Session 6

High energy population synthesis

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Population synthesis of binary relativistic stars

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Abstract. Population synthesis of binary stars with relativistic component is presented.

Keywords. population synthesis, binary stars, relativistic stars, high energy sources.

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1. Introduction

In the early 1980s, our understanding of binary star evolution based on the pioneer work by Paczynski (1971), Tutukov & Yungelson (1973), van den Heuvel & Heise (1972), allowed us to construct a general evolutionary scenario which successfully explained the genesis of well-studied normal stars and offered potential explanation for new X-ray sources discovered in space experiments. On the other hand, it was clear that dramatic new processes should occur after a compact star (white dwarf (WD), neutron star (NS) or black hole (BH)) has been formed in a binary system. Taking account of these processes was especially important in the cases of WD and NS as they can have strong magnetic field and rotate rapidly. Here, we come across a new phenomenon in stellar evolution - the evolution of gravitating magnetic compact stars (gravimagnetic rotators). The original idea goes back to pioneer work by Schwartzman (1971), Illarionov & Sunyaev (1975), Bisnovatyi-Kogan & Komberg (1975), Shakura (1975), Wickramasinghe & Whelan (1975), Lipunov & Shakura (1976), Savonije & van den Heuvel (1977), van den Heuvel (1977), and Lipunov (1982a). The astrophysical manifestations of the magnetized compact star are mainly determined by its interaction with the surrounding plasma by means of two types of physical fields: electromagnetic and gravitational, and the evolution itself represents a gradual change of the character of this interaction. The universality of such an approach is not only its ability to explain apparently such different objects as radiopulsars, X-ray pulsars, X-ray bursters, cataclysmic variables, polars, transient X-ray sources, etc., but also its ability to predict completely new and still undiscovered objects. Therefore, the realistic treatment of binary star evolution must include both types of evolution: the nuclear evolution for the normal stars, and the rotational evolution for the compact magnetized stars Lipunov (1982a). The last fact complicates the evolutionary tree to such a point that the need for a special numerical tool for studying binary evolution (the Scenario Machine), analysis of the observed picture and approval of the evolutionary scenarios becomes quite obvious (Kornilov & Lipunov (1983a), Kornilov & Lipunov (1983b)). Now it consists of a large numerical code that incorporates the crucial physical processes in binary systems and takes into account:

(a) mass exchange between binary components (van den Heuvel & Heise (1972), Tutukov & Yungelson (1973));

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(b) loss of the orbital momentum due to gravitational waves (Kraft (1965), Pachinski (1967), Tutukov & Yungelson (1979));

(c) loss of the orbital momentum due to magnetic wind (Skumanich (1972));

(d) common envelope (Paczynski (1976));

(e) spin evolution of magnetic compact stars (Schwartzman (1970), Lipunov (1982a));

(f) natal kick (Ozernoy (1965), Shklovskii (1970)).

The history of the Scenario Machine can be briefly summarized as follows:

a+e - Kornilov & Lipunov (1983a), Kornilov & Lipunov (1983b) Massive binaries

a+e +f - Kornilov & Lipunov (1984) Massive binaries

a+b + c+d+e - Lipunov & Postnov (1987b) Low Massive Binaries

a + d - Dewey & Cordes (1987) Massive Binaries + radiopulsar evolution

a+b+c+d+e+f - Scenario Machine Lipunov & Postnov (1987a), Lipunov & Postnov (1987b), Lipunov & Postnov (1988) All mass

a+b+c+d - Tutukov & Yungelson (1993) All mass

a+b+c - Kolb & Ritter (1992) Low massive binaries

a - Pols & Marinus (1994) Open Young Clusters

a+b+c+d+f -Portegies & Spreeuw (1996)

a+d+f -Arzoumanian *et al.* (1997) e - for Radiopulsars

a+d+f - Norci & Meurs (2001)

a+b+c+d+f -Kolb *et al.* (2000)

a+b+c+d+f - Tauris *et al.* (2000)

a+d+f - Kalogera & Belczynski (2001)

a+b+c+d+f - Pfahl *et al.* (2003)

