Pulsars and Pulsar Planets

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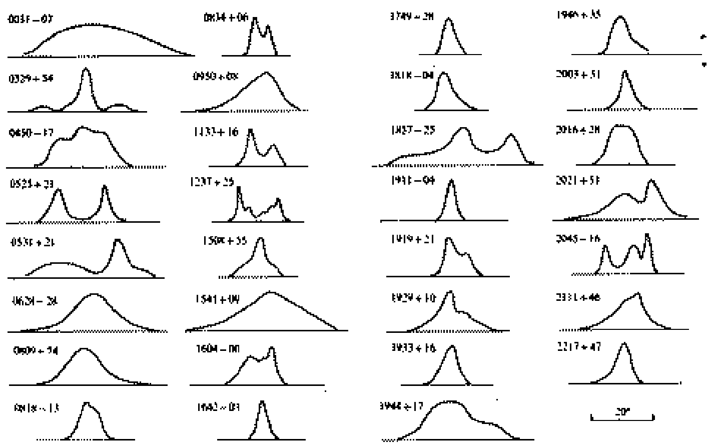
Today's lecture will explain

- What is a pulsar?
  A rapidly rotating magnetized neutron star
- Why do we (AST205) care about them?
  The first extrasolar planets (0.02, 4.3, and 3.9 $M_{\oplus}$) were discovered around PSR B1257+12 in 1992
  $M_{moon} = .012\ M_{\oplus}$!!
- How is it possible to detect such low mass planets?
  Precision timing of radio pulses

Pulsars Pulse

- Pulsars emit regularly spaced and periodically repeating pulses of radiation, usually at radio wavelengths:

  $\nu \sim 1500$ MHz $\rightarrow$ $\lambda = c/\nu \sim 20$ cm



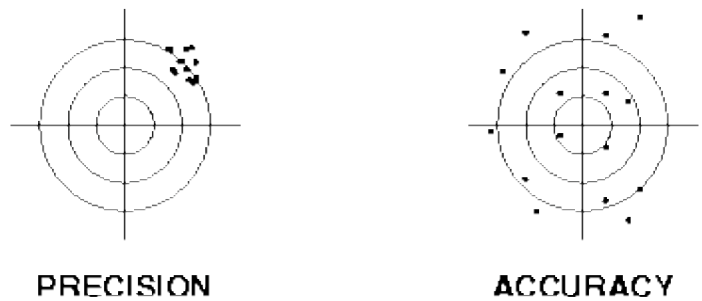
"Here was some silly lot of Little Green Men using my telescope and my frequency to signal planet Earth!"
-Jocelyn Bell, 1967

← (pulse profiles)

Pulsars Make Good Clocks

- Pulse period is quite fast: 1.1 ms < P < 4 s
  - Most have .25 s < P < 2 s, B1257+12 has P = 6.6 ms.
- Individual pulse arrival times can be measured with μs = 10^{-6} s precision.
  - This will make orbital motion of pulsar (and Earth) easy to detect.
- P is very stable, can be determined up to accuracy of 10^{-17} s!
- Pulses slow with time:
  - Change in P per unit time (dP/dt) around 10^{-15} s/s

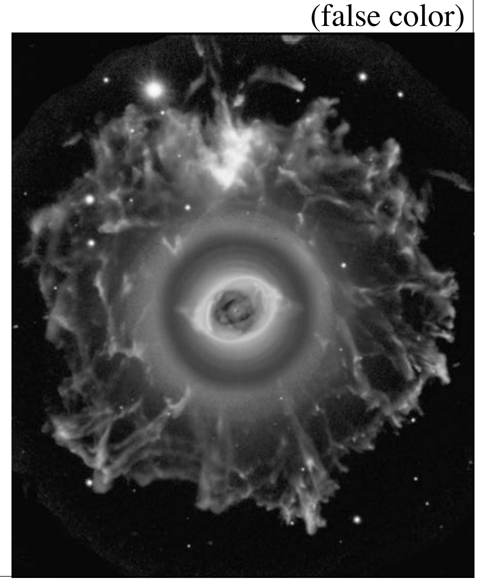
Precision vs. Accuracy



- Precise = well defined but not necessarily correct!
- Accurate = correct but perhaps with scatter
- Multiple accurate measurements (e.g. μs measurement of pulse arrival times) give an average value that is precise and accurate (e.g. P determined to 10^{-17} s).

Post Main Sequence Evolution of Low Mass (< 8 $M_\odot$) Stars

Cat's Eye Nebula (false color)



- A common, ordinary life
- Exhaust H in core, some He burning to C & O
- Expand to become red giants
- Lose outer atmosphere
- Fade into obscurity as white dwarfs supported by e^- degeneracy pressure
  - High densities: $\rho_{WD} \sim 3M_\odot/(4\pi R_\oplus^3) \sim 10^6$ g/cm^3!
- Novas and SN may occur in low mass binaries.

