Accreting Neutron Stars – tiny Galactic Powerhouses

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Neutron stars as laboratory

- The first neutron stars discovered by Bell-Burnell & Hewish in 1967 via their radio pulsations at $P \sim 1.3 \text{ s}$

Figure 15.13 Discovery of the first pulsar, PSR 1919+21 (“CP” stands for Cambridge Pulsar). (Figure from Lyne and Graham-Smith, Pulsar Astronomy, ©Cambridge University Press, New York, 1990. Reprinted with the permission of Cambridge University Press.)

Neutron stars in binaries…

Followed in 1972 by the discovery with the first satellite-borne X-ray telescope, Uhuru, of a neutron star (and X-ray pulsar!) with a binary companion: Cen X-3

Where do neutron stars come from?

Neutron stars are formed in supernova explosions of medium-sized stars.

Example: Cassiopeia A


http://chandra.harvard.edu
What do we know about neutron stars?

- About 2000 catalogued systems in our Galaxy, mostly radio (*rotation-powered*) pulsars
- Masses of about 1.4-1.8 times the mass of our sun; narrow range (in those systems where measured) and small radii ~10km
- Strong magnetic fields; $10^8-10^{14}$ Gauss
- Most observed to pulse, up to 700 times per second -> very rapid spins
- Possess a crust and/or internal structure (glitches, starquakes)
- Can be in *binary* systems, where accretion and hence profuse X-ray emission is possible

... and even some new flavours

- Rotating radio transients (RRATs); “intermittent” radio pulsars
- Soft Gamma-ray Repeaters (SGRs); isolated neutron stars that show (occasionally violent) gamma-ray outbursts & pulsations
- Anomalous X-ray pulsars (AXPs); isolated neutron stars with long pulse periods ~4-6s
- Latter two are both likely classes of magnetars, (possibly young) systems with extremely high magnetic fields $10^{14-10^{15}}$ G
- Compact central objects (CCOs) about which very little is known, associated with supernova remnants

What don’t we know?

Lattimer & Prakash, 2007

X-ray binaries

- Neutron stars are sometimes found in binaries, demonstrating that the supernova blast may not always disrupt the system.
- Should the stellar companion subsequently evolve to fill its Roche lobe, accretion will commence (also via stellar winds).
- Accreted gas is heated by liberated gravitational potential energy to \( \sim 10^7 \) K or so.

\[ \rightarrow \text{X-ray emission} \]

So why the supercar reference?

- Energy released from accretion material onto an object of mass $M$ and radius $R$ is
- i.e. the (specific) power-to-mass ratio is just a function of radius…

\[ \propto \frac{GM}{R} \]

- Neutron stars are the most compact objects in the universe
- And hence arguably have the highest power-to-weight ratio

Galloway, “Accreting Neutron Stars - tiny Galactic Powerhouses”
But what about black holes?

- Black holes are more compact but have no surface so energy may be lost through the event horizon.
- To eke out a final few ergs the accreted material on neutron stars may undergo stable and/or unstable thermonuclear burning.
Motivation

1. What happens when you compress matter to well beyond nuclear densities?

2. Does general relativity work under conditions of extreme curvature?

Motivation

1. What happens when you compress matter to well beyond nuclear densities?

A. “... above twice the equilibrium density of nuclear matter, $\rho_s \approx 2.7 \times 10^{14}$ g cm$^{-3}$, exotica in the form of hyperons, a Bose condensate of pions or kaons, or deconfined quark matter, will eventually appear. However, whether the threshold density for such exotica is around twice $\rho_s$, or much larger, is unclear.” (Lattimer & Prakash 2007, Phys. Rep. 442, 109)

... or possibly strange quark matter? (Witten 1984, Phys. Rev. D. 30, 272)
Picture this compressed into a grain of sand

Motivation

2. Does general relativity hold under conditions of extreme curvature?

A. There is yet much theoretical work on extensions/modifications to GR, but few experimental constraints. We are limited in our own solar system to gravitational redshifts of \( z = 10^{-6} \), where

\[
1 + z = \left( 1 - \frac{2GM}{Rc^2} \right)^{-1/2}
\]

& where \( M \) and \( R \) are the mass and radius of the gravitating object

1. Search for maximally spinning neutron stars to constrain the equation-of-state.
2. Search for redshifted spectral lines from the neutron star surface to measure the gravitational redshift.
3. Compare the behaviour of thermonuclear bursts with models to test our understanding of the crustal physics.
4. Measure the radiation radius and combine with other quantities to constrain the neutron star radius & mass, redshift etc.


