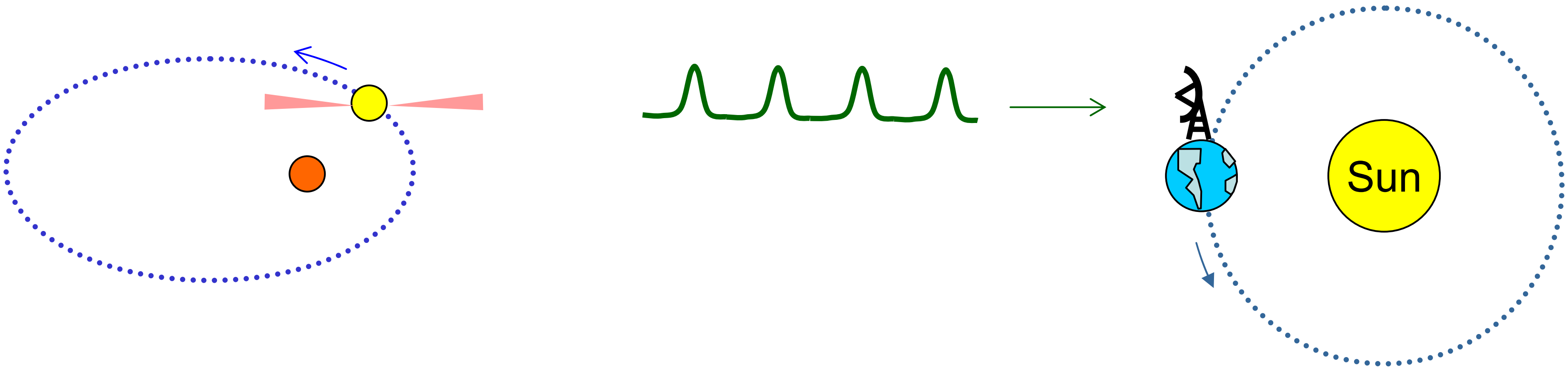
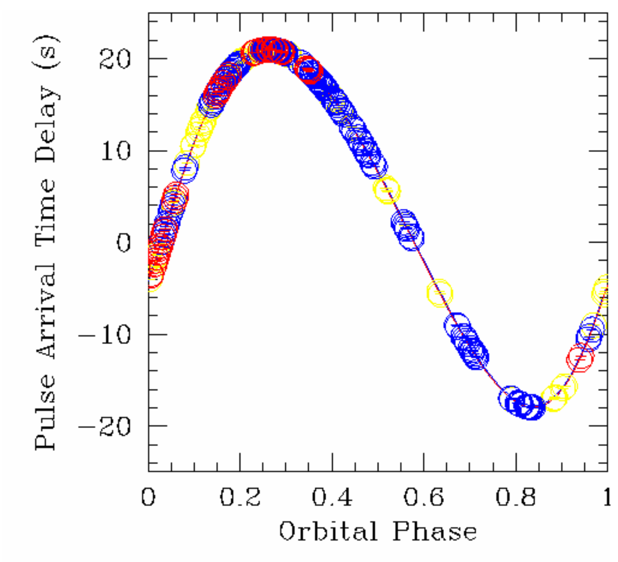

Pulse Arrival Time Delay (s)
20
10
0
−10
−20
0
0.2
0.4
0.6
0.8
1
Orbital Phase

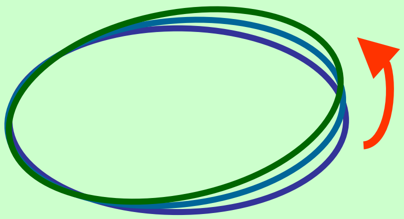
Gravitational Wave Background




Sun

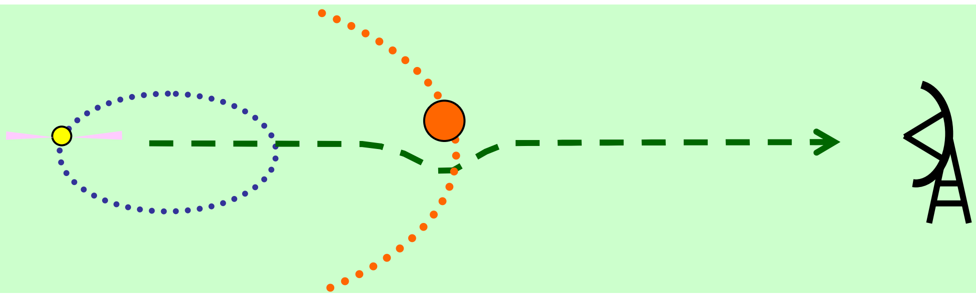

Pulse Arrival Time Delay (s)
20
10
0
−10
−20
0
0.2
0.4
0.6
0.8
1
Orbital Phase

Precession



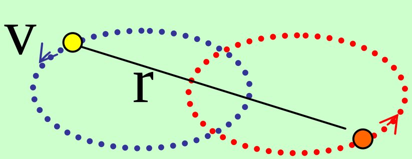
$$\dot{\omega} = 3\frac{G^{2/3}}{c^2}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}\left[(m_1+m_2)\right]^{2/3}$$

Shapiro Delay



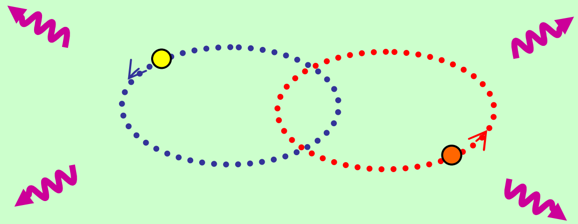
$$\Delta t = 2\frac{G}{c^3}m_2 \ln\left[1-\sin i\,\sin(\varphi-\varphi_0)\right]$$

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



$$\dot{P}_b = -\left(\frac{192\pi}{5}\right)\frac{G^{5/3}}{c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\frac{1}{(1-e^2)^{7/2}}\frac{m_1m_2}{(m_1+m_2)^{1/3}}$$

Masses of Neutron Stars in Neutron Star-Neutron Star Binaries

Pulsar	Recycled Pulsar	Companion Star
PSR B1913+16	1.4408±0.0003	1.3873±0.0003
PSR B2127+11C	1.349 ±0.040	1.363 ±0.040
PSR B1534+12	1.3332±0.0010	1.3452±0.0010
PSR J0737–3039	1.337 ±0.005	1.250 ±0.005
PSR J1756–2251	1.40 ±0.03	1.18 ±0.03
PSR J1518+4904	average mass=1.352±0.003	
PSR J1811–1376	average mass=1.300±0.450	
PSR J1829+2456	average mass=1.250±0.010	
PSR J1906+0746*	1.31 ±0.05	1.31 ±0.05

*Preliminary

Masses of Neutron Stars in Neutron Star-White Dwarf Binaries

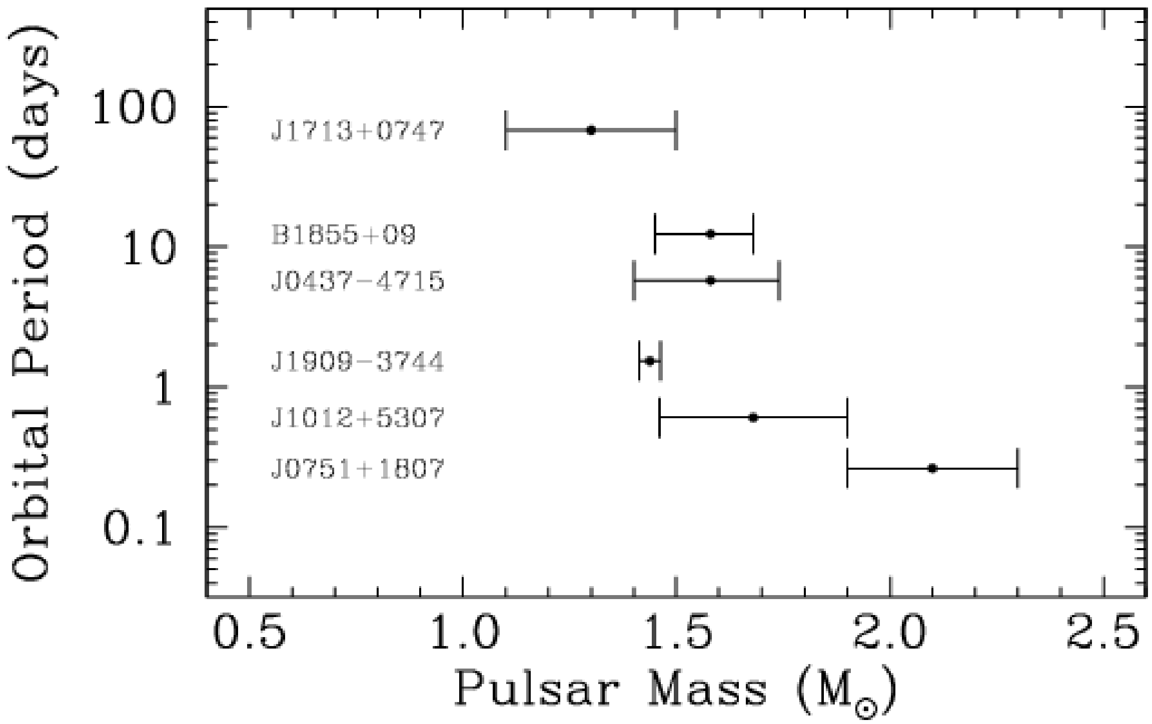
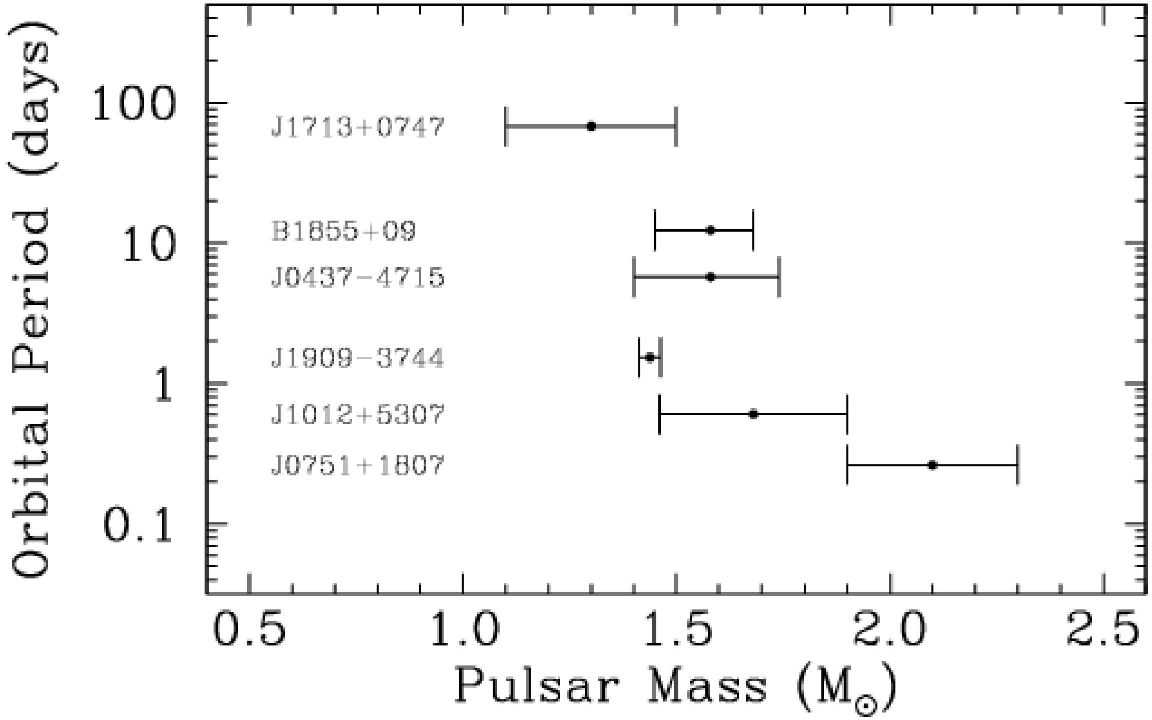


Figure: astro-ph/0508050

Masses of Neutron Stars in Neutron Star-White Dwarf Binaries



The precision of the mass values is directly proportional to the precision with which arrival times are measured.

