Il Colle di Galileo

The structure and signals of neutron stars, from birth to death

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Abstract. Neutron stars (NSs) represent an active area of research: from their birth following the collapse of massive stars in supernova explosions, through their lives as hot thermal sources, radio pulsars and/or magnetars, up to their catastrophic demise (when they reside in compact binaries) following gravitational wave-driven coalescence. Progress in understanding the structure and signals of neutron stars demands expertise across a wide range of disciplines: from theoretical and observational astrophysics to nuclear and particle physics, computational relativity and gravitational wave (GW) physics.

Several recent developments suggested that the time was ripe for a workshop focusing on all facets of NS science. These include: the recent discovery of a 2 solar mass neutron star; evidence for cooling of the NS in Cas A, suggesting a possible transition to neutron superfluidity; 'advanced' generation GW detectors LIGO and Virgo coming online in 2015; new observations challenging traditional models for gamma-ray bursts; new lab experiments which aim to probe the conditions of matter at ultrahigh densities and temperatures (e.g. NICA - Dubna); and new or planned electromagnetic observatories at radio (LOFAR/ASKAP/MeerKAT/SKA), optical (e.g. LSST), X-ray (NICER/LOFT/AXTAR/Athena+), and gamma-ray (e.g. CTA) wavelengths.

This workshop brought together theoretical and observational astrophysicists from across the electromagnetic and GW spectrum, as well as nuclear physicists interested in the behavior of matter under extreme conditions. The goal was to explore what has been learned from current observations, to review what is expected from new facilities and to assess what exploratory work is required to lay the groundwork for these new capabilities. Throughout the workshop, senior researchers delivered lectures to PhD students, young postdoctoral researchers, and to other senior researchers wishing to expand their own knowledge. Lectures covered topics in high density matter, superfluidity, cooling of neutron stars, explosive phenomena, analysis of data from x-ray satellites, and gravitational wave emission. A general conference was also organized during the workshop and about 150 people took part.

Keywords. equation of state of dense matter, including hyperon, kaon and quark degrees of freedom, neutrino emission and cooling of compact stars, superconductivity-superfluidity, constraints from EM observations, transients, gravitational wave emission; models for Supernovae and for Gamma Ray Bursts; magnetars

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The scientific case

Nuclear physics interest. NSs span an astonishing six orders of magnitude in density from the solid outer crust to the super-nuclear density fluid of the inner core. The densities at the core of an NS are higher than those that can be studied on Earth, and the predictions of nuclear theory admit many possibilities. The transition from nucleons (neutrons/protons) to de-confined quarks and gluons is of particular interest. This transition can be studied at low densities and extremely high temperatures by experiments on heavy ion collisions, such as those performed at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC). Intermediate densities and still high temperatures will be explored at the Facility for Antiproton and Ion Research (FAIR) and at the Nuclotron-based Ion Collider fAcility (NICA).

Matter at extremely high densities and low temperatures can be explored only by studying NSs. In this region of densities and temperatures, not accessible to lab experiments, new phases of matter have been theoretically proposed. For instance, matter at the core of NSs can behave as a color superconductor: since the superconducting gap vanishes at high temperatures it is unlikely that this hypothesis can be tested in heavy ion collisions. Moreover, the existence of a color superconducting region profoundly affects many properties of an NS. The connection between matter tested in heavy ion experiments at moderate energies (FAIR, NICA) and matter at the moment of the gravitational collapse preceding an SN explosion is also of the greatest interest. In this case, lab experiments can provide constraints to the EoS to be used in modeling SN explosion.

An intense theoretical activity has been developed over the years to describe NS properties and their relation to the nuclear EoS. The EoS determines properties such as the mass and the radius, the maximum rotational periods, the cooling rate, GW emission etc. The EoS is also crucial in calculating the energy released in an SN explosion. Moreover, the behavior of matter in the crust of an NS profoundly affects all the observables: cooling properties, formation of a magnetic field, pulsar glitches. It is only now, however, that observations are starting to yield results of sufficient precision to discriminate between different theoretical scenarios and thus genuinely advance our understanding of the microphysics underlying compact stars.

EM radiation as a probe of NS nuclear properties. Various measurements can be used to constrain the dense matter EoS. The analysis of observations based on electromagnetic emission can be used to measure or put limits on NS mass and radius (which relates to the EoS via the stellar structure equations). The recent discovery of a 2 solar mass pulsar by Demorest et al. 2010, for example, represents the most robust constraint on the EoS to date.

