Planets around pulsars and white dwarfs

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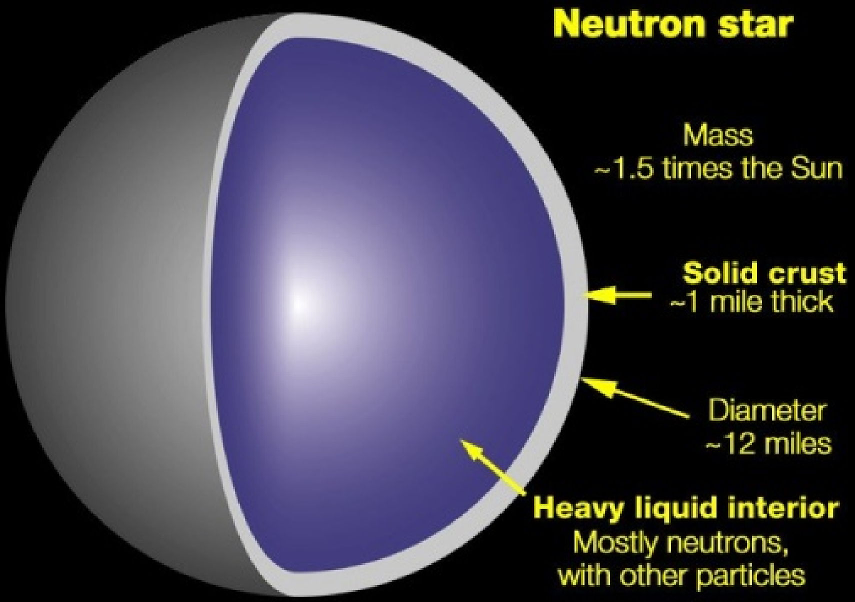
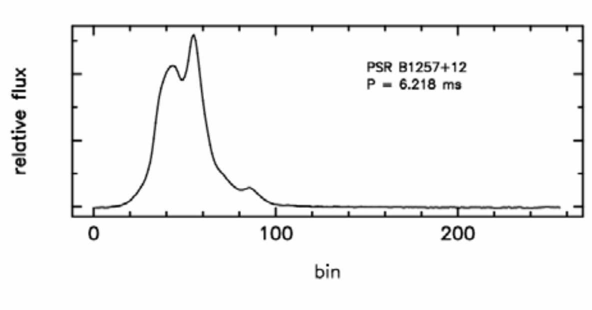
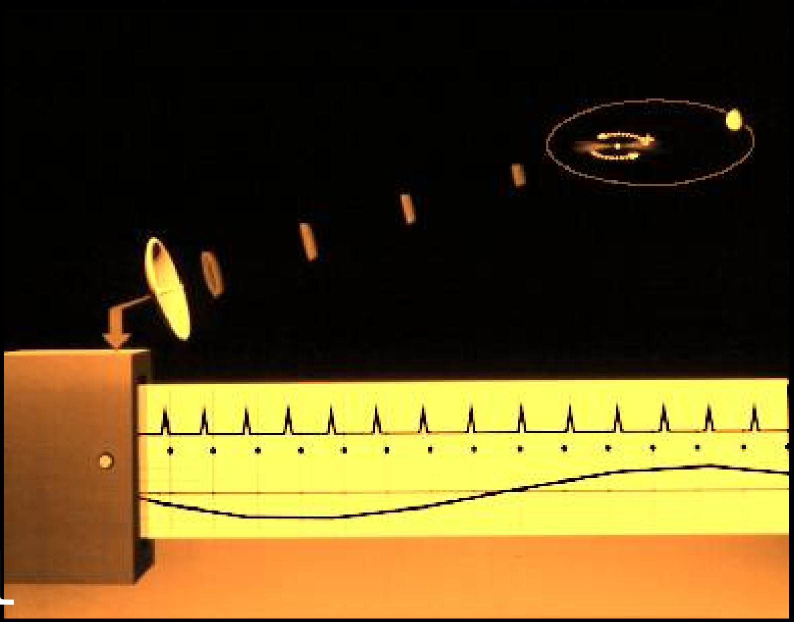
Pulsar timing

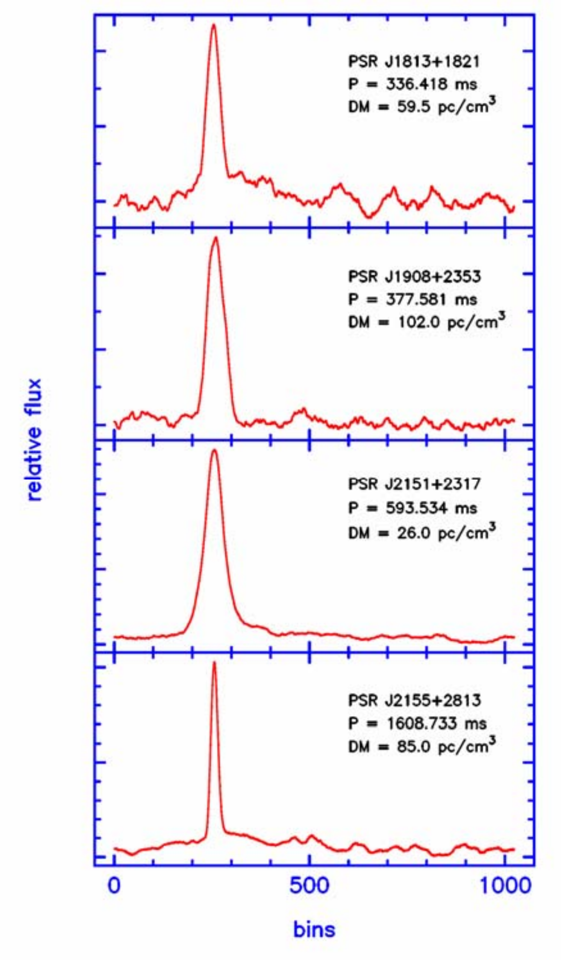






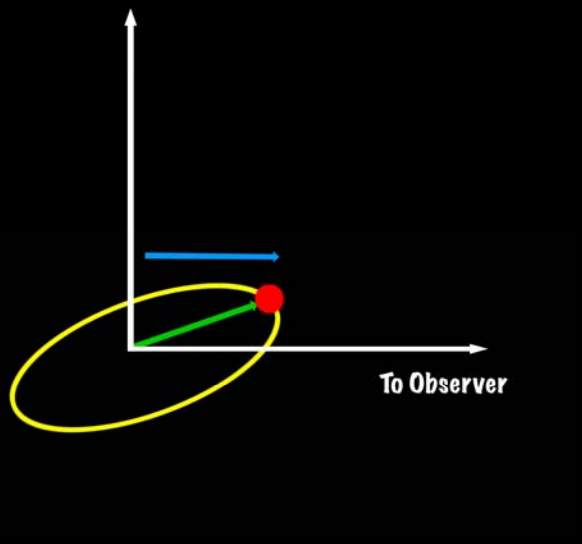
TOA = Time Of Arrival

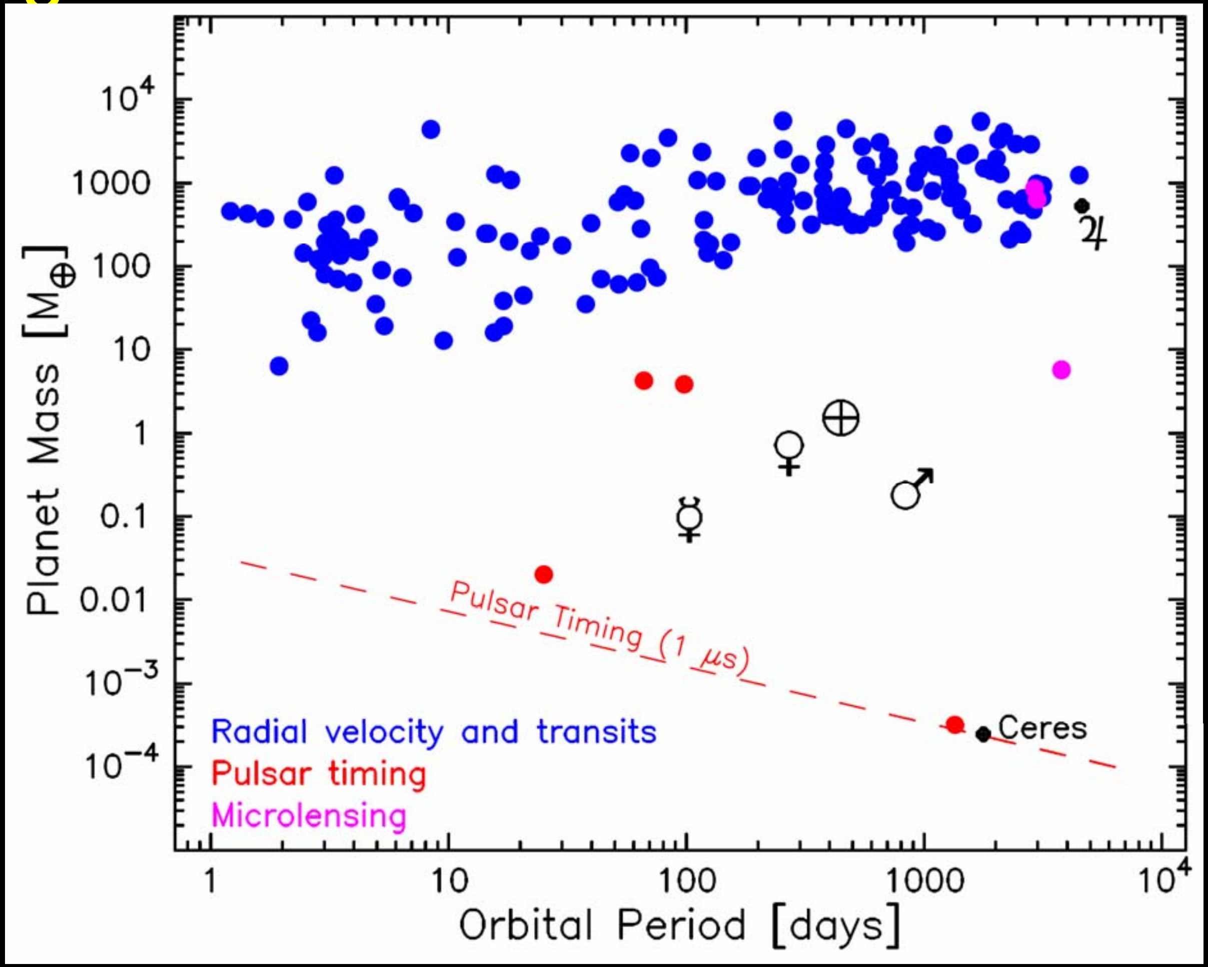
Pulsar timing: “Pulsar machine”



