The Hottest Superfluid and Superconductor in the Universe: Discovery and Nuclear Physics Implications

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We present recent work on using astronomical observations of neutron stars to reveal unique insights into nuclear matter that cannot be obtained from laboratories on Earth. First, we discuss our measurement of the rapid cooling of the youngest neutron star in the Galaxy; this provides the first direct evidence for superfluidity and superconductivity in the supra-nuclear core of neutron stars. We show that observations of thermonuclear X-ray bursts on neutron stars can be used to constrain properties of neutron superfluidity and neutrino emission. We describe the implications of rapid neutron star rotation rates on aspects of nuclear and superfluid physics. Finally, we show that entrainment coupling between the neutron superfluid and the nuclear lattice leads to a less mobile crust superfluid; this result puts into question the conventional picture of pulsar glitches as being solely due to the crust superfluid and suggests that the core superfluid also participates.

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1. Discovery of superfluid cooling of the Cassiopeia A neutron star

Neutron stars are created in the collapse and supernova explosion of massive stars, and they begin their lives very hot (with $kT > 10$ MeV) but cool rapidly through the emission of neutrinos. This neutrino emission depends on uncertain physics at the supra-nuclear densities ($\gtrsim 0.08$ fm^{-3}) of the neutron star core [1, 2, 3, 4]. Current theories indicate that the stellar core may contain exotica, such as hyperons and deconfined quarks, and matter may be in a superfluid/superconducting state [5, 6, 7]. By observing the cooling of neutron stars and comparing their temperatures to theoretical models, we can constrain the nuclear physics properties that govern the stellar interior.

The compact object at the center of remnant of the Cassiopeia A supernova was discovered in *Chandra X-ray Observatory* first-light observations [8] and subsequently identified as a neutron star [9]. The supernova explosion is estimated to have occurred in the year 1681 ± 19 [10]; this makes the Cassiopeia A neutron star the youngest-known neutron star at an age of ≈ 330 yr. A steady temperature decline of four percent was found using *Chandra* observations taken during the last 10 years [11]. If the rapid decline is due to passive neutrino cooling, then this is the first direct evidence for superfluidity and superconductivity in the core of a neutron star [12, 13].

The left panel of Fig. 1 (in particular, see inset) shows *Chandra* temperature measurements of the Cassiopeia A neutron star from 1999 to 2010 [11, 13]. Figure 1 also shows surface temperatures for three theoretical models of neutron star cooling: "N − normal matter" corresponds to neutron star matter that does not contain any sort of superfluid, "pSF − proton superfluid" is for superfluid protons in the core, and "npSF − neutron/proton superfluid" is for superfluid neutrons and protons in the core. Note the difference between the cooling behavior of models with normal matter (N) and matter containing superfluids (pSF or npSF) after ≈ 40 yr. In the latter models, a proton superconductor forms soon after neutron star formation, and this suppresses neutrino emission, so that the cooling rate is weaker than for normal matter. This enables the star to stay relatively warm, leading to a rapid temperature drop once neutrons become superfluid [14, 15]. The model with superfluid neutrons and protons (npSF) fits the data at an age of a few hundred years. The four circles trace the cooling curve predicted by this model from about 10 years after the supernova explosion (SN in ~ 1680) to about the time when neutrons become superfluid in the core: (1) At early ages, the neutron star core cools so rapidly by neutrino emission that the crust does not have time to react. Thus the crust is hotter than the core in 1690 (age ≈ 10 yr; protons are superconducting by this time), and the surface temperature declines very slowly. (2) The surface temperature eventually reacts to the "cooling wave" that sweeps through the crust and starts to drop off more quickly. After 1760, the temperature becomes almost constant throughout the star. (3) Then in ≈ 1900, the interior temperature drops below the critical value for a neutron superfluid to form and enhanced neutrino emission occurs in the core, as neutron Cooper pairs form. Energy is lost as the neutrinos are emitted, causing the core to cool off and another cooling wave to travel outwards. As neutrons in large regions of the core become superfluid, the surface temperature drops off quickly, beginning in ≈ 1930 (i.e., start of "Great Depression") and continuing through the present date. See Fig. 2 of [16], which shows evolution of interior temperature $T(\rho)$ and transition to neutron superfluidity.

