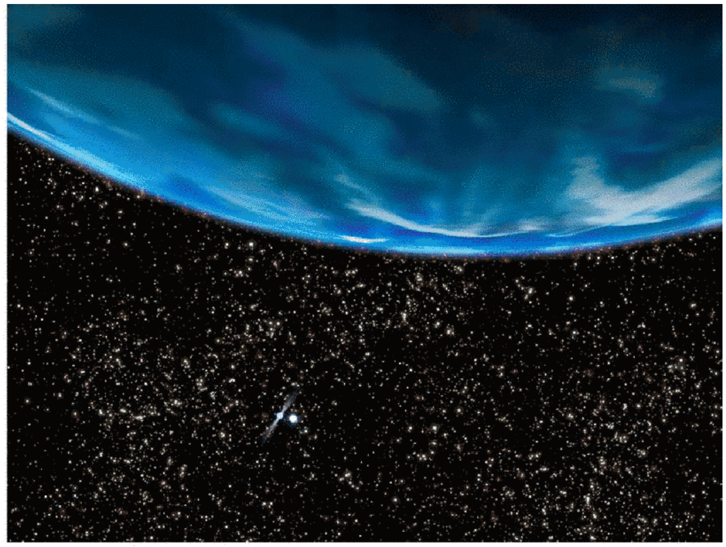
The Planet in M4



Fred Rasio

Theory: Eric Ford, Kris Joshi

Data: Ingrid Stairs, Steve Thorsett

Conclusions

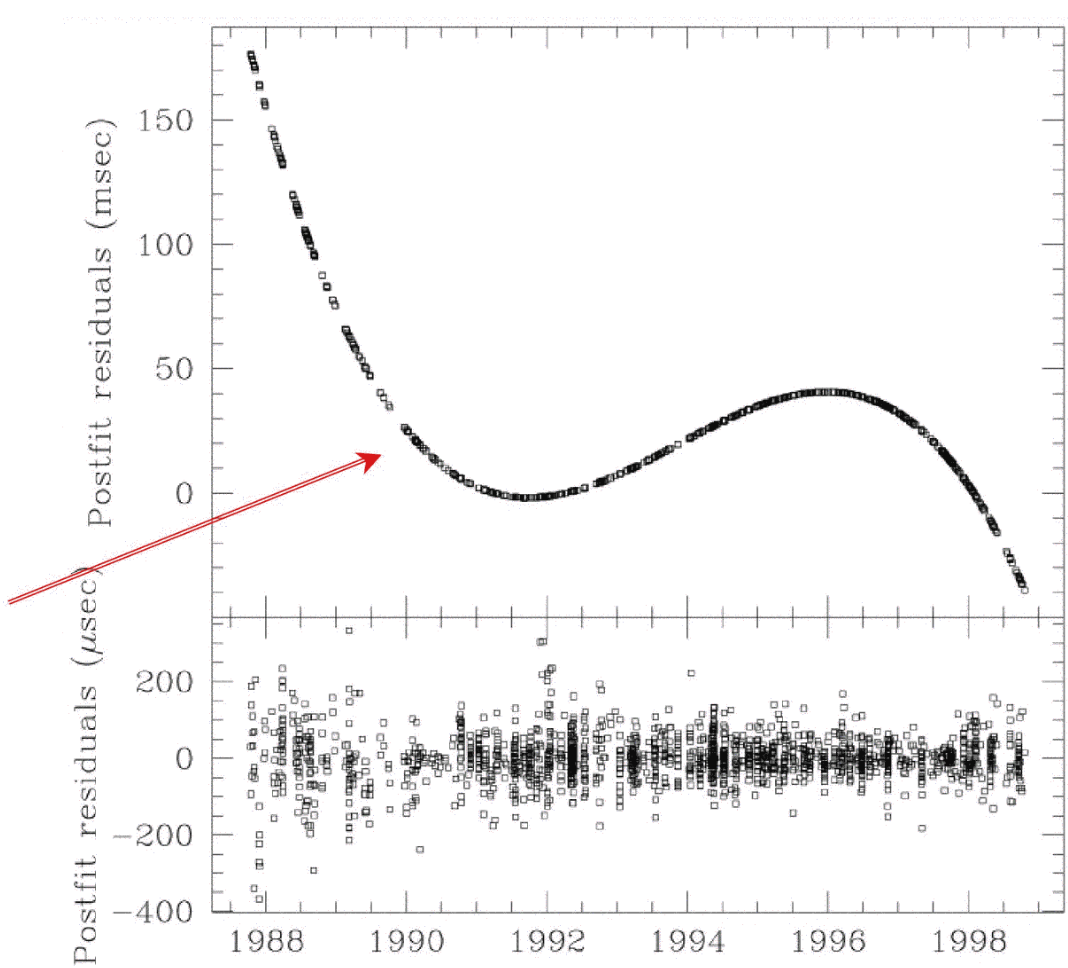
- Detection of a planet in M4 is confirmed
- Planet most likely came from ordinary planetary system around cluster star
- Planet became detectable by capture around MSP following dynamical interaction
- Implies high fraction of stars with planets in globular clusters (?)
- Implies planet formation common in low-metallicity environments (??)

