Summary of the search for inspiraling compact star binaries from TAMA300’s observation in 2000-2004

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Abstract. We summarize the results of the search for inspiraling compact star binaries from TAMA300’s observation. In this analysis, 2705 hours of data, taken during the years 2000-2004, are used for the event search. We obtain an upper limit on the rate of the coalescence of compact binaries in our Galaxy of 20 per year at a 90% confidence level.

1. Introduction
In this paper, we present the summary of the data analysis of the TAMA300 detector to search for gravitational waves produced by inspiraling compact star binaries, comprised of non-spinning neutron stars and/or black holes. Inspiraling compact binaries are considered to be one of the most promising sources for ground based laser interferometers.

TAMA300 [1] is a Fabry-Perot-Michelson interferometer with baseline length of 300m located in Mitaka, Tokyo (35°40’N, 139°32’E). TAMA300 has been performed nine observation runs of the detector since 1999. Among them, we use DT4, DT5, DT6, DT8, and DT9 data of TAMA300. The total length of data available for the data analysis, after removing bad quality parts of data, is 2705 hours. A part of DT6 data which was coincident with LISM was already analyzed in [2]. The initial results of the analysis of DT8 data were reported in Ref. [3]. A part of DT8 data which was coincident with LIGO S2 was already analyzed in [4]. In this paper, we analyze these data again together with the other data in a unified way. Until DT6 observation, TAMA300 was the only large scale laser interferometer which was operated. Thus, it is important to analyze such data to search for possible gravitational wave signals. Although all data mentioned above are analyzed, we do not use DT4 and DT5 data to set the upper limit for the event rate, because the length of data from these runs are much shorter than DT6-8-9, and because the quality of data of these runs are much worse than those of DT6-8-9. The total amount of data used for setting the upper limit is 2462.8 hours. We combine the results from DT6, DT8 and DT9 data and obtain a single upper limit on the rate of the coalescence of compact binaries in our Galaxy.

2. Search methods
To analyze the data, we use the matched filtering method, in which we search for the best matched parameters of the theoretical wave form by cross-correlating the data with the
theoretical wave form. As the theoretical wave form, we use the non-spinning, restricted post-Newtonian (PN) wave form in which the phase is given to high post-Newtonian order, but only the leading quadrupole term is contained in the amplitude.

The parameters which describe the wave form are the time of coalescence, \( t_c \), the phase of wave at the coalescence, \( \phi_c \), the total mass \( M \equiv m_1 + m_2 \) and the non-dimensional reduce mass \( \eta \equiv m_1 m_2/M^2 \) of the binary. We search for the parameters which give the maximum of the output of the matched filter, \( \rho \). The maximization over the phase, \( \phi_c \), can be taken analytically. The value of parameters, \( t_c, M \) and \( \eta \), which maximize \( \rho \) are searched numerically.

The data are divided into subsets of data with length 52.4 seconds. Each subset of data has overlapping data with adjacent data for 4.0 seconds. Each subset of data is Fourier transformed, and the components more than 5kHz are removed. The data are converted to the strain equivalent data by means of the transfer function. The power spectrum density (PSD) of noise is evaluated at neighbor of each subset. Details of the method to evaluate PSD was described in §IIIB. of Ref. [2]. With the subset of data, we compute \( \rho \). For each small time interval with length \( \Delta t_c = 25.6\text{msec} \), we search for \( t_c, M \) and \( \eta \) which give the maximum of \( \rho \). The value of \( \rho \) at all of \( t_c \) can be computed automatically from the inverse FFT with respect to \( t_c \). The search for the best matched \( M \) and \( \eta \) is done by introducing the grid points in the two dimensional mass parameter space. The range of masses of each member star of binaries is set to 1 to 3 \( M_\odot \). We define a trigger by the local maximum of \( \rho \) in each small time interval with length, \( \Delta t_c = 25.6\text{msec} \), and in the whole mass parameter region, together with the parameters, \( t_c, M \) and \( \eta \) which realize the local maximum.

The data of TAMA300 contain non-stationary, non-Gaussian noise. Such noise cause many triggers with rate much larger than that expected in the stationary Gaussian noise. In order to distinguish such spurious triggers from triggers caused by real gravitational wave signals, we compute \( \chi^2 \) value for each trigger with \( \rho \geq 7 \). We then define \( \zeta = \rho/\sqrt{\chi^2} \) as a new statistic [2]. The statistic, \( \zeta \), was used in our previous analysis [2], and was found to be useful to distinguish the spurious triggers from triggers caused by real gravitational wave signals.

