Recent Progress in Nuclear Astrophysics:
Slightly Skewed yet Gently Brewed

Andrew W. Steiner
Institute for Nuclear Theory (U. Washington, Seattle)

Nuclear Astrophysics Town Meeting
As of 5 years ago, 8-15 km was a typical range for neutron star radii, now 10.4 to 12.9 km.
One-third of Skyrme models ruled out
The EOS is determined to within 30-50% over a wide range of densities

Frontiers:

- What other observations constrain M and R
- What does this mean for neutron star composition?
- What are the neutron star initial mass functions?
- Need more constraints above the saturation density
- Need better burst/atmosphere models
Isospin Dependence of Strong Interactions

- Nuclear Masses
  - Neutron Skin Thickness
  - Isovector Giant Dipole Resonances
- Fission
  - Nuclei Far from Stability
  - Rare Isotope Beams
- Heavy Ion Collisions
  - Multi-Fragmentation Flow
  - Isospin Fractionation
  - Isoscaling
  - Isospin Diffusion

Many-Body Theory
Symmetry Energy
(Magnitude and Density Dependence)

- Supernovae
  - Weak Interactions
  - Early Rise of $L_{ve}$
  - Bounce Dynamics
  - Binding Energy
- Proto-Neutron Stars
  - $\nu$ Opacities
  - $\nu$ Emissivities
  - SN r-Process
  - Metastability
- Neutron Stars
  - Observational Properties
- Binary Mergers
  - Decompression/Ejection of Neutron-Star Matter
  - r-Process

QPO's
- Mass
- Radius

NS Cooling
- Temperature
- $R_\infty$, $z$
- Direct Urca
- Superfluid Gaps

X-ray Bursters
- $R_\infty$, $z$

Gravity Waves
- Mass/Radius
- $dR/dM$

Pulsars
- Masses
- Spin Rates
- Moments of Inertia
- Magnetic Fields
- Glitches - Crust

Maximum Mass, Radius
Composition:
- Hyperons, Deconfined Quarks
- Kaon/Pion Condensates

Steiner, Prakash, Lattimer, and Ellis (2005)
Quantitative Progress on the Nuclear Symmetry Energy

- Work from heavy-ion collisions, neutron star radii, nuclear structure, and chiral effective theory all suggest that $L$ is most likely in the 30-70 MeV range.

Frontiers:
- Challenging systematics lurk everywhere.
- Which nuclear structure and astrophysical observables are best for constraining $L$?
- Can we separate systematics of functional vs. systematics of many-body approximation?
Neutron Stars are Super(fluid)

Figure 2. Example of a light curve that fits the observed cooling of MXB 1659−29. The numerical model is shown as a solid curve and has $Q_{\text{imp}} = 4.0$ and $T_b = 3.8 \times 10^8$ K. The dotted curve shows the corresponding toy model light curve from Section 2.4, and we also show (gray dashed line) the slope given by Equation (12).

Brown and Cumming (2009)

- $^1S_0$ neutron superfluidity required to match crust cooling observations
- $^3P_2$ neutron superfluidity in the core required to explain the fast cooling of Cas A

Frontier: We don't yet fully understand composition and transport properties of the crust

Frontier: Some objects, i.e. SAX J1808, still appear to cool faster than the "minimal" cooling model. This remains unresolved.
· Great strides have been made in the past 13 years, most often from collaborations between nuclear experimentalists, astronomical observers, and theorists of many flavors.

· Frontiers:
  - What other observations constrain $M$ and $R$? Do we understand their systematics?
  - What about neutron star composition?
  - What are the neutron star initial mass functions?
  - We need more constraints above the saturation density.
  - We need better burst/atmosphere models.
  - Symmetry Energy: nuclear systematics lurk everywhere. We need to understand them.
  - Can we separate systematics of functional vs. systematics of many-body approximation?
  - We don't yet fully understand composition and transport properties of the crust.
  - How do we explain SAX J1808?