System summary

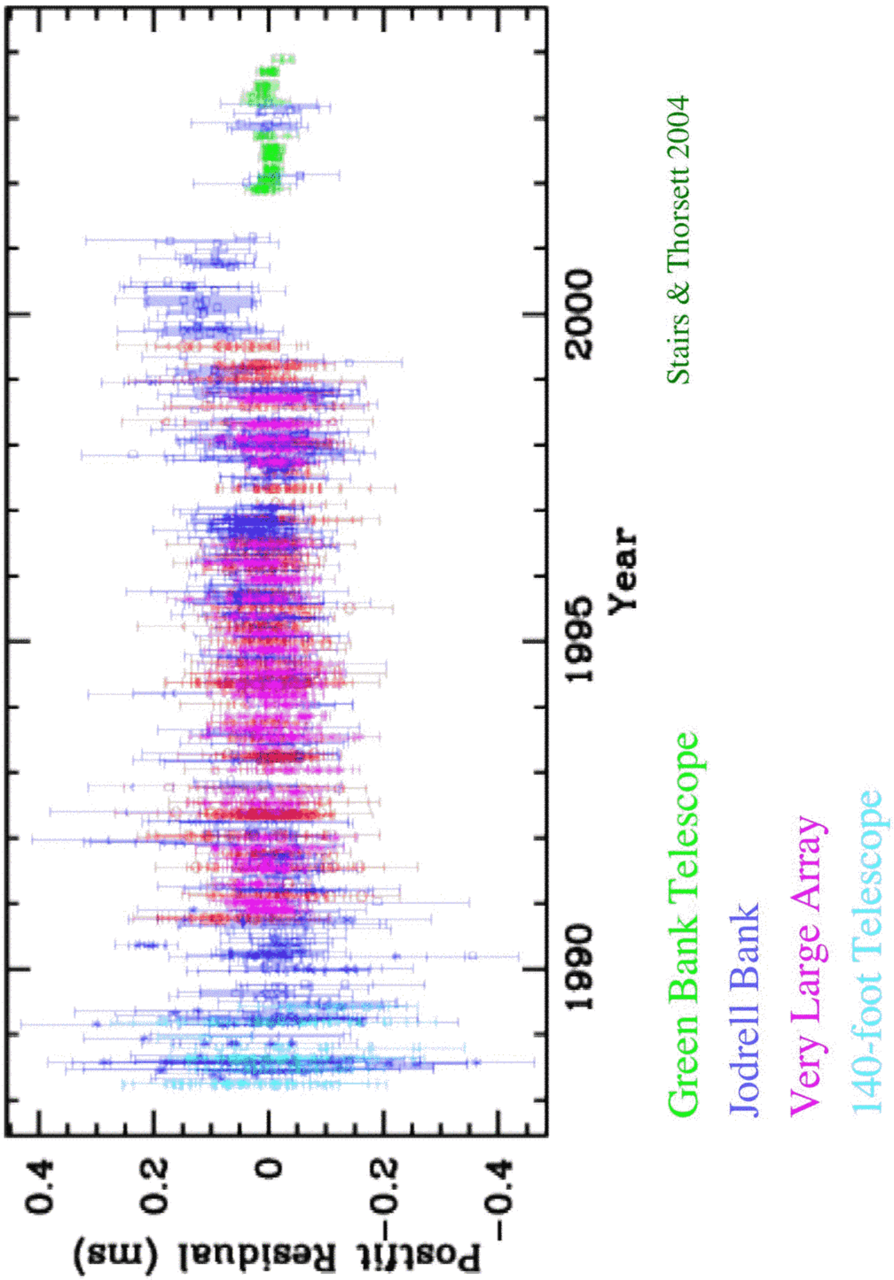
- Millisecond pulsar PSR B1620-26 (11 ms) discovered by Lyne *et al*. 1987
- In M4
  - Nearest globular cluster
  - Medium mass, density
  - Age 12.7 Gyr
- Binary companion
  - $P_b = 191$ d, e = 0.025
  - Companion mass m sin i = 0.28 M_o

