

# Extreme Astrophysics with Neutron Stars

A Whitepaper Submitted to the Astro 2010 Decadal Survey  
Committee

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# 1 Introduction

This white paper is directed primarily to the “Stars and Stellar Evolution” panel of the Astro 2010 Decadal Survey. Among the various questions that pertain to this panel, we identify two that are particularly important and relevant to this white paper:

- 1. What are the property and dynamics of matter and radiation under extreme astrophysical conditions far beyond the reach of terrestrial environments?**
- 2. What are the final products and their observational manifestations of massive stars as a function of their initial conditions (mass, metallicity, rotation and magnetic field)?**

While the second question is specific to the area of stellar evolution, the first question is relevant to all areas of astrophysics. Indeed, one of the appealing features of astrophysics among all sciences is that it allows us to probe extreme conditions far beyond the reach of terrestrial laboratories. As an end state of stellar evolution, neutron stars (NSs) are associated with some of the most exotic phenomena and environments in the universe since the big bang. Most uniquely, the supernuclear density in the interior, the strong magnetic field on the surface, and the intense radiation field in the magnetosphere, combined with the strong gravity, provide conditions that cannot be created in terrestrial laboratories. Understanding various observations of NSs necessarily entails exploring physics under extreme conditions. *The diversity of the extreme phenomena related to NSs and the variety of physics tools needed to understand them are what continue to make this area of research attractive to young researchers and general public alike.*

In the following we highlight recent progress in NS astrophysics and discuss prospects for the next decade. Due to space limitation, our choices of topics are necessarily selective<sup>2</sup>. But they clearly show that there are many important, unsolved problems related to NSs, and there exist strong connections with many areas of astronomy and fundamental physics. Given the observational and theoretical progresses in the last five years, we believe that the next decade holds great promise for significant advances in this field. *A strong program in theory, numerical simulation and phenomenological modeling, combined with new sensitive observations/surveys in radio and X-rays/gamma-rays, as well as closer interactions with other physics communities (gravitational waves and nuclear astrophysics), are needed to bring out the future advances.*

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<sup>2</sup>We are aware of several other whitepapers focusing on various specific topics related to NSs, such as using radio pulsar timing to test theories of gravity and to measure gravitational wave background, using X-ray timing and X-ray spectroscopy to constrain nuclear equation of state, etc. Here we focus on subjects that are not covered by these other white papers, though some overlap is unavoidable. In addition, several related topics, such as core-collapse supernova explosion mechanism and supernova remnants are left out in this whitepaper.

## 2 Neutron Star Diversity: Formation and Evolution

Over the last decade, it has become increasingly clear that even in isolation, NSs have diverse observational manifestations. More than 2000 radio pulsars are known today, emitting photons and particles as they slow down. A peculiar class of pulsars (“RRATs”, see section 3 below) have been discovered in the last few years. The enigmatic Soft Gamma Repeaters and Anomalous X-ray Pulsars have been firmly established as magnetars, NSs powered by the dissipation of superstrong magnetic fields ( $B \gtrsim 10^{14}$  G). In addition, a number of “clean”, thermally emitting and slowly rotating NSs have been studied extensively. What are the connections (if any) between these different populations of NSs? Inside supernova remnants (SNRs), not just radio pulsars and magnetars, but also another, diverse and puzzling set of young NSs are found (sometimes called Compact Central Objects), many with surprisingly little thermal emission. Indeed, a major puzzle is that in many SNRs, no discernable compact remnants are seen at all, despite detailed studies. Are these NSs that somehow cooled faster, maybe because they are more massive, and with fields and spins too slow to produce magnetospheric emission? Or are they supernovae that led to low-mass black holes?

Obviously, it is important to understand how these different types of NSs are related to each other, and how the collapse of massive stars may give rise to different flavors of NSs (and black holes).

Understanding the physical mechanism of core-collapse supernovae is a long-standing problem in astrophysics (and a subject which surely deserves a separate whitepaper). There has been significant progress over the last decade: The standard neutrino-driven “delayed” explosion mechanism has been supplemented to incorporate the important roles played by various hydrodynamical instabilities. With the continued improvement of computational capability, the effects of rotation and magnetic field have now begun to be addressed, as well as more refined treatment of microphysics, neutrino transport and general relativity.

The birth properties of NSs provide one of the most important constraints on SN theory. The inter-connection between the study of young NSs, supernova theory/simulation and the study of advanced stellar evolution of massive stars, will continue to be fruitful in the next decade.

Another reason we believe success is likely, is that, as will be clear below, our physical understanding of the emission processes of the NS surface and magnetosphere is catching up with the detailed observations. Furthermore, we are starting to see glimpses of how the diverse populations of NSs are related to each other. For instance, the nearby, thermally emitting NSs appear likely descendants of the magnetars – based on kinematic ages and magnetic fields inferred from timing studies; some of the central compact objects appear to be weakly-magnetized NSs – again based on timing studies.

