Surface Emission from Neutron Stars

and Implications for the Physics of their Interiors,
based on F. Ozel, arXiv:1210.0916

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Outline of This Talk

ANALYTIC EQUATIONS:
Neutron Star's EoS constrained by (R,M)

OBSERVATIONAL ASTROPHYSICS:
Many different observables and methods of observation, currently still not precise enough.

COMPUTATIONAL SIMULATIONS AND FITTINGS:
Surface is what you probe: Many theoretical models of atmosphere for many physical parameters.

ANALYTIC EQUATION OF STATE

Neutron Stars Overview

1. Objects with **most extreme densities (ρ)** and **strongest magnetic field (B)**.

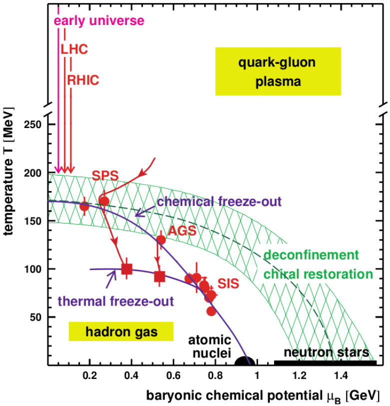
2. **Energetically favorable** for protons and electrons to form **free neutrons**, generating the **degeneracy pressure**.
   (but core exhibits collective behavior of particles)

3. Observations of NSs constrain the physics of their **interiors**:
   - **low temperatures**,
   - $\rho \gg$ **nuclear saturation density**.
     ($\rho_s \sim 2.7 \times 10^{14}$ g cm^{-3})

4. **Photons emitted** from the NS **surface** are direct probes of their **structure, composition, and magnetic field**.

5. Determining the **EoS** of this **cold ultradense matter** is a **challenge** of high-energy and nuclear astrophysics!

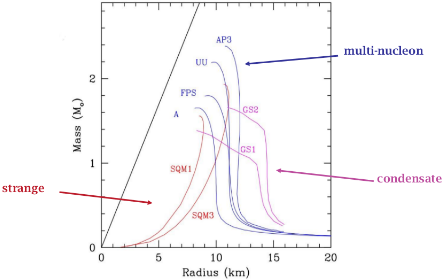
QCD phase diagram:



High-density/low T region is inaccessible to terrestrial experiments (Paerels et al, 2009).

Neutron Star Radii and Compactness

- **NS EoS** is hard to be obtained from first principles.
- Matter that can only be probed through astrophysical observations of **mass** and **radius** with **sufficient precision**!
  (Lattimer & Prakash , 2007)
- Unique map between microscopic **(P-ρ)** and macroscopic **(M-R)**.
- For instance, $M_{NS} = 1.4M_{\odot}$ gives determination of pressure at $2\rho_s$.
  (Lattimer & Prakash , 2011)



Mass-radius relations for a selection of NS EoS:

APR (Akmal et al., 1998), **MS** (Müller & Serot, 1996), **GS** (Glendenning & Schaffner-Bielich, 1999), **ABPR** (Alford et al., 2005), **BBB** (Brueckner-Hartree-Fock model), **SQM** (Prakash et al., 1995).

Some Initial Quantities to infer (M,R)

1. Observational appearance of NS affected by **redshift and lensing effects**.

2. The **redshift** is

$$1 + z = |g_{tt}|^{-1/2} = \left(1 - \frac{2GM}{Rc^2}\right)^{-1/2}.$$

3. The apparent radius at some distance D is then

$$R_\infty = R\left(1 - \frac{2GM}{Rc^2}\right)^{-1/2}.$$

4. **Lensing** from a **strong gravitational field** gives an area which appears to be large by

$$\frac{S_\infty}{4\pi R^2} = (1 + z)^2.$$

5. The **total flux** observed at distance D is

$$F_\infty = \sigma_B T^4_{eff,\infty}\left(\frac{R}{D}\right)^2 (1 + z)^2.$$

6. Uncertainties given by:
   - **distance** ($R_\infty \propto D$),
   - **interstellar H absorption**,
   - and **atmospheric composition**.

7. **Best probes**:
   - nearby isolated NS (parallax measurable),
   - and X-ray binaries in globular clusters.

Energy Sources in Neutron Stars:

1. Radiation of Residual Heat in Young NSs.
2. Re-radiation of deposition heat between accretion episodes.
3. Magnetic Field Decay.
4. Particle Bombardment onto Polar Caps.
5. **Thermonuclear Bursts**.