Better timing ⇒ Better science

Three of these (J1713+0747, J0437-4715, J1909-3744) are among the very best timed pulsars, around 100-200 ns precision

Improving on this is a challenge!

Figure: astro-ph/0508050

How has progress been made in pulsar timing?

Advances in telescopes themselves:

Bigger is better

(more telescope time is better, too!)

Advances in telescope receivers:

Less noise, more bandwidth

Advances in data acquisition systems:

Wider bandwidths

Coherent dedispersion

Move to higher radio frequencies

Get all the details right

Polarization Calibration, RFI Excision

All filters, clocks, etc. (100 nsec ~ 20 m of cable!)

Discover more pulsars

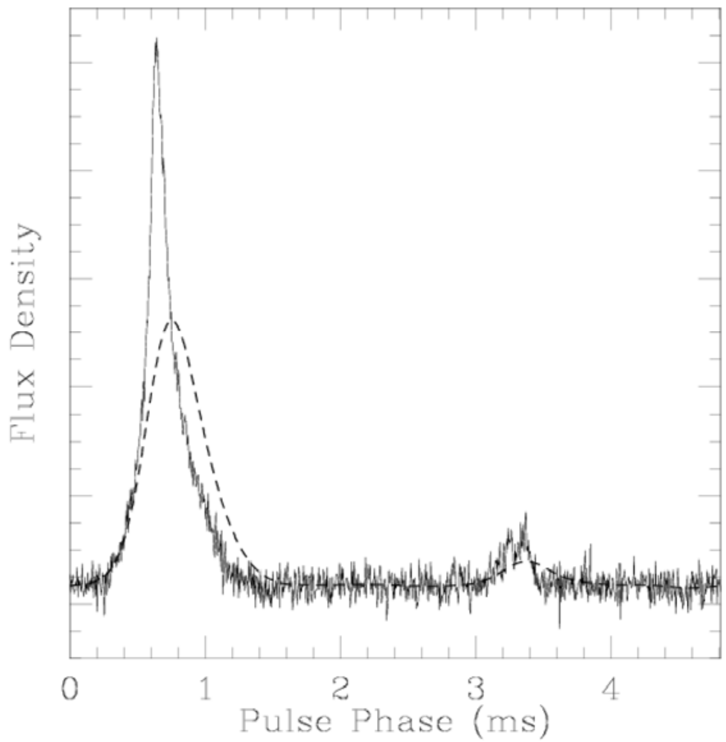
Progress in PSR B1913+16 Timing Precision

Observing System	Years Used	Radio Frequency (MHz)	Bandwidth (MHz)	System Temperature (K)	TOA Uncertainty (μs)
A	1974	430	8.0	175	275
B	1975-6	430	3.2	175	310
C	1975-6	430	2.5	175	890
D	1976	430	0.6	175	155
E	1976-7	430	0.6	175	150
F	1978-81	430	3.3	175	75
G	1977	430	8.0	175	75
H	1977	1410	8.0	80	55
I	1978	1410	8.0	80	50
J	1980-1	1410	8.0	80	85
Mark I	1981-4	1410	16.0	80,40	20
Mark II	1984-8	1410	8.0	40	31
Mark III	1988-2003	1408	40.0	40	16
WAPP	2003-6	1404	4×100.0	40	$13/\sqrt{4}$

Wider Bandwidths
and Lower System Temperatures
have lead to better timing precision

All data except WAPP parameters from Taylor & Weisberg 1989, ApJ 345:434

Better Data Acquisition Systems: Coherent Dedispersion



Completely removew dispersive smearing of the pulse by the ISM.

Narrower pulse ⇒ Better timing

Software-based coherent dedispersion systems are now in routine use. They are rapidly growing in bandwidth but are not (yet) able to cover the full bandwidths available at higher frequencies.

Just a question of cpu power.

Use Higher Radio Frequencies

PSR B1937+21 at 430 MHz

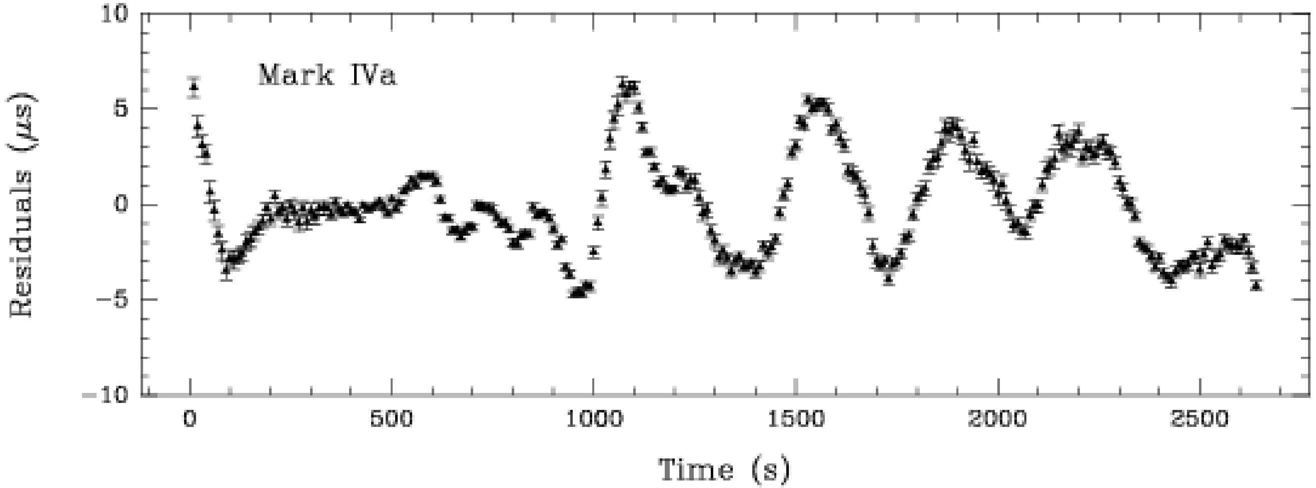


Figure:
Jay Shrauner
PhD Thesis

Variable scattering in the ISM causes wander in pulse arrival times; signficant for relatively distant pulsars.

Scattering ~ (radio frequency)$^{-4}$

Higher frequency ⇒ Better timing

1937+21 shows variability of ~100 ns at 1410 MHz
(much better than at 430 MHz, pictured above)

Use Higher Radio Frequencies

Higher frequency $\Rightarrow$ Better timing

But: pulsars are famously steep spectrum objects.
Can there be hope of observing them at high frequencies?

Yes, sometimes:

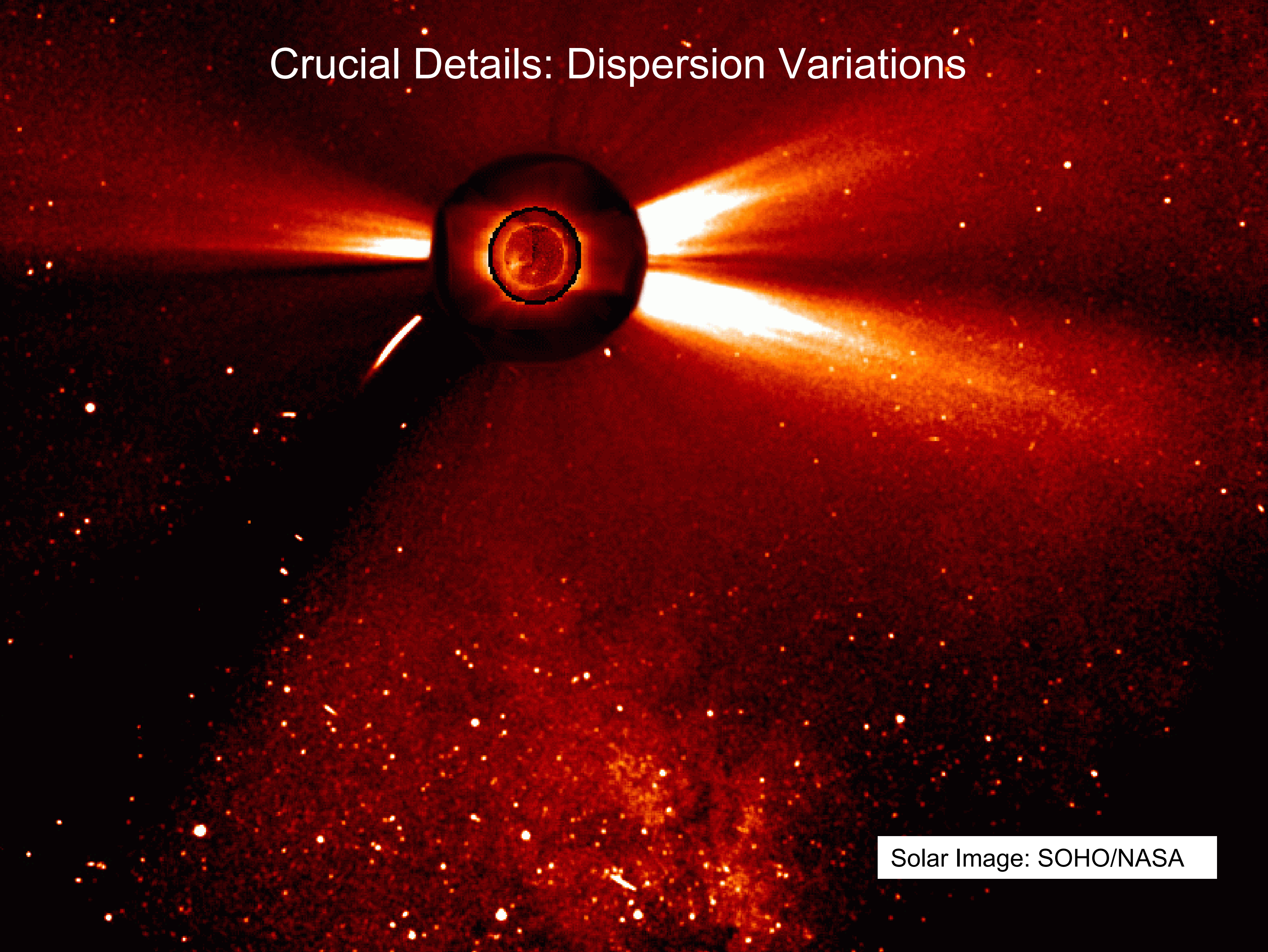
Recent surveys have been done at the “high” frequency of 1400 MHz, and some relatively shallow spectrum pulsars have been found.

Relatively large bandwidths at high frequencies partially compensate for fall-off in flux.

