Project: Equation of state and the magnetic evolution of neutron stars in binary stellar systems

MP1304: FINAL REPORT

1. Purpose of the visit.

The main purpose of the visit was a collaborative work with Profs. F.Burgio, M.Baldo and Dr. A.Bonanno. We planed to create the code for calculations of the magnetic and rotational evolution of neutron stars in low-mass binary systems, to consider the influence of the equation of state of nuclear matter on this evolution, to discuss the obtained results, and to start writting the paper on this subject.

Evolution of the magnetic field provides one of possible windows into neutron star interiors. This evolution is influenced through the electrical conductivity by the state of matter inside the star. The evolution of neutron stars in some binary systems is extremely long. This concerns particularly the so-called millisecond pulsars - a compact group of objects with the magnetic field within the range $10^8 - 10^9$ G and spin periods $\sim 0.001 - 0.01$ s. It is a generally accepted point of view that millisecond pulsars are formed as a result of the evolution in low-mass binaries. The neutron star born with more or less standard magnetic field and period passes throughout several evolutionary phases in a low-mass binary and, after these evolutionary transformations, we observe the star as a millisecond pulsar. We proposed to consider the magnetic evolution of a neutron star in such binary systems for a few possible equations of state. From computational point of view, the problem of the magnetic evolution of a neutron star can be reduced to a solution of the diffusion equation with the conductivity depending on time and coordinates (see, e.g., MNRAS, 295, 907 (1998)). Since the evolution is very long in low-mass binaries, even a relatively small difference in the equations of state will lead to substantially different magnetic evolutions. A comparison of the results of theoretical modelling with parameters of the observed millisecond pulsars will provide information about the most plausible equation of state.

2. Description of the work carried out during the visit.

The most important part of the work carried out during the visit is a creation of the code for numerical modelling of the magnetic and rotational evolution of the neutron star in binary systems According to the standard scenario of the evolution in a binary system, the neutron star should be processed in four main evolutionary phases:

Phase 1. During this initial phase, the neutron star is not affected by its companion because the pressure of magnetodipole waves emitting by a rapidly rotating neutron star is very high and prevents the wind plasma of the companion from interaction with the magnetosphere. Thus, the magnetic, thermal, and spin evolution follows that of an isolated star. The phase I lasts while the wind plasma is stopped by the pressure of magnetodipole radiation behind the radius of gravitational capture. The stopping radius, R_s, is determined by the balance between the dynamical pressure of the wind and the pressure of magnetodypole waves. The stopping radius decreases with time during the phase I because the neutron star spins down and the magnetic field decays. While R_s is greater than the radius of of gravitational capture R_G (Bondi 1952) the wind matter cannot be captured by the neutron star and does not interact with the magnetosphere. In our model, the condition $R_s = R_G$ determines the end of the phase I.

Phase II. When the condition $R_G > R_s$ begins to satisfy, the pressure of magnetodipole radiation cannot further prevent a fraction of the wind plasma from being captured by the neutron star. The rotation of the neutron star and its magnetosphere is rather fast at this phase and, therefore, the magnetosphere acts as a propeller, ejecting the wind plasma (Illarionov & Sunyaev 1975). Since accretion is forbidden during this stage, the thermal and magnetic evolution does not differ from that of an isolated neutron star. The rotation evolution can depart from that of an isolated star because a fraction of the stellar angular momentum is transfered to the wind plasma. It is assumed usually that the wind plasma interacts with the magnetosphere at the Alfven radius, R_A, which is determined by a balance of the magnetic pressure and the dynamical pressure of plasma. If the neutron star rotates rapidly and the angular velocity of its magnetosphere is larger than the Keplerian angular velocity at the Alfven radius, $\Omega_K(R_A) = (GM/R_A^3)^{1/2}$ (M is the neutron star mass), the wind plasma, penetrating to the Alfven radius and having the angular momentum smaller than the Keplerian one, should be provided some additional portion of the angular momentum from the rapidly rotating magnetosphere. The corresponding spin-down rate of the neutron star during the propeller phase is $\dot{P} \approx \beta P^2 B_p^{2/7} \dot{M}_G^{6/7}$, where $\beta = (GMR^2/8)^{3/7}/\pi I$ and I and R are the moment of inertia of the neutron star and its radius. The spin slows down until the angular velocity of the neutron star Ω becomes comparable to $\Omega_K(R_A)$. This condition determines the critical period, P_{eq}, at which the propeller phase ends. We have for P_{eq}

$$P_{eq} \approx \frac{5.2 B_{12}^{6/7} R_6^{18/7}}{\dot{M}_{-10}^{3/7}}\ \mathrm{s}, \tag{1}$$

where $B_{12} = B_p/10^{12}$ G, B_p is the magnetic field at the pole of a neutron star, $\dot{M}_{-10} = \dot{M}/10^{-10} M_\odot \mathrm{yr}^{-1}$, and $R_6 = R/10\mathrm{km}$.

