Entr'acte

Neutron stars are a unique probe of matter at supersaturation density

Masses and radii provide information about the EOS (pressure-density relation) of nuclear matter

Cooling tests the behavior of nuclear matter at high density; rapid cooling indicates presence of exotic particles or a high proton fraction (large symmetry energy)

Neutron stars accreting from a companion provide other probes of dense matter.

This lecture

Follow a fluid element from its deposition into the atmosphere to its assimilation into the core

- thermally unstable light-element reactions: X-ray bursts and superbursts
- deep crustal heating: electron captures and neutron emissions

Implications for studying dense matter

Thought question

Suppose you could send a probe to the surface of a neutron star. What is a likely value for the density?

$$
H_P = -\left(\frac{d \ln P}{dr}\right)^{-1} = \frac{P}{\rho g}
$$

and is \sim cm at the neutron star surface.

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unstable ignition of H/He

Hansen & van Horn; Fujimoto et al.; Narayan & Heyl; Cooper & Narayan

Start with

$$
T\frac{\mathrm{d}s}{\mathrm{d}t}=\varepsilon+\frac{1}{\rho}\frac{\partial}{\partial r}\left(K\frac{\partial T}{\partial r}\right).
$$

Since the accreted layer is thin, find steady-state solution and perturb T about the solution; look for unstable modes.

$$
\frac{\partial \ln \varepsilon}{\partial \ln T} > \frac{\partial \ln \varepsilon_{\text{cool}}}{\partial \ln T}
$$

$$
\varepsilon_{\text{cool}} \approx \frac{K\Delta T}{\rho(\Delta r)^2}
$$

vected to deeper column α and the tracks (solid lines) correspond to different local local different local α

Ropid Burster 66 bunsts (cont.) 62 shown 医本 医肺 球菌 1 平 田 田 **ANN B B B** 1. 2. 1. 2. 2. 2. 2. 2 ... KS 1731-260 26 bunnts **1.000** $1.7.1.1.1$ ----0 0 1 1 1 1 1 1 1 **A.A. ID. ID. ID.** *<i>A P P W W W W* 8: 8: 10: 10: $4 - 14 - 18 - 18$ u **E 10 10 20** 14 $m - m$ \overline{a} **** 相论原则 SLX 1735-269 1-burst 10 01 50 4U 1735-44 11 bursts 一部 $-2 - 1$ 3 $-1 - 1$ B $2.3 - 0.2$ $7.2 - 2.4$ $-2 - 7 - 3$ g.

MINBAR catalog (Galloway et al.): A sample of >1200 X-ray bursts from ≈50 sources

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Eddington limit: balance radiative force, gravitation

This defines the *Eddington limit*,

$$
L_{\rm Edd} = \frac{4\pi G M c}{Y_e \sigma_{\rm Th}/m_p}.
$$

For a solar mass, $L_{\text{Edd}} \approx 10^{38} \text{ erg s}^{-1} \approx 10^5 L_{\odot}$.

Some bursts show strong expansion of the photosphere

Fig. 10.— Top panel Distribution of (normalized) peak burst flux Fpk/FEdd for radius-expansion (dark gray) and non-radius expansion (light gray) bursts. The distribution of peak fluxes of the radius-expansion bursts is broad, with standard deviation 0.14.

An Empirical Dense Matter Equation of State

From X-ray bursts with photospheric radius expansion (van Paradijs, Özel et al., Steiner et al., Suleimanov et al.)

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

$$
\frac{F}{\sigma T_{\text{eff}}^4} = \left(\frac{R}{D} \right)^2 \left(1 - \frac{2GM}{Rc^2} \right)^{-1}
$$

Steiner et al.; data from Guver et al. '10

An Empirical Dense Matter Equation of State **Transients**

From observations of quiescent neutron stars with pure hydrogen atmospheres one gets emitting area (with redshift correction; Marshall '82)

$$
\frac{F}{\sigma T_{\text{eff}}^4} = \left(\frac{R}{D}\right)^2 \left(1 - \frac{2GM}{Rc^2}\right)^{-1}
$$