3. Results and summary

By using the method described in the previous section, we obtain the trigger lists from each observation run. We find that there are no triggers which deviate from the tail of the distribution of triggers significantly. This fact suggests that there is no candidate trigger which can be interpreted as real gravitational signal.

Next, we evaluate the upper limit to the event rate from each observation run, \( R_i \) (\( i = \text{DT6, DT8, DT9} \)), derived from \( R_i = N_i/(T_i \epsilon_i) \) where \( T_i \) is the length of data, \( \epsilon_i \) is the detection probability, and \( N_i \) is the upper limit to the number of event which is derived from the distribution of triggers. We evaluate the detection probability of Galactic signals by adding the signals to the real data, and by analyzing the data by the same analysis pipeline used in the real analysis.

We also evaluate the various error sources which affect the detection probability. They include the error of the threshold for the triggers, the error of the Monte Carlo injection test, the error of the calibration of the detector, the error of the theoretical wave form, and the error of the binary distribution model.

We obtain the upper limit to the Galactic event rate from each observation: \( 130^{+59}_{-29}\text{yr}^{-1} \) for DT6, \( 30^{+4.0}_{-4.4}\text{yr}^{-1} \) for DT8, and \( 60^{+8.0}_{-4.6}\text{yr}^{-1} \) for DT9, at a 90% confidence level. We combine these results and obtain a single upper limit, \( 17^{+2.0}_{-1.5}\text{yr}^{-1} \) at a 90% confidence level. By taking larger value as a conservative upper limit, we obtain \( 20\text{yr}^{-1} \). This value is much larger than an astrophysically expected value, \( 8.3 \times 10^{-5}\text{yr}^{-1} \) for the coalescence of neutron star binaries. However, this rate is smaller than that obtained by LIGO S2 search [6], \( 47\text{ yr}^{-1}\text{MPEG}^{-1} \), or by LIGO-TAMA joint analysis, \( 49\text{ yr}^{-1}\text{MPEG}^{-1} \) [4]. Here MEG stand for the Milky Way
|                 | DT6  | DT8  | DT9  |
|----------------|------|------|------|
| Observation time [hours] | 876.6 | 1100 | 486.1 |
| Threshold $\zeta^*$       | 21.8 | 13.7 | 17.7 |
| $N_{bg}^{(i)}$             | 0.1000 | 0.1255 | 0.0555 |
| Detection probability     | 0.18 | 0.60 | 0.69 |
| $(\delta R_t)_{\text{fluct}}$ [yr$^{-1}$] | +20.6 | +2.52 | +4.04 |
|                         | -24.0 | -2.82 | -3.77 |
| $(\delta R_t)_{\text{model}}$ [yr$^{-1}$] | +55.4 | +4.18 | +6.84 |
|                         | -16.6 | -1.53 | -2.60 |
| $R_t$ [yr$^{-1}$]         | $130^{+29}_{-29}$ | $30^{+4.9}_{-4.6}$ | $60^{+3.6}_{-3.4}$ |
| Combined upper limit [yr$^{-1}$] | $17^{+2.05}_{-1.51}$ |

**Table 1.** Summary of the upper limit to the Galactic event rate. The errors for the upper limit are evaluated in section VI in detail.

Equivalent Galaxy. Main reason for this is that the length of data used in our analysis is much longer than these analyses.

Recently, LIGO reported the results of the analysis from LIGO S3 and S4 data [7]. Their upper limit to the 1.4$M_\odot$ neutron star binaries can be interpreted to 2.0 yr$^{-1}$MWEG$^{-1}$. LIGO was conducting the 5th science run from November 2005 to September 2007, with its design sensitivity. It can detect the inspiraling binaries up to $\sim$10Mpc distance. They are expected to be able to set a much more stringent upper limit.

Despite of the improvement and long term observation of current detectors, the chance to detect gravitational waves by these first generation detectors will not be very large. We need more sensitive detectors, such like advanced LIGO [8] and LCGT [9].

More details of this work can be found in Ref:[10]

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