The Penn State Pulsar Machine II (PSPMII)
a 2 x 64 x 3 MHz filterbank

Pulsar timing

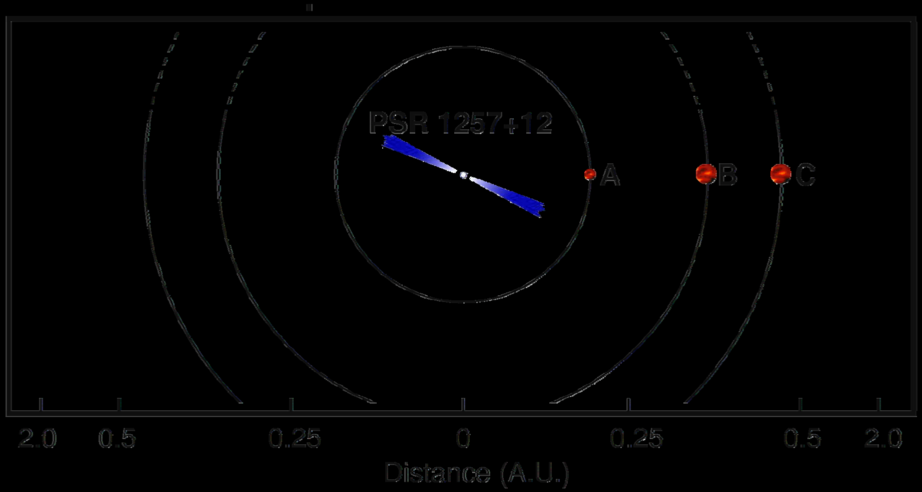




Orbital period
Eccentricity
M sin(i)

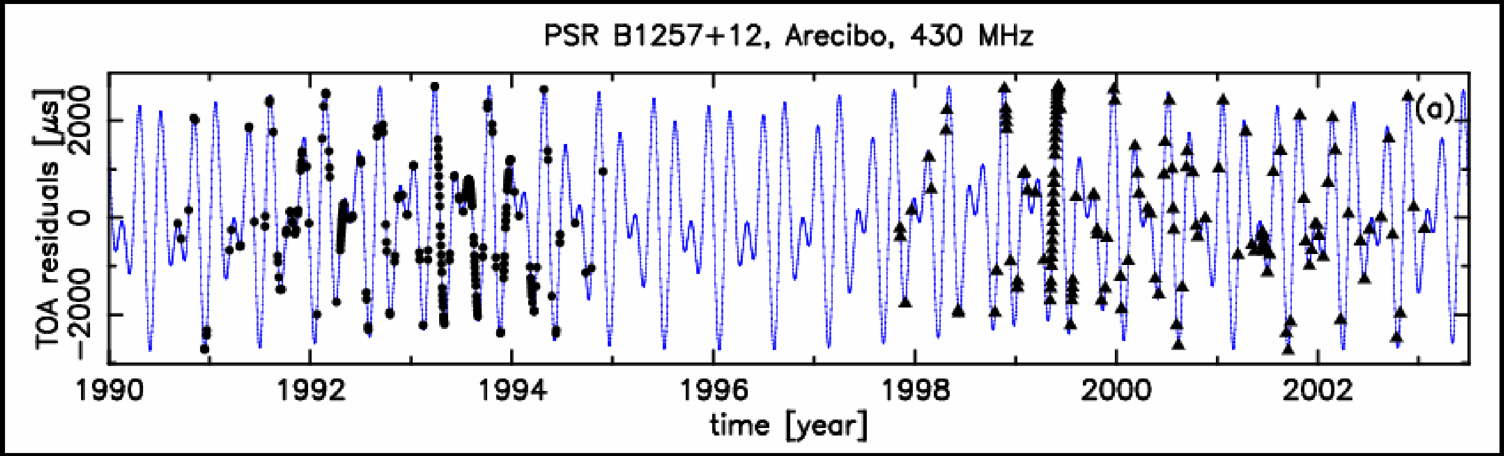
$$\Delta z_{\mathrm{pulsar}} = -\frac{M_{\mathrm{planet}}}{M_{\mathrm{pulsar}}}\Delta z_{\mathrm{planet}}$$

Pulsar planets



Wolszczan & Frail, Nature, 1992

300-m Arecibo



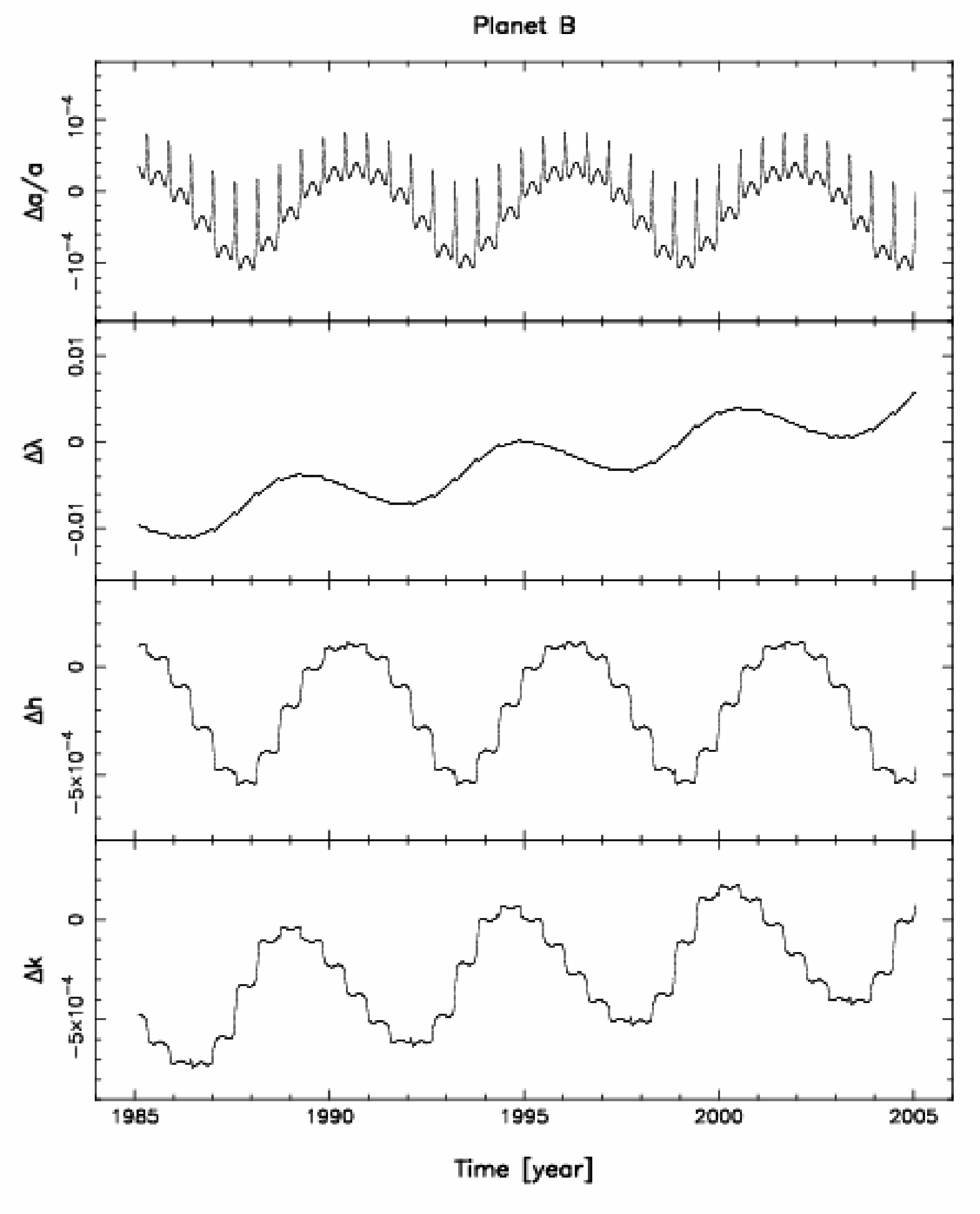
Orbital elements

	A	B	C
Semi-major axis	0.19 AU	0.36 AU	0.46 AU
Orbital period	25.26 days	66.54 days	98.21 days
Eccentricity	0.0	0.0186	0.0252
M sin (i)	0.015 M_{Earth}	3.4 M_{Earth}	2.8 M_{Earth}

Period commensurability:

3 Periods of planet B = 2 Periods of Planet C

Variations of orbital elements



$$\lambda = \frac{2\pi}{P}(t - T_p) + \omega$$

$$h = e\sin(\omega)$$

$$k = e\cos(\omega)$$

Time Of Arrival, Keplerian mode

$$\Delta t = -\frac{1}{c}\boldsymbol{R}_0 \cdot \hat{\boldsymbol{Z}}$$

$$\Delta t = x[(\cos E - e)\sin\omega + \sqrt{1-e^2}\sin E\cos\omega]$$

where

$$x = a\sin i/c, \quad E - e\sin E = n(t - T_p), \quad n = \frac{2\pi}{P}$$

3-Body Problem

Osculating orbital elements

$$a_j(t) = a_j^0 + \Delta a_j(t), \quad \lambda_j(t) = \lambda_j^0 + \Delta\lambda_j(t)$$

$$h_j(t) = h_j^0 + \Delta h_j(t), \quad k_j(t) = k_j^0 + \Delta k_j(t)$$

Hamiltonian of the system

$$H = H_K + H_P$$

3-Body Problem

$$\dot{a}_j = \frac{-2}{\mu_j M_j a_j} \frac{\partial H_P}{\partial \sigma_j},$$

$$\dot{e}_j = \frac{1}{\mu_j M_j a_j^2 e_j} \left[-\left(1 - e_j^2\right) \frac{\partial H_P}{\partial \sigma_j} + \sqrt{1 - e_j^2} \frac{\partial H_P}{\partial \omega_j} \right],$$