Monitoring of the temperature decline will allow improved constraints on the (1) critical temperature for neutron triplet pairing $T_{\rm nt}$ (maximum pairing gap energy; see Fig. 1 and Fig. 1 of [13]), (2) suppression due to collective effects of the axial vector current for pair formation (see Fig. 3 of
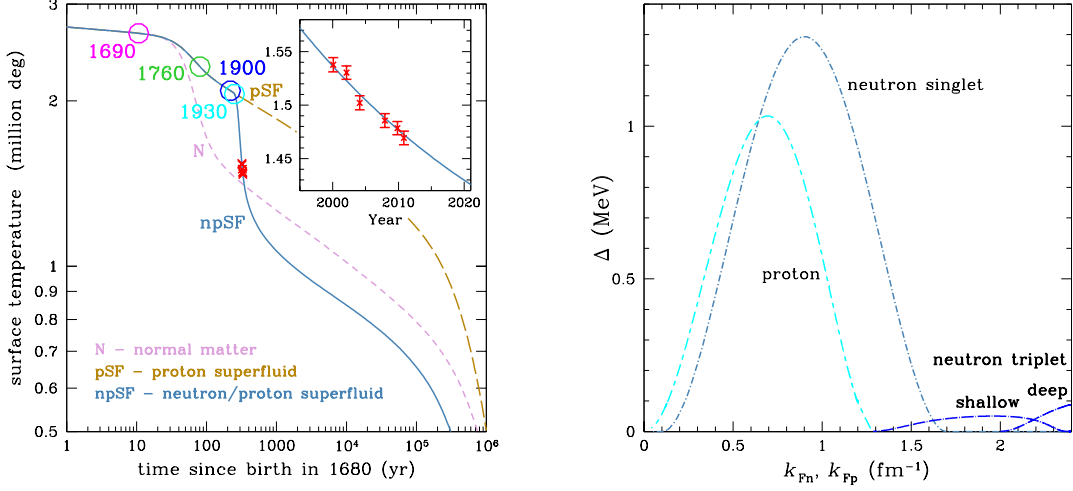
Figure 1: Left: Theoretical models of neutron star cooling with superfluid neutrons and protons (npSF − solid), normal neutrons and superfluid protons (pSF − long-dashed), and normal neutrons and protons (N − short-dashed). Circles indicate temperature for the npSF model at particular times/years. Crosses are *Chandra X-ray Observatory* measurements of the Cassiopeia A neutron star. Right: Superfluid pairing gap energies as a function of Fermi wavenumber for neutrons k_{Fn} and protons k_{Fp}. The maximum neutron triplet gap is taken to be *either* the shallow model or the deep model, and each triplet gap leads to cooling that can fit the Cassiopeia A data (see [12] and [13], respectively).

[13]), and (3) neutron star mass and nuclear equation of state (see Fig. 1 of [13] and Fig. 4 of [12]).

Guided by the discovery of a superfluid and superconductor in the Cassiopeia A neutron star, we examine three examples where measurement of the pairing gap energies has possible effects or where further constraints may be obtained.

2. Nuclear X-ray bursts and neutrino cooling by neutron superfluid

In contrast to the neutron star in Cassiopeia A, many old neutron stars are found in binary systems. These binaries can be seen in X-rays, which are produced when material from the companion star accretes onto the neutron star. If the companion has a low mass, the systems are known as low-mass X-ray binaries (LMXBs). Many LMXBs undergo bright X-ray bursts due to unstable thermonuclear burning of hydrogen and/or helium in the surface layers of the neutron star [17, 18]. Bursts are sometimes observed to recur in individual sources, and recurrence times between multiple bursts span a wide range, from minutes to days [18, 19]. However, recurrence times $\lesssim 1$ hr are too short for the neutron star to accrete enough fuel for subsequent bursts [17, 20].