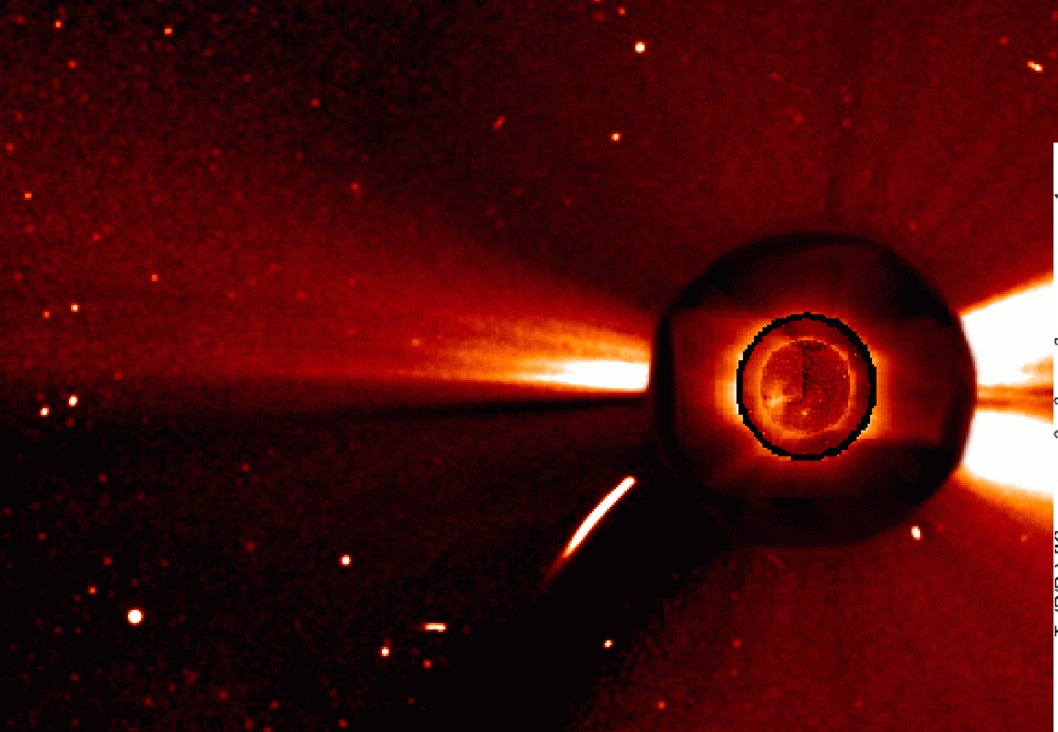
<u>Advertisement</u>

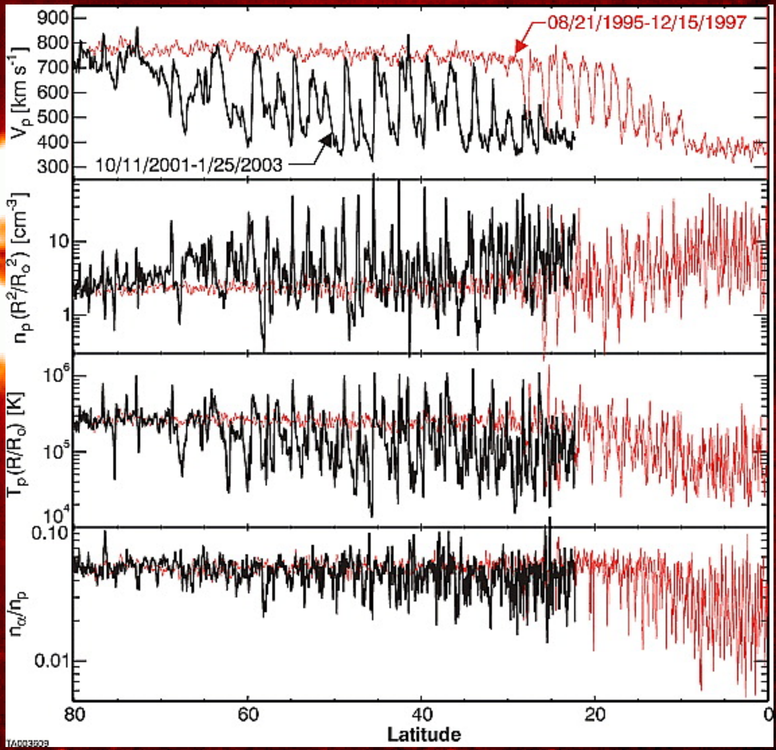
Arecibo “S-high” receiver: 3-4 GHz
- clean band
- low system temperature (25 K vs 40 K for “S-low” 2-3 GHz receiver)
- 800 MHz WAPP single-pixel capability available early ‘07

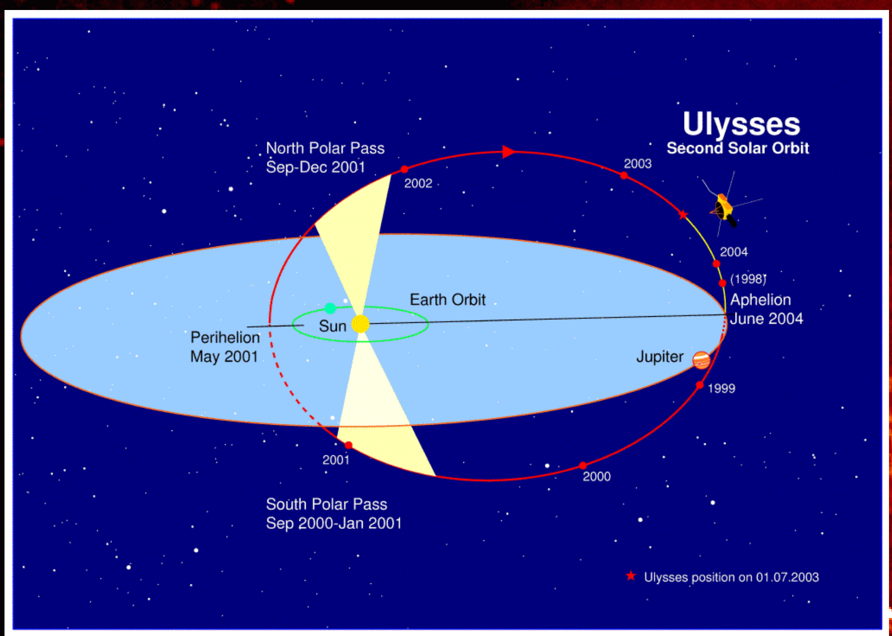
Crucial Details: Dispersion Variations



Solar Image: SOHO/NASA



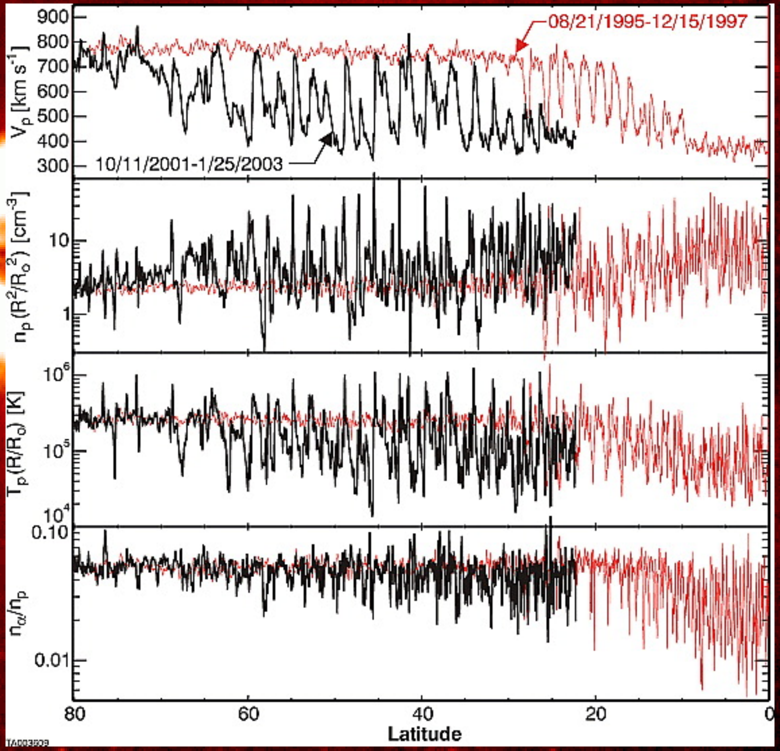




Twelve-Hour running average solar wind proton speed, density, temperature, and alpha-to-proton ratio over the equivalent portions of two orbits of Ulysses. From McComsas et al. 2003, Geophysical Research Leteers, 30: 1517.

Solar Image: SOHO/NASA
Ulysses Orbit Figure: ESA

Variations in dispersion on small scales are *inevitable* due to the solar wind. Multi-frequency observations at each epoch are *crucial* to removing imprint of these variations from the data.



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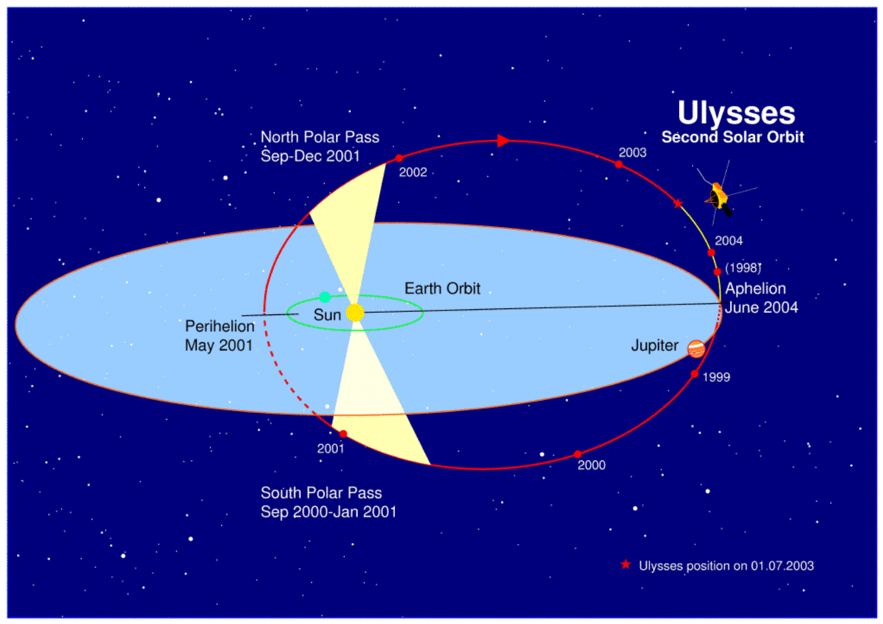