Plot from Webb & Barrett '07

$\overline{)}$ ation of state
Allians 2000 and 2000 and 2000 and 2010 and 2010 and 2011 and 2011 and 2011 and 2011 and 2011 and 20
Allian Caroline Company 2010 and 2011 and 2 several neutron stars, one equation of state

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An empirical M-R relation (Steiner et al. '10, '13)

comparison with theory, experiment (Steiner et al., 2013)

c3 = −2.2 GeV−1 (high pressure limit c1 = −2.2 GeV−1 = −2.2 GeV−1.4 GeV−1.4 GeV−1.4 GeV−1.4 GeV=1.4 GeV=1.4 Ge
C1 = −1.4 GeV=1.4 GeV=

c3 = −4.8 GeV−1, GeV+1, Ge
Desemble region corresponds to the band of the ban

densities is implicitly taken into account if α is implicitly taken into account if one regards α

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tative set of EOS used in the set of EOS used in the band in t corresponds to the band in Fig. 1 and the light region covers region covers region covers \sim $F \sim 1$ (2010 BDI) \blacksquare al. \blacksquare (\blacksquare) lines, corresponding to the left (right) \blacksquare branch, start from the low pressure limit c1 =−0.7 GeV−1 =−0.7 GeV−1 =−0.7 GeV−1 =−0.7 GeV−1 =−0.7 GeV−1 =−0.7
C1 == 0.7 GeV+1 == $\overline{}$ < 5% for densities ρ0/8 < ρ < ρ¹ = 3.0 × 10¹⁴ g cm−³ $t = 1$ (2010 DDI) consistent with Hebeler et al. (2010, PRL)

the range of polytropes allowed (see text for discussion).

(ρ1 corresponds to a new transfer of the neutron density p). We are neutron density p is neglected to a neutron density p

light shaded areas show the 90%-confidence and 99%-confidence constraints of the *R*NS measurement, respectively. The mass measurement of PSR J1614−2230 is shown as the horizontal band (Demorest et al. 2010). "Normal matter" EoSs are the colored solid lines. Other t

are included for comparison, with dashed lines. As mentioned in Section 5, the present analysis only places constraints on the "normal matter" EoSs since they are the

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only family of EoSs included in our assumptions. Among them, only the very soft density of \mathbb{R}^n here. The Eos are obtained from Eos are obtained from Lattimer \mathbf{P} (A color version of this figure is available in the online journal.) But not everything is settled…

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neutronization

$$
E \approx -a_V(N+Z) + a_A \frac{(N-Z)^2}{N+Z}
$$

In β -equilibrium, $\mu_e = \mu_n - \mu_p$, with

$$
\mu_n = \left(\frac{\partial E}{\partial N}\right)_Z, \quad \mu_p = \left(\frac{\partial E}{\partial Z}\right)_N
$$

$$
\frac{Z}{A} \approx \frac{1}{2} - \frac{\mu_e}{8 a_A}
$$

Comparison with reaction network calculation Gupta et al. '07

Reaction network run with pressure increasing in time (compression of fluid

neutronization

$$
E \approx -a_V(N+Z) + a_A \frac{(N-Z)^2}{N+Z}
$$

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$$

neutron drip

$$
E \approx -a_V(N+Z) + a_A \frac{(N-Z)^2}{N+Z}
$$

At neutron drip,

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$$
\mu_n = \left(\frac{\partial E}{\partial N}\right)_Z \rightarrow 0
$$

 $\mu_e \approx 2a_V \approx 30$ MeV

This is about 10-3 of saturation density

crust reactions

Sato '79; Haensel & Zdunk '90; Gupta et al. '07; Steiner '12; Schatz et al. '13; Lau et al. (in prep)

Many of these reactions are within reach of FRIB

Time-of-flight mass measurements for nuclear processes in neutron star crusts

A. Estradé,^{1, 2, 3, *} M. Matoš,^{1, 3, 4} H. Schatz,^{1, 2, 3} A. M. Amthor,^{1, 2, 3} D. Bazin,¹ M. Beard,^{5, 3}

A. Becerril,^{1, 2, 3} E. F. Brown,^{1, 2, 3} R. Cyburt,^{1, 3} T. Elliot,^{1, 2, 3} A. Gade,^{1, 2} D. Galaviz,^{1, 3}

S. George,^{1, 3} S. S. Gupta,^{6, 3} W. R. Hix,⁷ R. Lau,^{1, 2, 3} G. Lorusso,^{1, 2, 3} P. Möller,⁸ J. Pereira,^{1, 3}

M. Portillo,¹ A. M. Rogers,^{1, 2, 3} D. Shapira,⁷ E. Smith,^{9, 3} A. Stolz,¹ M. Wallace,⁸ and M. Wiescher^{5, 3}

¹National Superconducting Cyclotron Laboratory, Michigan State University, USA

experimental masses (green, solid), and for implementing input α in α in α in α in α in α in α

