ESF - Exchange Grant - Final Report

Luca Bonanno

1 Purpose of the visit

Rapidly rotating compact stars are unstable under R-mode oscillations, unless they are damped by the viscosity or by the formation of internal magnetic fields [1, 2, 3].

In a recent paper [4] it has been noticed that r-modes can generate very strong magnetic fields inside an accreting and rapidly rotating compact star. The same mechanism of generation of a magnetic field by r-modes was studied in the past by Rezzolla et. al [5, 6, 7] but in a different scenario, namely for the case of a newly born and rapidly rotating neutron star. The new scenario is particularly relevant to study the evolution of Low Mass X-ray Binaries (LMXBs).

The purpose of this project has been to extend the previous calculations to cases in which strangeness is present in the star. In particular case to study:

- The evolution of the instability window, in presence of the magnetic damping;
- The evolution of the internal magnetic field which depends on the composition controlling the crucial hydro-dynamical quantities such as the magnetic diffusivity, the anti-buoyancy force and the diffusion time scales.

The main purpose of this project has been to provide a more realistic description of the evolution of an accreting compact star, taking into account both the possible existence of exotic components and the possible generation of strong internal magnetic fields.

2 Description of the work carried out during the visit

In Heidelberg I found a very stimulating place to carry out my research project. As soon as I started I established a very fruitful collaboration with great expertises concerning the physics of compact stars, as e.g. Professor Jürgen Schaffner-Bielich, Dr. Giuseppe Pagliara, Dr. Basil Sa'd and Dr. Debarati Chatteerje [8, 9, 10, 11, 3, 12, 13, 14].

Although the projected period to be spent in Heidelberg was of 3 months, starting from the middle of June 2010, it has been extended until the beginning of October 2010. My work has been mainly focused on the study of the generation and of the evolution of magnetic fields in the core of strange stars inside LMXBs. I also treated the case of hyperonic stars, however the analysis of these stars has not been still completed.

The first and more difficult step has been the writing of a code in Fortran, which I used to perform numerical calculations. This code is devoted to study the temporal evolution of a rotating star, given its composition, its initial temperature and its initial rotational frequency. In order to describe the evolution of a star, one has to solve simultaneously a set of four coupled differential equations. Three of these equations give the evolution of the temperature, the rotational frequency and the r-modes amplitude, while the fourth is an extra equation which I included in order to take into account the generation of toroidal magnetic fields due to r-modes secular motion. This system of differential equations cannot be solved with standard numerical techniques (as e.g. the usual Runge-Kutta method) due to its stiffness, so I adopted a modified version of the Runge-Kutta method with adapted time intervals.

The most important ingredients appearing in the evolution equations are the values of the bulk and shear viscosity timescales, the magnetic diffusivity, the anti-buoyancy force and the diffusion time scales, which are strongly related to the composition of the star. While the bulk and shear viscosity are crucial for the determination of the instability window, the hydrodynamical quantities control the evolution of the internal magnetic field. For the case of strange stars, I used the values of these quantities found in literature. However, a more accurate study has been required in order to estimate the value of the magnetic diffusivity.

Once the code was ready and after several consistency checks (as e.g. I checked that the results obtained for the evolution of neutron stars were exactly coincident with the ones recently published by Cuofano and Drago [15]), I studied the evolution of rotating strange stars in LMXBs, in particular focusing my interest on the generation of toroidal magnetic fields. During the last part of my visit I started to write a paper containing the results which I obtained. I recently presented these results at the MODE-SNR-PWN Workshop in Bordeaux (15-17 November 2010), organised by Compstar.

3 Description of the main results obtained

Here follow the main results obtained during my research stay for the evolution of rotating strange stars in LMXBs, and the comparisons with the case of neutron stars:

- In the case of neutron stars, the region of instability is strongly suppressed by the generation of large toroidal magnetic fields ($B_\phi \sim 10^{12}$ G). Conversely, the instability window of strange stars is not modified by the new magnetic field. Therefore, the generation of toroidal fields actually does not affect the path followed by strange stars in LMXBs.

- The critical values of the magnetic fields at which Tayler instability sets in (Tayler instability generates a new poloidal component with approximately the same strength of the toroidal one) are not much different for neutron and strange stars ($B_\phi \sim 10^{12}$ G). However, while the former have a superconductive crust acting as a screen for the new internal mixed poloidal-toroidal magnetic configuration, whether the latter possess or not a crust is still controversial. If the crust is not present, such large poloidal component is not screened and diffuses outside of the star, preventing the star from further accreting mass. Therefore, if a strange star inside of a LMXB produces, due to the r-mode instability, an internal magnetic field larger than the Tayler instability threshold, then it should stop accreting mass. Thus, this represents an additional constraint on the highest rotational frequency of the strange stars in LMXBs (notice that this limit strongly depends on the value of the strange quark mass).

- Following the scenario discussed above, after stopping the accretion, a strange star should fastly (in a few thousands years) slow down, due to a large magnetic braking. Therefore such a star, previously observable as a LMXB, can recycle into an highly magnetised pulsar.

4 Future collaboration with host institution

Currently I am continuing the collaboration with the host institution, in particular the following works are planned:

- The extension of the previous calculations to hybrid stars and hyperonic stars.
- The study of the nucleation process during the transition from hadrons to quarks.

5 Projected publications/articles

I prepared an article, describing the results discussed above, which will be submitted soon.

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