The results obtained with the Scenario Machine include the following: 1) Prediction of nearly 100 new stages of binary systems with magnetized compact companions; 2) Prediction of millisecond X-ray accreting pulsars (see Kornilov & Lipunov (1983b)), later confirmed by discovery of A0538-66 (P = 0.067 s); 3)Explanation of some of the ultrasoft superluminous sources as superaccreting compact stars in binaries (Lipunov *et al.* (1993)), which was confirmed by the discovery of a transient X-ray pulsar RX J0059.2-7138 in the Small Magellanic Cloud (SMC) (Hughes (1994)); 4) Prediction of the strong dependence of the X-ray luminosity on star formation history in galaxies; 5) Prediction and estimation of the number of binary radiopulsars with OB-stars (1 per 700 visible galactic pulsars) (Kornilov & Lipunov (1984), Lipunov & Prokhorov (1987)), which was confirmed by discovery of PSR B1259-63 (Johnston *et al.* (1992)); 6) Estimation of the number of binary radiopulsars with black holes (Lipunov (1994)); 7) Calculation of the gravitational wave background formed by galactic and extragalactic binaries (Lipunov & Postnov (1987a), Lipunov & Postnov (1988); Lipunov *et al.* (1995a)); 8) Anisotropy of supernova explosions giving “kick”-velocities of young pulsars of 70-100 km/s (Kornilov & Lipunov (1984); similar estimates are given by Dewey & Cordes (1987)), a more detailed discussion will be given below; 9) A significant evolution of X-ray luminosity of the galaxies (discovered on RXTE, Chandra, INTEGRAL) as indicator of star formation rate history (Tatarintzeva *et al.* (1989)); 10) A significant evolution of supernova rates and binary NS merging rates at cosmological distances (Lipunov & Postnov (1988); Lipunov *et al.* (1995b)).

2. Full classification of NSs

The property that these objects have in common is that their astrophysical manifestations are determined by interaction with the surrounding matter. This interaction is

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provided by two kinds of physical forces, gravitational and electromagnetic. The importance of this fact was initially understood for NS (Schwartzman (1970), Schwartzman (1971)). In the early 1980s, this approach led to the creation of a complete classification scheme involving various regimes of interaction between neutron stars and their environment, as well as to the first Monte Carlo simulation of the NS evolution (see Lipunov (1982a) and Kornilov & Lipunov (1983a)).