OBSERVATIONAL ASTROPHYSICS

Observing Neutron Stars and their Surfaces

We probe NSs from:

1. Dynamics of **binary systems**.
2. Structure and energetics of **radio pulse sources**.
3. **Spectra and variability** of their high energy radiation.
4. **Direct observations** of the **surface emission** (often hidden from view).

We see evidences of NS surface emission from:

- **Thermonuclear bursters from (LMXB)**.
- **Accreting sources during quiescence**.
- Isolated cooling NS (DINS), central compact objects (CCO).
- Pulsating sources in radio (PSR).
- Accretion powered pulsars (AMSP) and accreting millisecond X-ray pulsars (MSP), Soft gamma-ray repeaters(SGR), anomalous X-ray pulsars (AXP).

Table 1. Categories of Neutron Stars with Surface Emission

Source Type	Other Names[a]	Age (yr)	Temp. (10^6 K)	Mag. Field (G)	Companion?	Pulsations?
Quiescent Accreting NS	qLMXB	$\gtrsim 10^9$	$0.6-2$	$\leq 10^9$	Y	N
Bursters	LMXB	$\gtrsim 10^9$	$10-35$	$\leq 10^9$	Y	S[b]
Accreting msec Pulsars	AMSP	$\gtrsim 10^9$	$5-10$	10^{8-9}	Y	Y
Rotation Powered MSP	MSP	$\sim 10^{9-10}$	$2-8$	10^{8-9}	S	Y
Isolated Cooling NS	PSR	$10^{3-5.5}$	$0.6-2$	10^{11-12}	N	Y
-"-	DINS, CCO	$10^{5.5-6.6}$	$0.6-1.3$	?	N	S
Magnetars	AXP, SGR	$10^{5.5-6.6}$	$3-8$	10^{14-15}	N	Y

Neutron Star Sources with Surface Emission

Surface emission detected in many NS sources, with **thermal spectra from optical to X-rays**:

Accreting NS in quiescence:

- Half of NS accreting from low-mass companion have X-ray transients.
- **X-rays transients** have several different accretion phases, varying flux level and spectral characteristics.
- **Outburst luminosity** $\sim 10^{36-38}$ erg s^{-1}, same order of their **quiescent luminosity**.

Accreting Bursting NS (from LMXB):

- 100 of $\sim$ 150 exhibit thermonuclear bursts, with X-ray flux rising $\sim 10 - 100$ s.
- Due to **unstable burning of He/H**, **accreted** to the NS surface from companion.
- **Evolution of the color temperature** in the burst: dip in the **T** rises **photospheric radius expansion** (PRE).

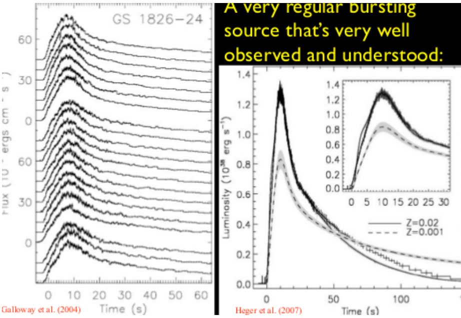
Type I X-Ray Bursters and LMXBs

1. **X-ray bursters** (XRB) are periodic and rapid increases in luminosity in the X-ray range.

2. XRB are composed of **an accreting compact object** (NS) and a **companion**, whose mass categorizes the system:
   - High mass ($M > 10M_\odot$), **(HMXB)**.
   - Low mass ($M < 1M_\odot$), **(LMXB)**.

3. **Low mass X-ray Bursters** (LMXB) are **thermonuclear** XRB that can put constraints on the NS EoS.

4. For instance, observations of **NS during thermonuclear bursts** have led to the **first constraining measurements of NS radii**: 9 km $<$ R $<$ 12 km.
   (Lattimer & Brown, 2010)



Photospheric Radius Expansion (PRE)

1. NS Observations are from the outermost layer of surface, the **photosphere**, in radioactive equilibrium given by a flux $F = \sigma_B T_{eff}^4$.

2. **PRE bursts** are a **bright** subset of TB where at the so-called **touchdown point** (where the **photosphere** returns to the NS radius), fluxes are close to $L_{Edd} = 4\pi R^2 \sigma_T T_{eff}^4$. on the surface.