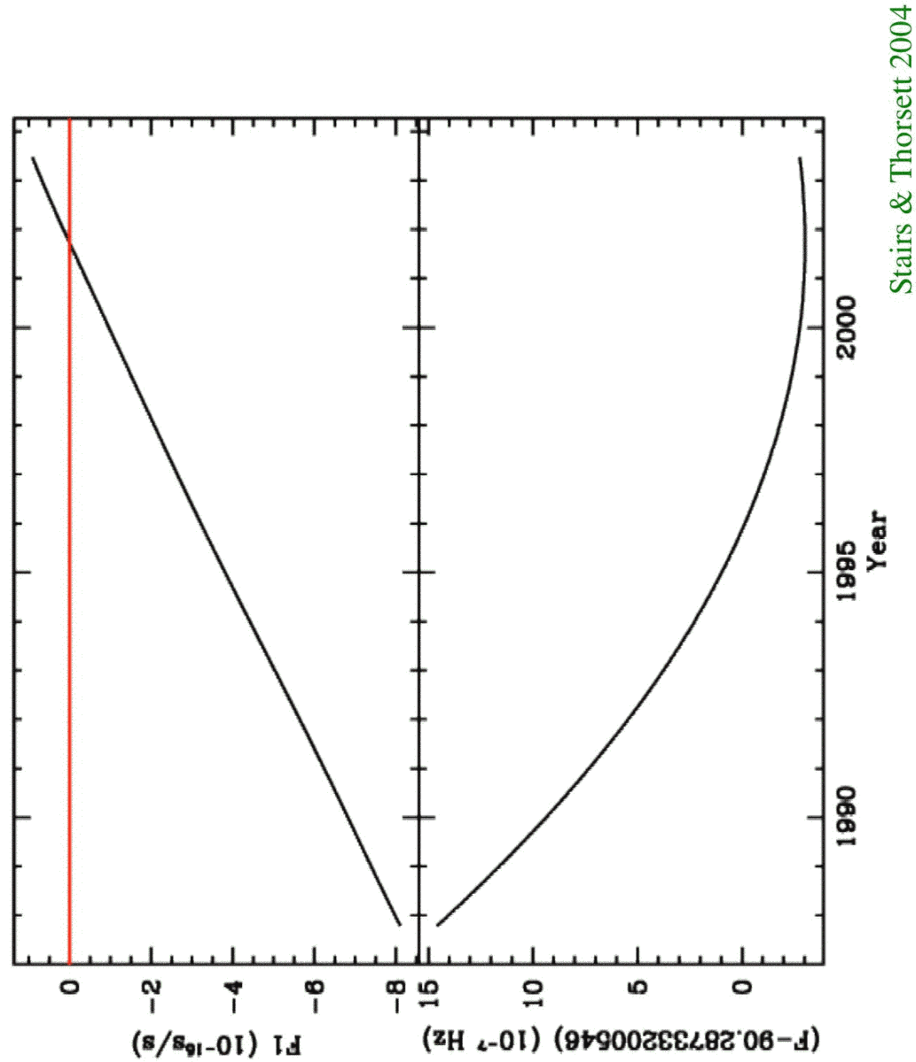
- Anomalous second frequency derivative: timescale for variation in spin-down rate ~ 10 yr
  - Too big to be intrinsic timing noise
  - Most obvious interpretation is varying gravitational acceleration
  - Even in a cluster, an unbound encounter (at ~10AU !) is extremely unlikely