 20 2011, PRL

2.4 2.45 2.5 2.55 2.6

 $\mathcal{F}_{\mathcal{A}}$ and $\mathcal{F}_{\mathcal{A}}$ show fit references

is other as a function of the interaction of the $\mathcal{S}_\mathcal{S}$

 547 557 557 557 557 557 557 557 557

 $\mathcal{G}(\mathcal{G})=\mathcal{G}(\mathcal{G})$ and $\mathcal{G}(\mathcal{G})=\mathcal{G}(\mathcal{G})$

 75.22 n, and 79.22 n, and 79.22

accrete for many years, sufficiently long to reach the many years, sufficiently long to reach the many years,

deep crustal heating

crust reactions deposit \sim 1.8 MeV/u in the inner crust 1.core temperature set by balance of heating, neutrino cooling 2.crust is not in thermal equilibrium with core

quasi-persistent transients Rutledge et al. 2002, Shternin et al.2007, Brown & Cumming 2009

a cooling slab

For
\n
$$
\frac{\partial T}{\partial t} = D \frac{\partial^2 T}{\partial x^2},
$$
\nthe flux at $x = 0$ is
\n
$$
D \frac{\partial T}{\partial x}\Big|_{x=0} \sim ?
$$

t

 $\sqrt{\tau}$

 \propto

For

where $\tau = a^2/(4D)$.

 91

dt

the flux at $x = 0$ is

 $\frac{\partial}{\partial x^2}$,

t

 $= D \frac{\partial^2 T}{\partial x^2}$

 $\int^{1/2} \left[1 - \exp\left(-\frac{\tau}{\tau}\right)\right]$

a cooling slab

quasi-persistent transients Rutledge et al. 2002, Shternin et al.2007, Brown & Cumming 2009

Summary

- A number of observational probes of the nuclear EOS are available
	- three examples
		- pulsar masses
		- masses and radii from X-ray bursts
		- cooling of isolated neutron stars, thermal relaxation of accreting transients
	- this is not inclusive: there are others
- No single observation is ideal and there are substantial systematic uncertainties—it's astrophysics

Superbursts!

superbursts are ≈1000 times more...

energetic, longer-lasting, and infrequent...

than regular X-ray bursts

KS 1731–260; Kuulkers 2002

Why weren't these predicted?

They were! Sort of...

Taam & Picklum 1978, Brown & Bildsten 1998

superbursts like it hot—perhaps too hot? Brown 2004, Cooper & Narayan 2005, Cumming et al. 2006

Going beyond 1-d **Could there be crust** \blacksquare "mountains" 1110011101113 "mountains"?

Haskell et al. 2006 Bildsten 1998 Ushomirsky et al. 2000

 $A_{\rm 1,4}$, $A_{\rm 2,4}$, $A_{\rm 3,4}$, $A_{\rm 3,4}$, $A_{\rm 4,5}$, $A_{\rm 5,4}$, $A_{\rm 6,4}$, $A_{\rm 7,4}$, $A_{\rm 8,4}$, $A_{\rm 9,4}$, $A_{\rm 9,4}$

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LIGO. Hanford, WA site: will it observe neutron stars?

Summary

A number of observational probes of the nuclear EOS are available

three examples

pulsar masses

masses and radii from X-ray bursts

cooling of isolated neutron stars, thermal relaxation of accreting transients

this is not inclusive: there are several others

No single observation is ideal and there are substantial systematic uncertainties—it's astrophysics; but

These observations, taken together, offer interesting constraints and complement theoretical and experimental efforts in nuclear physics

Stay tuned! There are lots of opportunities to make advances in the next few years.

From discussion section