3. F_{Edd} can be related to the **normalization of the burst spectrum** (blackbody normalization, K), which gives the **emitting area** (R):

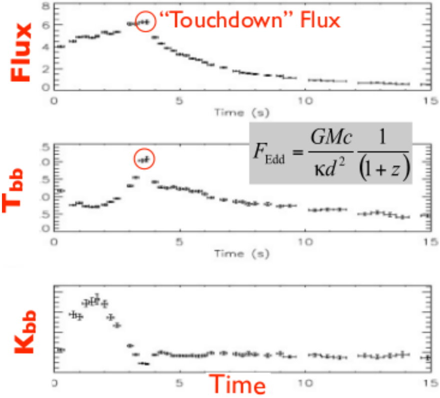
$$F_{Edd} = F_{touchdown} = \frac{GMc}{\kappa D^2}\left(1 - \frac{2GM}{Rc^2}\right)^{1/2},$$

$$A = \frac{R^2}{D^2 f_c^4}\left(1 - \frac{2GM}{Rc^2}\right)^{-1} = f_c K^{1/4},$$

f_c the color correction factor.

Debate about **systematic errors** that must be taken into account (**where is the touchdown?**).

(Suleimanov et al. 2011a; Guver, Ozel & Psaltis 2011)



COMPUTATIONAL SIMULATIONS AND FITTINGS

Parameters for Modeling Neutron Star Atmospheres

Detailed **Models of NS atmospheres** shape the **spectrum** and **pattern of radiation** from **crust and core**.

- Assumptions:
  1. **Plane-parallel** geometry.
  2. **Radioactive equilibrium**.
  3. **Hydrostatic equilibrium**.

- The **four parameters** in the models are:
  1. Magnetic field strengths;
  2. Chemical Compositions (e.g. H fraction, X);
  3. Temperature at surface, T_{eff};
  4. Gravitational acceleration at surface, g.

Some Results on Modeling and Fitting Spectra

1. Many different **physical conditions**: (Suleimanov et al, 211)
   - 6 different **chemical compositions** (pure H, pure He, solar mix, heavy elements).
   - 3 values of **surface gravities**.
   - 20 values of **luminosities** in units $l = L/L_{Edd}$.

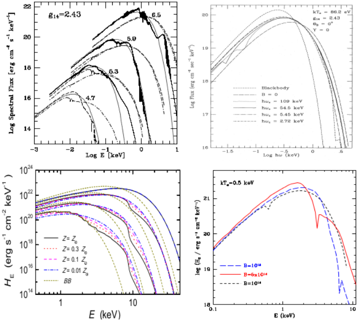
2. **NS spectra** look like blackbody, but shifted to higher temperatures by the **color coefficient factor**:

$$f_c = \frac{T_{BB}}{T_{eff}} = K^{-1/4} A$$

3. Fitting $f_c T_{eff} - l$ to the $K^{-1/4} - F_\infty$ on cooling LXRB at some D, gives

$$R_\infty = R(1+z) = R_{BB} f_c^2 .$$

4. **Others processes considered**: angular redistribution in scattering, electron conduction, **Compton scattering**...

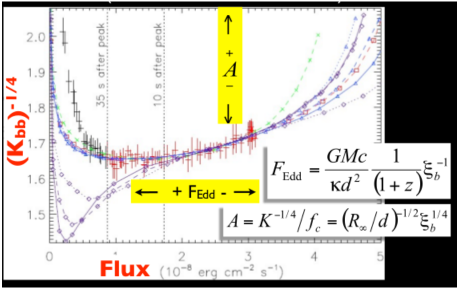


Model spectra for four different types of NS, $H_E = 4\pi H_E$:

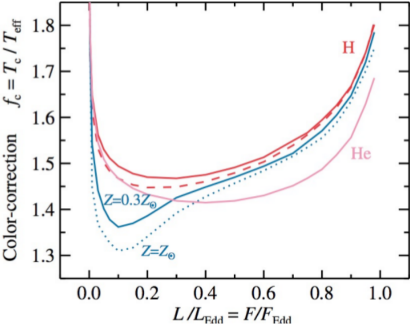
non-magnetic cool NS, cool with moderate B, hot bursting with

mentalities, strong B with H.

