Scientific Report

Defining the Neutron Star Crust:
X-ray bursts, Superbursts, and Giant Flares
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1 Summary of the workshop

Recent observations address specific questions relating to the structure, nuclear reactions, and transport properties of the neutron star crust. Explosive phenomena – X-ray bursts and superbursts on accreting neutron stars, and giant flares on magnetars – are providing new insights about the thermal and magnetic evolution of the crust. Theoretical models of these phenomena have identified the role of nuclear physics, neutrino cooling, and transport properties in the crust, and a standard model for the neutron star crust is beginning to emerge. However, fundamental questions remain unanswered. The purpose of this workshop was to bring together researchers in astrophysics, nuclear physics, plasma physics, and related areas, to identify and address the key issues of explosive phenomena and related questions about the thermal and magnetic evolution of the neutron star crust on longer timescales.

The workshop ran during four days, and we had four sessions: Superbursts and Physics of the Accreting Neutron Star Crust, Thermonuclear Burning and X-ray Bursts, Nuclear and Plasma Physics of the Crust, and Magnetar Thermal Evolution, Bursts and Flares, plus a poster session on Wednesday evening. There were two to four invited review talks (40+5 minutes) plus six to ten contributed talks (20+5 minutes) each day, and despite the intense agenda most people was participating in all sessions with interest. The final event was an open discussion about the future direction of the field and how to establish new links and foster collaboration between different communities.

2 Scientific content and discussion

In the first day, Andrew Cumming kicked off the workshop with a germane review of type I X-ray bursts, thermonuclear flashes on accreting neutron stars. X-ray bursts are of great interest because some bursts, specifically those for which hot CNO cycle burning does not set the temperature of the ignition region, can be useful probes of the interior temperature and thereby the crust and core properties. There are both great successes and failures in comparisons between observations and model results of "normal" H- and He-triggered bursts. Generally, models of individual bursts agree well with observations (e.g., GS 1826-24), whereas models of global bursting behavior disagree. Superbursts, extremely energetic flashes thought to be triggered by carbon burning, may be particularly useful probes of crust physics. Models predict that all crust and core parameters "must be turned to hot," to match observations, but the same predictions are inconsistent with complementary observations of other phenomena. Chuck Horowitz reviewed the Physics of the neutron star crust and discussed its breaking strain. In accreting Neutron Stars the new crust formed is a perfect crystal with some impurities, which could increase pycnocuclear reactions. Perhaps this provides the heat needed to explain superburst ignition. Jean in 't Zand talked about New phenomena in thermonuclear X-ray bursts and Superbursts Jean described two newly discovered X-ray burst phenomena: (1) long burst tails, (2) superexpansion bursts. Randall Cooper discussed the 12C + 12C Reaction Rate and Superburst Ignition. Thermal properties of crust and core sets ocean temperature and thereby the superburst ignition depth, so superbursts are probes of NS interiors. Nevin Weinberg told us about the physics of the superburst rise. This is relevant because the rise both (1) determines the energy released during the superburst and thereby the light curve morphology and (2) sets the composition of the deep ocean and crust. Nathalie Degenaar showed us new observations of crustal cooling for the source EXO 0748-676. This source just turned to be in quiescence. It would be interesting to compare the cooling behavior of KS 1731 and MXB 1659. Data are just coming out. Sanjib Gupta talked about Nuclear reactions in the crust and implications for superburst ignition and cooling. In the outer crust, electrons can capture into excited states of nuclei; the subsequent radiative de-excitation can release up to 4 times more energy than previous models predicted, which assumed electron capture into the ground state. Interestingly, Daligault & Gupta (2009) find that the outer crust is amorphous, i.e. it does not form a lattice! This result is exciting, but conflicts with previous calculations (like Chuck Horowitz's simulations). Dany Page described how as cooling depends on the thickness of the crust it should be possible to distinguish between neutron stars and strange stars - a strange star has a much thinner crust (a few hundred metres as opposed to km). So, relaxation of the crust should be a good test. Dmitry Yakovlev gives an interesting and entertaining overview of pyconuclear reactions. These density sensitive nuclear fusion processes are manifestations of the QED vacuum. The reaction rate of pyconuclear reactions is independent of temperature, but increases exponentially with increasing density. These processes are thought to allow for the formation of large nuclei in the neutron star crust. Milan Matos gave a nice summary of mass measurement techniques. Milan mentioned the importance of masses to neutron star modeling. He then summarized current techniques including direct measurements such as Penning traps, Schottky method, time-of-flight, and indirect measurements done with transfer reactions. Milan also mentioned capabilities of different facilities producing isotopes in different regions of the chart of nuclides.