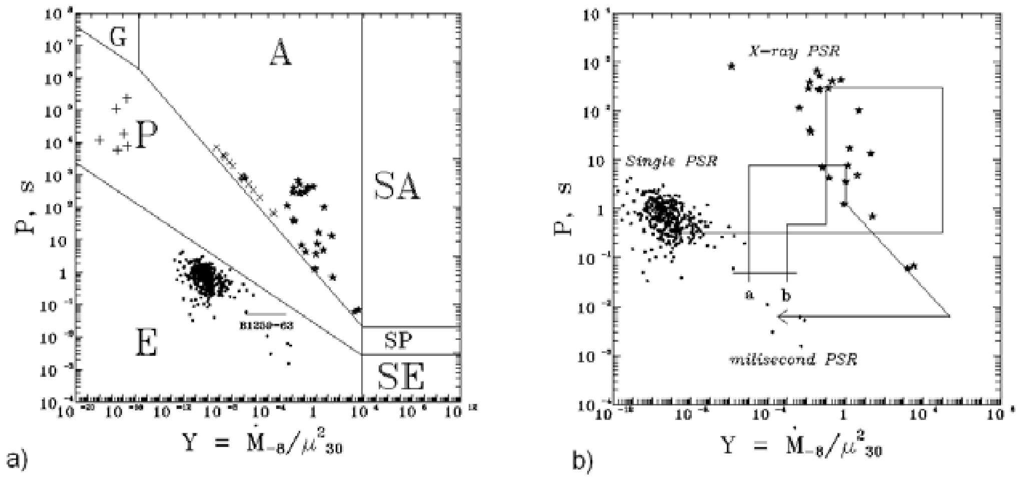

Figure 1. a)The observed magnetic rotators on the universal period - gravimagnetic parameter diagram: "+" - isolated WD $\times$ - intermediate polars; $*$ - accreting NS; $\bullet$ - radiopulsars. For isolated rotators, the accretion rate $\dot{M} = 10^{-16} M_{\odot}/yr$ is assumed. The horizontal bar shows the orbital eccentricity-induced accretion rate change in binary pulsar PSR B1259-63. **A** - Accretor, **P** - Propeller, **E** - Ejector, **G** - Georotator, **SA** - SuperAccretor, **SP** - SuperPropeller, **SE** - SuperEjector (Lipunov *et al.* (1996a)). b)The period-gravimagnetic parameter diagram for NS in binary systems. (a) with NS magnetic field decay (the oblique part of the track corresponds to "movement" of the accreting NS along the so-called "spin-up" line), (b) a typical track of a NS without field decay in a massive binary system (Lipunov *et al.* (1996a)).

The interaction of a magnetic rotator with the surrounding plasma to a large extent depends on the relation between the four characteristic radii: the stopping radius, R_{st}, the gravitational capture radius, R_G, the light cylinder radius, R_l, and the corotation radius, R_c. One can note that the magnetic dipole moment μ and the accretion rate $\dot{M}_c$ always appear in the same combination, $y = \frac{\dot{M}_c}{\mu^2}$, as was first noticed by Davies & Pringle (1981). Analysis of the nature of interaction of a magnetized star with the surrounding plasma allows us to write an approximate evolution equation for the angular momentum of a magnetic rotator in the general form (Lipunov (1982a)) $\frac{dI\omega}{dt} = \dot{M} k_{su} - \kappa_t \frac{\mu^2}{R^3{}_t}$, where k_{su} is a specific angular momentum applied by the accretion matter to the rotator and R_t is a radius of the interaction.

The evolution of NS in binaries must be studied in conjunction with the evolution of normal stars. For more detail see monographs (Lipunov (1992), Lipunov *et al.* (1996a)).

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3. The Effect of Kick Velocity on Binary Pulsar Populations

Let us consider what fraction of different types of binary radiopulsars can be obtained within the framework of the modern evolutionary scenario of binary stars if a phenomenological kick velocity caused by the collapse anisotropy is added. Several attempts of this kind have been made over the last 20 years (Kornilov & Lipunov (1984); Tutukov *et al.* (1984); Dewey & Cordes (1987)). The observational data existing at that time convincingly pointed to the presence of a small kick velocity of about 70-100 km/s. However, the statistics of binary radio-pulsars at that time was very poor. Of course, all such studies are restricted considering the evolution of an ensemble of stars that initially originated from binaries and were not tidally captured, as occurs in globular clusters; so the numerous binary pulsars observed in globular clusters and whose evolution is not yet fully understood must be excluded from consideration (see Kuranov & Postnov (2004)).

If we make comparison for a number of different binary species, we write this criterion in the form:

$COOC = \frac{\sum_i w_i (C/O+O/C)_i}{\sum_i w_i}, i = 1, 2...$

where the sum is taken for each i-th species, and w_i are corresponding weights. Obviously, this function reaches a minimum value of 2 once C=O for all species. Lipunov *et al.* (1997) compare the calculated ("C") and observed ("O") numbers of binary radio-pulsars with NS (PSR+NS), WD (PSR+WD) and normal OB-stars (PSR+OB).

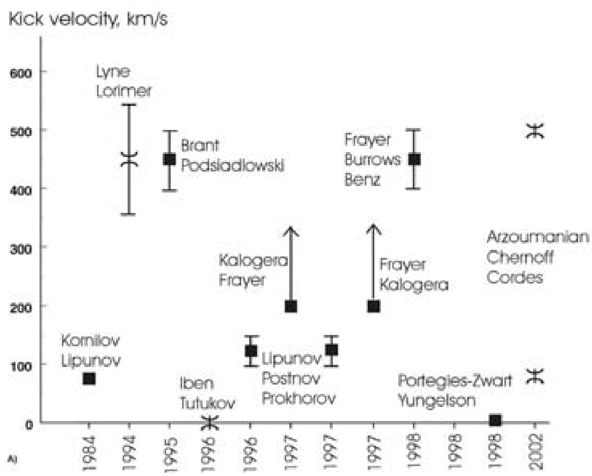

Figure 2. a)History of the kick estimations. b)The COOC criterion for binary radio-pulsar species as a function of the mean kick velocity (Lipunov *et al.* (1997)).