Phase III. This phase begins when the angular velocity of the neutron star becomes smaller than the Keplerian angular velocity at the Alfven radius and the star cannot work anymore as a propeller. The centrifugal force is not sufficiently strong to overcame gravity and accretion from the wind is allowed. Nuclear burning of the accreted material causes heating of the neutron star and heating leads to an increase of the crustal temperature. The crustal conductivity decreases with an increase of the temperature and, as a result, the magnetic field decays faster in accreting stars. Likely, the accreting matter carries some amount of the angular momentum and transfer this momentum to the neutron star. Due to this, the neutron star can experience spin up to a shorter period. However, the star cannot spin up to a period shorter than the Keplerian period at the Alfven radius because otherwise it will work as a propeller and expell the wind plasma instead of accreting it. It has been argued by Bhattacharya & Srinivasan (1991) that a balance may be reached in spin up and the rate of the field decay, thus the neutron star slides down the spin up line with the corresponding accretion rate. This evolution lasts until either the accretion regime is changed or the magnetic field becomes too weak to maintain a balance in spin up and the rate of the field decay.

The rotational evolution differs from that during the phase I and II. The angular momentum carried by the accreted wind plasma can be characterized by its Keplerian value , $\rho_w \Omega_K(R_A) R_A^2$, multiplird by some "efficiency" factor ξ, $\xi \leq 1$. This factor depends very much on the accretion flow. For example, if the accreted matter forms an accretion disk around the neutron star then $\xi \sim 1$. If the disk is not formed (that is more typical for a wind accretion in low-mass binaries), the factor ξ is much smaller ($\sim 0.1 - 0.01$). The rate of the angular momentum transfer from the wind to the neutron star is $\sim \xi 4\pi R_A^4 \rho_w \Omega_K v_r$. Then, the corresponding spin up rate is $\dot{P} \sim -\xi \beta P^2 B_p^{2/7} \dot{M}^{6/7}$, where $\dot{M}$ is the rate of accretion from the stellar wind.

Phase IV. After the end of the main-sequence evolution of a secondary star, it fills the Roche-lobe and accretion is substantially enhanced. Enhanced accretion heats the neutron star to a higher temperature and leadss to a more rapid field decay. In low-mass binary systems, accretion due to Roche-lobe overflow lasts as long as $10^7 - 10^8$ yrs and the magnetic field can be drastically reduced in the course of this phase.

Likely, the accreted matter forms the Keplerian disk during the phase IV that leads to a rapid spin up of the neutron star. The neutron star spins up until it approaches the spin-up line corresponding to an enhanced accretion rate. During the further evolution, a balance has to be reached in spin up and the rate of the field decay like the phase III. Due to this balance, the neutron star slides down the spin up line with the rate that is determined by the field decay. The star can leave the spin-up line either if accretion is exhausted or if the field becomes too weak to maintain a balance in spin up and the field decay.

Our developed code allows to take into account all these transformations of the neutron star. As a result of these evolutionary transformations, we obtain a rapidly rotating neutron star with a low magnetic field that can manifest itself as a radiopulsar. Since the magnetic field of this pulsar is weak, its further evolution proceeds very slowly and the location in the $B-P$ diagramm does not change.

3. Description of the main results obtained.

We have performed calculations for few models of the neutron star. These models correspond to different equation of state and have different radii, thicknesses of the crust, and cooling scenarios. We obtain that the evolution of these neutron star models in binary systems should be substantially different. A better agreement with observed properties of the millisecond pulsars is obtained for the neutron star model with the stiff equation of state. We plan to publish the obtained results in *Astronomy and Astrophysics*.

4. Future collaboration.

We plan to extend our collaboration with Profs. F.Burgio, M.Baldo and Dr. A.Bonanno. The created numerical code allows to solve various problems of the neutron star evolution in binary systems. We have started already a consideration of some problems and hope to obtain new results in a near future.

5. Projected publications.

1. M.Baldo, A.Bonanno, G.F.Burgio, V.Urpin. “Millisecond pulsars and the

state of nuclear matter". Astronomy and Astrophysics (in preparation)
2. A.Bonanno, V.Urpin. "The accretion rate and minimum spin period of accreting pulsars ". MNRAS (submittead)