BIRS – 12frg183:
The advent of Quark-Novae: Modeling a new paradigm in Nuclear Astrophysics

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Different aspects of the Quark-Nova model are being developed at universities around the world. For this workshop, contributors in this emerging field met to share and stimulate research in the astrophysics of the Quark-Nova.

First, we presented an overview of the progress made in the fundamental aspects of the quark-nova model and the quantum chromodynamics (QCD) phase transition at high density. Second, we examined the observational successes of the Quark-Nova model pertaining to nucleosynthesis and the chemical evolution of the Galaxy. Finally, we discussed new and general directions for the development and refinement of the Quark-Nova model. It was the intention to complete a thorough overview of the model, combining all aspects and making it accessible for an audience at the level of a physics or astrophysics graduate student.

1 What is a Quark-Nova?

A Quark-Nova (also referred to as a Quark Nova explosion; Ouyed et al. 2002) is the violent explosion resulting from the conversion of a neutron star core to quark matter. The result is a star made entirely of quarks; the quark star. The neutron star itself is formed from a SuperNova preceding the Quark-Nova.

The supernova explosion leaves behind a neutron star (the compact remnant) and the expanding stellar envelope (the supernova remnant). The fast rotation and misaligned magnetic field of the neutron star create an electromagnetic light-house effect. The iron crust encases a neutron-rich interior of the neutron star. The spin-down of the neutron star increases its core density to extreme densities (Staff et al. 2006), liberating quarks from neutrons through a process known as quark deconfinement. This phase transition releases neutrinos and photons that build up a fireball as the of the neutron star core collapses (Keränen et al. 2005). The outer layers are blown off during the Quark-Nova (Ouyed&Leahy 2009). If the delay between the super nova and Quark-Nova is on the order of weeks, the supernova remnant is re-energized by the Quark-Nova (Leahy&Ouyed 2008). This process would release immense amounts of energy, perhaps explaining the most energetic explosions in the universe (Ouyed et al. 2012); rough calculations have estimated that as much as 10^{47} joules of energy could be released from the phase transition inside a neutron star. Quark-novae could explain a multitude of astrophysical phenomena from gamma ray bursts through super-luminous super novae.

2 The Quark-Nova Model

2.1 Quark Deconfinement and Detonation

In the case of a neutron star burning into quark matter made up of Up (u), Down (d) and Strange (s) quarks, there is a radial density gradient in the interior core of the neutron star that the burning interface progresses through. As the interface burns outwards it reaches lower densities, making the interface move slower, until it reaches the critical point where the interface halts due to the deleptonization process (Niebergal et al. 2010). The critical point depends on a number of factors including the equation-of-state of neutron matter and quark matter, neutrino cooling efficiency, and most importantly the dynamics of the combustion in multiple dimensions (e.g. the wrinkling of the combustion front, sensitivity to instabilities, etc.; see Niebergal et al. 2010). The situation is then an under-pressured *(u,d,s)*-quark core, with the outer layers of the neutron star lying on top. The under-pressured core will eventually collapse - similar to the core collapse phase during a supernova - causing the outer lying material to fall onto the core, leading to a second explosion; *a Quark-Nova explosion*.

2.2 The QN neutron-rich Ejecta

Following a QN explosion, the neutron star's metal-rich outer layers are ejected. There are four possible scenarios for the state of the ejecta: first, if it is very light then it will become gravitationally unbound from the quark star (Ouyed&Leahy 2009); second, if the ejecta is too heavy it will fall back into the quark star releasing tremendous amounts of energy; third, the ejecta velocity can be low enough such that it remains bound to the QS and mass low enough that it can be suspended by the quark star's magnetic pressure; and in the fourth case, the ejecta velocity is also low enough to remain bound but its angular momentum is large enough (e.g. by the propellor mechanism) that the ejecta remains in a Keplerian orbit (Ouyed et al. 2007a; 2007b).

In this workshop we investigate the thermal and dynamic evolution of a relativistically expanding iron-rich shell from a QN explosion. The QN produces a photon fireball (Ouyed et al. 2005a) which acts as piston to eject and accelerate the crust of the parent neutron star to relativistic speeds. Although the presented model is based on physical arguments, the physics of the ejection is in reality more complicated and so would require more detailed studies and the help of numerical simulations. For example, the process of clumping, crystallization, and breakup of the ejecta, would require better knowledge of the ambient conditions surrounding the ejecta. The astrophysical implications will be discussed elsewhere.