The calculations presented above clearly demonstrate a strong decrease in number of binary pulsars with diverse secondary components on the assumed kick velocity the NS acquires at birth. Putting aside a thorough analysis of the observational data (which could well be influenced by a number of selection effects leading to an underestimation

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Table 1. The observational examples of Binary Stars with relativistic companion. Examples with references are the discoveries predicted by Kornilov & Lipunov (1984).

Optical & compact star's stage	Main Sequence	Giant	Roche Lobe Overflow	WR	Compact
E	PSRB 1259-63 Johnston *et al.* (1992)	?	?	?	PSR 1913+16
P	X0331+53 Corbet (1996)	?	?	?	?
A		Vela X-1	Her X-1	?	XTEJ0929-314 Galloway *et al.* (2002)
SE	No	No	?	No	?
SP	No	No	?	No	?
SA	No	No	SSS?	No	?
BH, SBH	?	CygX-1	SS433?UULXs,SSS?	Cyg X-3	?

of low-velocity pulsars; e.g. Tutukov *et al.* (1984)). Recently, Arzoumanian *et al.* (2002) practically confirmed it.

4. X-ray Binaries and Black Holes in Binaries

The first version of the Scenario Machine predicted a lot of different stages of binary stars with relativistic companion, which were discovered after 1983 (see Table 1).

Two different types of stellar BH formation exist: (1) direct core collapse of a massive star and (2) AIC of a NS. Recently calculation of the Black Holes Mass Function (Bogomazov *et al.* (2005)) predicted the Observable Number of Low Massive AIC Black Holes (1 per 20-40 usual Black Holes).

The discovery of binary radio-pulsars with massive unseen companions ($>3-5M_\odot$) would be of great importance to fundamental physics and modern theory of stellar evolution, providing a compelling evidence for the existence of BH in nature. The formation of binaries consisting of a BH in a pair with a radio-pulsar (PSR) has been predicted by Kornilov & Lipunov (1983b) and discussed previously by Narayan *et al.* (1991), Lipunov (1994). Lipunov *et al.* (2005) predicted observable number of such systems: (BH+PSR)/PSR $\sim 1/1500$.

5. X-ray luminosity function and Star Formation Rate

The total X-ray luminosity from different types of objects is traced separately at any instant. The X-ray luminosity evolution after an instantaneous star formation burst for $t > 2\times10^9$yr (long time scale) can be rather well fitted by a power law (Tatarintzeva *et al.* (1989)): $L(t) \approx 3\times10^{40}(\frac{N}{10^{12}})(\frac{t}{10^9 yr})^{-1.56} erg/s$. N is the total number of stars in the galaxy.

Lipunov *et al.* (1996b) studied the evolution of stellar populations on the time-scale of 10 Myr for starbursts. We estimate the expected number of X-ray transient sources (NS + MS star), super accreting BH, and BH + supergiant binaries, all as functions of time elapsed after the burst.

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The numerous point-like extragalactic X-ray sources were discovered in last years due to Chandra and XMM-Newton missions. Some authors (Grimm *et al.* (2002), Gilfanov (2004)) report about power law X-ray luminosity function: $\frac{dN}{dL} \sim L^{-\alpha} xSFR$, $\alpha \sim 1.5.$, which discussed by Postnov (2003) from theoretical point of view. My critical points concern both observational and theoretical aspect. There is no observed universal luminosity function because: a) The number of the bright X-ray binaries is very small per galaxy; b) All people build the cumulative function with very small number of examples (almost all statistically small population show power low cumulative declination in Log). We must test the differential luminosity distribution; c) We do not know real X-ray luminosity due to high variability binary X-ray sources (on scale from sec. to 100 years)