For the next decade, to understand the diverse populations of NSs and their origin and evolution, what is needed most would be further theoretical works on the properties of different classes of NSs (some of which are outlined in the next two sections) and higher-sensitivity X-ray and radio observations. In particular, X-ray observations are crucial to study the faint NSs in SNRs, and to either find NSs that appear to be missing or show no NSs are present.

# 3 Pulsars and Magnetars: Probing the Dynamics of Highly Magnetized Relativistic Plasma

## 3.1 Observations

More than 40 years after the discovery of pulsars, observations continue to reveal new, surprising behaviors of these enigmatic objects and raise new questions. For example, some of the new findings over the past five years include: (1) A number of radio pulsars appear to have magnetic fields comparable to those of magnetars. Could these pulsars turn into magnetars or vice versa (as recent observations seem to suggest), or are they intrinsically different? (2) Some radio pulsars have been found to exhibit distinct “on” and “off” states with a long term (weeks to years) quasi-periodicity. What is causing this quasi-regular behavior and intermittency? (3) A new class of neutron stars (dubbed *Rotating Radio Transients*, RRATs) has been discovered that is detectable only through isolated radio bursts, with typical burst duration of about 1 second and duty cycle of hours to a day. Some RRATs appear to have magnetar-like magnetic fields, while others have spin-down properties similar to those of regular pulsars. The origin of this “single pulse” behavior is not understood, and the discovery raises the possibility that the population of RRATs may be larger than that of normal radio pulsars. Searches for more of these different flavors of NSs (e.g., with *Arecibo*, *GBT* and future *SKA*), high-energy observations, and dedicated radio timing programs are necessary to elucidate their physical nature and to constrain the possible evolutionary relationships between them.

Pulsars, of course, have been detected in all wavelength bands, from radio to gamma-rays. In particular, the *EGRET* discovery of seven gamma-ray pulsars in the 1990s left important unsolved problems concerning the origin of these gamma-rays. The recently launched *Fermi Gamma-Ray Space Telescope* is finding many sources, with already more than three dozen gamma-ray pulsars found in six months. Intriguingly, about half these are found from their gamma-ray pulsations alone. These new discoveries are providing a major leap in our understanding of pulsar particle acceleration sites and pair cascades physics and also of the census of NSs in the Galaxy. Hard X-ray observations in the future (such as *NuStar* and the European *Simbol-X*) will add to these advances by finding the X-ray pulsations of the new gamma-ray pulsars and imaging their associated pulsar wind nebulae (PWN). Broadband phase-resolved spectroscopy will help identify the mechanisms producing the non-thermal emission. Modeling the geometry of the PWN can provide a measure of our viewing angle to the pulsar rotation axis, thereby constraining the pulsar emission geometry. X-ray polarimetry (e.g., such as would be provided by the recently proposed *Gravity and Extreme Magnetism SMEX*, *GEMS*) would add another puzzle piece that light curves and spectra alone cannot provide, as the polarization degree and position angle can be used to map out the magnetic field of the emission region.

Observations of magnetars in the last few years continue to reveal surprises, but also have had some nice confirmations of theory. An example of the latter is that the quiescent luminosities of several magnetars with sufficiently accurate distances are found to be around  $10^{35}$  erg s<sup>-1</sup>, as predicted. A recent surprising discovery was that apart from soft X-ray photons, the emission from quiescent magnetars is dominated by hard X-rays, with a spectrum peaking above 200 keV! Also, many magnetars have been observed to exhibit bursts and flares of various strengths and on various timescales, providing diagnostics of the dynamics of highly magnetized NS crusts (e.g., the yielding behavior of the solid) and magnetospheres.

Three giant flares have been detected in three (different) magnetars, with the December 2004 flare from SGR 1806–20 radiating energy exceeding  $10^{46}$  erg in a few seconds. Such giant flares are thought to be powered by global magnetic field rearrangement/dissipation in the star (e.g., due to a star quake). The quasi-periodic oscillations observed during these giant flares may be the first example of NS seismology. Yet another recent surprise was that at the end of the active phase of two (“transient”) magnetars, the stars switched on as bright radio pulsars on their way to quiescence, with an unusual, hard spectrum of radio emission. Future timing and spectral observations at different wavelength bands are important to elucidate many of emerging phenomenology of magnetars and their connections with radio pulsars.

