Observational Evidence for Neutron Stars

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What are Neutron Stars?

• Very compact stars, but not black holes
  \[ M \approx 1 \, M_\odot \quad R \approx 10 \, \text{km} \]
  \[ \rho_{\text{crust}} \sim 10^9 \, \text{kg/m}^3 \quad \rho_{\text{inner}} \sim 8 \times 10^{17} \, \text{kg/m}^3 \]

• The hot residue of the collapsed core of a massive star
  – Result from type II, Ib, and Ic supernovae
  – Before collapse: about same M \quad R \approx 1000 \, \text{km}

• n, p, nuclei, e\(^{-}\), \(\gamma\), and \(\nu\) held together by gravity
  – Mostly neutrons
  – n, p, and e\(^{-}\) are all degenerate
  – Plasma almost completely opaque to photons
  – Initial cooling dominated by escaping neutrinos
What are Pulsars?

- Sources of short radiation pulses at very regular intervals
  - Periods range from ms to s
  - In radio, X-ray, gamma-ray, or all bands
- Light curve:
  - Usually 2 peaks per period
  - Peaks can have very different shapes

(Becker, 2009, “Neutron Stars and Pulsars“)
Pulsars (cont.)

• Rapidly rotating magnetic dipole, two radiation beams
• Powered by rotation, accretion, or magnetic fields
• Identification with neutron stars:
  – Only neutron stars with very high density can rotate this fast
  – Neutron stars have very strong magnetic fields
Radio Pulsars

• Majority of neutron stars
• Many ms radio pulsars are thought to be old (t \simeq 10^9\ yr)
• Small magnetic fields (B \lesssim 10^8 - 10^9\ G)

• Radio cooling pulsars: Vela, Geminga
  – T_{\text{surface}} \sim 10^5 - 10^6\ K
  – Thermal surface radiation mainly emitted from hot polar caps in soft X-rays and extreme UV

• Radio dim neutron stars
  – Some in SNR and some not
  – Have black-body X-ray emission
Magnetars

- Very strong magnetic fields: \( B \sim 10^{14} - 10^{15} \) G
  - Estimated to decay in \( 10^4 \) yr
- Soft-gamma repeaters (SGR): SGR 0525-66
  - Repeating soft-gamma and X-ray bursts
  - Typical bursts: 0.1 s with energies of \( 10^{41} \) erg
  - Highly irregular bursting activity
  - Bursts most likely associated with episodic releases of stresses caused by the evolution of magnetic fields
- Anomalous X-ray pulsars (AXP):
  - Pulsed X-ray emission
  - Period: 6 - 12 s
  - Luminosity: \( 10^{33} - 10^{35} \) erg/s
X-Ray Binaries

- Material from companion accretes onto neutron star (NS)
  - Angular momentum and mass transferred to NS
  - Increases the spin of NS
  - Material heats up and emits X-rays

- QPOs:
  Oscillation frequencies associated with Keplerian frequency of the innermost stable orbit and resonant frequencies in the accretion disk
Pulse Features

• Radio pulsars sometimes show giant ($\sim 10^2 - 10^3 \times$ larger than usual) pulses as short as 2 ns

• Pulsar timing noise: slow irregular or quasiregular variations of pulses
  – Over timescales of months or years
  – Random walks in the pulsar rotating rate, spindown rate, or pulse phase

• Free precession of pulsar spin axis
  – Periods: 7 days, 500 days
  – Evidence for a rigid neutron star crust
Glitches

- Sudden jumps of pulsar spin frequencies
- Followed by a slow partial relaxation
- Mainly observed in young radio pulsars

(Becker, 2009, “Neutron Stars and Pulsars“)
Nulling Behavior

- Abrupt cessation of emission for many pulse periods
- More frequent in older long-period pulsars

Pulsar Death Line

$P - \dot{P}$ diagram

$P =$ pulsar spin period

(Becker, 2009, "Neutron Stars and Pulsars")
Some Properties of Neutron Stars

• Surface gravity: \( \sim 7 \times 10^{12} \text{ m/s}^2 \)
  – Gravitationally lenses parts of its rear surface

• Escape velocity: \( \sim 100,000 \text{ km/s} \)

• \( T_{\text{inner}} \sim 10^{11} - 10^{12} \text{ K} \) of a newly formed star
  – Cools to: \( 10^9 \text{ K after a day } \quad 10^8 \text{ K after 100 years} \)
  – \( T_{\text{surface}} \sim 10^5 - 10^6 \text{ K} \) for older stars (\( > 10^4 \text{ yr} \))

• EoS poorly known

• Rotation slows down \( \sim 10^{-15} \text{ s per rotation} \)
  – Magnetic dipole radiation

• Born with high speed (\( \sim 400 \text{ km/s} \))
  – Imparted momentum-kick from supernova asymmetry
Measuring Mass

• Measuring mass and radius simultaneously of isolated neutron stars is difficult.

