RELATIVISTIC BINARY MERGING RATES

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Abstract

The Invited Review on Joint Discussion "High Energy Transients" on XXIIIrd General Assembly of IAU, Kyoto, 1997 is presented. The simulated rates of neutron star + neutron star, neutron star + black hole and black hole + black hole mergings are considered in relation with the problem of GRBursts origin and gravitational waves detection.

Observations

After the outstanding experiment BeppoSAX (Costa et al., 1997, IAUC 6572) and discovery of optical afterglow phenomenon in GRB 970228 (Groot et al., 1997, IAUC 6584; Sahu et al., 1997, IAUC 6606) and discovery of spectral lines in GRB 970508 (z = 0.835) (Metzger et al., 1997, IAUC 6655) we know that in the Universe there are real sources with luminosities more than $10^{50}$ erg/s. The mergings of binary relativistic stars are the most powerful high energy transients in the Universe: the released power is of order of the Planckian one $\dot{E}/G \sim 10^{58}$ erg/s.
The mergings of relativistic binaries may underlie the origin of cosmic gamma–ray bursts (GRB) (Blinnikov et al., 1984; Pazczyński, 1986; Meszaros and Rees, 1992).

There are three types of merging reactions (“M–reaction”) of relativistic stars:

\[ NS + NS \rightarrow GWB + \nu B + GRB(?) + NS/BH \]
\[ NS + BH \rightarrow GWB + BH + \nu B + GRB(?) \]
\[ BH + BH \rightarrow GWB + BH \]

We see two branch of theoretical research:

a) physical investigation of M–reactions (Mergingology: fairball formation, numerical relativity, hydrodynamics. The pulsar mechanism also can act (Lipunov & Panchenko 1996b), (Lipunova 1997).

b) astrophysical calculation of “crosssection” or “probability” of the M–reaction in our Universe (Population synthesis).

In a few years several initial ground–based laser interferometers aimed at searching for gravitational waves (GW) will start to work (LIGO (Abramovici et al.1992), VIRGO (Ciufolini 1992), GEO–600 (Schutz 1996), TAMA-300 (http://tamago.mtk.nao.ac.jp/)), so at present time the question: what kind of events and how frequently will the interferometer register? — is very important. Undoubtedly, the most reliable GW sources are the merging compact binary stars — double neutron stars (NS) and black holes (BH) of different stellar masses.

The current observational data:

1. A few binary radiopulsars are known to have the secondary NS component.

2. Three of these binary pulsars must coalesce due to the orbital angular momentum removal by GW in a time scale shorter than the age of the Universe (the Hubble time \( t_H \approx 15 \cdot 10^9 \) yrs).

3. No binary pulsars with BH is known yet (although from evolutionary considerations one may expect one such object to be formed in the Galaxy per about 1000 single pulsars, (Lipunov et al.1994))
4. No binary BH has been found so far.

5. In contrast, 10 BH candidates are already known in X-ray binary systems with normal companions (Cherepashchuk 1996). Note that the mean BH mass in these systems is $< M_{\text{BH}} > \simeq 8.5 \, M_\odot$, i.e. BH formed in stellar evolution are notably more massive than NS (with the typical mass $1.4M_\odot$).

**Population synthesis: key parameters**

**Binary NS Merging Rate Estimates**

At present time, it is possible to estimate binary NS merging rate in two ways: using the binary radiopulsar statistics observed and making various computations of binary stellar evolution (Population Synthesis).