2.3 The Compact Remnant (the Quark Star)

The Quark-Nova leaves behind a quark star in a superconducting quark matter phase (Vogt et al. 2004). Once the neutron star has made the transition from hadronic to superfluid-superconducting quark matter, and through a Meissner effect, the quark star's interior magnetic field is forced inside rotationally induced vortices of the superfluid quark matter. The vortices and interior magnetic field are aligned with the rotation axis of the star. The exterior dipole field is forced to align with the rotation axis immediately after the neutron star has made the transition to superconducting quark matter, as simulated in Ouyed et al. (2006); see also Ouyed et al. (2004).

3 Scientific Progress Made

The different aspects brought by each participant were combined to allow a discussion of what impact the QN Ejecta and Compact Remnant would have in the environment where a Quark Nova occurs. The discussion led to predictable observations that would lend support for the existence of Quark Novae.

3.1 Impact of the QN Ejecta in the environment

A promising source for the production of ultra high energy cosmic rays (UHECRs) is the relativistic shocks resulting from the interaction of the QN ejecta with its environment. Such a connection has been reported and investigated in Ouyed et al. (2005b). QNe as possible UHECR sources seem to account for the observed extragalactic flux and can contribute at least partially to the galactic cosmic rays. The QN model for the acceleration of UHECRs seems to possess features that can be tested in future cosmic ray detectors. We thus predict UHECRs to be seen in connection with some events involving QNe.

3.2 Impact of the Compact Remnant in the environment

The fate of the ejected neutron star crust is determined by the initial conditions of the remnant (i.e. rotation period, magnetic field, and shell mass). One example of such an outcome is the propeller mechanism. This results in a degenerate Keplerian torus (Ouyed et al. 2007b) forming from the ejected matter rather than a co-rotating shell (Ouyed et al. 2007a).

4 Outcome of the Meeting

Aside from reviewing the progress made on each aspect of the model, the meeting was also used to solidify the general and future directions of research into the Quark Nova. During the workshop we started the process of writing a review paper on Quark-Novae. Currently we are in the late stages of finishing the paper.

4.1 Predictions and Observation

Surveys that search for Type-II Supernovae such as the Palomar Transient Factory (PTF) have the potential to observe a Quark Nova. These surveys search for transient events and follow up using larger telescopes around the world. If a Quark Nova were to be observed, a characteristic double-hump would be observed as the luminosity peaked twice (see Ouyed et al. 2009). Once for the supernova explosion (preceding the Quark-Nova), and again for the Quark-Nova proper. This would constitute a unique photometric signature of a Quark-Nova (Ouyed et al. 2012; Ouyed&Leahy 2012).

Which astrophysical phenomenon will produce measurable gravitational waves is still an open question. Once gravitational wave detectors begin to collect data we may learn that core collapse Supernovae produce a distinct gravitational wave signature. If this is the case then we would expect an event where a Supernova is followed by a Quark-Nova to produce the unique gravitational wave signature of two successive pulses separated in times (by a few hours to a few weeks; see Staff et al. 2012).

4.2 Spatial Simulations Needed

From the meeting, it became apparent that simulations of the hadronic-to-quark-matter phase transition inside the neutron star need to be extended to 2D and 3D in order to capture the QN explosion in details.

4.3 Mathematical Model

Another outcome of the meeting was an answer to the need to build a more robust mathematical model to describe in more detail the interaction between the Quark-Nova ejecta and the proceeding Supernova ejecta/envelope. We were able to devise an approach to make the mathematical model used for the Quark-Nova more mathematically sound and go beyond current approximations.

Our current Superluminous Supernovae calculations assume a completely uniform Supernova envelope and do not account for an inhomogeneous density profile or element stratification (distribution of different elements in the envelope) Aside from leaving these assumptions, a more realistic model would take into account opacities and shock physics.

The nuclear spallation calculations for the Quark-Nova model (Ouyed et al. 2011; Ouyed 2012) will be extended with a more accurate mathematical framework (beyond the layer approximation) and keeping track of individual isotopes. This involves working will more refined interaction cross-sections, and using up-to-date spallation cross-sections from literature. We will then make the calculations taking into account all of the heating mechanism used by spallation reaction. The production of heavy elements during the expansion of the QN ejecta (Jaikumar et al. 2007) will be explored in more detail in the future.

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