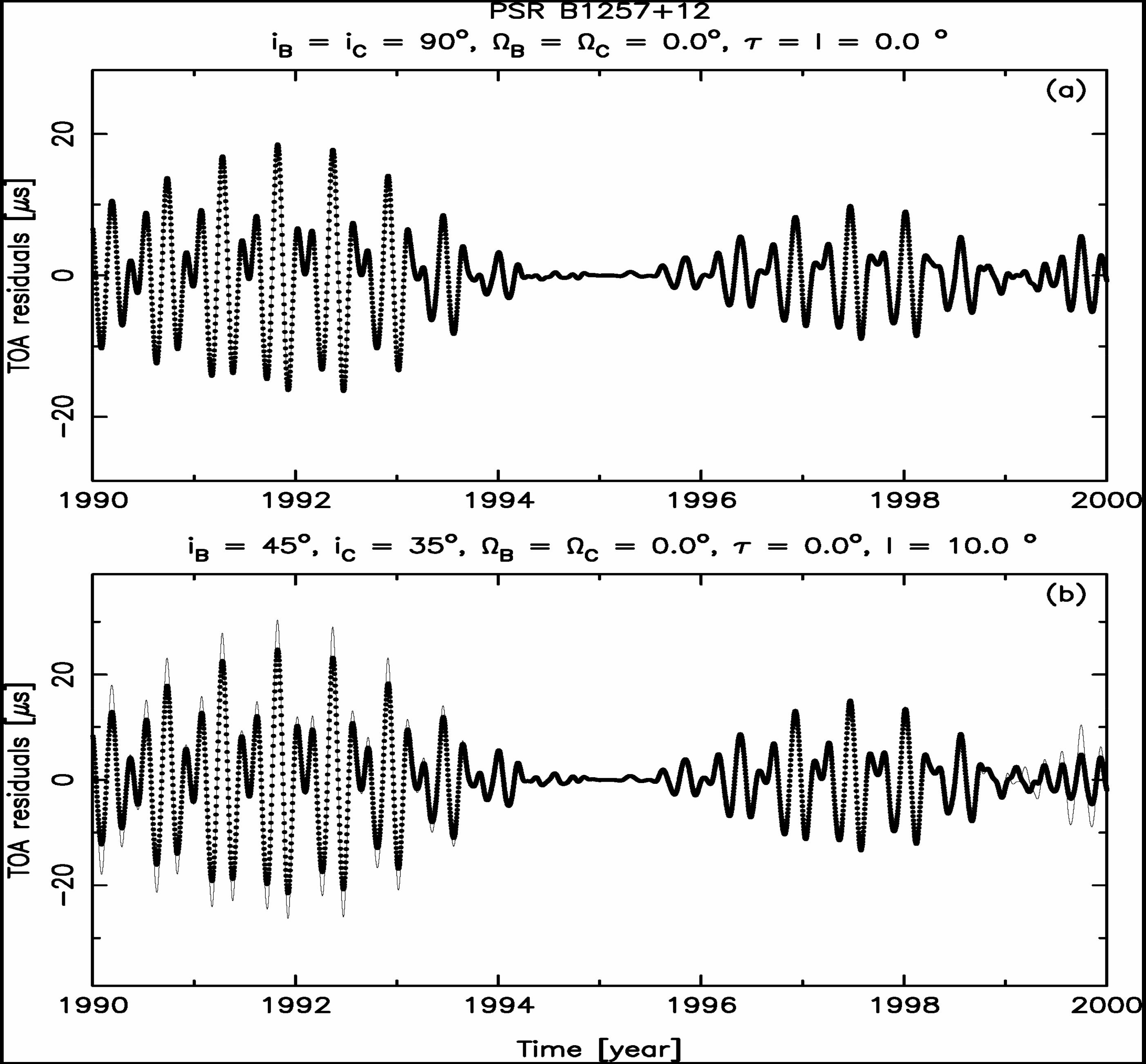
$$\dot{\omega}_j = \frac{-\sqrt{1 - e_j^2}}{\mu_j M_j a_j^2 e_j} \frac{\partial H_P}{\partial e_j},$$

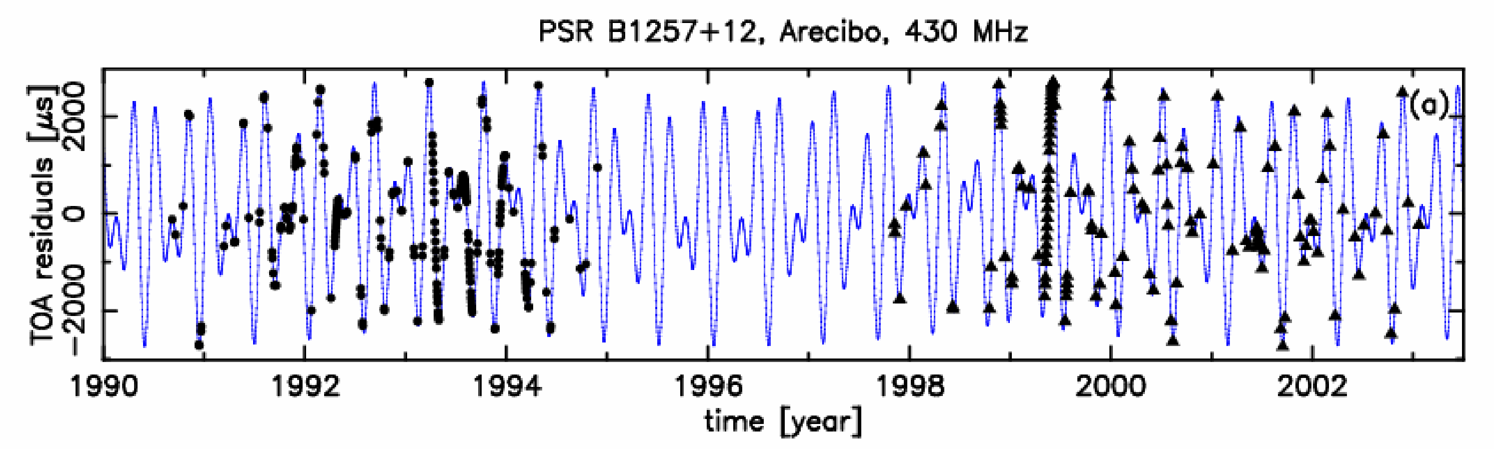
$$\dot{\lambda}_j = M_j + \frac{2}{\mu_j M_j a_j} \frac{\partial H_P}{\partial a_j} - \frac{e_j \sqrt{1 - e_j^2}}{\mu_j M_j a_j^2 \left(1 + \sqrt{1 - e_j^2}\right)} \frac{\partial H_P}{\partial e_j},$$

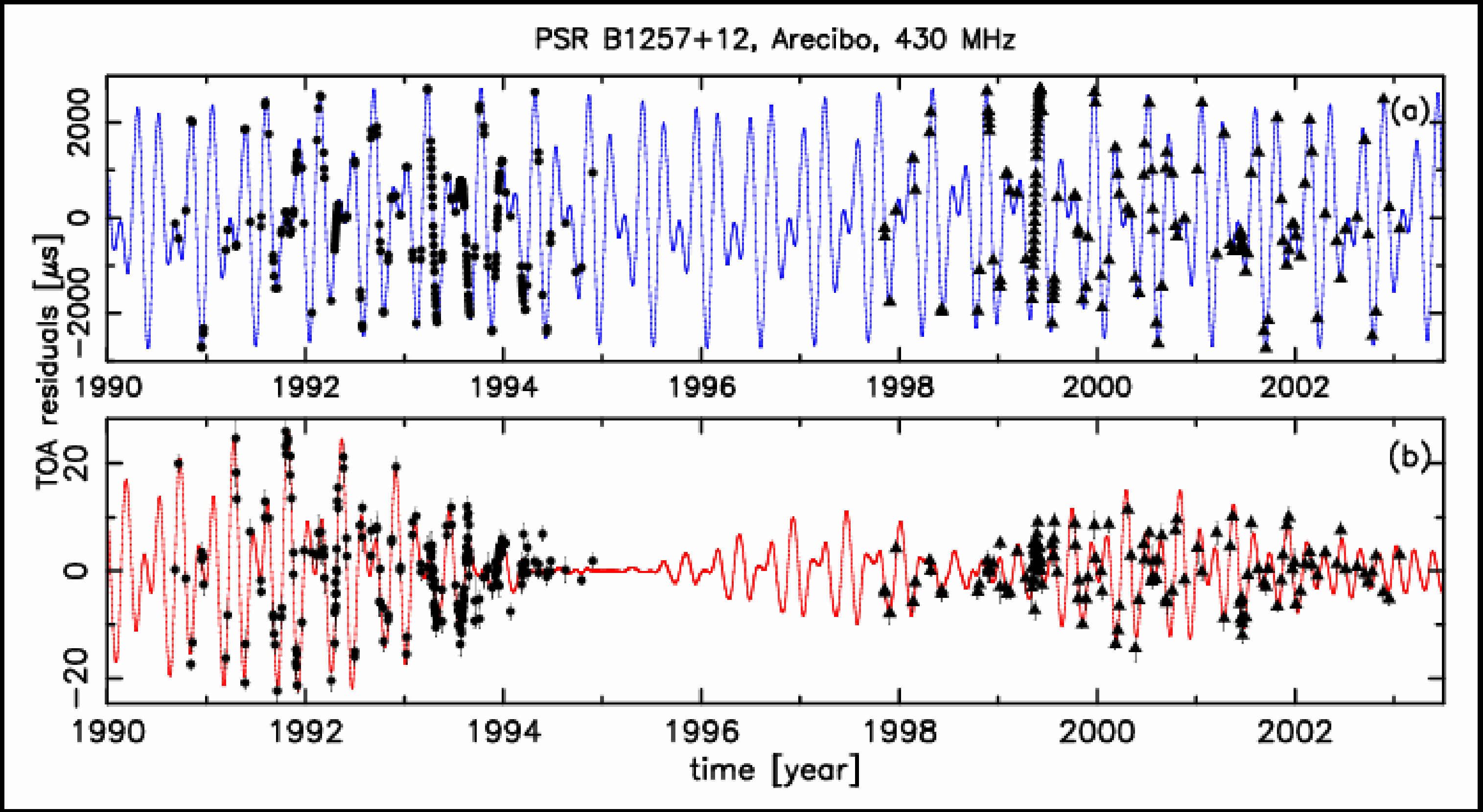
$$j = 1, 2, \quad \mu_1 = M_{psr} + m_1, \quad \mu_2 = M_{psr} + m_1 + m_2$$

$$\lambda_j = M_j t + \sigma_j + \omega_j,$$

Konacki, Maciejewski & Wolszczan, ApJ, 2000


PSR B1257+12
$i_B = i_C = 90°, \Omega_B = \Omega_C = 0.0°, \tau = I = 0.0°$
(a)
TOA residuals [μs]
20
0
−20
1990
1992
1994
1996
1998
2000
$i_B = 45°, i_C = 35°, \Omega_B = \Omega_C = 0.0°, \tau = 0.0°, I = 10.0°$
(b)
TOA residuals [μs]
20
0
−20
1990
1992
1994
1996
1998
2000
Time [year]