There is no theoretical simple (with one slope) universal luminosity function because: a) the X-ray population is the mixing of different types of binaries with different mass exchange types: Roche Lobe (thermal time scale, magnetic wind time scale, gravitational waves time scale), Wind Fed, Be-stars disk like wind flow, eruptive mass exchange. For example in our Galaxy most of the X-ray pulsars belong to Be+NS systems. There is not any simple connection between mass loss and for example stars mass (rotational effects). In same time we see less than 5 percent of Be-+NS X-ray systems due to variability of the mass transfer processes; b) The number of the systems with some luminosity depends on spin evolution of the NS which not directly connects with mass of the companion; c) The theoretical arguments cited above are not correct because they exclude the life-time which depends on the optical companion mass of binary stars on accretion stage.

We must observe at least two order more galaxies with determination of the type of the X-ray sources for correct luminosity function. In any case this function must have a different inclination for different type, age, SFR history of the galaxies.

Kraft *et al.* (2005) presented unexpected results from Chandra observation of the nearby galaxy NGC 5102. They ask: Where are the X-Ray Binaries? The deficit of LMXBs is even more striking, because some of these sources may in fact be high-mass X-ray binaries (HMXBs). NGC 5102 is unusually blue for its morphological type and has undergone at least two recent bursts of star formation, only $\sim 1.5 \cdot 10^7$ and $\sim 3 \cdot 10^8$ year ago. If the lack of X-ray binaries is related to the relative youth of most of the stars, this would support models of LMXB formation and evolution that require wide binaries to shed angular momentum on a timescale of Gyr.

6. Ultraluminous X-ray sources

Ultraluminous X-ray sources (ULXs) with $L_x > 10^{39}$ erg/s have been discovered in great numbers in external galaxies with ROSAT, Chandra and XMM-Newton. Rappaport *et al.* (2005) have carried out a theoretical study to test whether a large fraction of the ULXs, especially those in galaxies with recent star formation activity, can be explained with binary systems containing stellar-mass BHs. To this end, we have applied a unique set of binary evolution models for BH X-ray binaries, coupled to a binary population synthesis code, to model the ULXs observed in external galaxies. They find that for donor stars with initial masses $\gtrsim 10 M_\odot$ the mass transfer driven by the normal nuclear evolution of the donor star is sufficient to potentially power most ULXs. This is the case during core hydrogen burning and, to an even more pronounced degree, while the donor star ascends the giant branch, although the latter phases last only 5 per cent of the main-sequence phase. They show that with only a modest violation of the Eddington limit, e.g. a factor of 10, both the numbers and properties of the majority of the ULXs can be reproduced. One of our conclusions is that if stellar-mass BH binaries account for a significant fraction of ULXs in star-forming galaxies, then the rate of formation of such systems is $3 \cdot 10^{-7}\,\mathrm{yr}^{-1}$ normalized to a core-collapse supernova rate of $0.01\ \mathrm{yr}^{-1}$.

I would like to remember the old consideration of the supercritical accretion onto magnetized neutron stars (Lipunov (1982b)). The Maximum energy release proves to be $L = 46 L_{Edd}(\mu_{30})^{4/9}$, where μ_{30} is the magnetic dipole moment of NS in $(10)^{30}(Gs)(cm)^3$.

7. Relativistic Binary Merging

There are 3 type of merging relativistic stars (GWB - gravitational wave burst):

NS + NS → GWB + GRB?+?
NS + BH → GWB + BH+GRB ?+?
BH + BH → GWB + BH

Binary relativistic stars merging - the most powerfull high energy transients in the Universe. That is equal to Planck luminosity (Lipunov (1992)). After discovery of spectral lines in GRB 970508 (Costa *et al.* (1997), Metzger *et al.* (1997)) we know that in the Universe there are real sources with luminosity more than 10^{50}. The observations of 3 short GRBs this summer (for detail see review of van den Heuvel in these proceedings) in elliptical galaxies make it possible that short GRBs are results of relativistic binary merging. Lipunov *et al.* (1995) calculated the evolution of Double Neutron Stars Merging Rate and the Cosmological Origin of Gamma-ray Burst Sources including history of the star formation rate in the Universe. The calculations demonstrate a good agreement with GRB-statistic and existence of the dark energy $\omega(\lambda) = 0.5 - 0.8$. Recently calculations of the Log N - Log S function separately for long and short GRBs demonstrate good agreement with NS-NS merging for short GRB (Bogomazov *et al.*, 1996).