### 3.2 Theories

Along with the new observational/phenomenological progresses of pulsars and magnetars described above, there has been significant recent advance in our understanding of the physics of NS magnetospheres, which are responsible for the nonthermal emission from the stars. The magnetosphere is dominated by highly magnetized, relativistic electron-positron pairs produced by electromagnetic cascades. As mentioned above, the *Fermi* Telescope is providing important information on the site of particle acceleration and pair cascades in pulsars. On the theoretical side, the global configuration of the dipolar magnetosphere of a rotating NS has recently been established by means of numerical simulations. In particular, the distribution of electric current density in the magnetosphere was found to be inconsistent with previous models of plasma flow above the polar caps of pulsars — these models will be revised in the coming years. New approaches to modeling  $e^\pm$  discharges together with state-of-the-art numerical simulations hold great promise in this regard. Solution of this fundamental problem, which depends on the application of modern kinetic plasma simulation techniques not available in earlier decades and which will make direct contact with observations through modeling of the pulsed gamma-ray emission, holds much promise for creating successful models for the mysterious collective radio emission. Theoretical modeling of plasma interactions in the double pulsar system, and others that may be found in upcoming surveys, offers a valuable means to probe pulsar magnetospheres directly.

In contrast to ordinary pulsars, magnetars exhibit large temporal variations in their spin-down rates, which indicate that their magnetospheres are *dynamic*. They are likely twisted by starquakes — sudden strong deformations of the crust. The theory of twisted magnetospheres, analogous to solar corona, has been developed in the last few years to account for various observations of magnetars. Like the solar corona, the twisted magnetosphere of a NS contains free energy, which is gradually dissipated and radiated away. A new electrodynamic theory for dissipative, resistively untwisting magnetospheres has recently been developed, which attempts to describe the post-starquake evolution of the luminosity and spindown rate of magnetars. It is useful to note that because of the dynamic nature of magnetars, the combination of spectral and torque information provides more observational constraints on the current flow in the magnetosphere than available for ordinary radio pulsars. Thus the magnetospheres of magnetars may be more trackable than those of radio pulsars. Future progress in understanding magnetar dynamics may significantly impact the landscape of NS research. Importantly, the superstrong magnetic fields in the magnetar magnetosphere offer a unique laboratory for the study of exotic quantum electrodynamic effects, in a regime that is inaccessible for other astronomical objects or terrestrial laboratories.

## 4 Thermally Emitting Neutron Stars: Probing Ultra-Dense Matter

It has long been recognized that thermal, surface emission from NSs has the potential to provide invaluable information on the physical properties and evolution of NSs (equation of state at super-nuclear densities, superfluidity, cooling history, magnetic field, surface composition, different populations). With *Chandra* and *XMM-Newton*, the last decade has seen significant observational progress, revealing the surface magnetic field geometry of isolated pulsars with phase-resolved spectroscopy, and constraining the cooling physics from thermal emission of young NSs in SNRs. In addition, thermal emission from the seven isolated, radio-quiet NSs as well as from NSs in quiescent X-ray binaries has been studied in detail. Overall, the goal is to measure temperatures and luminosities, and thus radii, as well as gravitational redshifts and surface gravities. The former requires emission from the whole surface, the latter the presence of spectral features. Both, of course, require detailed understanding of the emission processes.

In the last decade, a major break-through has been the discovery of absorption features at energies below 1 keV in six of the seven nearby, thermally emitting neutron stars, in one NS in a SNR, and in one of the RRAT sources. In all these, the features almost certainly arise from the NS surface, but their identification has, so far, remained uncertain, mostly because we know neither the composition nor the state of the surface, with suggestions ranging from gaseous hydrogen to solid iron (or combinations thereof). Fortunately, the different models make clear predictions; e.g., for an electron or proton cyclotron line one expects much larger variation in energy with rotational phase than for atomic lines. These predictions are being tested with *XMM* and *Chandra*, but definitive measurements will require better sensitivity with good energy resolution, especially at low energies, preferably with polarization information. This would require the proposed *International X-ray Observatory (IXO)*.

Another breakthrough has been the identification of the cooling radiation of NSs in quiescent X-ray binaries. An advantage of these sources is that they likely have weak magnetic fields and known composition: pure hydrogen, from accretion and subsequent gravitational settling (of course, this comes with the disadvantage that they do not have observable spectral features). During the active accretion phase, reactions in the deep crust heat the interior; when accretion halts and the source enters quiescence, the deposited heat is radiated from the surface. Spectral fitting of this thermal emission can determine the radiation radius,  $(R/D)(1 - 2GM/Rc^2)^{-1/2}$ , where  $R$  and  $M$  are the neutron star mass and radius. Both *Chandra* and *XMM* observations have been used to constrain the NS radius in this way, although the accuracy is not yet sufficient to constrain the EOS. but with *IXO*, we would have the capability to simultaneously measure both the NS mass and radius to a few per cent (with *GAIA* and/or *SIM* providing the required accurate distances to binary companions and/or host globular clusters). Having a sample of different masses and radii would in principle allow one to infer the dense matter EOS by inverting the  $R(M)$  relation.