PSR B1257+12, Arecibo, 430 MHz
TOA residuals [μs]
2000
0
−2000
(a)
1990
1992
1994
1996
1998
2000
2002
time [year]


PSR B1257+12, Arecibo, 430 MHz
(a)
(b)
TOA residuals [μs]
2000
0
−2000
20
0
−20
1990
1992
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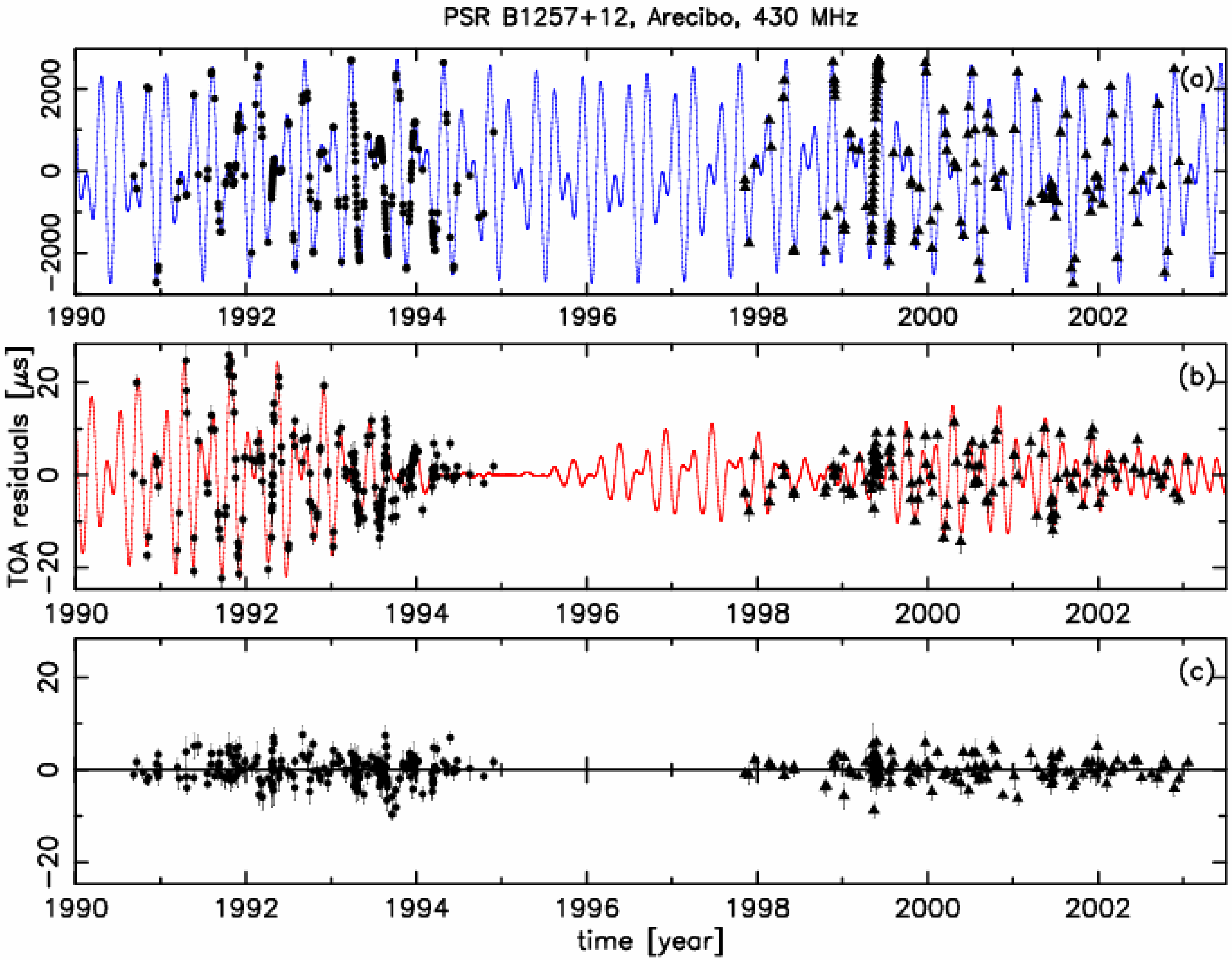
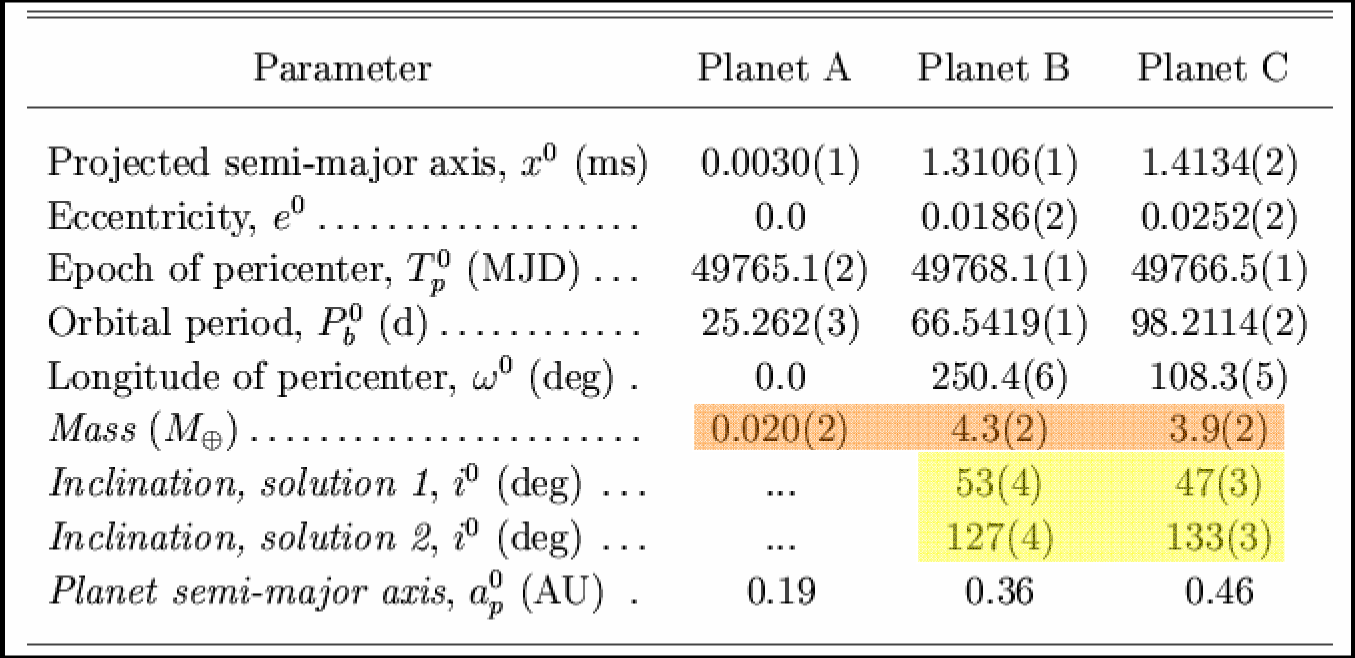
1996
1998
2000
2002
time [year]


PSR B1257+12, Arecibo, 430 MHz
(a)
(b)
(c)
2000
0
−2000
20
0
−20
TOA residuals [μs]
1990
1992
1994
1996
1998
2000
2002
time [year]

Planets A, B and C



Parameter	Planet A	Planet B	Planet C
Projected semi-major axis, x^0 (ms)	0.0030(1)	1.3106(1)	1.4134(2)
Eccentricity, e^0	0.0	0.0186(2)	0.0252(2)
Epoch of pericenter, T_p^0 (MJD) ...	49765.1(2)	49768.1(1)	49766.5(1)
Orbital period, P_b^0 (d)	25.262(3)	66.5419(1)	98.2114(2)
Longitude of pericenter, ω^0 (deg) .	0.0	250.4(6)	108.3(5)
Mass ($M_\oplus$)	0.020(2)	4.3(2)	3.9(2)
Inclination, solution 1, i^0 (deg) ...	...	53(4)	47(3)
Inclination, solution 2, i^0 (deg) ...	...	127(4)	133(3)
Planet semi-major axis, a_p^0 (AU) .	0.19	0.36	0.46

Konacki, Ph.D. Thesis, 2000

Konacki & Wolszczan, ApJL, 2003

Dispersion measure

$$DM = \int_0^L n_e dl \equiv < n_e > L$$

n_e - electron density [e^-/cm^3]

L - distance to pulsar [pc]

$$\Delta t \sim DM / f^2$$

Δt - timing delay [s]

f - frequency [MHz]

