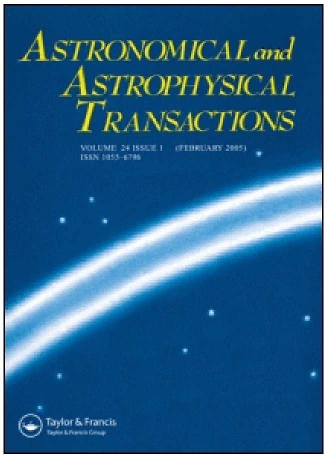

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V. M. Lipunov [a]; S. N. Nazin [a]; I. E. Panchenko [a]; K. A. Postnov [a]; M. E. Prokhorov [a]

[a] Sternberg Astronomical Institute, Moscow, Russia

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GRAVITATIONAL WAVE SKY

V. M. LIPUNOV, S. N. NAZIN, I. E. PANCHENKO, K. A. POSTNOV, and M. E. PROKHOROV

Sternberg Astronomical Institute, 13, Universitetskij pr., Moscow 119899, Russia

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A view of the sky seen in gravitational waves (GW) in a wide frequency range ($\sim 10^{-9}$–10^3 Hz) is considered. Stochastic gravitational wave background (GWB) produced by binary systems, both galactic and extragalactic in origin, studied in more detail. Critical frequencies above which the galactic and extragalactic GWB becomes transparent for a GW detector with 1° angular resolution are about 2×10^{-3} Hz and ~ 10 Hz, respectively. A realistic "map" of the GW sky is constructed based on realistic matter distribution within a distance of ~ 50 Mpc according to Tully's Catalogue of Nearby Galaxies. Rates of coalescence of binary neutron stars (NS) and of supernova explosions for these galaxies are about 3 and 40 per year, respectively. The calculated rate of binary NS merging, about 10^{-4} per year per 10^{11} $M_\odot$, yields $\sim 10^3$ events for a LIGO limiting sensitivity $h_c \simeq 10^{-21.9}$ at the frequency 100 Hz.

1 INTRODUCTION

The GW sky consists of several different components (see Grishchuk, 1988; Thorne, 1988 for reviews). In view of future GW experiments (LIGO, VIRGO, LISA – see Thorne, 1994), it is important to know what kind of astrophysical sources fall into the frequency range to be covered by these experiments ($\sim$10–1000 Hz for LIGO/VIRGO, $\sim 10^{-4}$–1 Hz for LISA).

Here we summarize properties of the galactic binary GWB and extragalactic GWB and study at which frequencies this background becomes transparent for a GW detector with high angular resolution $\theta \approx 1^\circ$ (Thorne, 1994). A realistic GWB and event rate contour maps are constructed for galaxies lying within a distance ~ 50 Mpc from the Tully's Catalog of Nearby Galaxies (Tully, 1988). For more detailed discussion see Lipunov *et al.* (1995).

2 TRANSPARENCY OF THE STOCHASTIC BACKGROUND

The "transparency" of the background is the ability of the observer to detect GW signal other than that produced by binary systems, as a function of parameters of the GW detector used (angular resolution θ and frequency band), so that less than

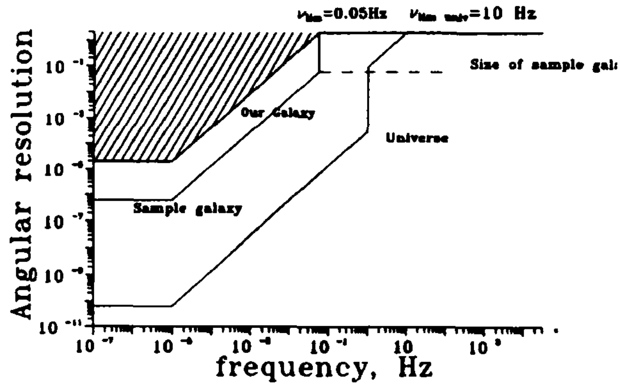

Figure 1 The regions of transparency (defined as $N(\nu > \nu_{cr}) < 1$) of the GWB from different objects in the angular resolution of the detector – critical frequency ν_{cr} diagram. The GWB from a homogeneous model of our Galaxy (the total number of stars is 10^{11}) is transparent below the line "Our Galaxy". The line marked as "Sample galaxy" shows the transparency boundary for a Milky Way-type galaxy with apparent angular size $\simeq 8°$. The break at 0.05 Hz is caused by continuity limit of coalescing binary white dwarfs at a rate 1 per 100 yrs. The bottom curve shows transparency boundary for the GWB from 10^{11} external galaxies. The upper horizontal line corresponds to an all-sky detector ($\theta = 2$). The hatched region corresponds to "absolute hopelessness".

one occasional binary system falls into the detector's beam at a given frequency in a given direction (Figure 1).

It is clear from the figure that for an all-sky detector the Galaxy becomes transparent above the frequency $\nu_{cr} \simeq 0.05$ Hz. For a realistic LIGO detectors network angular resolution of about 1° this frequency reduces to $\sim 2 \times 10^{-3}$ Hz.