⇐Triple system

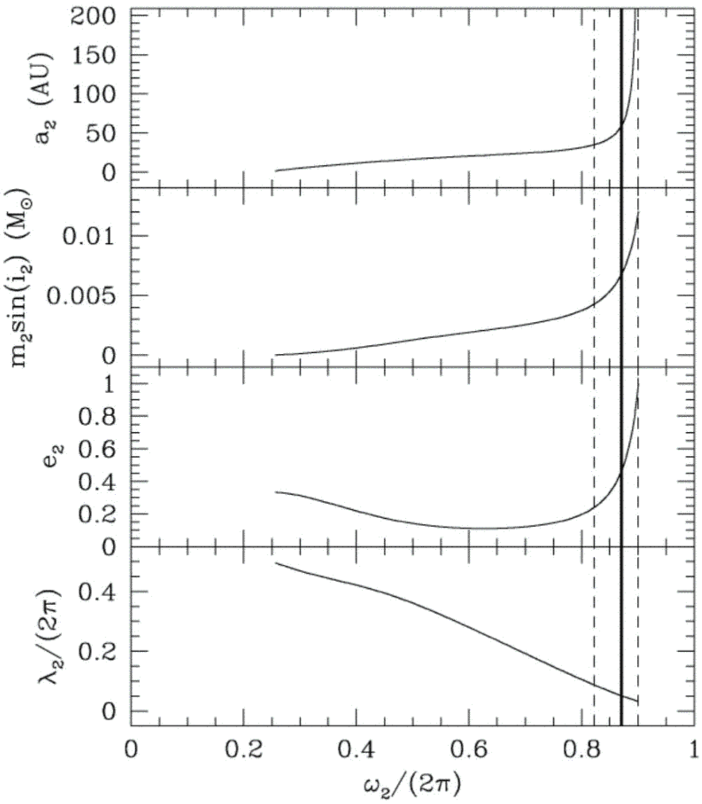


Best model with f, f-dot, and Keplerian orbit removed

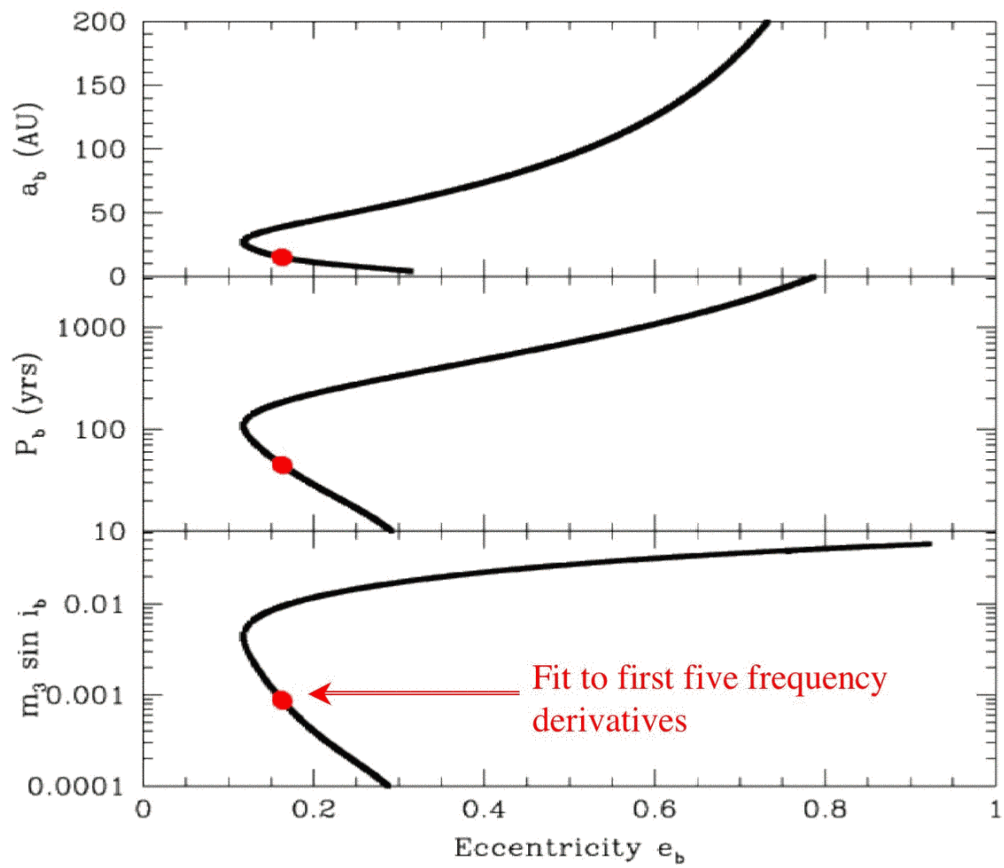

Postfit Residual (ms)
0.4
0.2
0
-0.2
-0.4
1990
1995
2000
Year
Stairs & Thorsett 2004
Green Bank Telescope
Jodrell Bank
Very Large Array
140-foot Telescope


F1 (10-16s/s)
0
-2
-4
-6
-8
(F-90.28733200546) (10-7 Hz)
15
10
5
0
1990
1995
2000
Year
Stairs & Thorsett 2004

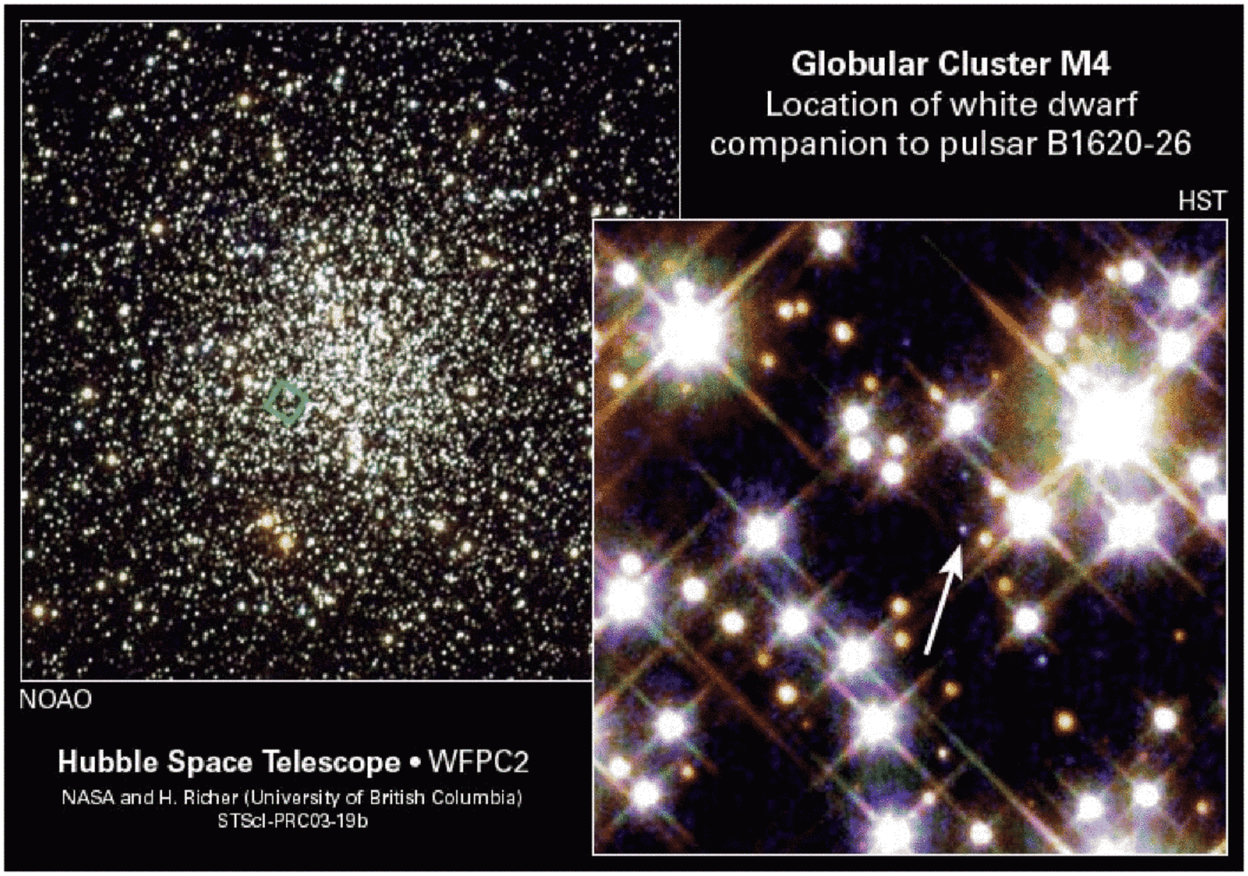
Orbit determination from frequency derivative data



Ford et al. 2000



Stairs & Thorsett 2004



RE

A Young White Dwarf Companion to Pulsar B1620-26: Evidence for Early Planet Formation

Steinn Sigurdsson,[1]* Harvey B. Richer,[2] Brad M. Hansen,[3] Ingrid H. Stairs,[2] Stephen E. Thorsett[4]

The pulsar B1620-26 has two companions, one of stellar mass and one of planetary mass. We detected the stellar companion with the use of Hubble Space Telescope observations. The color and magnitude of the stellar companion indicate that it is an undermassive white dwarf (0.34 ± 0.04 solar mass) of age $480 \times 10^6 \pm 140 \times 10^6$ years. This places a constraint on the recent history of this triple system and supports a scenario in which the current configuration arose through a dynamical exchange interaction in the cluster core. This implies that planets may be relatively common in low-metallicity globular clusters and that planet formation is more widespread and has happened earlier than previously believed.