In [21], we revisit the method used to infer core temperatures T_c of neutron stars in LMXBs. Compression by accreted matter induces nuclear reactions in the deep crust, which release ≈ 1.5 or 1.9 MeV nucleon^{-1} [22], and this heats the core directly by a luminosity $L_{heat} \approx 0.0078 L_{acc}$, where L_{acc} is the time-averaged X-ray luminosity of the LMXB [23, 24]. Figure 2 shows the measured heating rate L_{heat}, as well as the theoretical neutrino luminosity L_ν, which depends on the neutron triplet pairing gap energy (or critical temperature T_{nt}). The intersection of the curves L_{heat} and L_ν yields the neutron star core temperature. We see that the core temperature in relatively

high luminosity LMXBs may not be uniquely determined. If $T_{\rm nt,max} \lesssim 8 \times 10^8$ K, there can be two thermally stable values[1] of the core temperature associated with a single observed accretion luminosity. For example, there is a factor of < 3 difference in the inferred $T_{\rm c}$ if $L_{\rm acc} \sim (0.2 - 9) \times 10^{37}$ ergs s^{-1} and $T_{\rm nt,max} = 4.3 \times 10^8$ K. The luminosities of all LMXBs that show short burst recurrence time lie within this range [19]. To highlight this point, we place the LMXBs with "short time" on the high-temperature branch and LMXBs with "long time" on the low-temperature branch. Thus the sources with short time and higher temperatures have normal neutrons in the stellar core, while sources with long time and lower temperatures have superfluid neutrons.

If short burst recurrence time LMXBs do indeed possess hotter core temperatures, then measurements of the minimum and maximum accretion luminosities of bursts from short time LMXBs and long time LMXBs, respectively, can be used to constrain the neutron superfluid critical temperature $T_{\rm nt}(\rho)$. This is illustrated in Fig. 2, where it is clear that the accretion luminosities for LMXBs can constrain $T_{\rm nt,max}$ and $\rho_{\rm nt,peak}$, while the width of $T_{\rm nt}(\rho)$ is not as important in determining the qualitative behavior of L_ν.
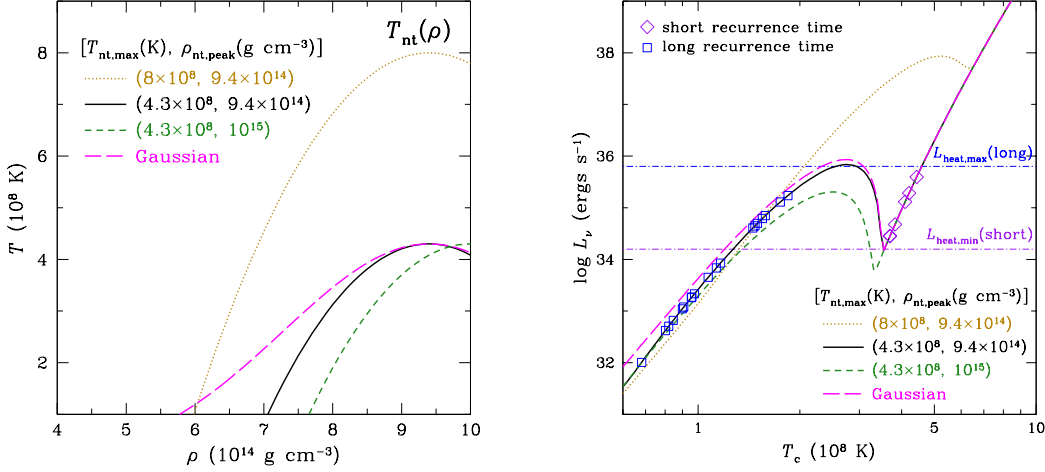