Solar Image: SOHO/NASA
Ulysses Orbit Figure: ESA

Crucial Details: Polarization Calibration

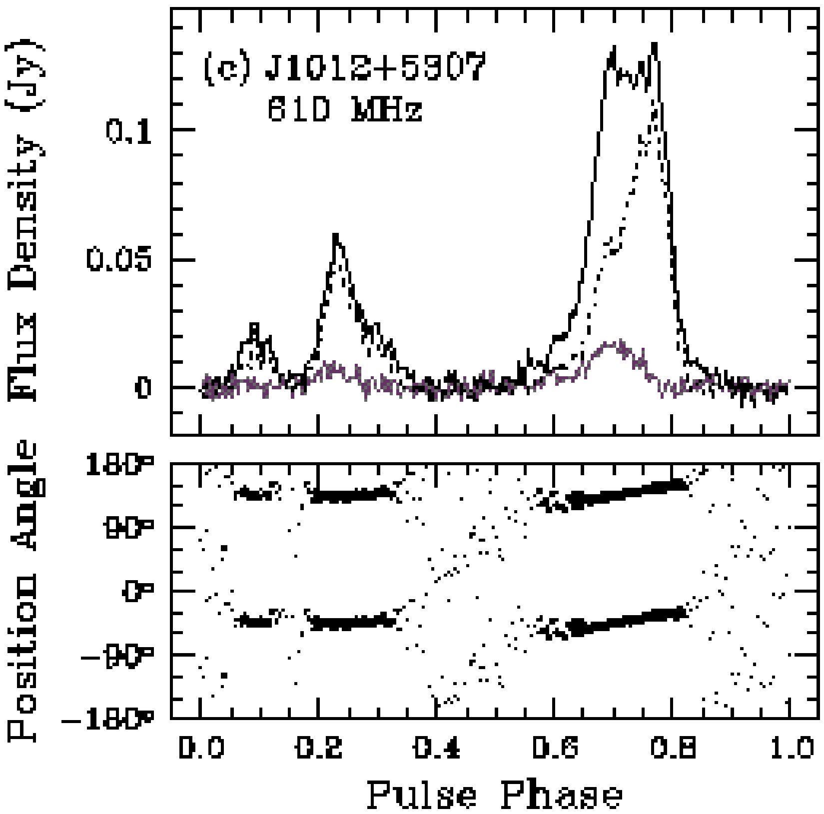
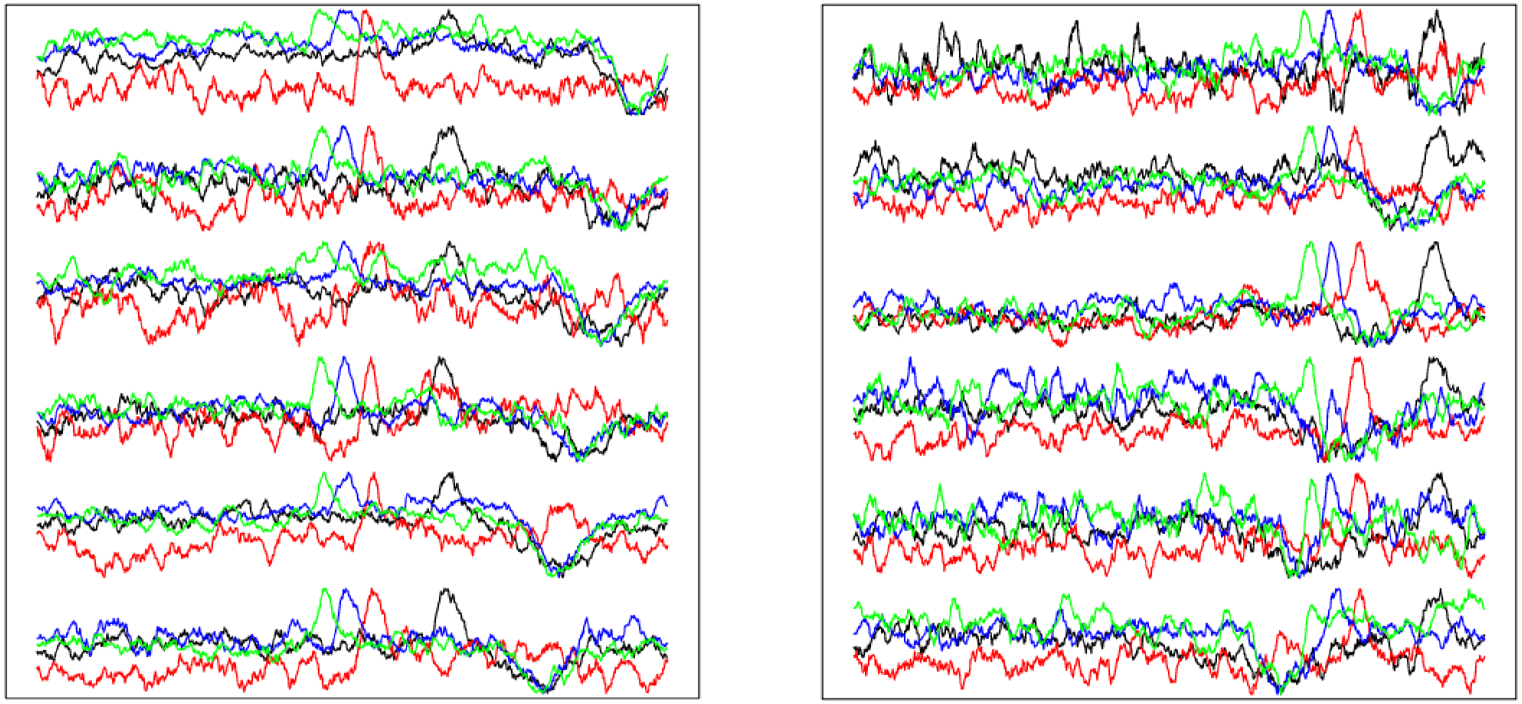


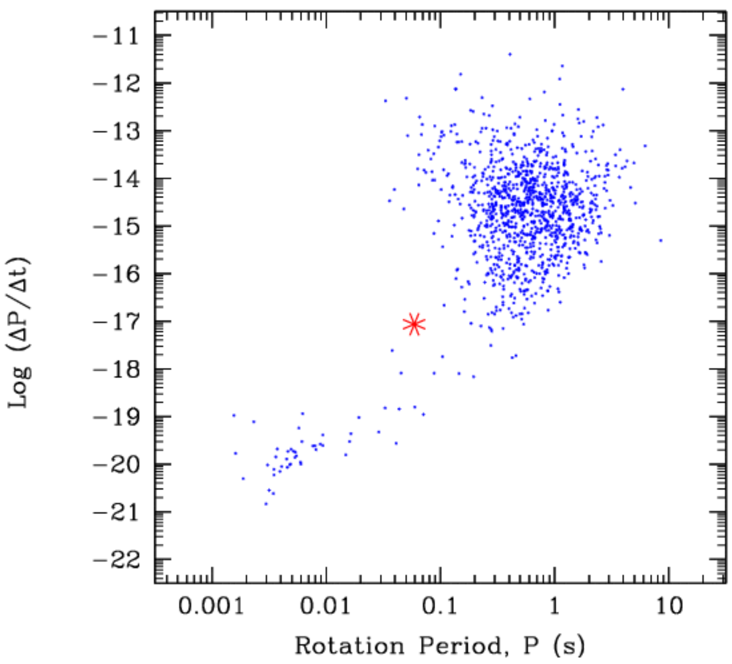
Figure: Stairs et al. 1999, ApJS, 123, 627

Crucial Details: Interference Excision

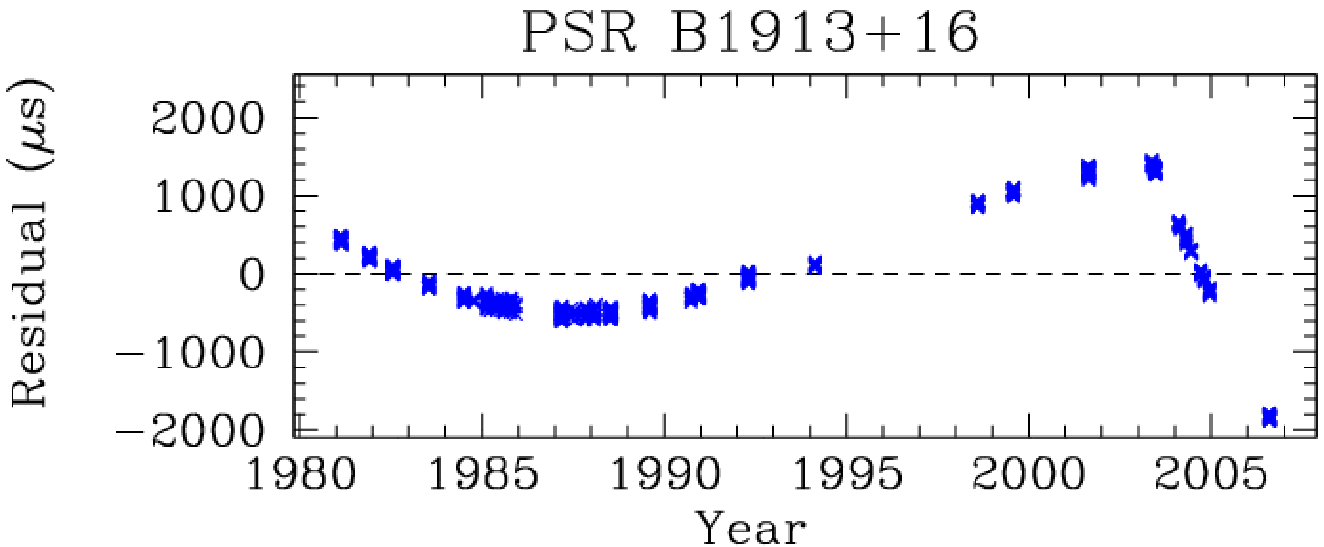


PSR J1953+27

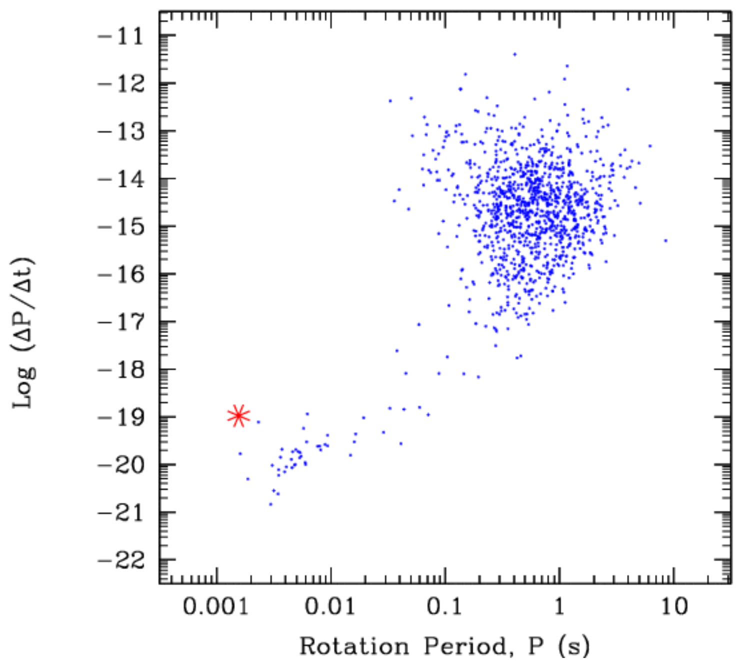
So, what about the long-term stability of recycled pulsars?