Messier 4 (M4 equals NGC 6121 and GC 1620−264) is a medium mass [$\sim 10^5$ solar mass ($M_\odot$)] globular cluster and the one closest to the Sun. It has a moderately dense ($\rho_0 \approx 3 \times 10^4\ M_\odot\ pc^{-3}$) core. The metal content of the cluster is 5% that of the Sun, with little variation in composition or age between different member stars. The cluster has a substantial population of white dwarfs (stellar remnants which have exhausted their nuclear fuel), recently detected in deep Hubble Space Telescope (HST) observations (*1*, *2*), that have been used to determine an age for the cluster of $12.7 \times 10^9 \pm 0.35 \times$

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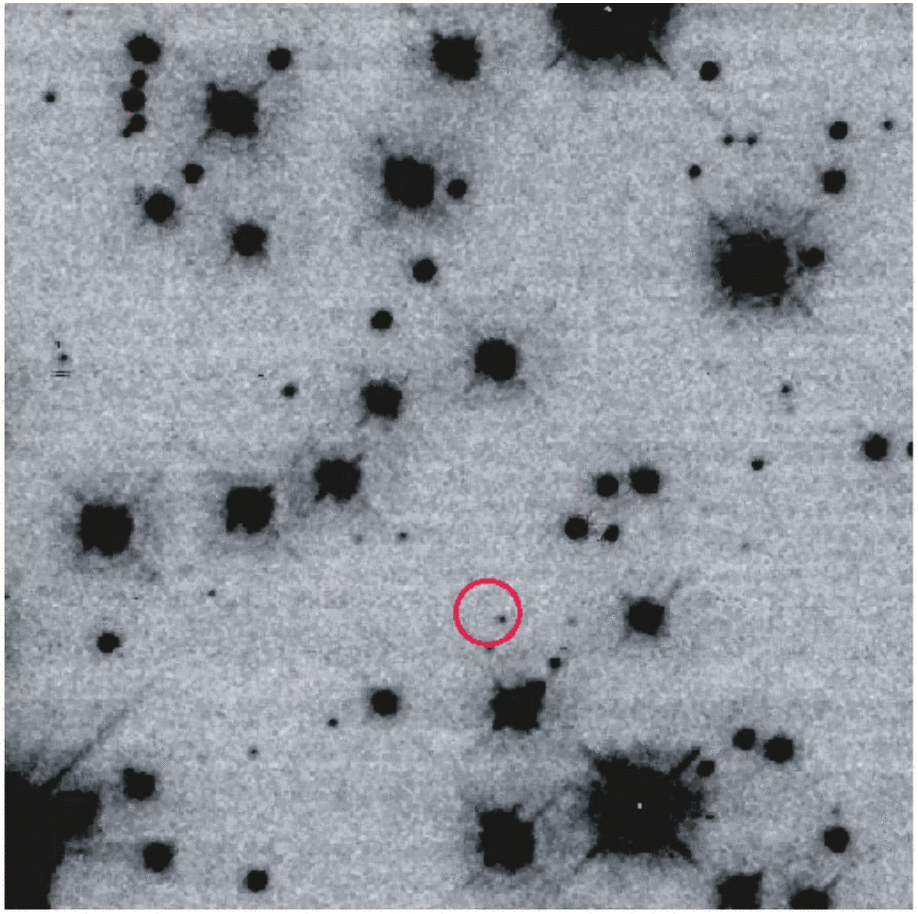
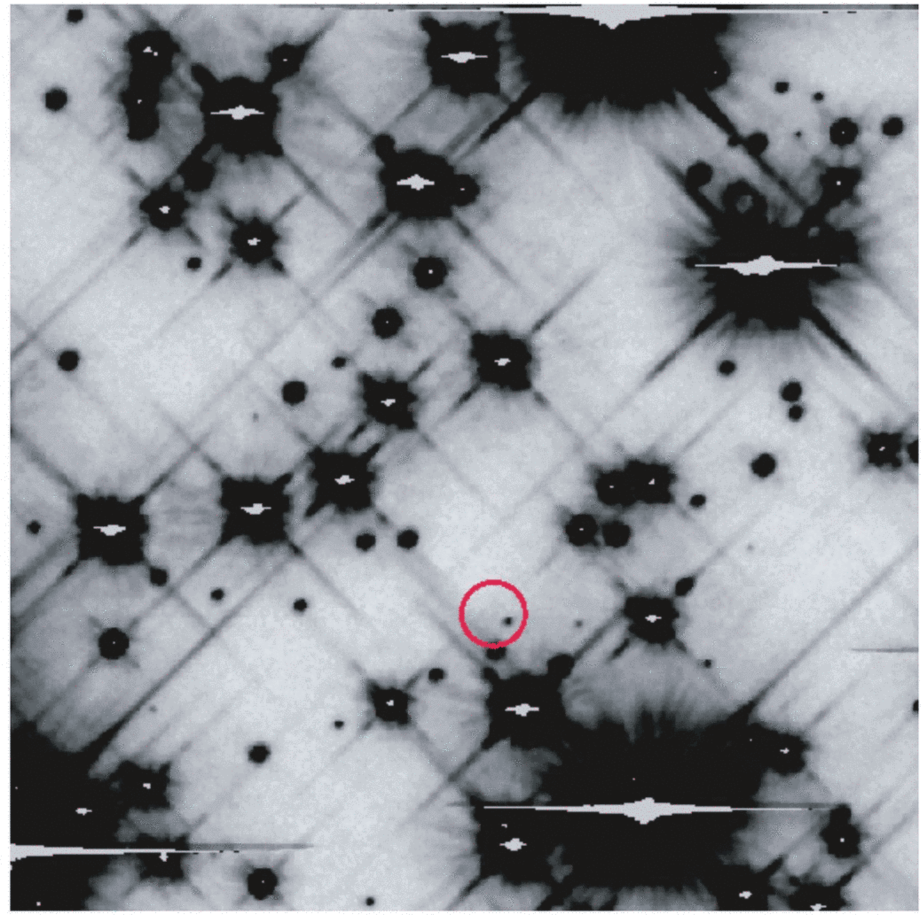
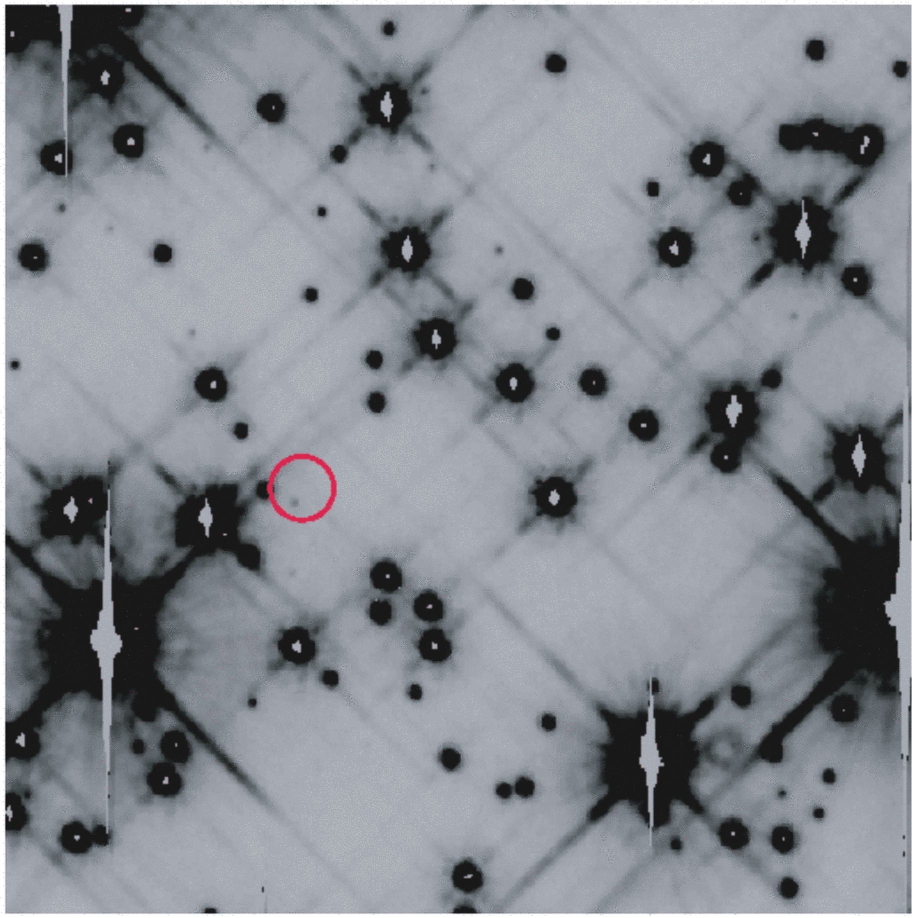


U (F336W)
0.7 arcsec circle



V (F555W)

I (F814W)