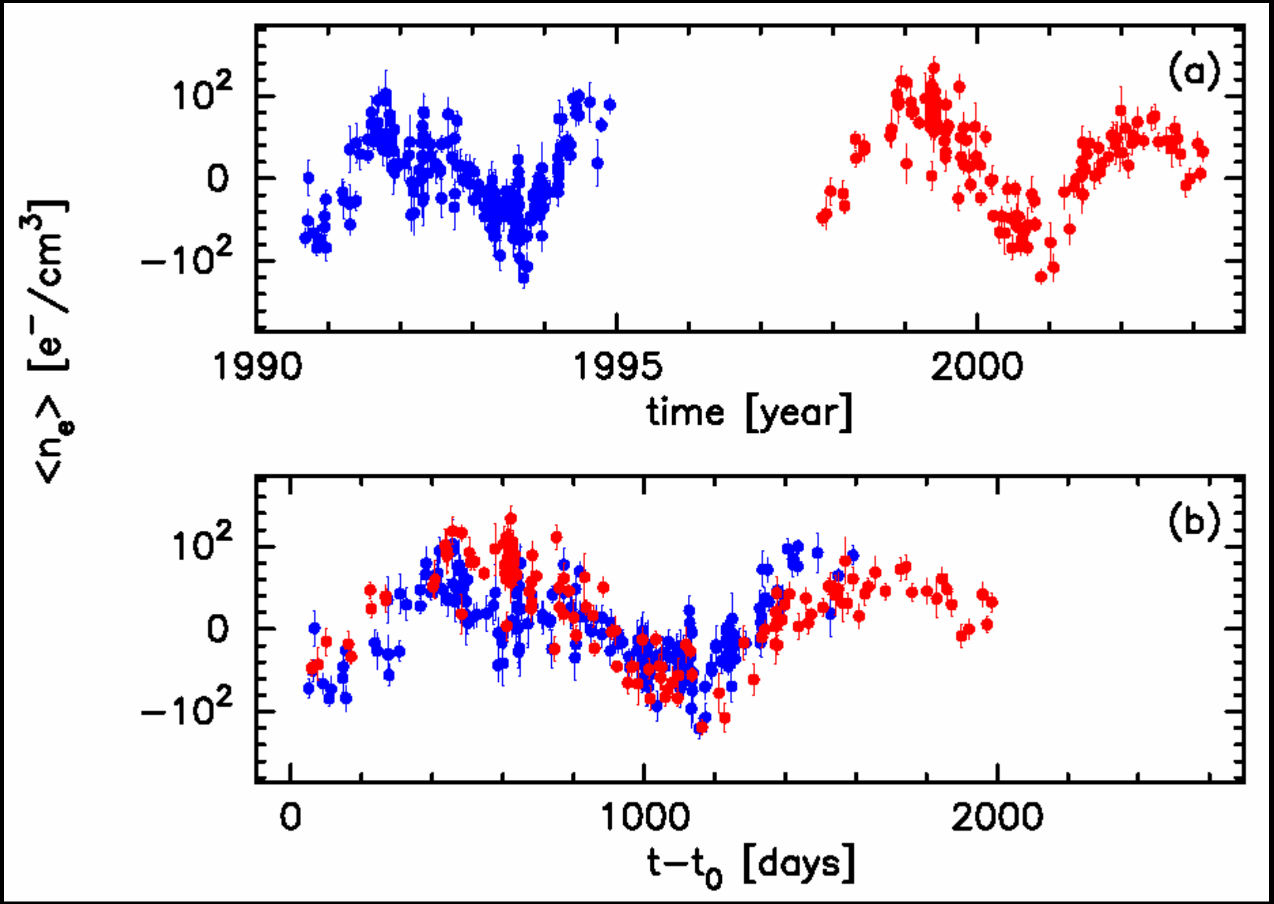
PSR B1257+12

distance: 600 +/- 100 pc

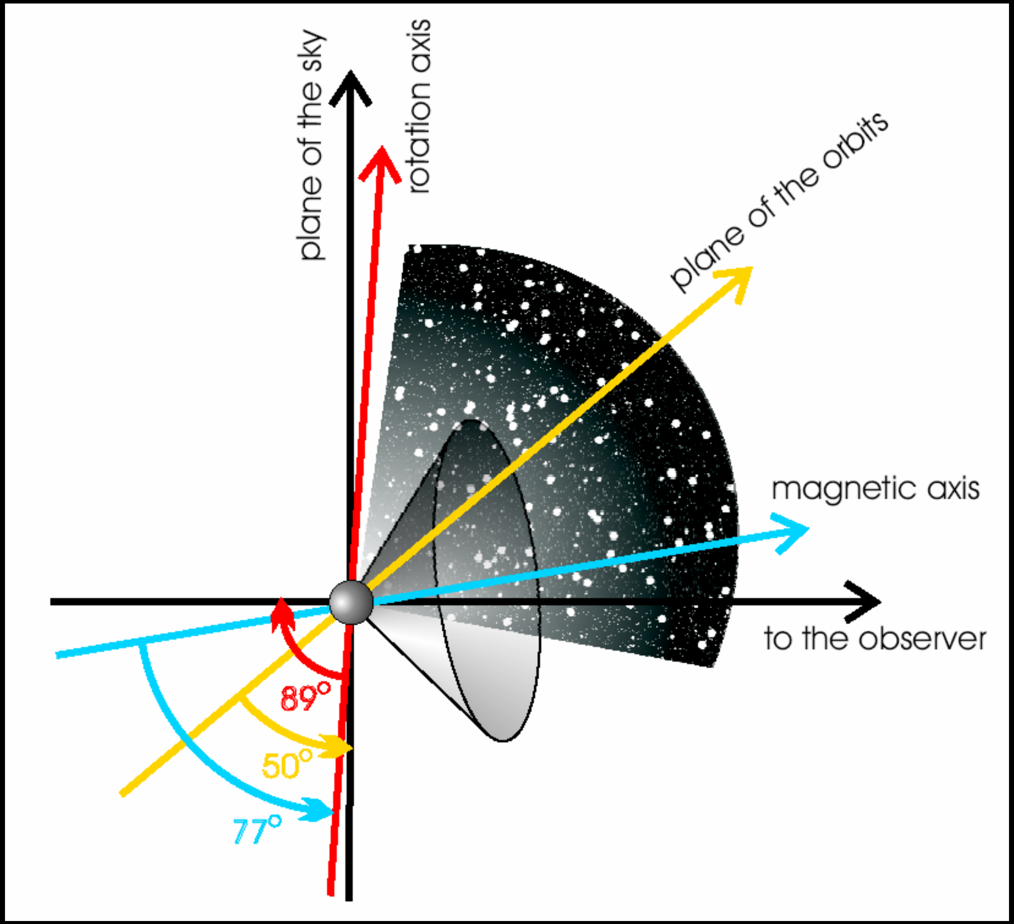
frequency: 430 and 1400 MHz

DM: 10.165 [pc e^-/cm^3]

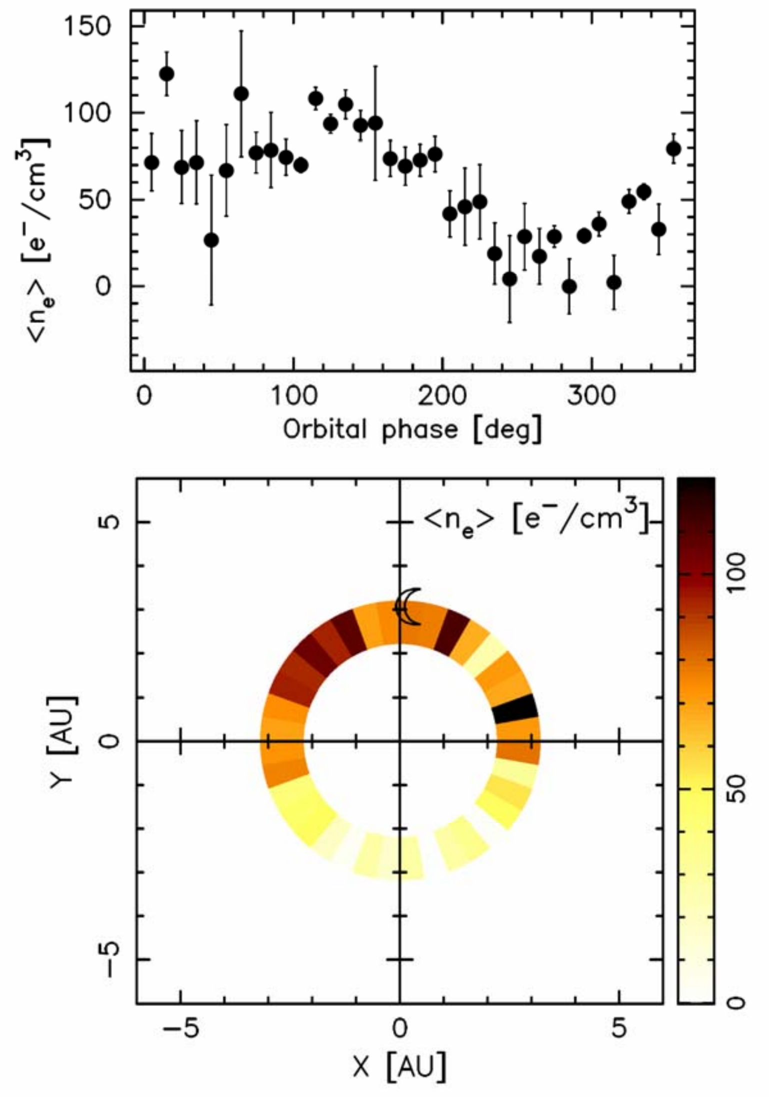
Electron density variations

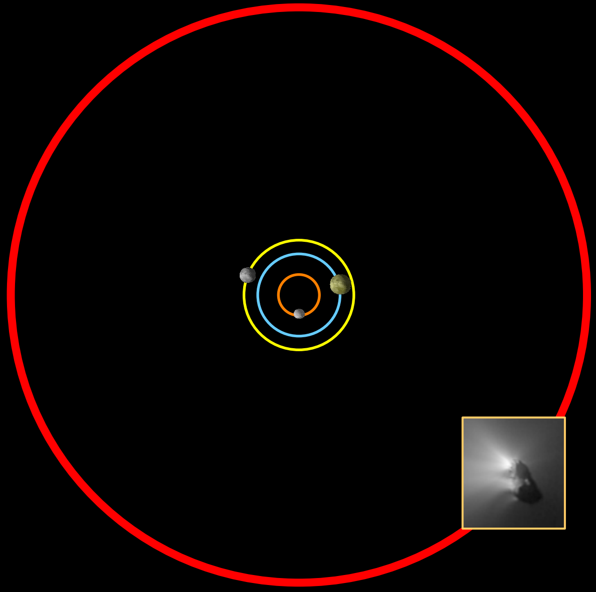


Electron density variations



Planet “D” and its gas cloud





$M \sin(i) = 0.15\ M_{Pl}$

$a = 2.7$ AU

$P = 3.7$ yr

Not yet published, collaborator: A. Wolszczan

Formation Scenarios

Pre supernova scenarios

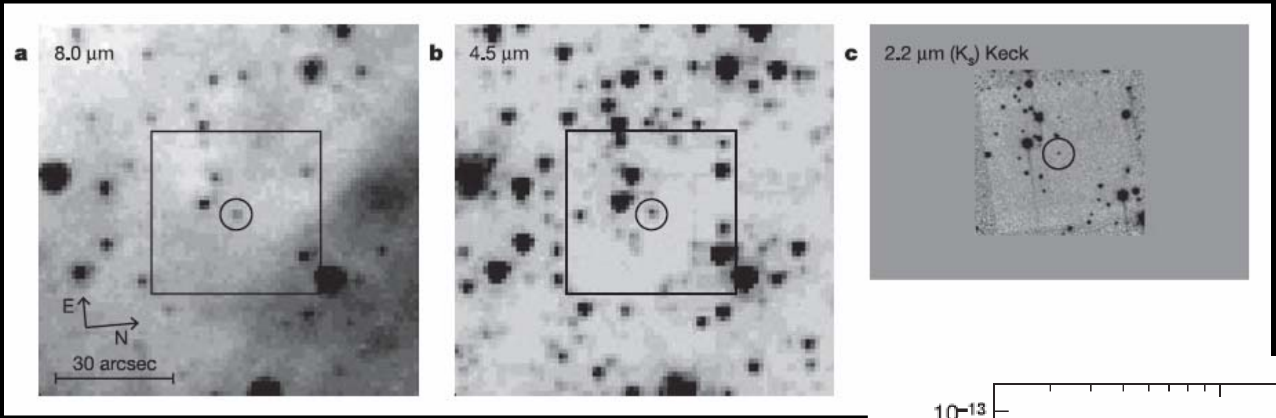
- Planets survive the supernova
- Planets are acquired during a stellar collision
- Planets form in orbit around a massive binary