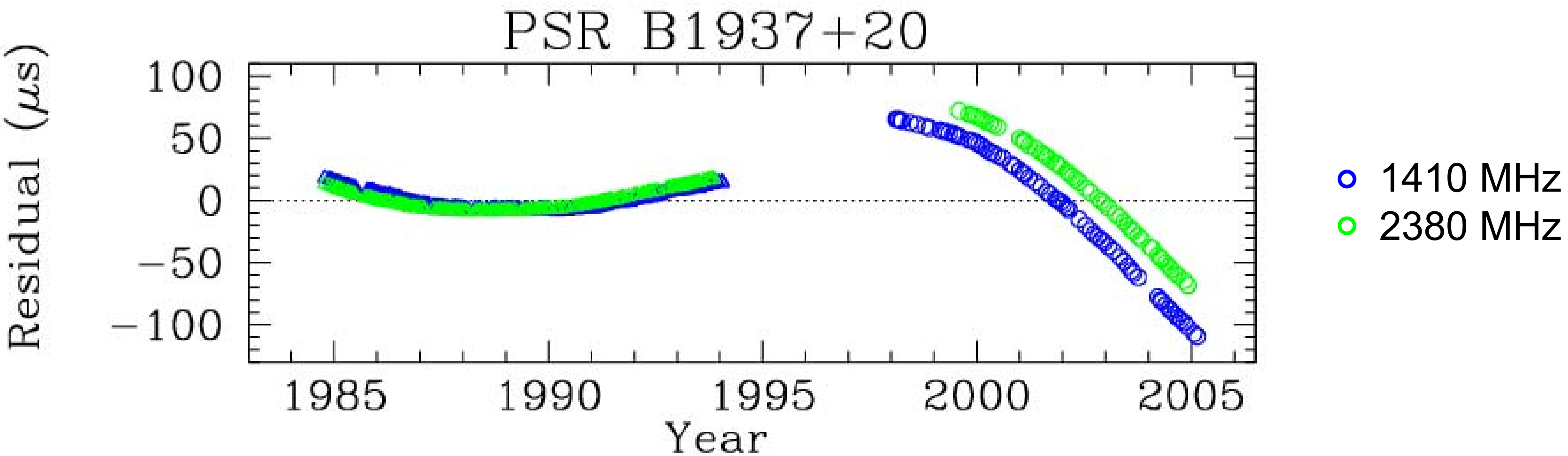
Log (ΔP/Δt)
Rotation Period, P (s)



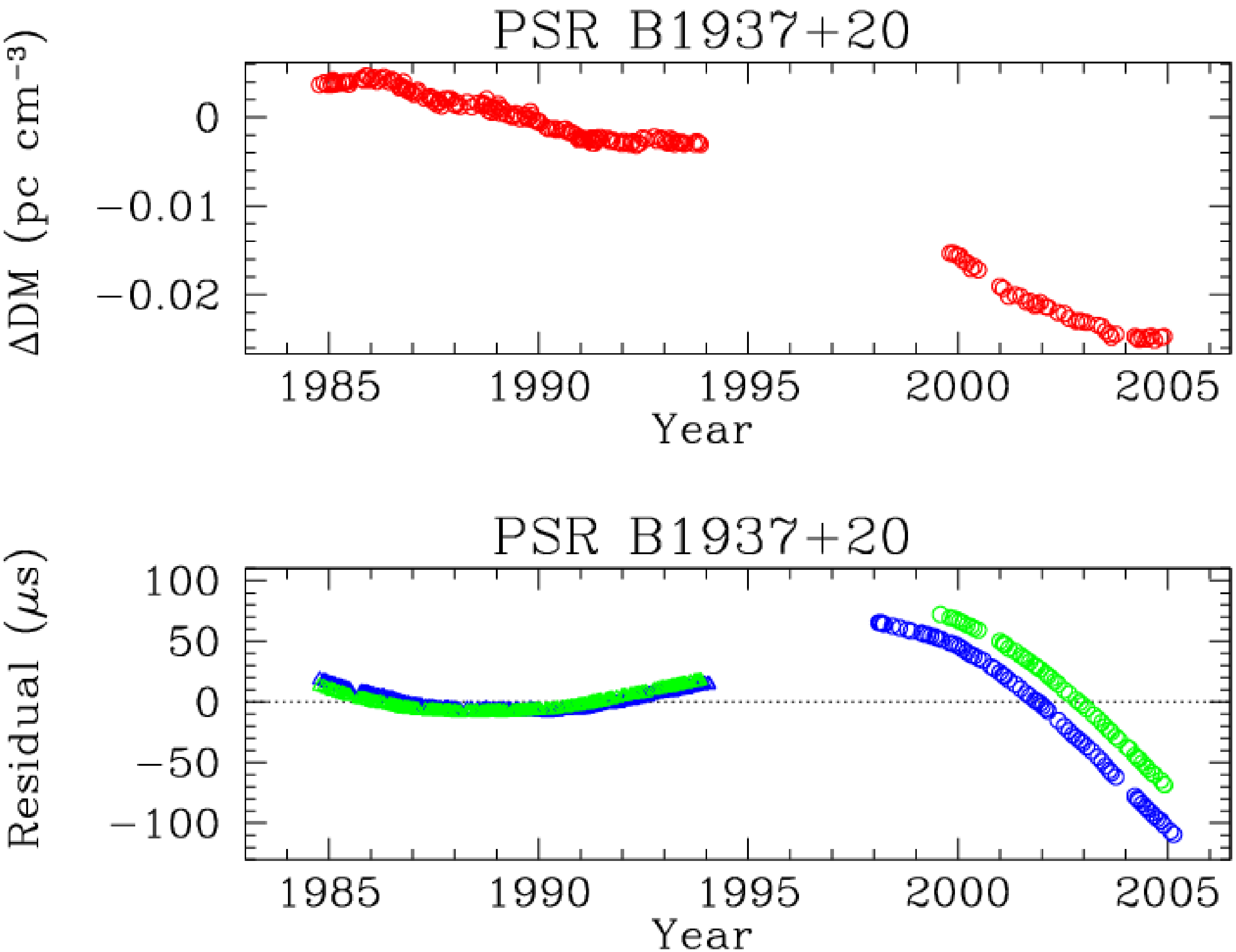
PSR B1913+16
Residual (μs)
Year



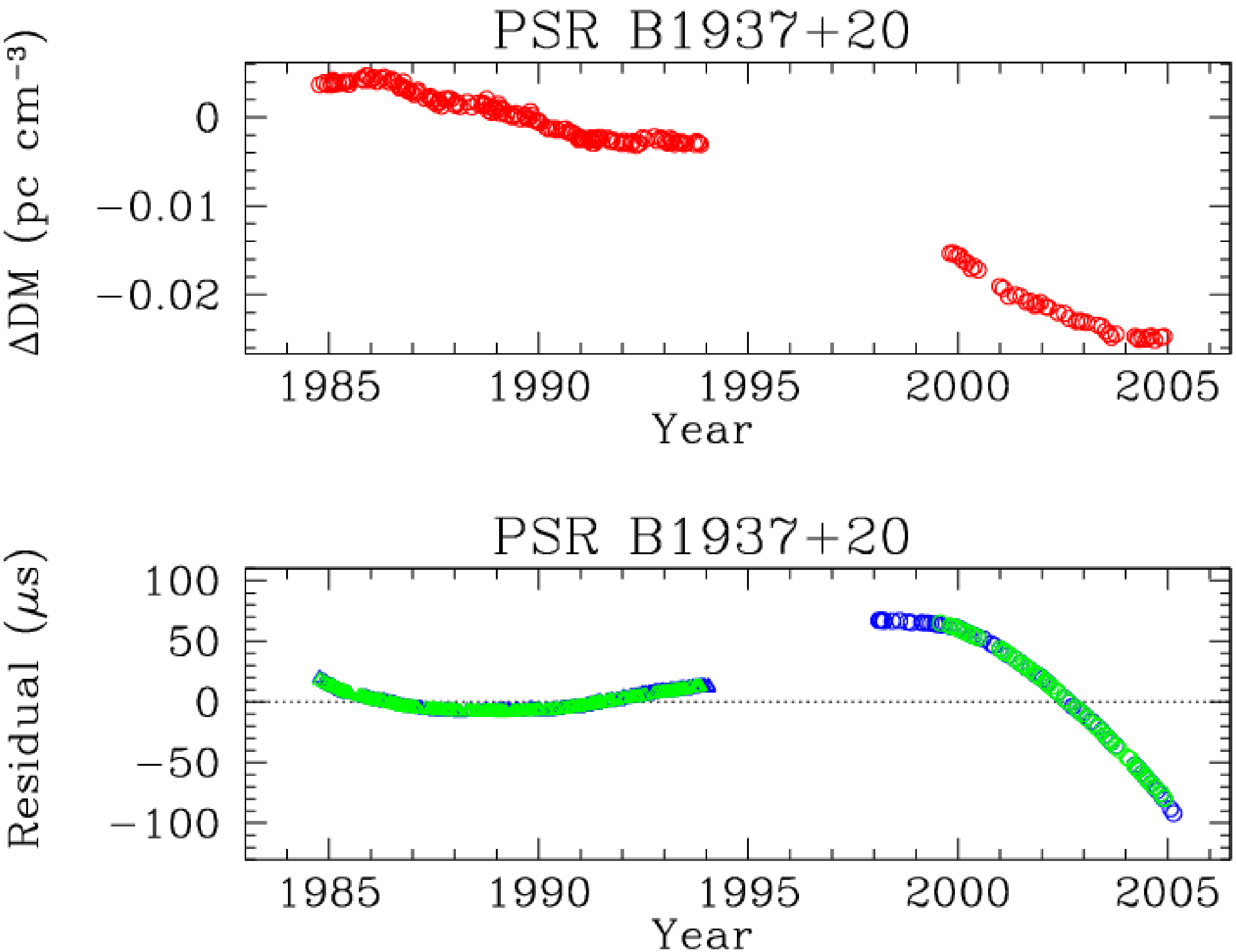
Log (ΔP/Δt)
Rotation Period, P (s)