3 A GW MAP OF NEARBY GALAXIES

Here we discuss a view of the GW sky above the critical frequency of the transparency of the stochastic background. We will consider the Tully's Nearby Galaxy Catalog (Tully, 1988) comprising 1771 galaxies with known luminosities lying within a distance of $\sim$50 Mpc from the Sun.

3.1 GW from Supernova Explosions

The observed supernova frequencies of different types (SN Ia, Ib, II) in different types of galaxies (E–. . .–S–. . .–Ir) (see van den Bergh and Tammann, 1991) immediately provide us with the SN frequency distribution in space. In Figure 2 we plot a projection of this distribution onto the celestial sphere in terms of lines of constant SN frequencies per one square degree for all galaxies from the sample.

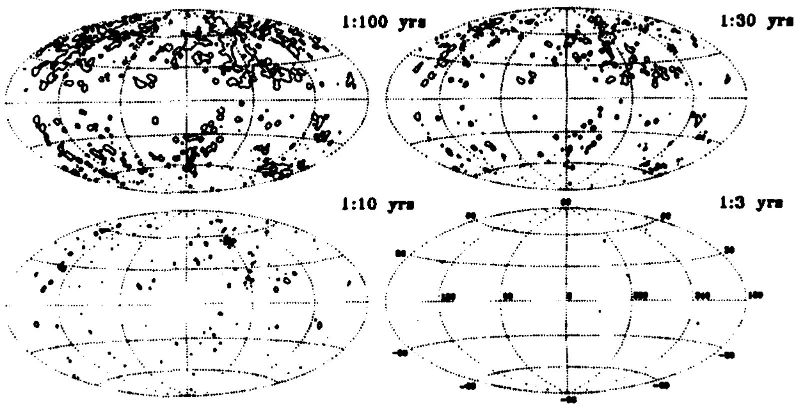

Figure 2 Lines of constant SN frequency per square degree where the total SN frequency exceeds 1 per 3, 10, 30 and 100 yrs per a square degree, respectively. This figure represents the cross-sections of the projected mass density per square degree by mass.

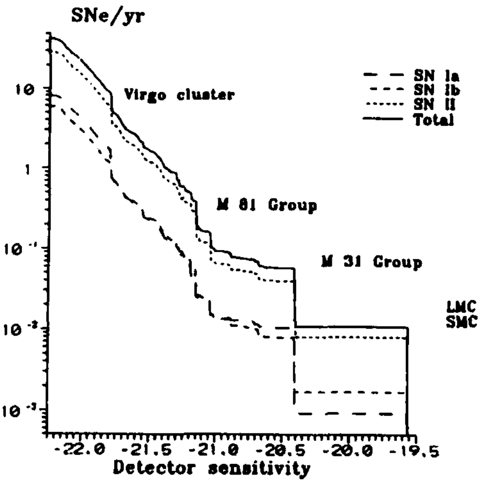

Figure 3 SN rates of different types integral over the whole sky as a function of a given detector sensitivity in terms of characteristic strain h_c.

Figure 3 presents the integrated event rate with characteristic strains greater than h_c. We assume 0.01% rest mass - energy conversion into GW. Clearly seen are contributions from the closest groups of galaxies and the Virgo cluster (assuming a Hubble constant of 75 km/s). At better sensitivities ($h_c < 10^{-21.2}$) a power law with a slope of -3 is seen, $N(h_c) \propto h_c^{-3}$, which reflect nearly isotropical distribution of matter beyond ~7 Mpc. The total rate of SN events over the sky for nearby galaxies is about 40 per year.

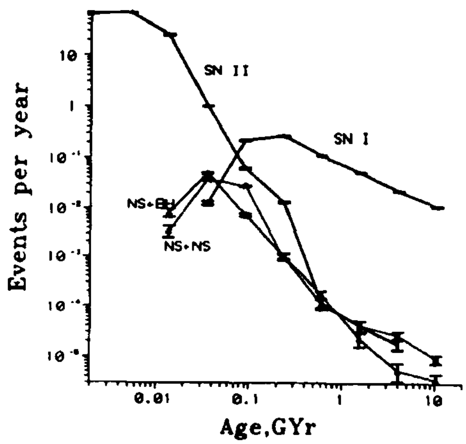

Figure 4 Rate of coalescences of binary NS and NS+BH in a model elliptical galaxy consisting of 10^{11} $M_{\odot}$, depending on time elapsed since the (assumed instantaneous) star formation. The rates of SN explosions are also shown.

3.2 CW from Coalescing Compact Binary Stars

The GW from coalescing compact binaries composed of neutron stars and black holes are the best understood of all astrophysical GW sources. A conservative lower limit to the event rate of galactic binary neutron star coalescence of about 1 per ~100,000 yrs follows from double pulsar statistics studies (Narayan *et al.*, 1991; Phineey, 1991). Theoretical estimates, however, give much higher values, of about 1 per ~3,000–10,000 yrs (Lipunov, Postnov and Prokhorov, 1987; Tutukov and Yungelson, 1993).