Post supernova scenarios

- Planets form out of accreted matter from a stellar companion
- Planets form from fallback matter from the supernova

Merger of two white dwarfs

A debris disk around an isolated young neutron star



4U 0142+61

isolated young (10^5 yr) neutr
X-ray pulsar, 8.7 sec
distance 3.9 kpc

Wang et al, Nature, 2006

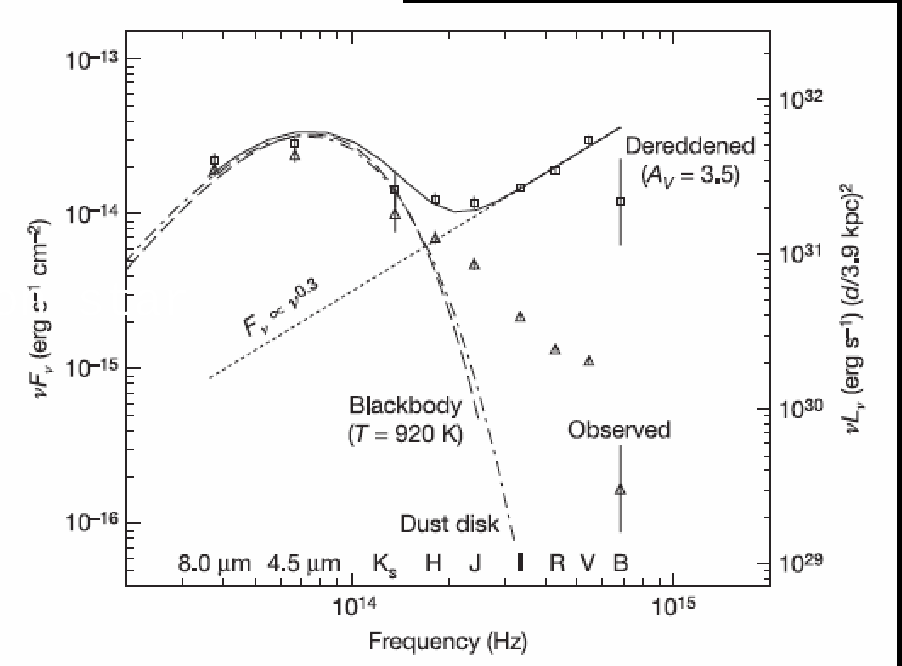
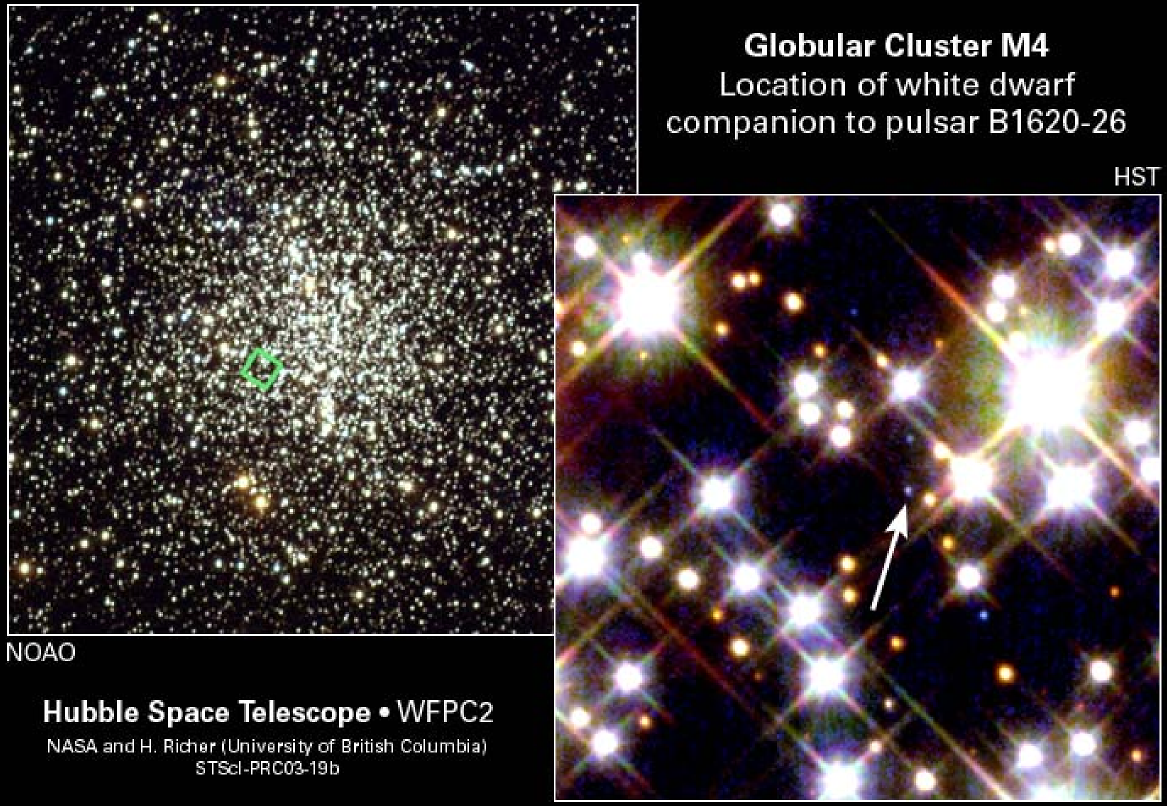


Figure 3 | Optical/infrared spectral energy distribution of 4U 0142+61.

A millisecond pulsar PSR B1620-26 in the globular cluster M4



Globular Cluster M4
Location of white dwarf companion to pulsar B1620-26

Hubble Space Telescope • WFPC2
NASA and H. Richer (University of British Columbia)
STScI-PRC03-19b

M4: 13 billion years old, medium mass 10^5 M_{Sun}, metal poor 5% of

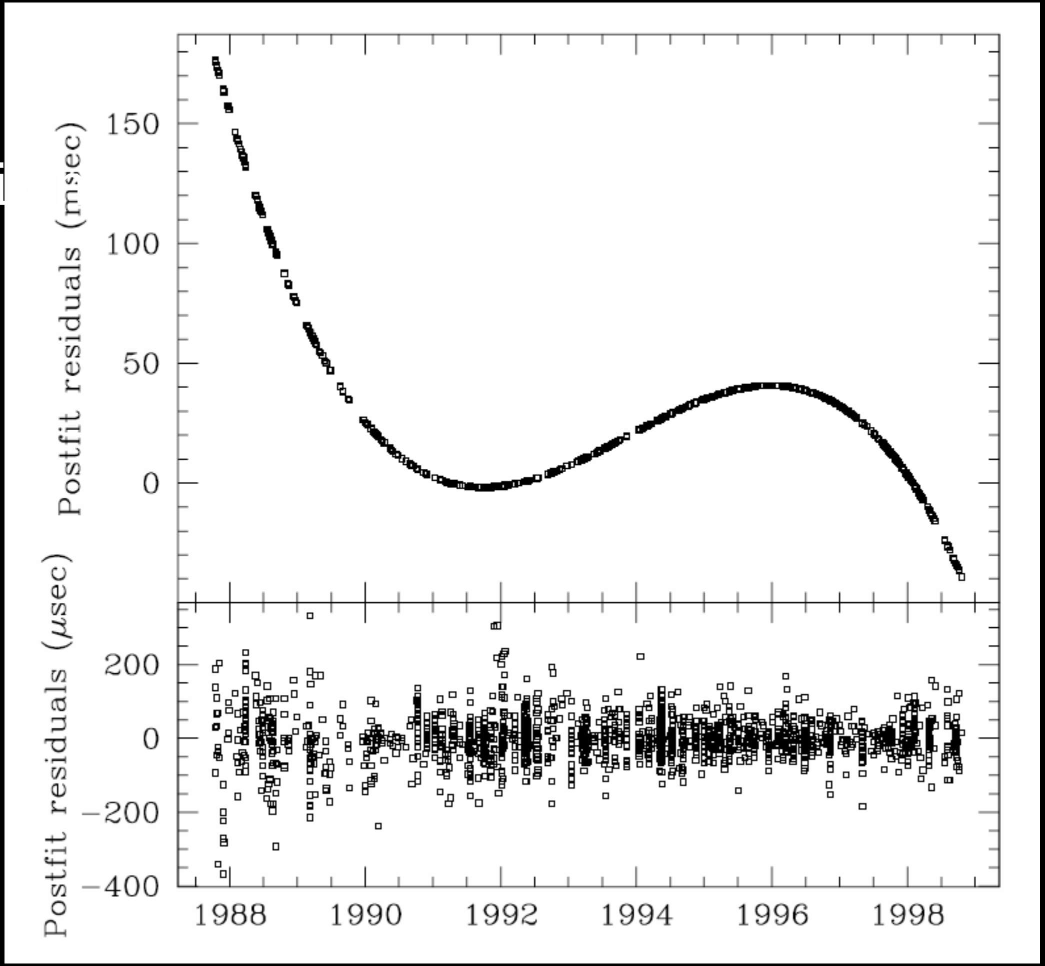
PSR B1620-26: has a white dwarf companion in a 191 day, low eccentricity orbit ($e = 0.025$)