Figure 2: Left: Simple models of the neutron triplet critical temperature $T_{\rm nt}(\rho)$. Right: Neutrino luminosity as a function of neutron star core temperature, where the different curves are L_ν calculated using the models of $T_{\rm nt}(\rho)$ shown in the left panel. Upper (lower) horizontal dot-dashed line is the highest (lowest) observed $L_{\rm heat}$ from among all long (short) recurrence time bursts. Squares and diamonds are where $L_{\rm heat} = L_\nu$ (with 4.3×10^8 K, 9.4×10^{14} g cm^{-3}) for each LMXB with long and short recurrence times, respectively.

3. Neutron star spin and damping of r-mode oscillations

One of the main mechanisms that is expected to affect the spin evolution of an accreting neutron star in a LMXB is the instability associated with r-modes, which are a class of oscillations in a star whose restoring force is the Coriolis force. The emission of gravitational waves can excite r-modes in the stellar core and cause the oscillations to grow [25]. The r-mode instability is interesting for many reasons, mainly because the associated gravitational wave signal may be

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[1]There can be three values of $T_{\rm c}$ that intersect each horizontal $L_{\rm heat}$. But the intermediate temperature is thermally unstable since a temperature decrease leads to an increase in neutrino luminosity which causes even more rapid cooling.

detectable, but also because its understanding requires knowledge from a wide range of nuclear physics. A primary agent that enters the r-mode discussion is damping mechanisms related to shear and bulk viscosities and exotica like hyperons, quarks, and superfluid vortices [26] (see also C.J. Horowitz, this volume). The instability depends primarily on the neutron star spin rate ν_s and core temperature T_c. This leads to an instability "window," determined by a critical curve in the ν_s-T_c plane, inside which the instability is active. What has not been appreciated is that this leaves the majority of the observed systems significantly inside the instability window: rapidly rotating neutron stars (i.e., pulsars) should not possess spin rates at their observed levels [27, 28].

One solution to this dilemma is to change the window so that r-mode growth is stabilized at relatively high spin rates. However in order to do this, a revision of our understanding of damping mechanisms is required. In [27], we explore the possibilities. For example, there may be resonances between the r-mode and torsional oscillations of the elastic crust [29]. Such resonances could have a sizeable effect on the instability window. Figure 3 shows an example; the illustrated instability window has a broad resonance at 600 Hz, which is the typical frequency of the first overtone of pure crustal modes.

Another possibility is an instability spin frequency that increases with temperature in the range of interest here [30, 31]. If this is the case, then neutron stars may evolve to a quasi-equilibrium where the r-mode instability is balanced (on average) by accretion and r-mode heating is balanced by cooling. This solution is interesting because it predicts persistent (low-level) gravitational radiation. Figure 3 shows a model using hyperon bulk viscosity suppressed by superfluidity. This explanation has a major problem though. It must be able to explain how observed pulsars with millisecond spin rate emerge from accreting systems. Once the accretion phase ends, the neutron star will cool, enter the instability window, and spin down to ~ 300 Hz. In other words, it would be very difficult to explain the formation of a pulsar spinning at 716 Hz [32].

An intriguing possibility involves mutual friction due to vortices in a rotating superfluid. The standard mechanism (electrons scattered off of magnetized vortices) is too weak to affect the instability window [33]. However, if we increase (arbitrarily) the strength of this mechanism by a factor ~ 25, then mutual friction dominates the damping, as shown in Fig. 3. Moreover this would set a spin threshold for instability similar to the highest observed ν_s and would allow systems to remain rapidly rotating after accretion shuts off. Enhanced friction may result from the interaction between vortices and proton fluxtubes in the outer core.