Lattimer & Prakash, 2007
1. Maximally-spinning neutron stars

- About 20% of neutron stars with low-mass companions have measured spins in the 100s of Hz range.

2. Redshifted spectral lines

- Long a high priority for X-ray spectroscopy! Can measure surface redshift trivially
- A long history of failed claims... but we are still looking!

\[ z = \frac{\Delta \lambda}{\lambda} \]

3. Burst behaviour

- Compare burst behaviour (cooling curves, recurrence times, energetics) with models to deduce physical properties.

...other times less so (e.g. 4U 1728-34)

Galloway, "Accreting Neutron Stars – tiny Galactic Powerhouses"
4. Radiation radius

Spectral curves for blackbody radiators

Neutron stars are blackbodies, too

- For the vast majority of bursts the X-ray spectra are consistent with a Planck (blackbody) spectrum.
- Such spectra are characterised by two parameters: the temperature and the radius of the emitting object.
- We observe a flux at the earth which depends also upon the distance (assuming isotropy).
- The spectrum also is distorted slightly so we must correct based on assumptions about the photosphere.
- Blackbody normalisation $R_{bb}$ measured throughout tail...

Our data


• Analysis results consisting of time-resolved X-ray spectral analyses covering each burst, as well as high-time resolution lightcurves for pulsation searches

• Continuing to extend the catalog with additional newly public *RXTE* bursts, *BeppoSAX/WFC* bursts (+2200) and also *INTEGRAL/JEM-X* (+1000?) bursts -> MINBAR

Measuring radius not so simple

Radius measurements are subject to gravitational redshift and spectral distortion


<table>
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<tr>
<th>$T_{\text{eff}}$</th>
<th>$\log g$</th>
<th>$T_c/T_{\text{bb}}$</th>
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</table>

& $X=0.6$, as for the burst model
Radiation radius

• To put this all together,

\[ R = R_{bb}d f_c^2 \xi^{1/2} (1 + z)^{-1} \]

where \( R_{bb} \) is the blackbody normalisation, \( d \) the distance, \( z \) the redshift (which also depends upon \( R \ldots \)) and \( f_c \) the spectral correction factor.

• Unraveling these various observational and systematic parameters is quite a challenge (see recent papers by Özel, Guver, Steiner).

Systematics

- Radiation radius is not even constant for most bursts (e.g. Bhattacharyya et al. 2010)
- Can increase or decrease throughout the burst tail, although we expect the burning has spread to cover the neutron star by that time
- We don’t understand why! But making efforts to resolve (or circumvent) these issues e.g.
  - Can you just select “good” bursts and measure the radius from those?
  - Can you measure the radius from just part of the burst, where it agrees better from burst to burst?

Tests of GR

- GR permits only certain combinations of Eddington flux and radiation radius
- Both these parameters can be measured for a sample of 33 sources for which radius-expansion bursts have been observed
- Still need to correct for distance, spectral distortion...


FIG. 2: *Solid lines:* Contours of constant Eddington luminosity at infinity, in units of $10^{38}$ erg s$^{-1}$, as a function of the coordinate radius and the redshift of the surface of the bursting neutron star
*Dashed lines:* Contours of constant apparent radius of the neutron star, in units of 1 km, as inferred from the cooling tail of a burst, on the same parameter space. In this calculation the atmosphere of the neutron star was assumed to consist of pure hydrogen and the color correction factor was set to 1.34.

thanks!

Astrophysics @ Monash

• This is just one of the research efforts under way in astrophysics at Monash
• You can find astrophysicists both in the School of Mathematical Sciences and the School of Physics
• You can always ask me Duncan.Galloway@sci.monash.edu.au
  http://users.monash.edu.au/~dgallow