The Spectacular Demise of High Mass Stars (> 8 $M_\odot$)

- Live fast & die young like rock stars
- Core fuses H all the way to Fe (iron)
- No energy can be extracted by fusing Fe
- Lacking support, core collapses and bounces, giving a supernova (Type II) explosion.
- At these extremely high temperatures and pressures heavy nuclei disintegrate into p^+, n, and e^-, undoing much of the fusion. (Easy come easy go!)
- Collapse cannot be halted by e^- degeneracy neutronization occurs:

  $p^+ + e^- \rightarrow n + \nu$ (ν is the puny neutrino particle)

Neutron Stars as End State of (Type II) Supernovae

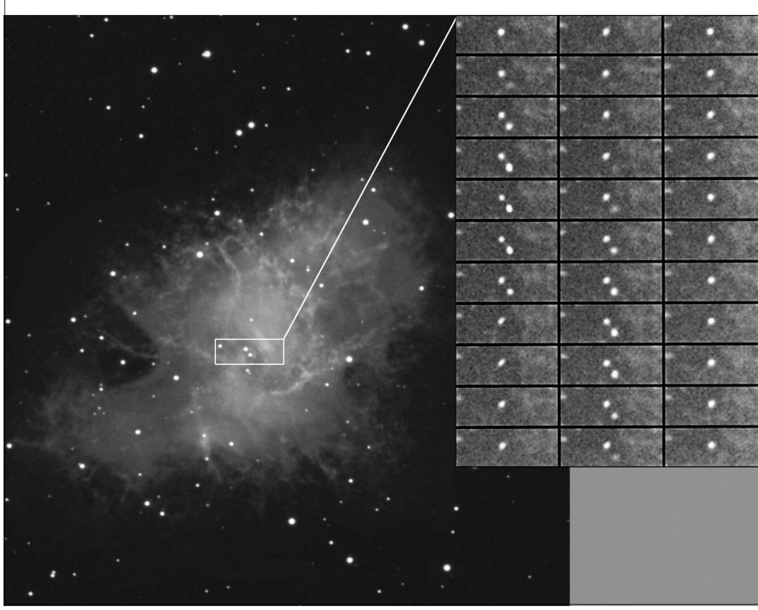
- A neutron-rich core is left behind, supported by neutron degeneracy pressure.
- Density of an atomic nucleus $\rho_{NS} \sim 10^{14}$ g/cm^3:
  - $M_{NS} \approx 1.4\ M_\odot$, $R_{NS} \approx 15$ km
- Collapse gives:
  - Rapid rotation by angular momentum conservation
  - A strong magnetic field by "field freezing," i.e. the field strength increases when compressed rapidly.
- Note that very high mass stars (> 20 $M_\odot$) collapse all the way to a black hole.

Pulsars in Supernova "Remnants"

- Supernova explosions glow for a "short" time: ~10^5 yr
- Neutron stars pulse for ~10^7yr
- Some young pulsars should be in SN remnants: 3 are found!
- Confirms the connection between pulsars & SN.

Crab Nebula, remnant of a supernova that appeared on July 4, 1054 A.D., an event recorded by Chinese and Anasazi Indian astronomers. It was visible in daylight for 23 days!

A Visibly Pulsing Crab

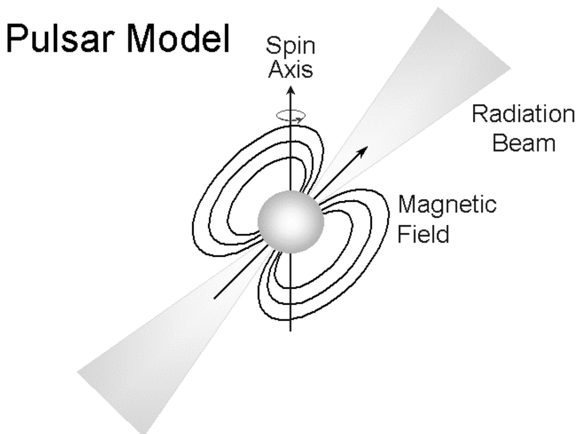


These images taken at 1 ms intervals show optical pulses of the Crab Pulsar.

P = .033 sec

(Phase adding over 2 hrs needed.)

Pulsars as Lighthouse Beacons



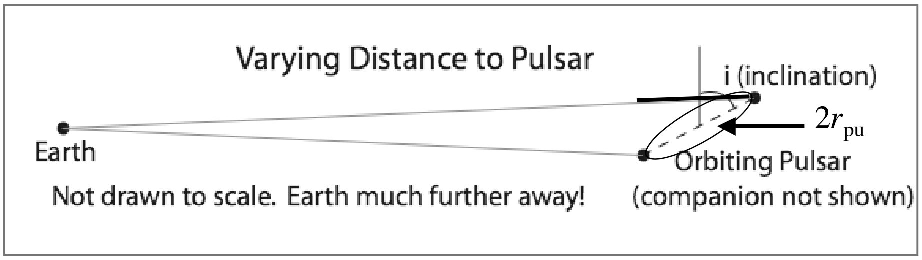
Pulsars are spinning, magnetized neutron stars that emit light in direction of mag. field.