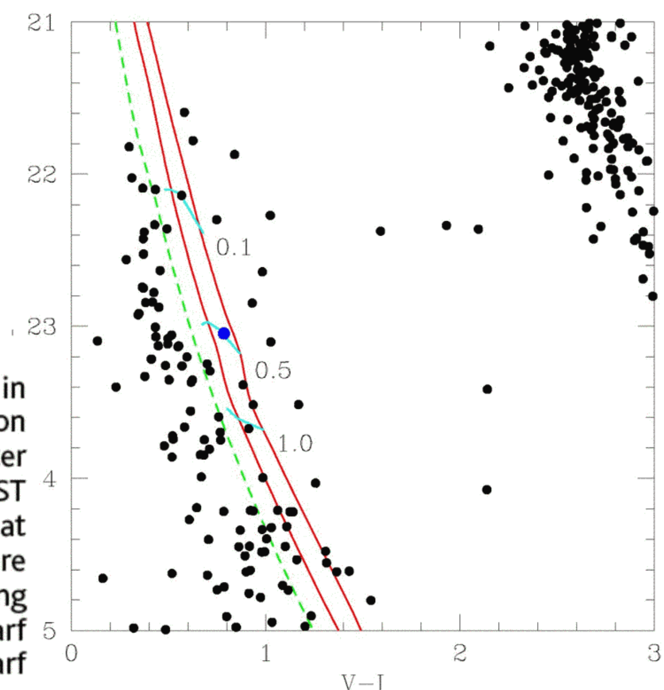


Fig. 2. The location of the pulsar companion in the color-magnitude diagram. The companion is plotted in blue and the rest of the cluster stars [including those from several other HST fields covering a much wider area than that discussed in (*22*) and that shown in Fig. 1] are in black. The green dashed line is the cooling curve for a 0.5-$M_\odot$ carbon-oxygen white dwarf (the upper envelope of the normal white-dwarf cooling sequences). The red curves are cooling curves for 0.3- and 0.4-$M_\odot$ helium-core white dwarfs with hydrogen envelopes. The three short cyan curves are isochrones (helium core only) at 0.1×10^9, 0.5×10^9, and 1.0×10^9 years, respectively. Thus, the pulsar companion is clearly undermassive and young, as expected from the evolutionary scenario.

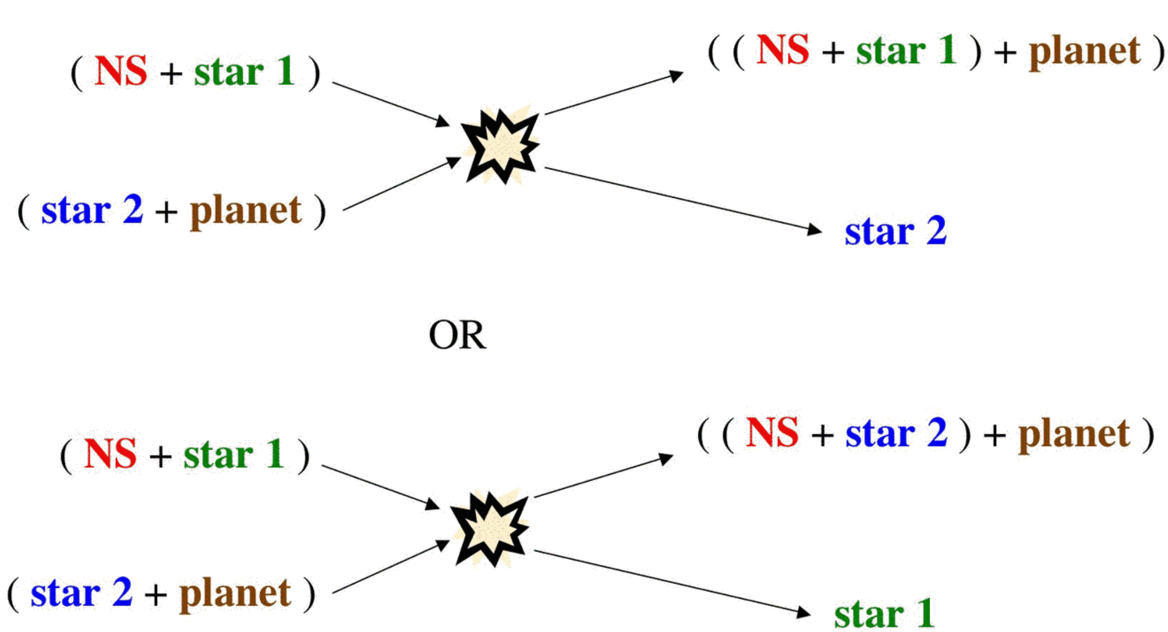
Dynamical Formation Process

- Dynamical interactions occur at high rates in dense globular cluster cores (density of stars in M4 core is ~ 10^6 times higher than in solar neighborhood!)
- Objects most likely to interact are binary systems (**star** + **star** or **star** + **planet**) since they have the largest cross sections

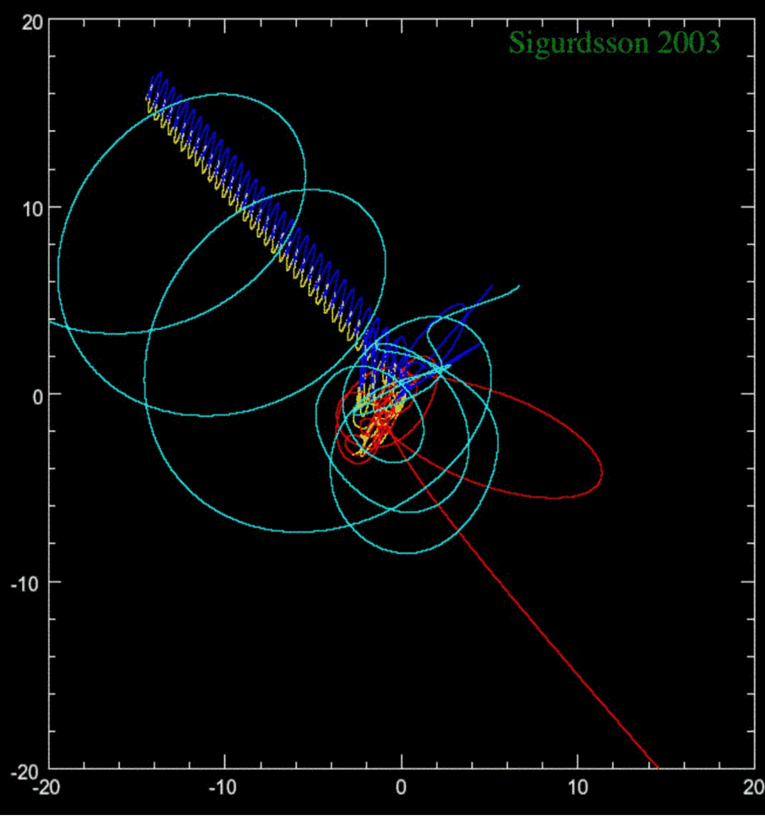
$$T = \frac{3 \times 10^9}{\langle n_4 \sigma_{AU} v_{10} \rangle} \text{ yr}$$