‘Observational” estimates

| Reference                  | Rate            |
|----------------------------|-----------------|
| (Phinney 1991)             | $1/10^6$ yr     |
| (Narayan et al.1991)       | $1/10^6$ yr     |
| (Curran & Lorimer 1995)    | $3/10^6$ yr     |
| (van den Heuvel & Lorimer 1996) | $8/10^6$ yr |
| “Bailes limit” (Bailes 1996) | $< 1/10^6$ yr |

‘Theoretical” estimates

| Reference                  | Rate            |
|----------------------------|-----------------|
| (Clark et al.1979)         | $1/10^4$–$1/10^6$ yr |
| (Lipunov et al.1987)       | $1/10^4$ yr     |
| (Hils et al.1991)          | $1/10^4$ yr     |
| (Tutukov & Yungelson 1993) | $3/10^4$–$1/10^4$ yr |
| (Lipunov et al.1995a)      | < $3/10^4$ yr   |
| (Portegies Zwart & Spreeuw 1996) | $3/10^5$ yr |
| (Lipunov et al.1997a)      | $3/10^4$–$3/10^6$ yr |

We emphasize that although theoretical merging rates are systematically higher than observational ones, both estimates do not contradict each other.
The main argument is that the first (observational) estimates of binary NS merging rate are based on the statistics of binary systems, in which only one of the components shines as radiopulsar, which is not at all the necessary conditions for merging to occur (Lipunov et al. 1997a).

To calculate binary evolution, we have used the population synthesis method (the Scenario Machine code), which is in fact a version of Monte–Carlo calculations. The most important (and practically unique) parameter changing the galactic binary NS merging rate is the distribution of an additional (kick) velocity imparted to NS at birth.

The kick velocity distribution, widely accepted now, is derived from the analysis of spatial velocities of single radiopulsars (Lyne & Lorimer, 1994). One can approximate this 3–dimensional distribution as

\[ f_{LL}(x)dx \propto x^{0.19}(1 + x^{6.72})^{-1/2}dx \]

where \( x = w/w_o \) and the characteristic velocity \( w_o \) is a parameter in our calculations. The Lyne & Lorimer (1994) pulsar transverse velocity distribution corresponds to \( w_o = 400 \) km/s. But statistic of binary PSRs gives Kornilov and Lipunov (1984):

Mean Kick = 75–100 km/s – for Delta–function distribution

Lipunov, Postnov & Prokhorov (1996a, 1997a):
Mean Kick = 100–200 km/s – for Maxwellian or Lyne & Lorimer distribution

New space velocity distribution for Radio–Pulsars (Hansen & Phinney, 1997):

Maxwellian + mean velocity = 250–300 km/s.

**Binary BH merging rate**

In contrast, for BH, two additional parameters appear. First of them is a threshold main sequence stellar mass \( M_{cr} \) for the star to collapse into a BH after its nuclear evolution has ended. This parameter is still poorly determined and varies in a wide range: e.g., according to (van den Heuvel & Habets 1984), \( M_{cr} = 40–80M_{\odot} \); (Tsujimoto et al. 1997) give 40–60\( M_{\odot} \); (Portegies Zwart & Spreeuw 1996) derive \( >20M_{\odot} \).

The second parameter is the fraction of the presupernova mass, \( k_{bh} \), collapsing into BH. This parameter is fully unknown, so we varied it from 0.1 to 1 in our calculations.
Detection rate of binary compact star merging

Under the assumptions made above, we can calculate the binary merging rate \( R \) in the Galaxy. The results are presented in Fig. 1. After having found the merging rate \( R \) in a typical galaxy, we need to go over the event rate \( D \) at the detector. Applying the optimal filtering technique (Thorne 1987), the signal-to-noise ratio \( S/N \) at the spiral-in stage is

\[
\frac{S}{N} \propto \frac{M_{ch}^{5/6}}{d}.
\]

Here \( M_{ch} = (M_1 M_2)^{3/5}(M_1 + M_2)^{2/5} \) is “chorp”—mass of the binary system. This means that for a given \( S/N \) our detector can register more massive BH from larger distances than NS. The volume within which BH or NS is to be detected should be proportional to \( M_{ch}^{15/6} \). Then the ratio of detection rates of BH and NS can be written as (Fig.2):

\[
\frac{D_{BH}}{D_{NS}} = \frac{R_{BH}}{R_{NS}} (\frac{M_{BH}}{M_{NS}})^{15/6}.
\]

Gamma–Ray Bursts

Using the dependence on time of compact binary merging rate for ”elliptical” galaxy (Lipunov et al.1995b) and assuming the cosmological origin of GRBs as products of binary NS/NS coalescences, we can compute the theoretical log \( N \)–log \( S \) curve.