- Magnetic field axis and rotation axis are misaligned
- Light (not blackbody) emitted in a cone along magnetic field
- Radiation enters our line of sight once per rotation period (if we are aligned correctly)
- Shape of pulse tells us about the structure of the cone, e.g. how narrow and how many peaks.

Detecting planets by reflex motion of stars (review)

- Radial velocity technique
  - Periodic wobble of star gives Doppler shift in stellar absorption lines.
  - Measure Δ□□ $v_{\star}\sin(i)$ and P_{pl}
  - Gives a (semimajor axis) and $M_{pl}\sin(i)$
  - Works for larger, close-in planets
  - 100 planets found
- Astrometric motion
  - Measure changing positions of stars in 2D, and P_{pl}.
  - Gives a and M_{pl}, independent of inclination
  - Should detect distant, massive planets
  - Better instruments needed to find planets.

Detecting Pulsar Companions (including planets)



- Motion of pulsar changes distance to Earth and pulse time of arrival (TOA)
- A circular pulsar orbit of radius r_{pu} changes the TOA by

$$\Delta t = \pm r_{pu}\sin(i)/c.$$

- With μs pulse precision, 0.3 km motions are detectable!

Detecting Pulsar Planets

- Observables
  - $\Delta t = r_{pu}\sin(i)/c$ the amplitude of TOA variations
  - P_{pl}, the orbital period
    - can be expressed in terms of $a \approx r_{pl}$, the semi-major axis or size of planet's orbit using:
      - Kepler's Law $(P_{pl}/2\pi)^2 \approx r_{pl}^{\,3}/(GM_{pu})$ (assumes $M_{pl} << M_{pu}$)
      - $M_{pu} \approx 1.4\ M_\odot$ for the pulsar mass
- Express Δt as function of r_{pl} and M_{pl} (planet mass)
  - Center of mass relation: $r_{pu} = r_{pl}\, M_{pl}/M_{pu}$
  - Detecting pulsar planets is "easy":

$$\Delta t = \frac{r_{pl}}{c}\,\frac{M_{pl}\sin(i)}{M_{pu}} \approx 1.1\,\frac{r_{pl}}{\mathrm{AU}}\,\frac{M_{pl}\sin(i)}{M_{\oplus}}\ \mathrm{ms}$$

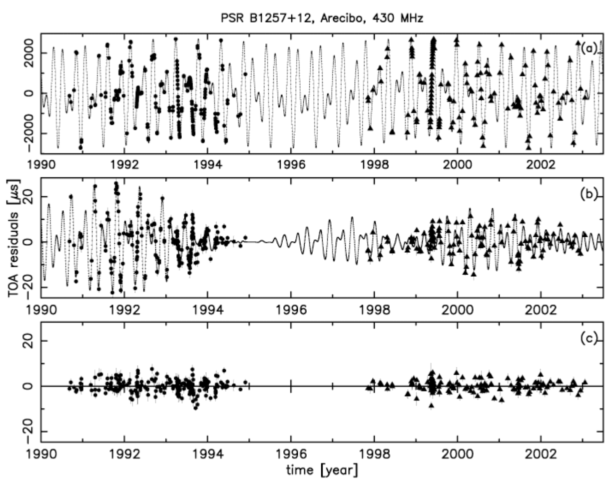
Comparison of Planet Detection Methods

Method	Signal	Scaling
Radial Velocity	$v_\star \sin(i)$	μ $M_{pl} \sin(i)/\sqrt{a}$
Astrometry	Δ	μ $a\, M_{pl}/D$
Pulsar Timing	$\Delta\, t$	μ $a\, M_{pl} \sin(i)$

- D is distance to star. All methods require that the star is close enough to observe a strong signal.
- Δ is the change in angular position due to position wobble

Pulsar B1257+12

- 3 planet system
  - A: 0.020 $M_\oplus$, $a = 0.19$ AU
  - B: 4.3 $M_\oplus$, $a = 0.36$ AU
  - C: 3.9 $M_\oplus$, $a = 0.46$ AU
- The first (1992) and only confirmed pulsar planets
- B & C interact strongly (by gravity) since they're near resonance: $P_C/P_B = 1.491 \approx 3/2$
- These non-Keplerian interactions give $\sin(i)$
- Coplanarity ($i_B = 53°$, $i_C = 47$ °) implies disk origin



Konacki & Wolszczan (2003)

Implications of Pulsar Planets

- How can Earths be rare if they form in the extreme environment that follows a supernova explosion?
- Pulsar planets certainly not in "habitable zone."
- Cannot draw strong conclusions from a single system in a small sample:
  - There are ~1000 known pulsars. So aren't pulsar planets rare?
  - Only ~10 millisecond pulsars lack a stellar binary companion … and one has planets.