PSR B1620-26

12 years

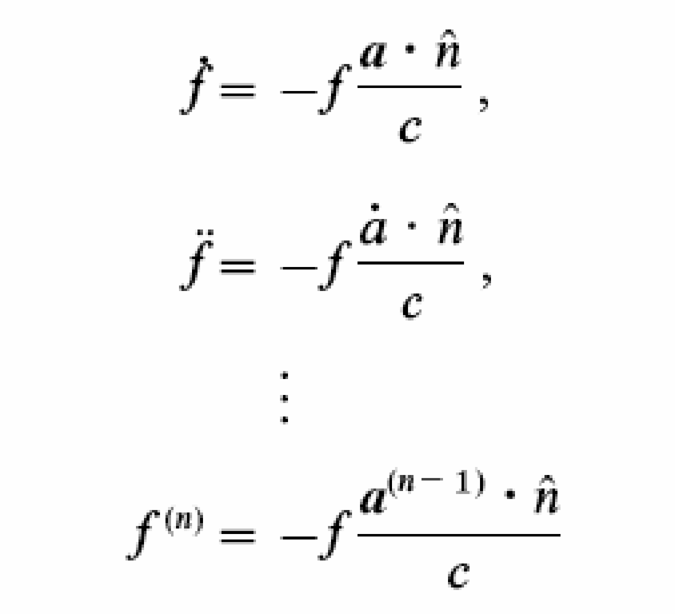
~31 000 000 000 rotati
40 ms precision

Spin period P (ms)	11.0757509142025 (18)
Spin frequency f (Hz)	90.287332005426 (14)
$\dot{f}$ (s^{-2})	-5.4693 (3) $\times 10^{-15}$
$\ddot{f}$ (s^{-3})	1.9283 (14) $\times 10^{-23}$
$f^{(3)}$ (s^{-4})	6.39 (25) $\times 10^{-33}$
$f^{(4)}$ (s^{-5})	-2.1 (2) $\times 10^{-40}$
$f^{(5)}$ (s^{-6})	3 (3) $\times 10^{-49}$



Thorsett et at, ApJ, 1999

Acceleration of PSR B1620-26 along the line of sight

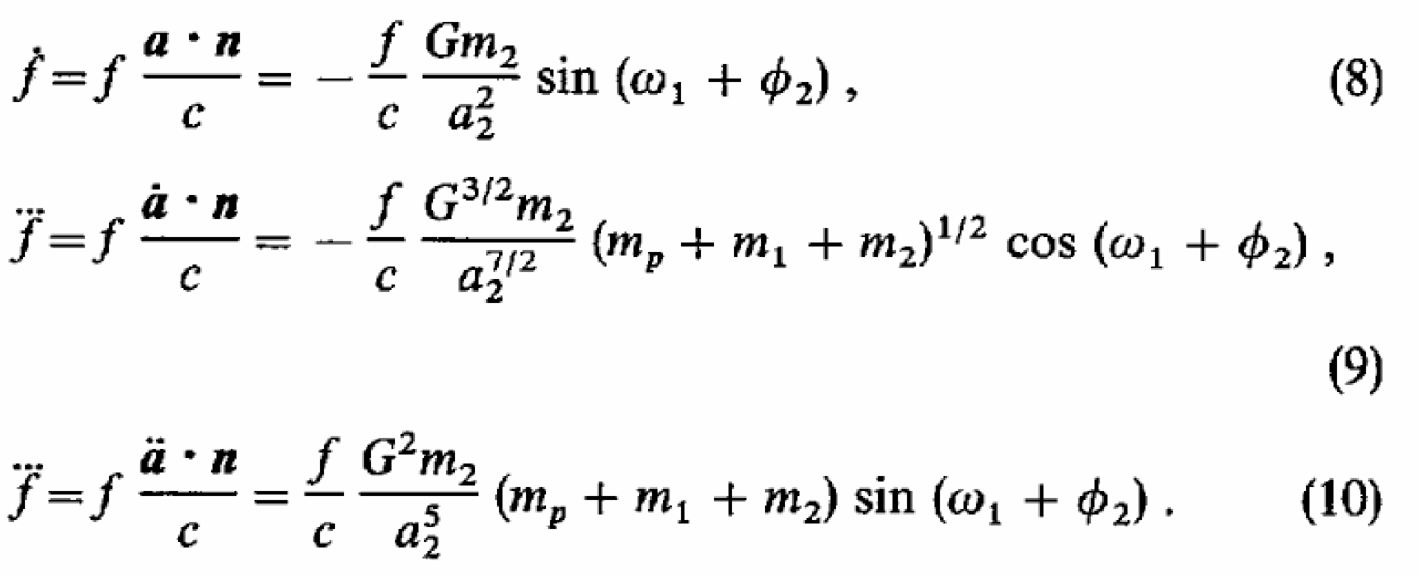


$$\dot f = -f\frac{\mathbf{a}\cdot\hat{n}}{c},$$

$$\ddot f = -f\frac{\dot{\mathbf{a}}\cdot\hat{n}}{c},$$

$$\vdots$$

$$f^{(n)} = -f\frac{\mathbf{a}^{(n-1)}\cdot\hat{n}}{c}$$



$$\dot f = f\,\frac{\mathbf{a}\cdot\mathbf{n}}{c} = -\frac{f}{c}\,\frac{Gm_2}{a_2^2}\sin(\omega_1+\phi_2)\,, \tag{8}$$

$$\ddot f = f\,\frac{\dot{\mathbf{a}}\cdot\mathbf{n}}{c} = -\frac{f}{c}\,\frac{G^{3/2}m_2}{a_2^{7/2}}(m_p+m_1+m_2)^{1/2}\cos(\omega_1+\phi_2)\,, \tag{9}$$

$$\dddot f = f\,\frac{\ddot{\mathbf{a}}\cdot\mathbf{n}}{c} = \frac{f}{c}\,\frac{G^2m_2}{a_2^5}(m_p+m_1+m_2)\sin(\omega_1+\phi_2)\,. \tag{10}$$

Rasio, ApJL, 1994

HST images of M4

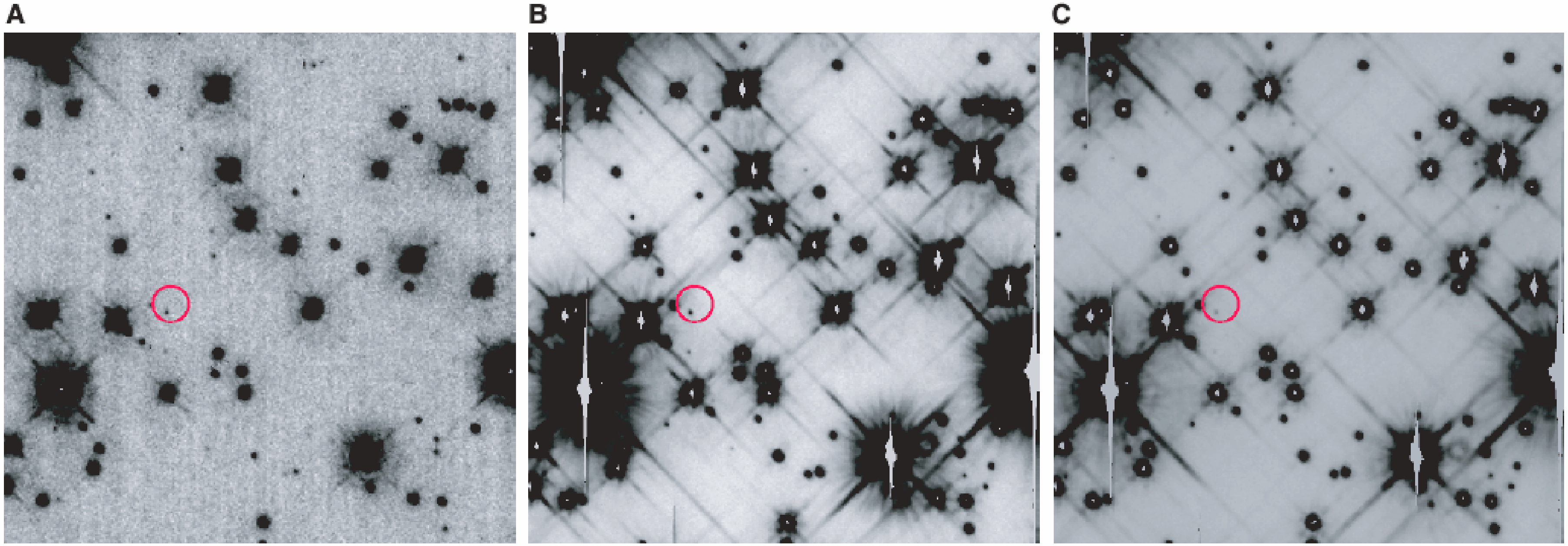


Fig. 1. (A to C) Hubble Space Telescope images of the field where the pulsar is located. The position of the pulsar is indicated by the center of the circle, which has a radius of 0.7″. The three images are the U (F336W), V (F555W), and I (F814W) bandpasses, which are wide-band filters centered on 336 nm, 555 nm, and 814 nm, respectively.