Results on Modeling and Fitting NS Spectra



(Suleimanov et al, 2011)



(October/2012)

OUTLOOK

State of Art:

1. Measuring different **NSs (M-R)** can **constrain the EoS** of cold ultradense matter.
2. More than 10 years worth of **Rossi X-ray Timing Explorer**(RXTE), the **Chandra X-ray Observatory**, and the **XMM-Newton observations**, with many NSs showing **thermal emission**.
3. **X-ray bursts** useful for inferring **NSs (M-R)**, but systematic and statistical errors **currently do not allow to pin down a unique EoS**.

Future Missions and Challenges:

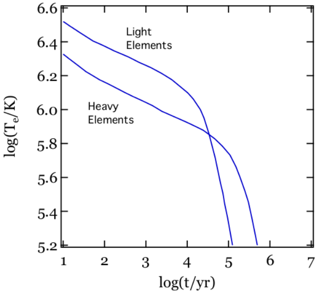
1. Future observations with **high spectral energy resolution**: **Astro-H**, **ATHENA**.
2. **GAIA** mission will allow **precise measurements of source distances**, constraining D for the radius determination of **thermally emitting stars**.
3. Observations of NSs with **high timing resolution** will be possible with **LOFT** mission.
4. **Other approaches to constrain (M-R)** can be explored, e.g. modeling the **pulse profiles** from **non-uniform emission from surface of rotating NSs**, looking for primary **GR effects**.
5. Achieving **overconstrained measurements** in the EoS allows testing **effects of strong gravitational fields** on NS surfaces.

What are X-ray bursts

- More than 2000 NSs have been discovered in the Galaxy, from **pulsating sources in radio** to **bright persistent sources in X-Rays**.
- They are **bright**.
- We see the **neutron star surface**.
- Spectra well fit by **Planck curves**.
- **Type I X-ray bursts** to infer **(M,R)**.
- The large observational catalogues of type I X-ray bursts now available.

Radiation of Residual Heat in Young NSs

1. **After Supernova explosion**:
   - Hot protoneutron star with $T \sim 10^{11} K$;
   - Cools by ν emission from the interior to surface.
2. **After the supernova explosion**:
   - NS divided into a stellar interior and an outer heat blanketing envelope;
   - The interior becomes isothermal within few years.
   - The envelope sustains strong ∇ **T**, is ~ 100 m deep, and has short time relaxation, stationary, plane-parallel in hydrostatic equilibrium.
   - The thermal evolution of the core (described by the GR solutions of a spherical symmetric star) depends on the heat capacity (degenerate constituents) of the core and neutrino emissivity (composition).
3. **First 10-100 years**: stellar envelope thermally relaxes by radiating its thermal energy.
4. **Following 10^5 years**: temperature of the crust is set by the temperature of the isothermal core.



Thermonuclear burst from 4U 1636+536 showing PRE

(a) compared to an ordinary burst in panel (b).

Reradiation of deposition heat between accretion episodes:

- Electron capture and pycnocuclear reactions at $\rho \sim 10^{12}$ g cm^{-3} at the crust, releasing $Q_{nuc} \sim 1.5 - 2$ MeV per accreted baryon.

- A fraction of energy missed by neutrino radiation but some is deposit in the interior, sufficient to power quiescent emission.

Magnetic Field Decay:

- Decay of strong B ($> 10^{14}$ G) releases hot from crust fracturing under stress. (Cumming et al 2008, Arras et al, 2004)

- $E \sim 10^{44}$ erg over hundred section.

Particle Bombardment onto Polar Caps:

Relativistic electron-positron in the magnetosphere of pulsar bombard the polar caps on the surface, thermal emission peaked in the UV to X-ray.

Surface Composition

- Composition of NS determined by: abundance of material during supernova explosion, abundance of material accreted from companion or ISM, gravitational ?? of heavy elements.
- Even light elements like O can remain in the photosphere and give atomic lines on the spectrum if there is no lighter elements or if its continuously fueled by accretion or convection (short timescale for sedimentation of heavy elements).
- The amount of H to cover the surface of a NS down to its photosphere (non B) is

$$M_H = 4\pi R^2 h N_p m_p,$$

with gas ionized ($N_H = N_p$), which shows to be very small, and the timescale for accretion of sufficient H to cover surface $\ll$ 1 yr to $\sim 10^3$ yr, dominant H and He.