Aside from direct mass determinations, one of the most effective insights into the interior is through observations of the thermal properties. NS cooling curves are sensitive to the internal composition and also to the superfluid characteristics of its components. Indeed, the interior of the star cools through the emission of neutrinos, which is very sensitive to composition and possible superfluidity. Observations of cooling trends in the young NS Cas A, for example, have recently enabled detection of the transition to neutron superfluidity. It is now clear that the behavior of the symmetry energy of dense matter is crucial in determining the relative rate of neutrino cooling. This is because the symmetry energy not only controls the rate of cooling for a mixture of nucleons, establishing the proton fraction and the possibility of observing the direct URCA process, but also determines at which densities exotic material, such as hyperons, Bose condensates, or de-confined quark matter appear, all of which could allow relatively rapid cooling even if neutrino processes involving nucleons were slow.

Techniques discussed during the workshop and the conference included the following: NS masses and moments of inertia via pulsar timing; NS cooling (for isolated and transiently accreting systems); thermonuclear X-ray burst spectroscopy; NS rotation (with the potential discovery of rapidly rotating systems and torque mechanisms); glitches and precession as a probe of superfluidity, and pulse profile modelling (for isolated and accreting systems). Such techniques are being actively exploited using current facilities, and are major drivers for future radio and X-ray telescopes including the Square Kilometer Array and the Large Observatory for X-ray Timing.

Gravitational wave emission. GWs are generated by the motions of matter, and the denser the matter, the stronger the waves. This makes compact objects ideal for emitting strong detectable GW signals, potentially carrying information about the state of matter at the very highest densities reached in the cores of compact objects. Indeed, much of the data analysis effort of the Virgo Scientific Collaboration and the LIGO Scientific Collaboration has been directed towards detecting signals from both known and currently unknown compact objects. Interest in GW emission is very high at present: the LIGO (US/UK) and Virgo (Italy/France) GW detectors are currently being upgraded to the 'Advanced' configurations. New data collection is expected to begin as soon as 2015, with the first detections expected soon after.

However, having better detectors is not enough. A better theoretical understanding of the ways in which compact objects emit these waves is crucial, for two reasons. Firstly, the waves are weak, so having an accurate idea of where to look, and what the wave should look like, makes detection more likely. Secondly, in the event of detection, a good theoretical model is required to interpret the observation and use it to place constraints on fundamental theory. It was precisely these issues that we proposed to address in this workshop.

Compact objects can in fact emit GWs in a variety of different ways, each sensitive to somewhat different aspects of the high density EoS. Firstly, and perhaps most simply, if a steadily rotating NS is deformed away from axi-symmetry, it will emit a steady GW signal. Such a deformation might be produced by a strong magnetic field threading the stellar interior, or else by strains in the solid part(s) of the star. In either case, the presence of an 'exotic' state of matter, e.g. a quark condensate, might be signaled by a stronger-than-expected signal. Equally interestingly, compact objects have a whole zoo of normal modes of oscillations, just like any other fluid self-gravitating star. The frequency and lifetimes of these modes encode detailed information about the EoS, including information on the fluid shear viscosity, bulk viscosity and the existence (or not) of superfluid and superconducting phases. The possible role of instabilities in these modes is also of interest, particularly as it may play a part in limiting the spin frequencies of pulsars.

Finally, the first sort of GW source that is expected to be detected is that of binary in-spiral, where two compact objects gradually coalesce while emitting a steadily strengthening GW signal. The final stages of this are sensitive to the finite size of the constituent stars, with less compact objects affecting the phasing to a greater extent than more compact objects. This is an important effect, and one of immediate interest to GW astronomers worldwide.

Modelling Supernovae and Gamma Ray Bursts. The mechanism for core collapse SNe remains elusive. Only fairly recently have spherically symmetric models achieved a sufficient level of sophistication to eliminate past model uncertainties and lay a sound foundation for multi-dimensional models. Observations continue to disclose a wealth and continuum of phenomena that modelling efforts must explain: the recent discovery of anomalously energetic SNe with characteristics both similar and dissimilar to ordinary SNe, and the association of some core collapse SNe with gamma ray bursts, are just two examples. Fundamental issues related to the physics of compact stars, such as the super-nuclear EoS, and the interaction of neutrinos with ultra-dense matter, play a key role in solving the SN problem.

The origin of GRBs also remains a mystery. The prevailing models involve core collapse SNe and NS mergers, proposed to produce long (> 2 s) and short (< 2 s) GRBs, respectively. For a handful of long bursts, there is indeed observational evidence for an SN connection; however the nature of the central engine powering the relativistic jet remains elusive. Competing models include rapidly-accreting black hole and a rapidly-spinning, strongly-magnetized NS (a so-called «millisecond magnetar»), but further progress will be required to distinguish between these possibilities. In this model for GRBs the structure, formation and evolution of a magnetar plays a crucial role, establishing a direct link between the study of GRBs and the study of the EoS of NSs.