The second day was opened by Alex Heger. Alex began with an overview of type I X-ray bursts and their various accretion rate regimes. He then described his numerical simulations of bursts using the 1D Kepler hydro code which he coupled to a large reaction network. Runs with H/He accreting at high accretion rate with low Z show long (200s) tails due to rp-process burning and little 12C in the ashes of burning (X12 0.001). In runs with low Mdot and high Z, the ignition takes place in a pure He layer, leading to a very quick burst rise (1 ms) and near Eddington luminosity at peak. Runs with very low accretion rate undergo weak hydrogen flashes. Next, Andrew Melatos gave a discussion of magnetic field evolution and its consequences in accreting neutron stars. Magnetic field burial and flux freezing together distort the initial dipole and decrease the magnetic moment; however, the local field strength may increase. The interesting claim is that the end state could be an internal $10^1$5 G (!!!) magnetic field "wall" that could affect type I X-ray bursts, for example. The idea is exciting because there are severe discrepancies between observations and X-ray burst models that are difficult to explain through nuclear physics uncertainties alone, but the presence of such a structure, particularly at the ignition pressures of X-ray bursts, are difficult to believe. Jeff Blackmon stressed the importance of experimental measurements of (p,g) and (a,p) reactions to accreting neutron stars. Current experiments are using indirect techniques to locate important resonances for these reactions. Specifically mentioned two direct measurements, the first was performed at Oak Ridge andthe second at CRIB (RIKEN). Jordi José described his group's simulations of type I X-ray bursts using the 1D SHIBA hydro code coupled to a large network. In models with solar abundance of metals he finds very little 12C in the ashes (1% by mass), peak nuclei with A 60, and, in general, results that approximately match those found by Heger et al. Sub-solar models (Z=0.001) had less energetic but longer bursts, lower alpha (alpha 30), synthesized heavier species (A 100), and smaller 12C mass fractions (0.1%). Richard Cyburt compared results for XRB lightcurves coming from two different methods: Multizone and single zone calculations. Overall the two methods agree quite well, both for composition and light curves. Both compositions peak in the interval A =60,80. Richard shared with us a very useful piece of information about the JINA REACLIB project. REACLIB is a huge data base with nuclear reaction rates. Users can create their own libraries there too. Anuj Parikh continued describing another x-Ray burst sensitivity study. The study explored sensitivity of model to peak temperature, duration, and initial composition. Then, using one-zone post processing models the study varied individual reactions (¿2000), simultaneous varied multiple reaction rates, and individual variation of Q-values (¡1MeV). Anuj also showed that Q-values are important for calculating forward reactions from theory and for detailed balance in reverse rate calculation. Q-value uncertainty is most important when the Q-value is small. The sensitivity study identified the Q-value from ge64(p,g) as having the most significant impact. Wanpeng Tan told us about three reactions, alpha captures on waiting points, that are important for type I X-ray bursts: 14O(a,p), 15O(a,g), and 26Si(a,p); such reactions are some of the first that occur at ignition 15O(a,g) is particularly crucial for burst ignition. Tan's analysis of the measurements result in a rate that is sufficiently precise to constrain the critical accretion rate above which burning is thermally stable to within 10%; the critical rate is roughly the Eddington limit. Jerome Chevenez showed that the INTEGRAL satellite is an important tool for the detection of intermediately long X-ray bursts. What I find quite impressive is that bursts from different sources can be detected within one detector lightcurve, thanks to the large field-of-view of the instrument. There are several sources for which different types of X-ray bursts are detected at roughly the same mass-accretion rate, so this must be near the transition rate of the different burst types. Laurens Keek gave a nice talk discussing the problem of X-ray bursts with short recurrence times. He uses a combined RXTE-PCA and BeppoSAX-WFC archive, containing over 3000 bursts, for his studies. For a large range of mass-accretion rates, bursts are found that are followed up by more bursts minutes later (double and triple bursts). Such time-scales are too short to create a brand new fuel layer through accretion, which suggests that there must be some left-over fuel after the initial burst. It remains a mystery how and where this fuel could be stored. The second day was closed by Craig Heinke who told us about a possible problem in explaining the quiescent luminosity of the accreting millisecond X-ray pulsar SAX J1808. X-ray observations of SAXJ1808 in quiescence put tight upper limits on the luminosity of thermal emission from the neutron star surface, indicating that the surface is quite cold. It has been suggested that this can be explained by having a high mass neutron star (which can give a higher neutrino emissivity). Recent optical observations of SAXJ1808 have, however, constrained the mass of the neutron star, and it seems to have a low (rather than high) mass. To complicate things further, another transient, Aql X-1, which seems to have a surface temperature (from quiescent X-ray observations) consistent with standard cooling, may have a high neutron star mass, so it might have been expected to be colder than actually observed. Craig asked if anyone had any ideas on how to explain this, particularly, can more massive neutron stars emit less neutrinos than lighter neutron stars?