- Most likely formation process for triple: 4-body collision between **NS** + **star** binary and **star** + **planet** system (Sigurdsson 1992, ApJ 399, L95; 1993, ApJ 415, L43; Rasio, McMillan, & Hut 1995, ApJ 438, L33; Ford et al. 2000, ApJ 528, 336)

Exchange Interactions



A Typical Exchange Interaction

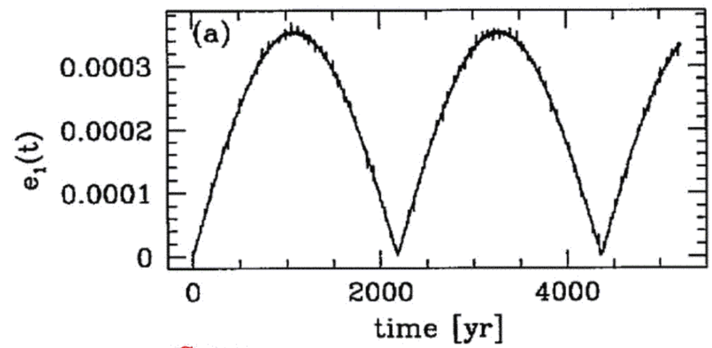


Eccentricity Perturbations

- Inner orbit has e = 0.025
- This is unusually large! (Typicallly e ~ 0.0001 - 0.000001 from tidal circularization)
- Possible explanations:
  - Perturbation by a passing star: very unlikely! (would have removed planet)
  - Secular perturbations in triple: not from Newtonian gravity alone! (Rasio 1994, ApJ 427, L107)
- Current best explanation: resonance between Newtonian (octupole) perturbations and GR precession of the inner orbit (Ford et al. 2000, ApJ 528, 336)

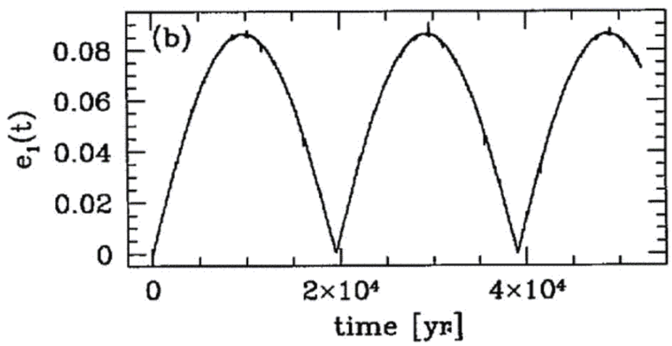
Eccentricity Perturbations: Newtonian only

Planet:

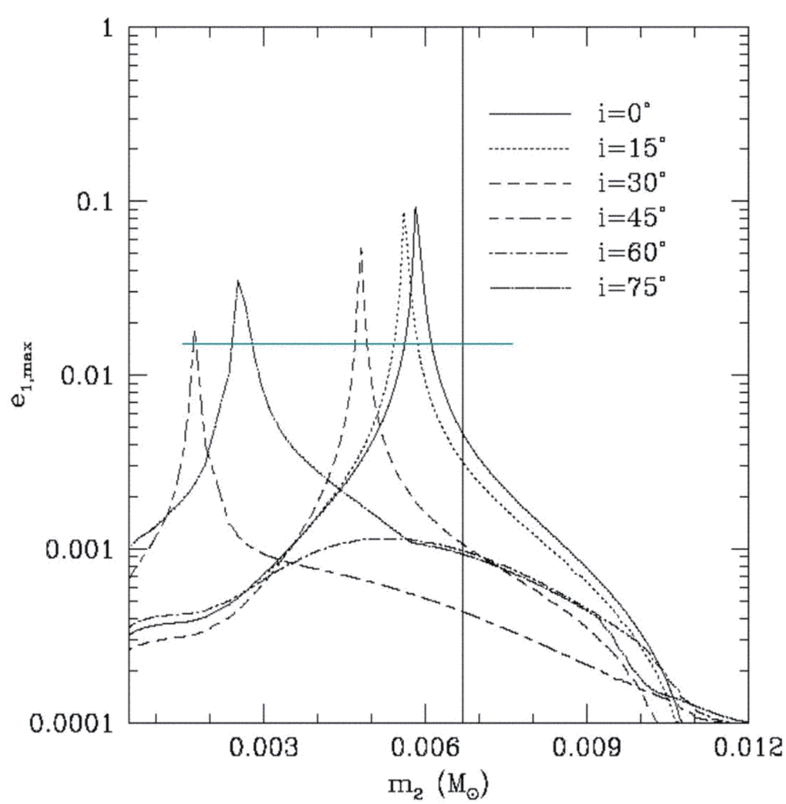


Rasio 1994

Star:



Eccentricity Perturbations: Newtonian + GR



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- Planet became detectable by capture around MSP following dynamical interaction
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