Another crucial link is between GRBs and GW emission. As discussed above, the most promising sources for GW detection are the final in-spiral and merger of compact object binaries containing NSs and/or black holes. When matter is present, these sources are also expected to produce brilliant EM fireworks, which will aid in the detection, localization and interpretation of the GW signals. Example counterparts include short GRBs powered by accretion onto the newly-

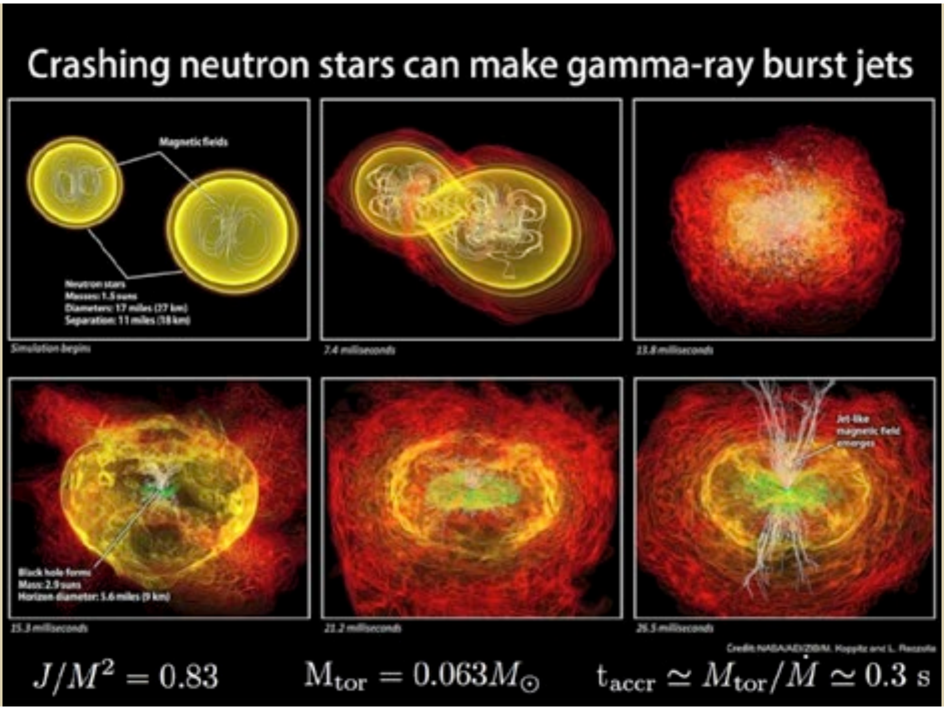

Figure 1. In the figure (from the talk given by Luciano Rezzolla) we can see a numerical simulation of the merger of two neutron stars into a black hole. During the process, extremely strong magnetic fields are generated which can be crucial for powering a jet. The internal shocks taking place inside a jet between components travelling at different velocities generate the electromagnetic emission that we observe as a GRB, in this case a short one. During the merging, a strong GW signal is also generated and it bears the imprint of the EoS of the matter constituting the NSs before the merger. In this way the detection of GWs will make it possible to place precise constraints on the long-standing problem of the internal composition of NSs.

formed black hole, or an SN-like transient powered by the radioactive decay of exotic heavy nuclei synthesized in the neutron-rich matter ejected during the merger. These mergers provide a formidable example of an astrophysical case in which all the aspects discussed in the workshop (GW emission, explosive phenomena and structure of the compact stars) contribute to the understanding of the phenomenon.

Outcome of the workshop and conference.

Many scientific discussions during the workshop helped to frame new possibilities and develop new collaborations. Among the main outcomes, it should be noted that a document was produced, "Properties of matter at high baryonic density: a fundamental discovery within reach". This document stresses the importance of closer collaboration between people working in nuclear physics and people working in astrophysics. There are a few fundamental questions which can hopefully be answered in the near future, such as:

- At which baryonic densities do quarks start to deconfine? Is there any critical density for deconfinement?
- Is there a critical point in the phase diagram of matter at high densities and temperatures?
- Is Witten's hypothesis about the absolute stability of strange quark matter borne out in compact stars?
- Are supernova explosions and gamma-ray bursts associated with phase transitions in dense matter?

These questions are intrinsically linked to a fundamental question: at which densities can strange hadrons be produced and what is their impact on the equation of state of matter?

In order to answer these questions, the collaboration among various research areas is not merely useful but essential. The reason is that results obtained only from laboratory experiments or only from X-ray satellites cannot address the above questions. For instance, the discovery that Witten's hypothesis is indeed borne out in Nature can come only from: a) laboratory experiments revealing at which densities strange hadronic matter starts being formed; b) theoretical studies investigating the implications of strangeness deposition on the stability of matter and, obviously, c) the measurement of masses and radii of compact stars via observations from gravitational-wave detectors and X-ray satellites. Separately, each of these investigations can provide some hints, but cannot give a definitive answer.

This document was signed by numerous scientists working in nuclear physics and in astrophysics and it can be considered as one of the most significant outcomes of the workshop.