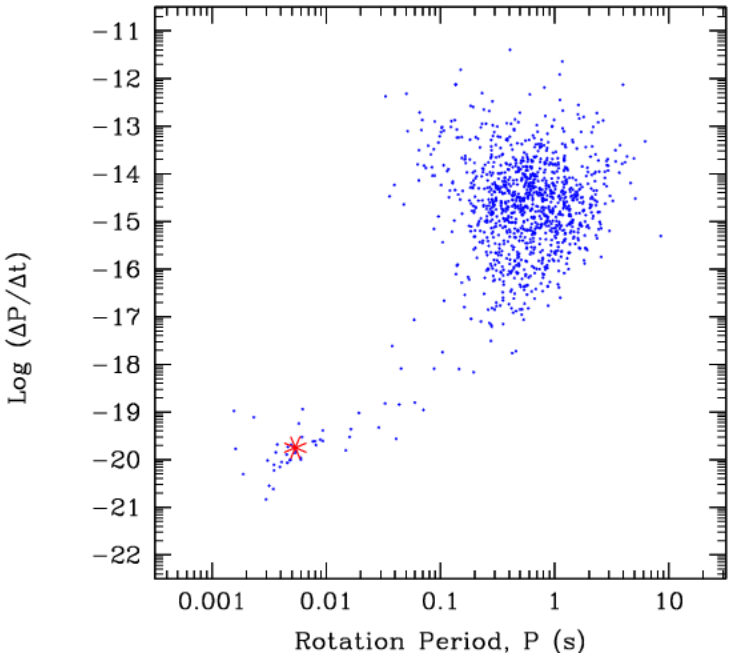


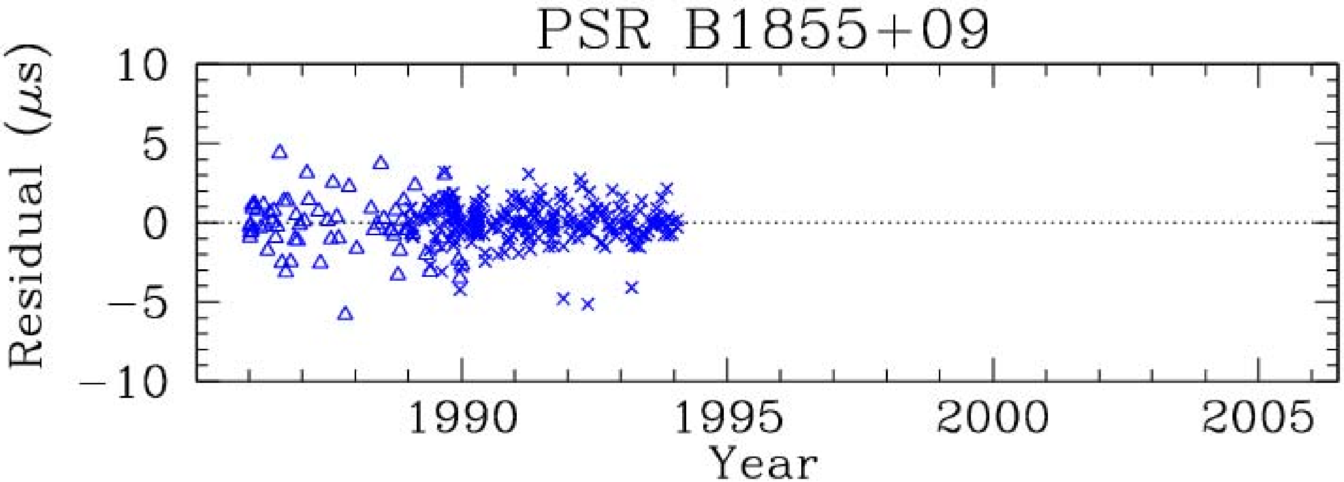
PSR B1937+20
Residual (μs)
Year
1410 MHz
2380 MHz



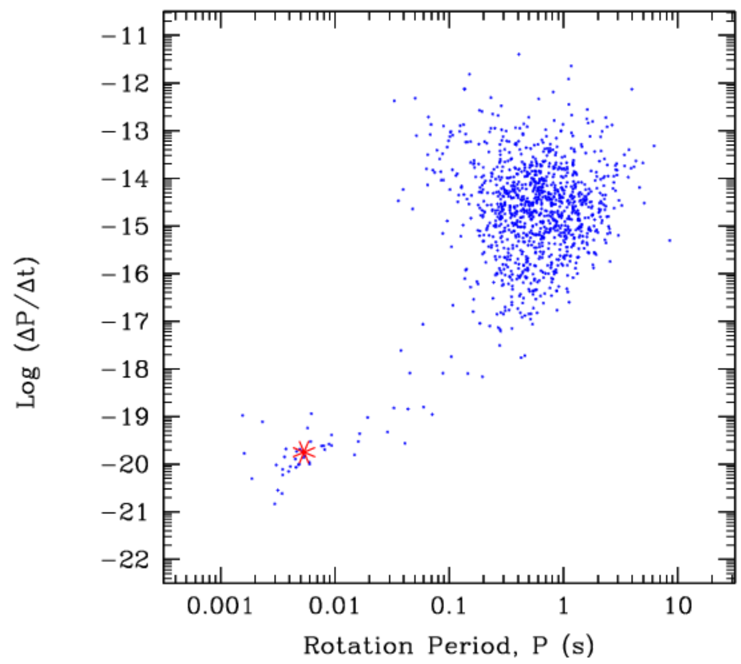
PSR B1937+20
ΔDM (pc cm^-3)
0
−0.01
−0.02
1985
1990
1995
2000
2005
Year
PSR B1937+20
Residual (μs)
100
50
0
−50
−100
1985
1990
1995
2000
2005
Year

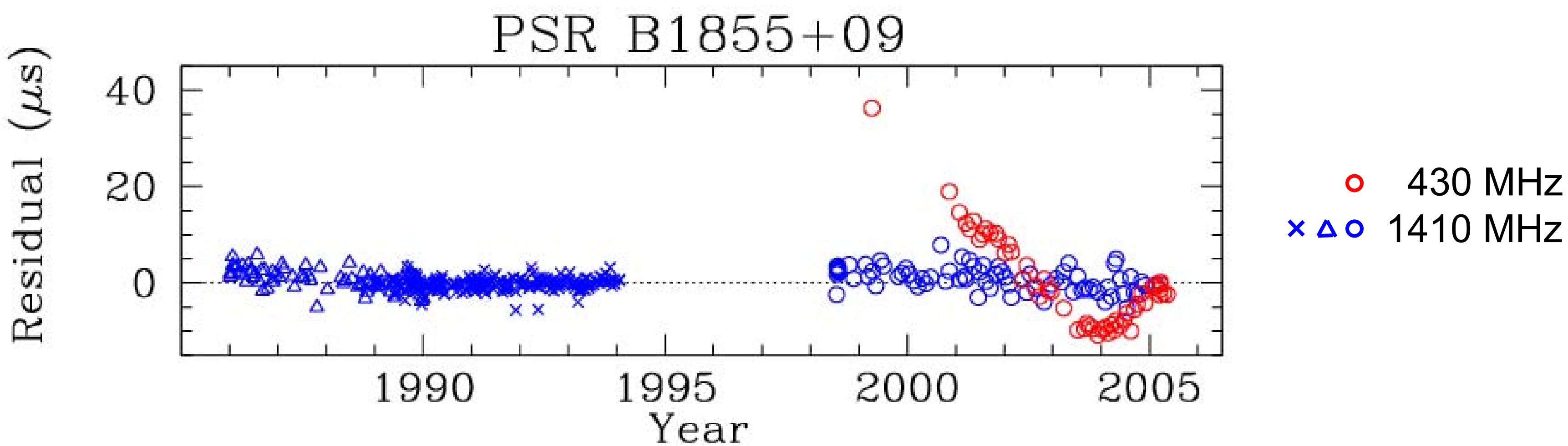

PSR B1937+20
ΔDM (pc cm^{-3})
0
−0.01
−0.02
1985
1990
1995
2000
2005
Year
PSR B1937+20
Residual (μs)
100
50
0
−50
−100
1985
1990
1995
2000
2005
Year

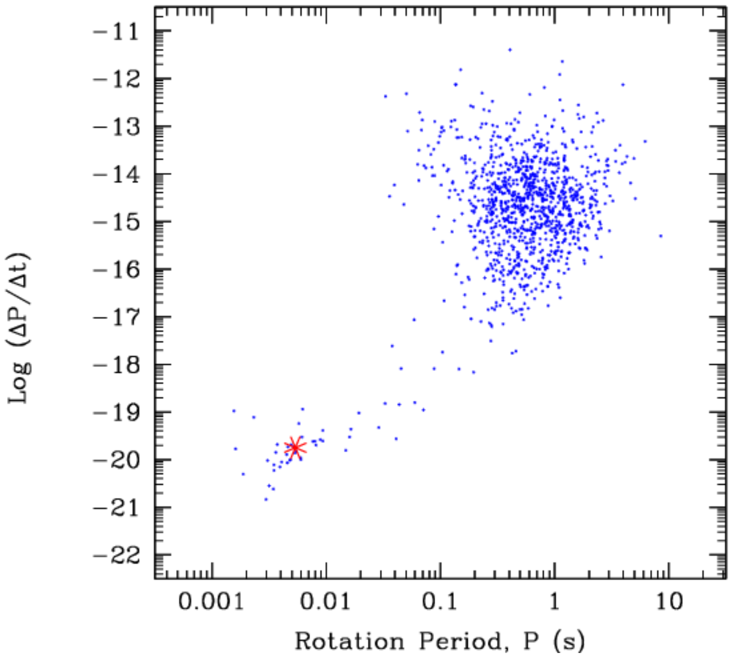




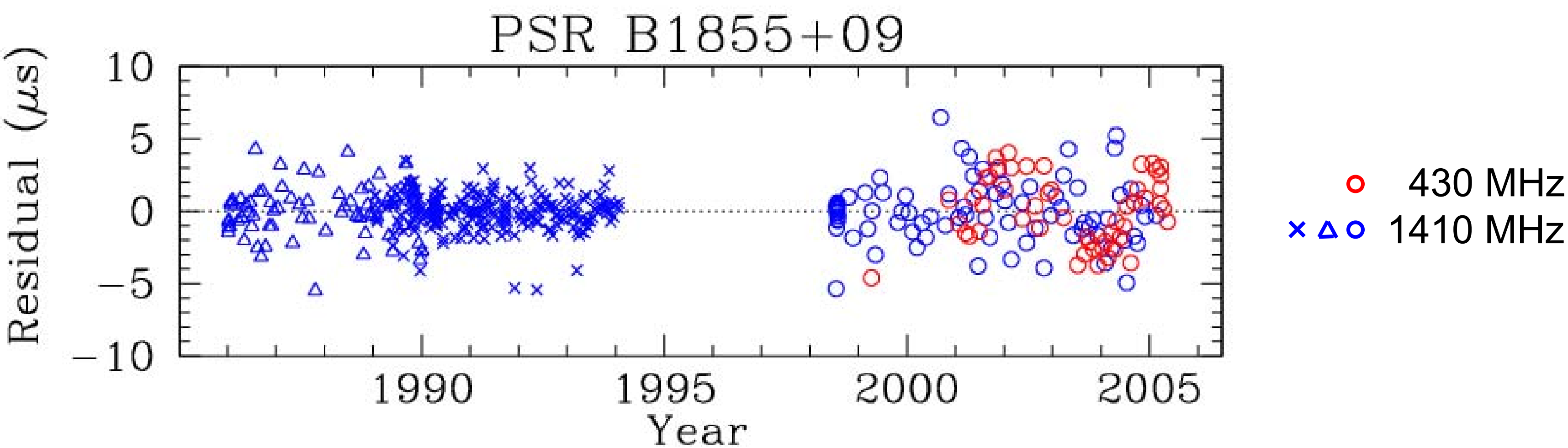
Kaspi, Taylor, & Ryba (1994)


Log (ΔP/Δt)
Rotation Period, P (s)
−11
−12
−13
−14
−15
−16
−17
−18
−19
−20
−21
−22
0.001
0.01
0.1
1
10