We calculated change of binary coalescence and supernova explosions rate with time by using "Scenario Machine" code, which allows us to simulate evolution of large ensembles of binary stars in an artificial galaxy using Monte Carlo method (see Lipunov 1992; Lipunov *et al.*, 1994 and references therein). Evolution of supernova rates in elliptical galaxies was first modelled by Lipunov and Postnov (1988).

We approximate star formation burst in a newly born galaxy by δ-function. Then no new stars are formed in an elliptical galaxy, so evolution of sources (for example, coalescence rate of binary neutron stars $f_e(t)$) can be treated as a Green function for calculation of the sources evolution in a galaxy with given star formation rate $\phi(t)$: $f_s(z) = \int_{z_*}^{z} f_e(z_* - z')\phi_s(z')\,dz'$ where z_* is the redshift of the star formation beginning. For spiral galaxies, $\phi(t) = \mathrm{const}$ was assumed.

We assumed initial distributions of binary stars similar to those presently observed in our Galaxy (Salpeter function for mass M_1 of the primary component, $f(M_1) \propto M_1^{-2.35}$; flat distribution of initial binary separations $d\log A = \mathrm{const}$). We accepted the best values of key parameters of the evolutionary scenario (initial mass ratio distribution of the binaries in the form $f(M_2/M_1) \propto (M_2/M_1)^2$; efficiency

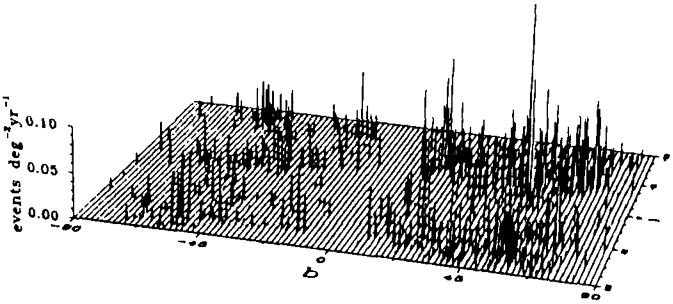

Figure 5 Realistic map of coalescence rate of binary NS in terms of events per one square degree per year.

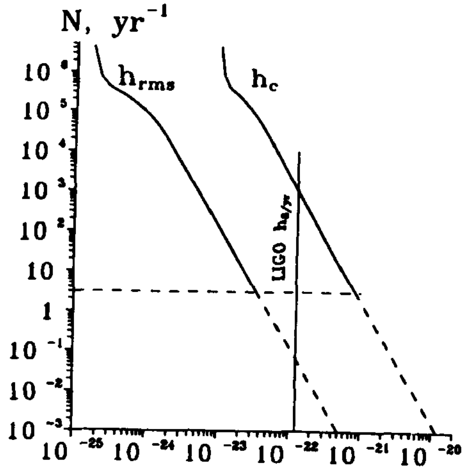

Figure 6 Cumulative event rate vs. characteristic strain h_c for coalescing binary NS at the frequency 100 Hz. Rms strains h_{rms} averaged over binary inclination angle are also shown. The estimated LIGO sensitivity h_{3yr} is shown by vertical solid line.

coefficient of angular momentum removal at common envelop stage $\alpha_{CE} = 0.5$), found by Lipunov *et al.* (1995).

The results are presented in Figure 4.

The resulting map of coalescence rate of binary neutron stars is shown in Figure 5 in terms of events per one square degree per year. The event rate integrated over the whole sky is ~3 per year. The integrated event rate of binary coalescences with characteristic strains greater than h_c (see Thorne, 1988 for definition of h_c) is shown in Figure 6. For expected LIGO sensitivity $h_{3yr} = 10^{-21.9}$ at the frequency 100 Hz the obtained NS coalescence rate $\sim 10^{-4}$ per year per 10^{11} $M_\odot$ yields about 10^3 events per year, an order of magnitude higher than the previous estimation (Kochanek and Piran, 1993).

4 CONCLUSIONS

For the first time, an expected map of the sky in gravitational radiation has been constructed on the basis of the observed stellar matter distribution within the 50 Mpc distance from the Sun. The expected gravitational wave sources taken into account include binary stars and supernova explosions. In particular, it was studied under which conditions the gravitational wave background (noise) produced by binary stars in our Galaxy becomes transparent for observation of extragalactic sources.

The estimate of the event rate for the neutron star coalescences has been revised on the basis of evolutionary tracks with the corrected values of parameters describing the initial mass distribution and common envelope stage. The derived event rate is about one per 10,000 years which is significantly higher than the previously published estimates (one per 100,000 years) based on the binary pulsar statistics only. This encouraging result may be important for correcting the strategies of observations in the LIGO/VIRGO experiments.

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