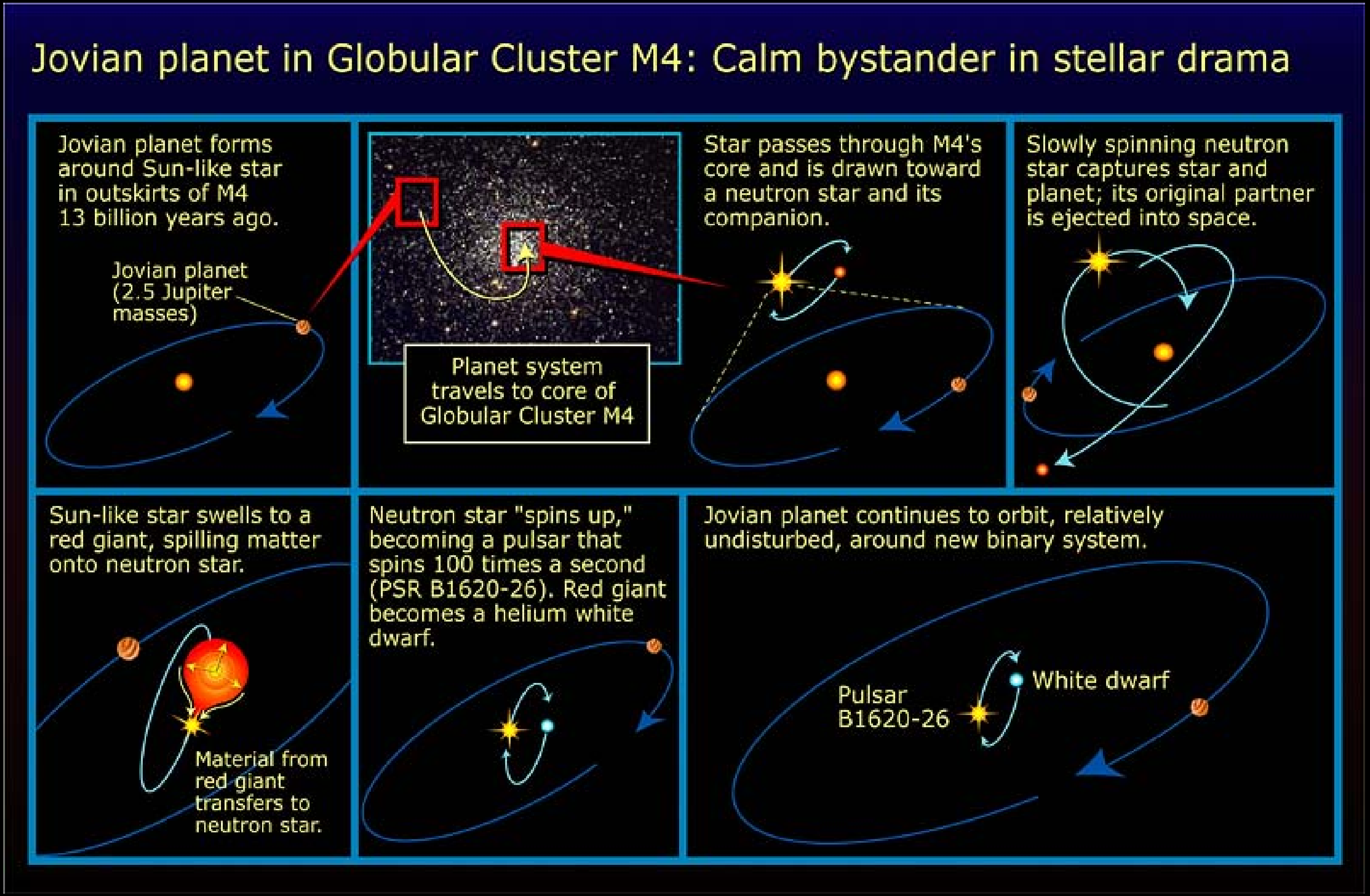
White dwarf: 0.34 +/- 0.04 M_{Sun}, age ~500x10^6

Orbital inclination of the pulsar-WD system: ~55 deg
(assuming the pulsar mass of 1.35 M_{sun})

Planet: semi-major axis of 23 AU, mass ~2.5 +/- 1 M_{Jup}

Sigurdsson et al, Science, 2003

A possible formation scenari



Jovian planet in Globular Cluster M4: Calm bystander in stellar drama

Jovian planet forms around Sun-like star in outskirts of M4 13 billion years ago.

Planet system travels to core of Globular Cluster M4

Star passes through M4's core and is drawn toward a neutron star and its companion.

Slowly spinning neutron star captures star and planet; its original partner is ejected into space.

Sun-like star swells to a red giant, spilling matter onto neutron star.

Material from red giant transfers to neutron star.

Neutron star "spins up," becoming a pulsar that spins 100 times a second (PSR B1620-26). Red giant becomes a helium white dwarf.

Jovian planet continues to orbit, relatively undisturbed, around new binary system.

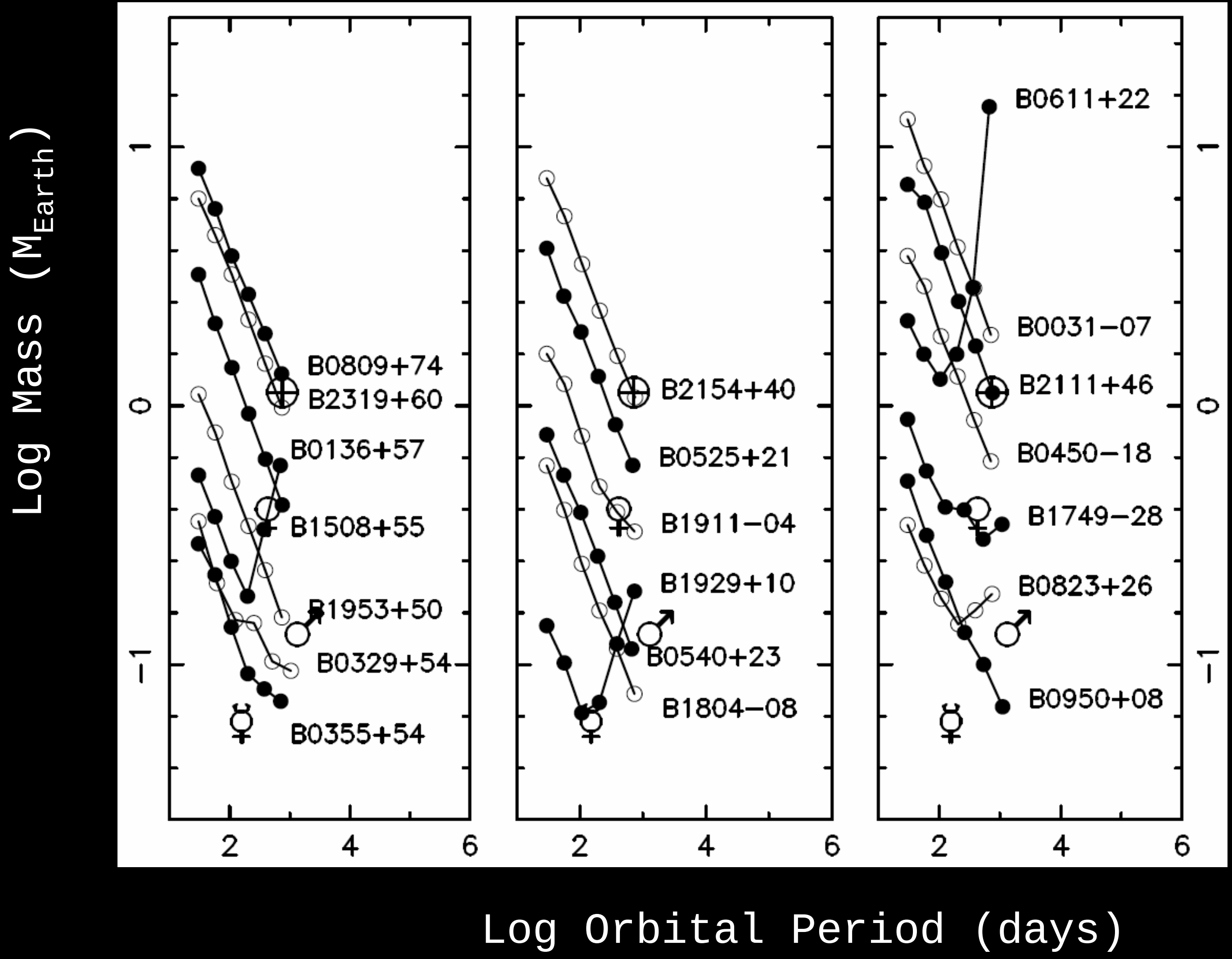
Implications

- No transiting planets (i.e. short period ones, “hot Jupiters”) were found in the globular clus 47 Tucanae

- Planets can form in low metallicity environment all

- These two facts may reflect a metallicity depen in the migration mechanisms or that the crowding the clusters may suppress migration but not forr of planets

Limits to planets around normal pu



Konacki, Ph.D. Thesis, 2000

Planets around white dwarfs

- Stars with masses <= 8 M_{Sun} end up as white dwa

- Even though stars will loose a significant par mass on the way to WD, planets with orbits larg (a > 5 AU) will easily survive RGB and AGB phas

- We are already finding long period planets aro giants

- White dwarfs are 10^3-10^4 times less luminous th progenitors - this opens the opportunity to det around WD by direct imaging

Bureligh et al, MNRAS, 2002

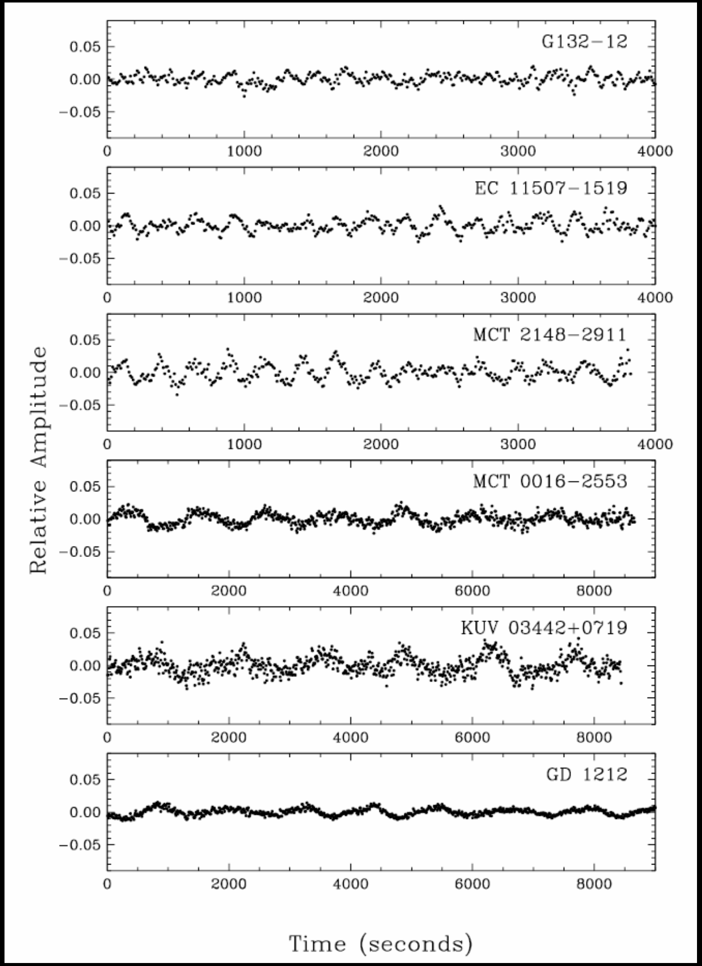
Imaging of white dwarfs

- Debes et al, ApJ, 2005, 2006, with HST and f
the ground, no planets found

- Mullally et al, infrared photometry with Spi
no planets found

Photometry of pulsating white dwa

- Papers by Kepler et al and Winget et al - no planets found



Gianninas et al, astro-