4. Pulsar glitches and neutron superfluidity in the crust

Mature neutron stars tend to have extremely stable spin rates, with some pulsars possessing a timing stability that rivals the best terrestrial atomic clocks. However, young neutron stars may behave in a less ordered fashion. In particular, many young pulsars exhibit regular glitches, where the observed spin rate suddenly increases [36]. The consensus view is that these events are due to a superfluid component in the stellar interior [37]. Anderson & Itoh [38] envisaged a glitch as a tug-of-war between the tendency of the neutron superfluid to match the spindown rate of the rest of the star by expelling vortices and the impediment experienced by moving vortices that are pinned to crust nuclei. Strong vortex pinning prevents the superfluid from spinning down and creates a spin lag with respect to the rest of the star (which slows by magnetic dipole radiation). This situation
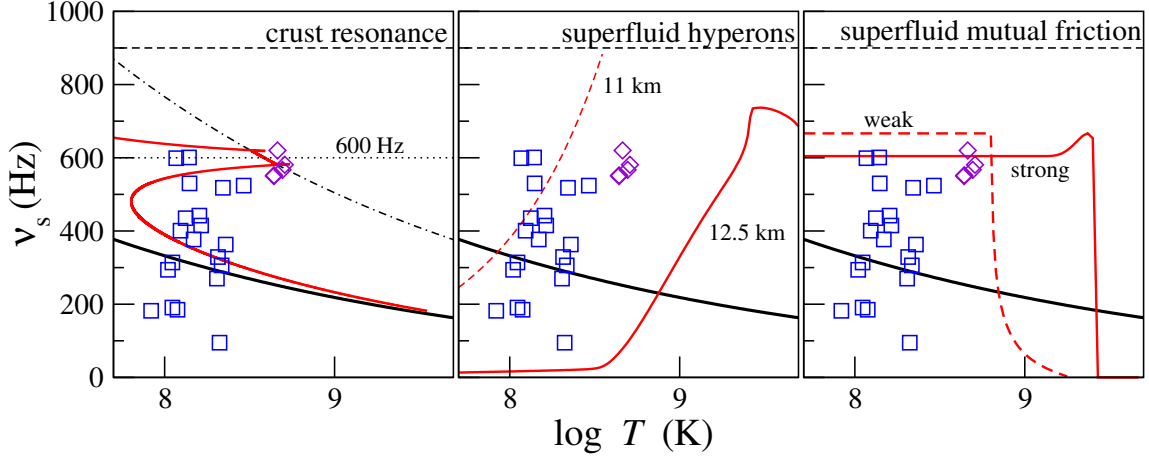
Figure 3: Three scenarios that could explain r-mode stability in the observed LMXBs (squares and diamonds; see Fig. 2). R-mode growth is stable below (i.e., at lower ν_s) the various curves, while the dashed lines at 900 Hz indicate the break-up limit. Left: Crust mode resonance at 600 Hz. Middle: Superfluid hyperons (based on [34] with $\chi = 0.1$). Right: Strong vortex mutual friction (based on the strong/weak superfluidity models from [35] with $\mathcal{B} \approx 0.01$).

cannot persist forever. The increasing spin lag leads to a build-up in the Magnus force exerted on the vortices. Above a threshold, pinning can no longer be sustained, vortices break free, and excess angular momentum is transferred to the crust. This leads to the observed spin-up, i.e., glitch.

A previous analysis by [39] suggests that glitches involve a superfluid reservoir with moment of inertia $I_n/I \sim 1\%$, where I and I_n are the moments of inertia of the entire star and the neutron superfluid component, respectively. The similarity of the inferred I_n to the theoretically estimated moment of inertia of the crust (which is dominated by free neutrons in the inner crust) for realistic nuclear equations of state [40] supports the idea that glitches involve only the crust region. In [41], we show that this logic breaks down when one accounts for non-dissipative entrainment coupling between the neutron superfluid and the crust lattice, an effect which can be expressed in terms of an effective neutron mass m_n^*. Recent work indicates that this effective mass may be significantly larger than the bare neutron mass m_n [42] (see Fig. 4). This implies a decreased superfluid mobility with respect to the lattice and the need for a larger angular momentum reservoir for glitches. Combining the latest glitch data [36] with a general relativistic multifluid model that includes entrainment, we find that the requisite superfluid moment of inertia is above the capacity of the crust superfluid [41] (see Fig. 4). Some solutions are briefly discussed below (see also [41]).