• Binary systems:
  – Keplerian orbits
  – Easier and more accurate measurements for radio pulsar binaries than for X-ray binaries
  – Deviations: accretion, tidal forces, and oscillations of companion

( Haensel, Potekhin, and Yakovlev, 2007, “Neutron Stars 1, Equation of State and Structure” )
Measuring Radius

- Infer from mass and gravitational surface redshift
- Analyzing thermal emission from surface
  - Have to assume a composition model
  - Unfortunately non-thermal emission usually dominates
  - But it is sufficient enough in older neutron stars \( (\gtrsim 10^4 \text{ yr}) \)
- Optical photometry of cooling isolated neutron stars
  - Good determination of the parallax (distance)
  - Vela: \( d = 293^{+19}_{-17} \text{ pc} \) \( R = 2.5 \pm 0.2 \text{ km} \) \( T_s = 1.5 \times 10^6 \text{ K} \)
- Using X-ray bursts from binary accretion
  - Depends on well-formulated theory of X-ray spectrum formation
  - Cygnus X-2: \( d = 11 \text{ kpc} \) \( R = 9.0 \pm 0.5 \text{ km} \) \( M = 1.44 \pm 0.06 \text{ M}_\odot \)
- QPOs: \( R \) is smaller than the innermost stable orbit
Crab Nebula and Pulsar

- SNe seen in China in 1054AD
- Pulsation in every spectral band
- Period of 33ms
- Slowing down:
  - Period increases by a ms every 90 yr
- $B_{\text{surface}} \approx 10^{12} \text{ G}$
- Pulsar energy loss by rotation: $4.6 \times 10^{31} \text{ W}$
- Nebula luminosity:
  - $5 \times 10^{31} \text{ W}$
- Magnetic dipole energy loss yields an age of 1253 yr
Vela Pulsar

( Haensel, Potekhin, and Yakovlev, 2007, “Neutron Stars 1, Equation of State and Structure” )
Bow Shocks

- High velocity pulsars’ winds interact with the ISM
- Bow shock: pulsar wind confined by ram pressure

Population

- 2000 known neutron stars in the Milky Way and the Magellanic clouds
  - ~1700 radio pulsars
  - ~100 non-radio isolated neutron stars
  - ~100 low mass ($M_2 \approx M_\odot$) X-ray binaries and ~40 high mass ($M_2 \gtrsim 2 - 3 M_\odot$)
- More than 30 pulsars known in globular clusters
- Neutron stars found in the local group and beyond
  - X-ray bursters in the galaxy M31
  - Eclipsing binary in M101 (outside local group)
- Most rapid pulsar: PSR J1748-2446ad 716 rev/s
- Closest neutron star: PSR J0108-1431 130pc
Binary Systems

- About 5% of all neutron stars are in binary systems
- Companion:
  - ordinary star,
  - white dwarf,
  - neutron star, or black hole

Population Predictions

• $10^8 - 10^9$ neutron stars estimated to exist in the Milky Way
  – Only small fraction observed because many are obscured by gas clouds and dust

• Very young neutron stars can’t be observed because they are hidden by the SNR for several years

• Majority of neutron stars are not related to observed SNR because the remnants dissolve in $\sim 10^5$ yr
Galactic Distribution

• X-ray binaries concentrate to the galactic bulge and disk

• Radio pulsars have a much wider vertical distribution
  – Proper motions $v \geq 500 \text{ km/s}$
  – A sufficient fraction will likely escape the Galaxy
    Escape velocity: $450 - 650 \text{ km/s}$
  – Fastest known: PSR B2224+65 in the Guitar Nebula
    $\sim 1600 \text{ km/s}$ nearly $\perp$ galactic plane

( Becker, 2009, “Neutron Stars and Pulsars“)
Summary

- Neutron stars are born by the core collapse of massive stars
- They are very dense: $M_{\text{max}} = 1.6 M_{\odot}$, $R \approx 10$ km
- Their EoS is poorly known
- They spin rapidly and have high magnetic fields
- Neutron stars are pulsars
- Pulse features are well observed
- Neutron stars are multiwavelength emitters
Discoveries

• 1932: Chadwick discovered the neutron
• 1934: Baade and Zwicky linked supernovae and stellar collapse to neutron stars
• 1939: Oppenheimer and Volkoff formed the first theoretical neutron star model
• 1967: Hewish and Bell accidentally discovered pulsars
• Late 1960s: Pulsars identified with neutron stars
Present / Future Observatories

- Neutron stars are multiwavelength emitters
  - Radio: ground-based telescopes and arrays: Arecibo, Parkes
  - Near infrared and optical: large ground-based telescopes: Keck, VLT, Subaru
  - UV (and optical): weak emission: Hubble Space Telescope
  - Extreme UV, X-ray, and Gamma: space observatories: Chandra, XMM-Newton, RXTE, HETE-2, INTEGRAL

- Splash of detectable neutrinos for a few 10 s expected when a neutron star forms: SNO, KamLAND

- Gravitational waves should be emitted when a neutral star looses axial symmetry: LIGO, LISA, VIRGO
  - Already detected indirectly by observing relativistic decay of pulsar orbits
Gravitational Surface Redshift

• Electron positron annihilation at the surface: \( e^+ + e^- \rightarrow 2\gamma \)
  – Intrinsic energy of annihilation quanta: 0.511 MeV

• GRB 790305 magnetar:
  – Emission line observed at 430 ± 30 keV
  – With FWHM of \( \approx 150 \) keV
    \[ \Rightarrow z_{\text{obs}} = 0.23 \pm 0.07 \]

• If formed at surface, then this is the full redshift