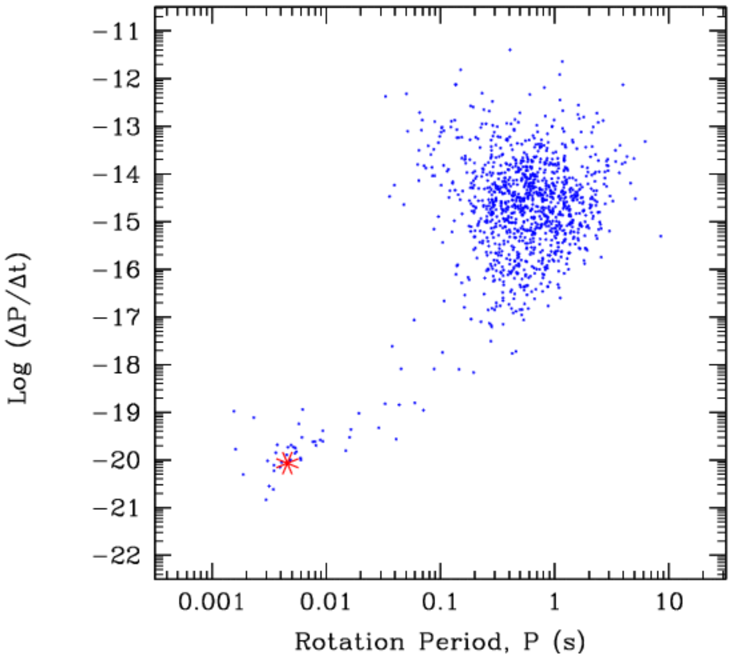

PSR B1855+09
Residual (μs)
40
20
0
1990
1995
2000
2005
Year
430 MHz
1410 MHz



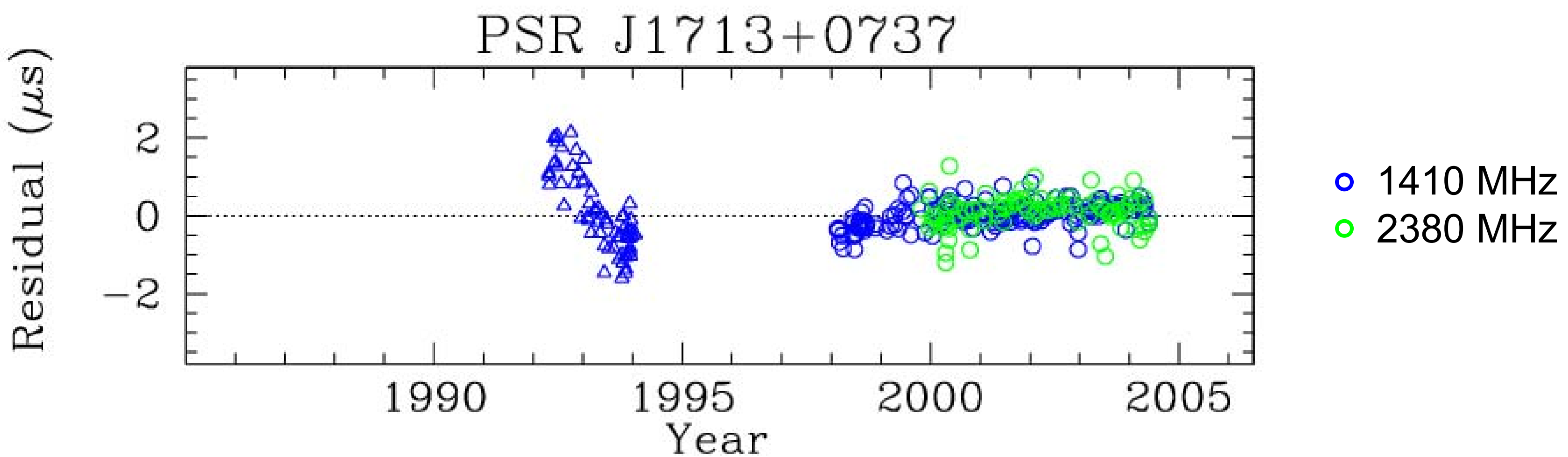
Log (ΔP/Δt)
Rotation Period, P (s)



PSR B1855+09
Residual (μs)
Year
430 MHz
1410 MHz



Log (ΔP/Δt)
Rotation Period, P (s)



PSR J1713+0737
Residual (μs)
Year
1410 MHz
2380 MHz

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Advances in telescopes themselves:

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Get all the details right

- Polarization Calibration, RFI Excision
- All filters, clocks, etc. (100 nsec ~ 20 m of cable!)

Discover more pulsars

PULSARS – THE PAST

1965
— PULSARS DISCOVERED

1970

1975 — RELATIVISTIC BINARY

1980 — MILLISECOND PULSAR

1985

1990 — FIRST EXTRASOLAR PLANETS

1995

NEUTRON STARS   MAGNETIC SWEEP
NS-SNR ASSOCIATION   SCINTILLATION   GLITCHES
SPINDOWN   OPTICAL, GAMMA EMISSION
SCINTILLATION

TIMING NOISE, MODE CHANGES
STABILITY OF AVERAGE PROFILE

REFRACTIVE SCINTILLATION

WHITE DWARF - PSR SYSTEM
GLOBULAR CLUSTER PULSARS
COMPANION - EVAPORATING PULSARS
SHAPIRO DELAY
PULSAR – MAIN SEQUENCE BINARIES
MAGELLANIC CLOUD PSRS
NON-RADIO-EMITTING PSRS

PULSARS – THE PAST

1965 — PULSARS DISCOVERED

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1995

— ???

2000

2005 — ???

2010

— ???

2015

2020 — ???

NEUTRON STARS MAGNETIC DIPOLE
NS-SNR ASSOCIATION SCINTILLATION GLITCHES
SPINDOWN OPTICAL, GAMMA EMISSION
SCINTILLATION

TIMING NOISE, MODE CHANGES
STABILITY OF AVERAGE PROFILE

REFRACTIVE SCINTILLATION

WHITE DWARF - PERSISTENT
GLOBULAR CLUSTER PULSARS
COMPANION - EVAPORATING PULSARS
SHAPIRO DELAY
PULSAR - MAIN SEQUENCE BINARIES
MAGELLANIC CLOUD PSRS
NON-RADIO-EMITTING PSRS

GBT era

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1975 — RELATIVISTIC BINARY

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1985

1990 — FIRST EXTRASOLAR PLANETS

1995

— ???

2000

ECLIPSING DOUBLE PULSAR SYSTEM

2005 — ???

2010

— ???

2015

2020 — ???

NEUTRON STARS MAGNETIC DIPOLE
NS–SNR ASSOCIATION SCINTILLATION GLITCHES
SPINDOWN OPTICAL, GAMMA EMISSION
SCINTILLATION

TIMING NOISE, MODE CHANGES
STABILITY OF AVERAGE PROFILE

REFRACTIVE SCINTILLATION

WHITE DWARF – PERSISTENT
GLOBULAR CLUSTER PULSARS
COMPANION – EVAPORATING PULSARS
SHAPIRO DELAY

PULSAR – MAIN SEQUENCE BINARIES
MAGELLANIC CLOUD PSRS
NON-RADIO-EMITTING PSRS

GBT era

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1985

1990 – FIRST EXTRASOLAR PLANETS

1995

– ???

2000

ECLIPSING DOUBLE PULSAR SYSTEM

2005 – ???

2010

– ???

2015

2020 – ???

NEUTRON STARS
MAGNETIC [illegible]
NS-SNR ASSOCIATION
SCINTILLATION
GLITCHES
SPINDOWN
OPTICAL, GAMMA EMISSION
SCINTILLATION

TIMING NOISE, MODE CHANGES
STABILITY OF AVERAGE PROFILE

REFRACTIVE SCINTILLATION

WHITE DWARF - PSR SYSTEM
GLOBULAR CLUSTER PULSARS
COMPANION - EVAPORATING PULSARS
SHAPIRO DELAY
PULSAR – MAIN SEQUENCE BINARIES
MAGELLANIC CLOUD PSRS
NON-RADIO-EMITTING [illegible]

GBT era

Most interesting new developments in pulsar science arise from serendipitous discoveries of interesting new pulsars.

The future of pulsar timing will be driven, more than anything else, by future discoveries of interesting pulsars.

Pulsars – The Past

1965 — Pulsars discovered

1970

1975 — Relativistic binary

1980 — Millisecond pulsar

1985

1990 — First extrasolar planets

1995

— ???

2000

ECLIPSING DOUBLE PULSAR SYSTEM

2005 — ???

2010

— ???

2015

2020 — ???

Neutron stars
Magnetic dipole
NS-gas association
Scintillation
Glitches
Spin down
Optical, gamma emission
Scintillation

Timing noise, mode changes
Stability of average profile

Refractive scintillation

White dwarf - perihelion
Globular cluster pulsars
Companion - evaporating pulsars
Shapiro delay
Pulsar - main sequence binaries
Magellanic cloud PSRs
Non-radio-emitting PSRs

GBT era

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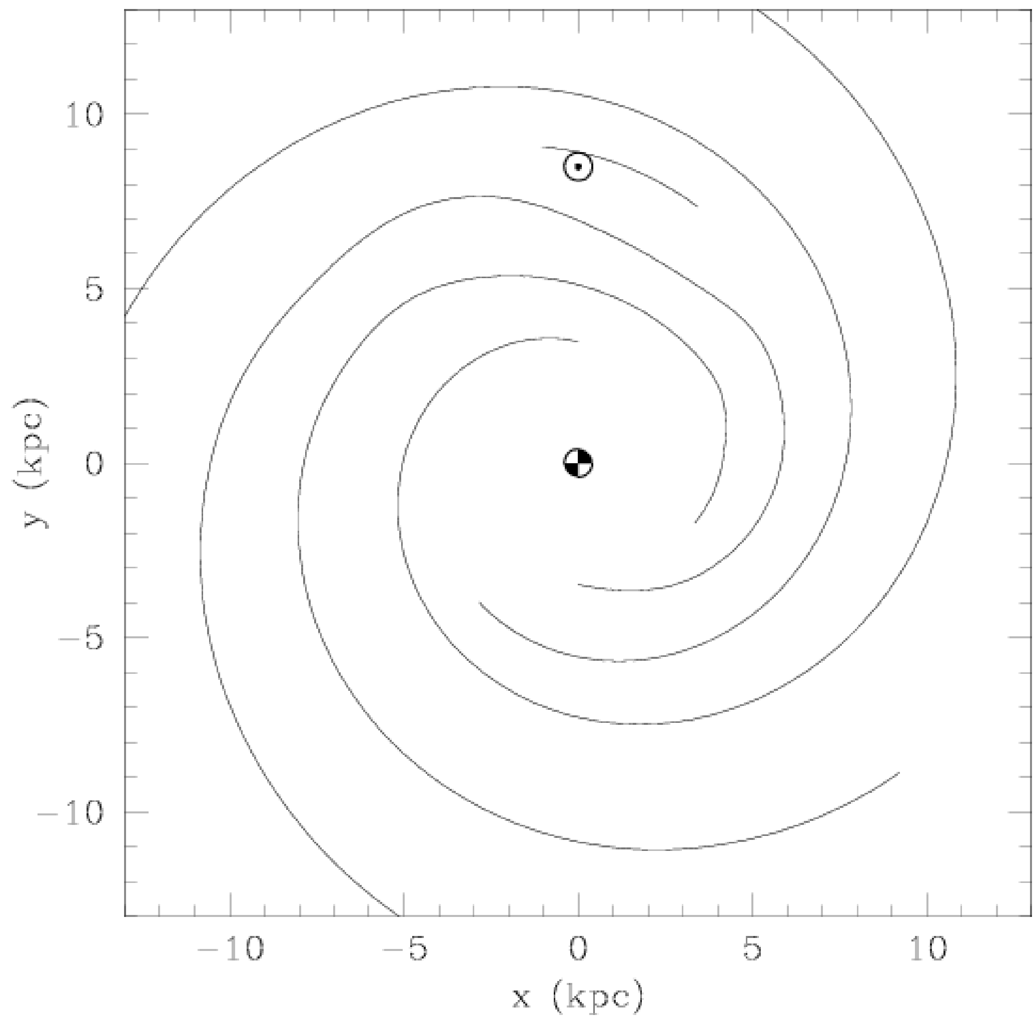
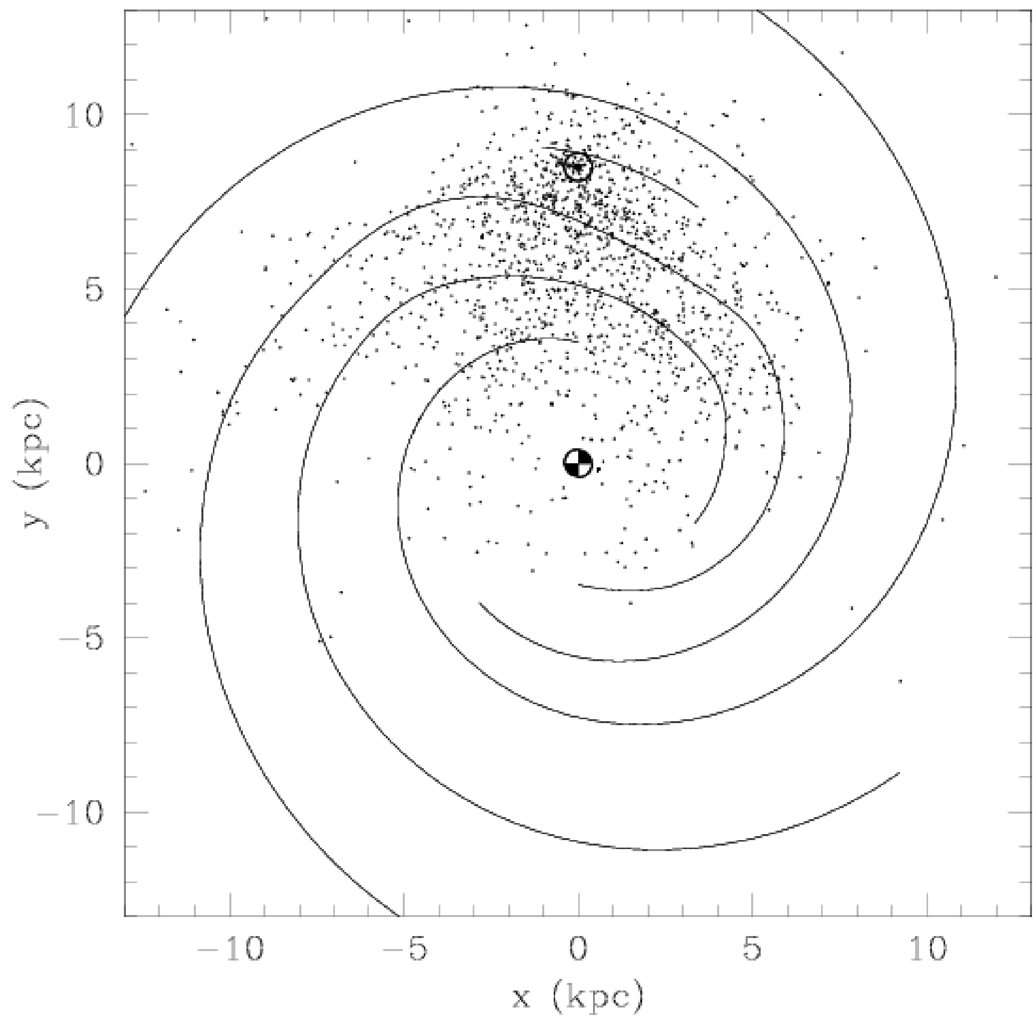
The future of pulsar timing will be driven, more than anything else, by future discoveries of interesting pulsars.