The cooling of NSs in X-ray transients with long outbursts, such as KS 1731-260, has also been used to follow the thermal relaxation of the crust into equilibrium with the core. This has opened a new probe into the physics of the NS crust. First, the cooling timescale is set by the thermal conductivity of the deep inner crust, while the power-law cooling within the first month is directly related to the heat flux in the outer layers of the NS crust. The inferred NS core temperature, when combined with information about the long-term accretion history,

can be used to constrain the strength of neutrino emissivity of bulk nuclear matter. Here, again, progress is limited by current sensitivities, which would be improved greatly with *IXO*. The project also requires, however, continued all-sky monitoring in the X-ray, so that follow-up observations can map out the cooling within the first two weeks of quiescence. It is during this early time that observations can reveal the distribution of heat sources in the shallow outer crust; these shallow heat sources control the behavior of “long” X-ray bursts (helium- and carbon-powered explosions).

To capitalize on these observations and obtain useful constraints on NSs, it is important to continue the theoretical study of the physical properties of the NS surface layers (including atmospheres and crusts). For example, the NS atmosphere consists of highly nonideal, partially ionized Coulomb plasma, and the properties of atoms and molecules (which are likely responsible for the observed spectral lines) can be significantly modified by the magnetic field. Radiative transfer can also be strongly affected by exotic QED processes such as vacuum birefringence. Future observations with proposed X-ray polarimeters, such as *GEMS*, may directly probe such QED signatures. The physical state of the NS crust (e.g., crystalline or amorphous) and its transport properties determine the rate of heat transfer from the interior to the surface. There is already a community of nuclear physicists interested in matter at supernuclear density, with whom continued communication and exchange will be fruitful.

Over the next decade, the information obtained from NS thermal emission discussed here, especially if taken together with what is obtained from different methods covered in other white papers (such as using pulsar timing to measure NS masses and rotation rates, using X-ray timing to measure NS mass to radius ratio, etc.) has the potential to place neutron stars in their long-hoped position as excellent probes of the physics of the densest matter in the universe.

## 5 Neutron Stars as Sources of Gravitational Waves

In the coming decade, it is likely that advanced LIGO (and its European counterpart VIRGO) will achieve sufficient sensitivity to detect gravitational waves (GWs) from astrophysical sources, thus opening up a new window onto the universe. Neutron stars will feature prominently in this window:

The most promising (and conservative) sources of GWs are coalescing NS/NS binaries. It is even possible that NS/BH will be detected first in the next few years by the “enhanced LIGO” if some nonstandard (but physically possible) binary evolution scenario proves correct. During the binary inspiral phase, the masses of the compact objects (NS or BH) can be accurately measured from the inspiral waveform. The GW waveform generated in the final merger (or tidal disruption of the NS by the BH) may allow us to infer the NS radius and the stiffness of the nuclear matter, thus giving a completely new constraint on the nuclear equation of state. It may be possible that prior to merger, dynamical tides on the NS (if it has relatively large radius) lead to detectable imprints on the GW signals, again shedding light on the NS internal structure.

Numerical relativity has advanced significantly in the last few years, and it is now becoming feasible to simulate numerically the whole inspiral and merger process for many dynamical times. It will be useful to incorporate more sophisticated microphysics in the simulations (e.g., hot nuclear EOS and neutrino transport), as well as to study and simulate the effects of magnetic fields. The latter is particularly challenging but potentially important, as there has been mounting observational evidence in the last few years that merging NS/NS or NS/BH binaries lie at the heart of the central engine for (short/hard) gamma-ray bursts.

Accreting NSs in binary systems may also be detectable sources of GWs for LIGO. As matter accretes onto the NS, an asymmetric mass distribution (quadrupole moment) may develop due to various mechanisms (“magnetic mountain”, asymmetric nuclear reactions or overstable Rossby waves driven by gravitational radiation reaction). There is significant uncertainty in the estimate for the expected GW strength and much more theoretical work is needed. Direct detection of GWs from such sources would allow us to diagnose both the accretion process and the NS structure.

A large body of observational and theoretical work over the last decade has suggested that core-collapse supernovae (SNe) and NS formation involve highly asymmetric dynamical processes, which are largely hidden from the electromagnetic window, but can generate GWs. The detection of such GWs from nearby SNe by LIGO would reveal much about the explosion mechanism. If rotation is dynamically important (a big “if” since there is much uncertainty about the angular momentum evolution of pre-SN stars), much enhanced and qualitatively different GW signals would be generated.