Jim Lattimer launched the third day of the workshop with a nice discussion of the application of the equation of state (EoS) to properties concerning the crust. For instance, he discussed how the thickness of the crust has a simple dependence on mass and radius and the chemical potential at core/crust boundary. He pointed to several types of observations that are dependent on the crust thickness, e.g., crustal cooling and neutron star seismology. Jim finished with a summary of measured neutron star masses. What was particularly exciting is a recent well constrained mass measurement of 1.67 +/- 0.01 solar masses (Champion et al. 2008). Duncan Galloway discussed a promising approach to constrain the neutron star parameters from type-I X-ray bursts. Comparing observed burst lightcurves with theoretical models allows for an independent distance measurement, whereas the neutron star radius can be constrained from fitting the spectral data and the Eddington flux can be estimated from modeling the temperature profile in the neutron star crust. This combination allows one to put constraints on the neutron star mass and radius. The technique is applied to the bursters GS 1826-24 and KS 1731-26. Eddington limited X-ray bursts have been detected from the latter, which provides additional constraints. Jorge Piekarwicz started his talk with a description of the correlation between neutron skin and pressure of pure neutron matter which then effects the neutron star radius. Also, mentioned the Garvey-Kelson Mass Relations which has very general assumptions but seems to work extraordinarily well. More general and robust than expected hinges on smoothness of M(N,Z). Finally, Jorge was trying to understand if nuclear pasta is robust or model dependent. Do we have to go through pasta or is there another possibility? His work showed that there is no pasta formation if there are no long range forces or if neutron skin is large. Achim Schwenk talked about how to calculate nuclear reaction rates determined by spin relaxation time. This method allows to calculate scattering of neutrinos from one or two nucleons. The spin response is embedded in the dynamical structure factor of the nucleons. The nucleon interactions are described by chiral effective field theory. Tod Strohmayer started the afternoon session with a detailed overview of the fascinating oscillations seen during giant flares on magnetars. In the two objects where these oscillations have been seen, a wide range of frequencies have been detected. It is highly suggestive that these are torsional oscillations due to vibrations in the crust. With further understanding and detections there is the exciting possibility to constrain neutron star properties from these oscillations. As Tod discussed, there are still a number of theoretical issues, and lots of complexity in the observations. For example, does the crust fracture (analogy to earthquake fractures)? And, while what we observe are modulations in X-ray flux - can these actually be produced by crust motions? Yuri Levin followed with a discussion on MHD aspects of magnetar's oscillations. There are two types of torsional modes in the neutron star: shear modes in the crust and alfven modes in the core. These two modes have similar frequencies, so we expect coupling between the modes. The timescale for energy exchange is much smaller than the duration of the QPO's, so we expect many exchanges to occur. Therefore, we need a realistic model of the coupled crust and core to really understand magnetar QPO's. Andrew Steiner told us about how oscillations detected in magnetar giant flares may quantitatively constrain nuclear physics, in particular the ubiquitous nuclear symmetry energy. The symmetry energy is one of the largest uncertainties of the crust parameters; this uncertainly leads to uncertainties in the shear modulus and shear speed. The afternoon finished with a poster session after the coffee break. Many people engaged lively discussions about the twenty posters presented.