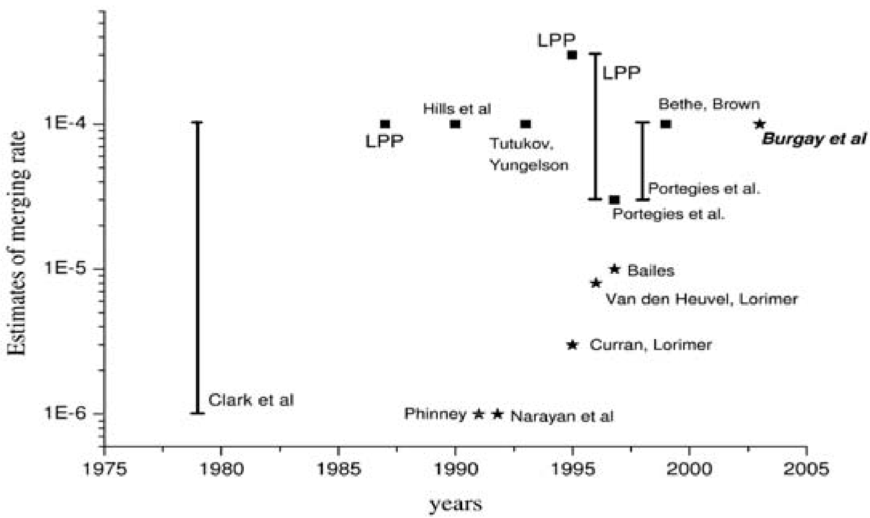

Figure 3. Merging Rate estimation by different authors. Squares are the "theoretical" method, stars are the observational one. LPP = Lipunov,Postnov,Prokhorov.

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8. Gravitational Waves

The GW from coalescing compact binaries composed of NS and BH are the best understood of all astrophysical GW sources and very important for LIGO-type experiments. A conservative lower limit to the event rate of galactic binary neutron star coalescence of about 1 per 10^6 year follows from double pulsar statistics studies (Narayan *et al.* (1991), Phinney (1991)). Binary population synthesis, however, give much higher values, of about 1 per 3000 - 10000 year (Lipunov & Postnov (1987a), Tutukov & Yungelson (1993), Lipunov *et al.* (1995b)). Fortunately, discovery of double pulsars J07373039B (Burgay *et al.* (2003)) close the disagreement between radiopulsars merging rate estimation and population synthesis one (see history on Fig. 3). 1) Population synthesis estimations give us the merging rate $10^{-4\pm0.5} yr^{-1}$ from Lipunov *et al.* (1987c). One must accentuate, that the most full and correct model of binary stars evolution is the "Scenario Machine", that takes into account the evolution of magnetized neutron star (see for details Lipunov *et al.* (1996a)) 2) The "observed" estimations, that used radio-pulsars data, were always burdened by selection effects. 3) The gravitation impulses from the merging with black holes participations must be the first events on the interferometers like LIGO. This work is supported by RFFI 04-02-16411 grant.

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Discussion

Eracleous: How important is the proper treatment of stellar evolution in binary evolution calculations?

Lipunov: This is very important because we do not have many other ways of learning about stellar rotation (for example) other than using population synthesis of binaries.

Fabbiano: Granted that stellar populations and their evolutions are complicated, do you think we can constrain these parameters by comparing your models with e.g. XLFs?

Lipunov: In principle, yes. But we must use separate X-luminosity function for each type of X-ray sources. 16 years ago we predicted high strong dependence of X-ray population on star formation rate, in this sense the most suitable situation in elliptical Galaxies. For spirals and irregulars we must have much more statistics. Another problem connected with variability of X-ray sources, for example, in our Galaxy more than 10^3 Be + XPSR systems, but we see only 10%.

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