Magnetic Field Strengths

- From $< 10^8$ G to steadying accreting NS to $\sim 10^{15}$ magnetars.
- Profound effects on the surface, most important parameter for emission properties.
- Affects propagation of photons in the atmosphere, together with polarization of magnetic vacuum (plasma density low)
- Photos interact primary with virtual pairs, vacuum polarization is affected by B, in the presence of a plasma with density gradient (ns atm): resonance on the normal modes of photon propagation, from circular at high e dens (deeper atm) to linear (low densities), so critical density depending on the photon energy, the conversion of photons between the two polarization modes is enhanced, together by chance in the opacities of the normal modes., resonances five rise to broad absorption-like feature. (Ozel 2001)

Flux and Spectrum of NSs Surface Emission

- Initially the energy is in the crust or core, deeper than atmosphere.
- Modeling: assumption of hydrostatic equilibrium, valid if the flux of radiation emitted from the NS does not lead to force $>$ the gravitational force on surface (As long as the radioactive flux remains below the EL, there is hydrostatic equilibrium).
- Defining **local Eddington limit (EL)** as the luminosity at which radiation balances gravitational forces: $L_{Edd} = \frac{8\pi GMm_p c}{(1+X)\sigma_T}$
- Very large gravitational acceleration on the NS surface:

$$g \sim \frac{GM}{R^2} \sim 1.9 \times 10^{14} \left(\frac{M}{1.4M_{cdot}}\right) \left(\frac{R}{10m}\right)^{-2} cms^{-2}.$$

- This leads to a very small **scale height** for atmosphere (matter taken as fully ionized):

$$h \sim 2\frac{k_B T}{m_p g} \sim 8.8 \left(\frac{T}{10^7 K}\right) \left(\frac{M}{1.4M_{cdot}}\right)^{-1} \left(\frac{R}{10m}\right)^2 cm.$$

- Since the scale height $\ll$ NS radius: plane parallel atmosphere in the models.
- (timescale protons exchange E with matter in photosphere is much shorter than the timescale the interior cools)

Finally, with the right fits...

From fits the spectral models, we derive A and F_{Edd}

If one additionally has a distance d and anisotropy ξ, one can solve for R, M:

$$R^2 = \frac{d^2\xi_b}{A^2}\left[\frac{1}{2} \pm \frac{1}{2}\sqrt{1 - 8\kappa d F_{\mathrm{Edd}} A^2 \xi_b^{1/2}/c^3}\right]$$

$$M = \frac{Rc^2}{2G}\left[\frac{1}{2} \mp \frac{1}{2}\sqrt{1 - 8\kappa d F_{\mathrm{Edd}} A^2 \xi_b^{1/2}/c^3}\right]$$

If ξ or d are unknown or poorly constrained, however..

$$R^2 = \frac{d^2\xi_b}{A^2}\left[\frac{1}{2} \pm \frac{1}{2}\sqrt{1 - 8\kappa d F_{\mathrm{Edd}} A^2 \xi_b^{1/2}/c^3}\right]$$

The condition that the discriminant must be ≥ 0 yields a condition on R_∞ [R(1+z)]:

$$R_\infty \leq \frac{1}{8}\frac{c^3}{\kappa}\frac{1}{A^4 F_{\mathrm{Edd}}}$$

No dependence on distance or anisotropy ξ!

Thermonuclear Bursts (TB)

1. **Recurrent X-ray flashes** with rise time of ~ 1 s and duration of ~ 10 s (Type I X-ray bursts, with luminosities up to twice to the **accretion luminosity**).

2. Accreting NSs with **weak B** $(< 10^{10}$ G), where **He and H** come from the **binary company**.

3. **Several mass accretion rate regimes** leading to thermonuclear flashes with different characteristics. They are typically expressed in units of **Eddington mass accretion rate**:

$$\dot{M}_E = \frac{8\pi m_p c R}{(1+X)\sigma_T} = 1.8 \times 10^{-8} \left(\frac{R}{10\ \text{km}}\right) \left(\frac{1+X}{1.7}\right)^{-1} M_\odot\ \text{yr}^{-1}.$$

where

- $\dot{m} = \dot{M}/\dot{M}_E < 0.01$: **H burning is unstable and triggers unstable He burning**.
- $0.01 < \dot{m} < 0.1$: **H burns stably into He between bursts, until He ignites**.
- $0.1 < \dot{m} < 0.9$: **He ignites unstably**.