Recently, Lipunov, Postnov and Prokhorov (1997c) estimated the redshift of GRB 970228 and GRB 970508 using the mean statistical properties of observed GRBs. They assume the cosmological origin of GRBs as standard–candle binary neutron star mergers.

Same result was obtained independently by Totany (1997). Recent progress of observations of high redshift galaxies, however, gives more detailed information on the cosmic star formation history (Lilly et al., 1996; Madau et al., 1996). The Canada–France Redshift Survey (CFRS) revealed a remarkable evolution of 2800 Å luminosity density, that is considered to be a star formation indicator, as \( L_{2800} \propto (1 + z)^{3.9 \pm 0.75} \) to \( z \sim 1 \) (for \( \Omega_0 = 1 \), Lilly et al., 1996). The constant SFR approximation in spiral galaxies is therefore no longer justified even at \( z < 1 \).
The redshift of GRB 970508 is apparently about 2, just below the upper limit that is recently determined, and the absorption system at $z = 0.835$ seems not to be the site of the GRB.

**Conclusion**

1. We estimate **NS + NS** merging rate as follows:

   \[ \frac{1}{10^4} \text{ yrs per Galaxy} \]
   \[ \frac{1}{\text{yr}} \text{ for GEO-600, VIRGO, TAMA-300, LIGO-type detector (} h > 10^{-21} \}) \]
   \[ \frac{1}{\text{minute}} \text{ per Universe} \]

2. **BH + BH** merging rate:
   First LIGO–type interferometer events shell give us the simultaneous discovery of GRavitational WAVES and BLACK HOLES (Lipunov et al.1997d), as the expected detection rate for BH+BH merging is

   \[ 10^{-100/\text{yr}} \text{ for LIGO–type detector (} h > 10^{-21} \}) \]

3. **GRB mystery:** assuming the relativistic binary merging as the origin of the GRBs we obtain:
   - that log $N$–log $S$ is fine;
   - reasonable estimates of redshifts for February and May Beppo–Sax GRBs;
   - (NS + NS) needs collimation (several degree);
   - (NS + BH) needs no anisotropy.
Figure 1: Lipunov, Postnov & Prokhorov, 1997a The dependence of different compact binary systems coalescence rates on the characteristic kick velocity $w_0$ in a spiral galaxy with $10^{11} M_\odot$. 
The total merging rate of NS+NS, NS+BH, and BH+BH binaries which would be detected by a laser interferometer with $h_{\text{rms}} = 10^{-21}$ as a function of $k_{\text{bh}}$ for Lyne–Lorimer kick velocity distribution with $u_0 = 200$–$400$ km/s and BH progenitor’s masses $M_* = 15$–$50M_\odot$, for different scenarios of binary star evolution. NS+NS mergings are shown separately. In all cases BH+BH mergings contribute more than 80% to the total rate. The filled “Loch–Ness–monster–head”–like region corresponds to BH formation parameters $M_* > 18M_\odot$ and $k_{\text{bh}} > 0.5$. 

Figure 2: Lipunov, Postnov & Prokhorov, 1997b
Figure 3: Lipunov, Postnov & Prokhorov, 1997c The log $N$–log $F_{\text{peak}}$ distribution of 3B BATSE GRBs from 256-ms 1–3 (50–300 keV) channels fitted with the cosmological model distributions in a flat, $\Omega = 1$, Universe with a cosmological term $\Omega_{\Lambda} = 0.7$ assuming gamma-ray photon power law $s = -1.1$. The locations of Beppo–SAX GRBs are shown. GRB970228 and GRB970508 are marked with asterisks.
The redshift – peak flux dependence in the cosmological models assumed for different $z_*$ and $s = -1.1$. 3B BATSE catalog data are also plotted.
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