Are there, in fact, interesting new pulsars, just sitting in the Galaxy just waiting for us to find them?



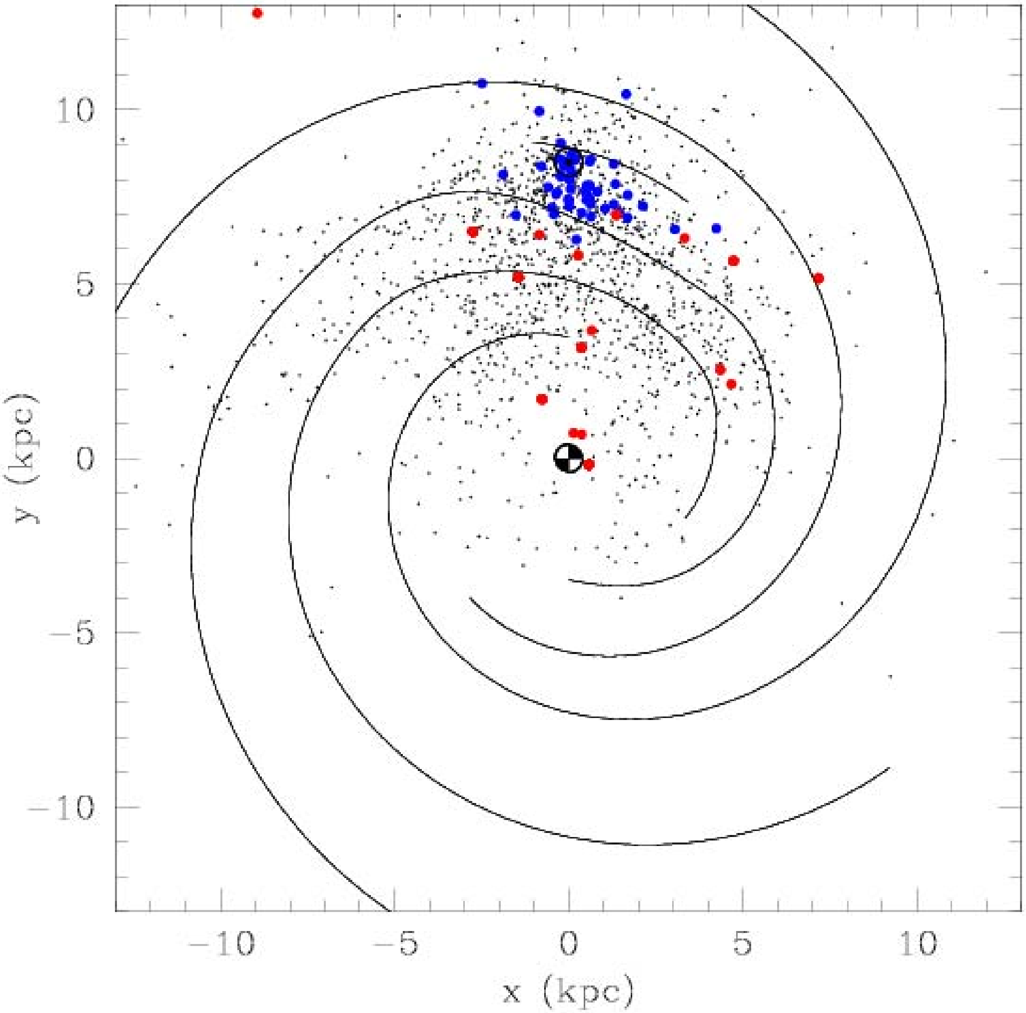
Spiral Arms from NE2001 Galaxy model



All Pulsars

●

ATNF Pulsar Catalog
Distances from NE2001 or ATNF catalog
Spiral Arms from NE2001 Galaxy model



Millisecond Pulsar

● Field

● Globular Cluster

Other Pulsar

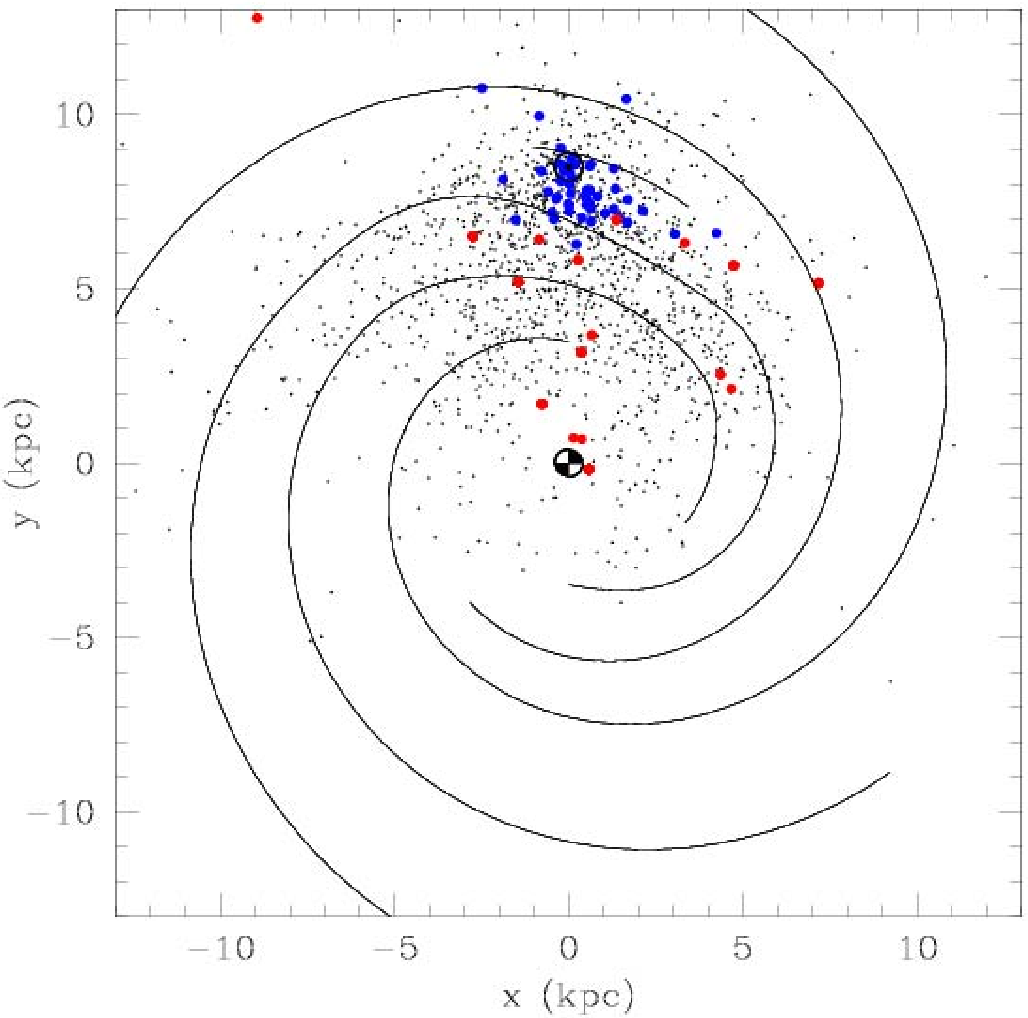
●

ATNF Pulsar Catalog
Distances from NE2001 or ATNF catalog
Spiral Arms from NE2001 Galaxy model
Millisecond pulsars: period < 10 ms

Most of the Galaxy has *not* been searched for millisecond pulsars.

There are many interesting discoveries waiting to be made!

But: many discovering distant millisecond pulsars require a very large telescope (ska) and much telescope time (multibeaming)



Millisecond Pulsar

- Field
- Globular Cluster

Other Pulsar

- ●

ATNF Pulsar Catalog
Distances from NE2001 or ATNF catalog
Spiral Arms from NE2001 Galaxy model
Millisecond pulsars: period < 10 ms

How has progress been made in pulsar timing?

Advances in telescopes themselves:
- Bigger is better
- (more telescope time is better, too!)

Advances in telescope receivers:
- Less noise, more bandwidth

Advances in data acquisition systems:
- Wider bandwidths
- Coherent dedispersion

Move to higher radio frequencies

Get all the details right
- Polarization Calibration, RFI Excision
- All filters, clocks, etc. (100 nsec ~ 20 m of cable!)

Discover more pulsars