The last day of the workshop was opened by Vicky Kaspi reviewing the observational properties of anomalous X-ray pulsars (AXPs). AXPs form a class of highly magnetized neutron stars, denoted as magnetars, together with soft gamma repeaters (SGRs). Vicky showed the results of phase-coherent timing studies of 5 AXPs (SGRs are too faint to detect with RXTE when not bursting or flaring) using a long-term monitoring program with the RXTE satellite. The AXPs appear to display many glitches; sudden spin-up events that may be explained by a faster rotating crustal superfluid suddenly transferring angular momentum to the crust. Glitch studies can possibly help to constrain the superfluid properties of neutron stars. The AXP glitches are rather peculiar compared to those observed from rotation powered pulsars and sometimes result in a net spin-down rather than an increase in the spin period. It was follwed by Maxim Lyutikov talking about the evolution of magnetic fields in magnetars and Roberto Turolla discussing magnetospheric models and comparing emission properties with observations. To wrap up the final session Jose Pons gave a review on magneto-thermal evolution of magnetars, focusing on the effects of crustal magnetic fields, Steve Price told us about the thermo-resistive instability in magnetar's crusts and Rishi Sharma closed the program with a discussion on superfluid heat conduction and its observable effects in neutron star cooling observations.

3 Assessment of the results and impact of the event on the future direction of the field

We think that this workshop was an ideal venue to discuss future developments in theory, observations, and experimental nuclear physics that would influence the direction of the field and form new collaborations to address the open questions. We had an equal mix of observers, nuclear/astro theorists and nuclear experimentalists actively participating in all sessions and interacting with each other. Many interventions during the last open discussion raised interesting questions and pointed towards open problems in the field. Some of this were:

- Multi-dimensional models for X-ray bursts.Connects nuclear experiment directly to astrophysical observer, the most distant line this community needs to cross. HS suggests the nuclear physics remains uncertain for multi-dimensional model, and therefore must pinned down.

- Lots of phenomenology from many different angles: crust cooling, X-ray bursts, and code-to-code comparisons of X-ray bursts. Need to set up some benchmark cases with identical physics. This will be important with plots of NS mass and radius, with different constraints from different phenomena, one wants to be sure that the inputs at the microphysical level are identical.

- At Michael Smith's repository at nucastrodata.org, the whole community has access to the same primary dataset – this is intended to act as a benchmark.

- Duncan Galloway's X-ray burst lightcurve repository is a resource for the modeling community.

- Modelling the crust: is it amorphous or crystaline, and do magnetic field evolution affect the the crust. A model of the magnetic field evolution with amorphous conductivity, to see if the crust blows up.

- Next year, the European NSF collaboration COMPSTAR will provide training and codes for students for neutron structures, NS rotation, magnetic field structure, supernova hydrodynamical codes, etc.

- JINA has a series of schools, dedicated to giving away R-matrix code to analyse reaction codes; some network codes; shell model.

- An important question: Where are the condensed matter people in all this? For example, they have been working with rotation in superfluid 3He for some time, they must be able to inform our understanding of rotation in neutron stars. We need to do outreach to condensed matter physicists, who study superfluidity and strong magnetic fields in matter, because they were not represented at this workshop.

- When the new generation of gravitational wave detectors is built, the Gravitational Physics community will continue to grow in importance to neutron stars. We should be embedding them with us, as soon as possible.