One possible explanation could be that the superfluid in the core is involved in the glitch (see, e.g., [44]), and the combined superfluid moment of inertia reservoir is just large enough to explain the observations. If this fine-tuning resolves the problem, then a more detailed calculation would constrain the singlet pairing gap for neutrons. This would be an interesting complement to the constraints on core superfluids (singlet protons and triplet neutrons) discussed in Sections 1–3.

Another solution could be the result of superfluid behavior at the crust-core transition. Unless the superfluid is confined to the crust, one would have to explain why the crust component decouples from the core during the glitch event. This would be particularly vexing if the singlet pairing gap is such that the neutron superfluid reaches far into the core. A central issue concerns the na-
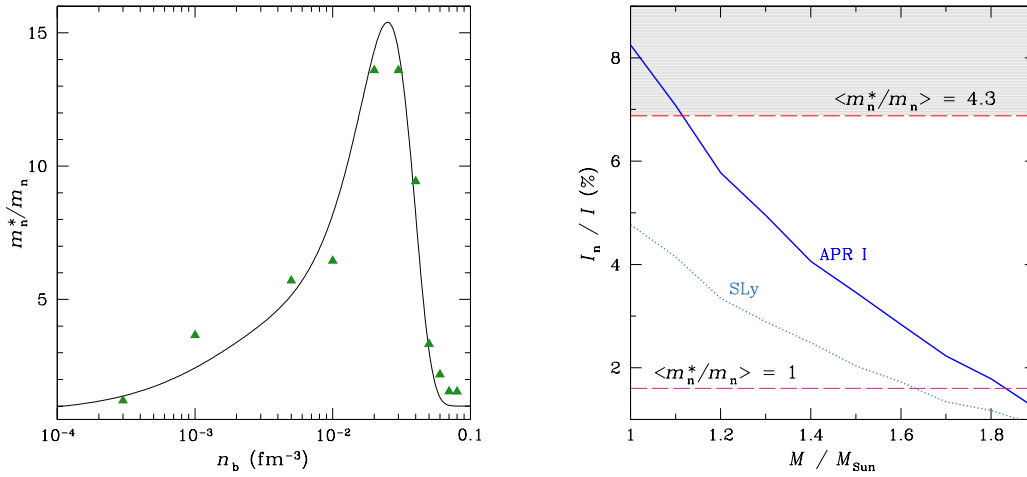
Figure 4: Left: Neutron effective mass as a function of baryon number density. Triangles are from [42], while the curve is a fit from [43]. Right: Moment of inertia ratio I_n/I as a function of mass for neutron star models built from the APR I (solid) and SLy (dotted) nuclear equations of state. If glitches in the Vela pulsar are to be explained solely by a crust superfluid, then the moment of inertia ratio must satisfy $I_n/I \gtrsim 0.016 \times (<m_n^*>/m_n) \approx 0.07$, where the average effective mass is calculated from that shown in the left panel; also shown is the constraint when entrainment is not taken into account, i.e., when $<m_n^*>/m_n = 1$.

ture of superfluid vortices extending across this interface. The standard picture is that vortices are magnetized in the core [45], due to entrainment and the presence of superconducting protons, but not in the crust. This suggests a more complicated transition behavior than is usually assumed.

Full details of the work presented in Sections 1–4 can be found in [13] (see also [12]), [21], [27] (see also [28]), and [41] (see also [46]), respectively.

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