Search for Gravitational Waves from Ringing-Down Black Holes

Yoshiki Tsunesada[1], Nobuyuki Kanda[2], Hiroyuki Nakano[2], Daisuke Tatsumi[1], Hideyuki Tagoshi[3], Hirotaka Takahashi[3], and the TAMA Collaboration
(1) National Astronomical Observatory of Japan, Tokyo, Japan
(2) Department of Physics, Osaka City University, Osaka, Japan
(3) Department of Earth and Space Science, Osaka University, Osaka, Japan

Abstract

We present the status of the TAMA300 data analysis for black hole ringdown detection. The detector sensitivities, signal-to-noise ratios, and the detection probabilities for Galactic ringdown events are described.

1. Introduction

Black holes (BHs) are of great interest in general relativity and astronomy to which the gravitational wave observations could give significant contributions. The linear perturbation theory of a BH spacetime shows that a BH has a set of damped modes known as *quasi-normal ringing modes* (QNRMs) characterized by its mass M and angular momentum a. This suggests that it is possible to observe a BH directly by detecting gravitational waves of characteristic waveforms predicted from the perturbed Einstein equations, and determine its physical parameters.

In this paper, we study a method to search for ringdown gravitational waves and report the current status of the TAMA300 data analysis. The description includes the detector sensitivities at the time of the observations in 2001 and 2003, expected signal-to-noise ratios (SNRs) for Galactic ringdown events, the template construction for the matched-filtering analysis, and the detection efficiencies.

2. Quasi-Normal Modes of Black Holes

The properties of the Teukolsky equation which describes perturbation of rotating BHs and QNRMs were extensively studied in 1970's and 1980's [1,5]. The ringdown waveform can be expressed in terms of the central frequency f_c and the quality factor Q,as $h(t) = e^{-\pi f_c t/Q}\cos(2\pi f_c t)$. Echeverria proposed semi-analytical formulae for the fundamental mode of $l = m = 2$ [2],

$$f_c \simeq 32\,[\mathrm{kHz}] \times \left[1 - 0.63\,(1-a)^{0.3}\right]\left(\frac{M}{M_\odot}\right)^{-1}, \quad Q \simeq 2.0\,(1-a)^{-0.45} \qquad (1)$$

where $M/M_\odot$ is the BH mass in the solar mass unit, and a is the dimension-less spin angular momentum.

pp. 3055–3058

Several mechanisms that excite the BH perturbations are claimed, as a core collapse in a supernova explosion, a merger of two neutron stars or black holes to form a single BH. It is noted that the perturbation theory does not make any predictions on the magnitude of radiated gravitational waves. Numerical studies on binary coalescences show that the fraction of total mass energy radiated as the ringdown gravitational waves is typically $\sim 3\%$ for equal-mass BH binaries [3].

3. Analysis

3.1. Matched Filter

To extract the ringdown signal of a waveform $h(t)$ possibly embedded in the detector output $s(t)$, the conventional matched-filtering technique is employed,

$$(s,h) \equiv 2\int_{-\infty}^{\infty} \frac{s(f)h^*(f)}{S_n(|f|)}\,\mathrm{d}f \tag{2}$$

where $s(f)$ and $h(f)$ are the Fourier transforms of $s(t)$ and $h(t)$ respectively, and $S_n(|f|)$ denotes the one-sided power spectrum density of the detector noises. Normalized to be a Gaussian distribution with zero mean and unity standard deviation, this statistic gives the SNRs.

3.2. Noise Spectrum and Pipeline Processes

Since a behavior of the detector noises is non-stationary in nature, the noise power spectrum in the matched-filtering analysis should reflect the actual detector conditions correctly. To filter the k-th data chunk, we use the "averaged inverse noise power spectrum" instead of $1/S_n$ in (2), given by

$$\left\langle \frac{1}{S_n^k(|f|)} \right\rangle = \frac{1}{N}\left[\frac{1}{S_n^{k-1}(|f|)} + (N-1)\left\langle \frac{1}{S_n^{k-2}(|f|)} \right\rangle\right] \tag{3}$$

with $N = 5$. In the TAMA300 observations, the noise fluctuations are continuously monitored: The detector outputs digitized by the ADC module with 20 kHz sampling frequency are split into data chunks of lengths 2^{20} samplings (about 52 seconds), Fourier transformed, and the noise power spectrum for the matched-filtering analysis is calculated by (3) for each data chunk. These procedures are performed *on-line* throughout the observations [6].

3.3. TAMA300 Data, Sensitivities, and Signal-to-Noise Ratios

The TAMA300 data used in this work were obtained in the observations in 2001 (DT6) and 2003 (DT8) *. The total lock time lengths in both of the observations exceed 1000 hours. The strain sensitivity of the interferometer and expected SNRs are shown in Fig. 1.. One can see that good SNRs are expected for ringdown events of frequencies in the range $f_c = 100 \sim 2500$Hz, which corresponds to BHs with masses $M/M_\odot = 10 \sim 200$.

---

*Analyses are not completed at the time of this manuscript.

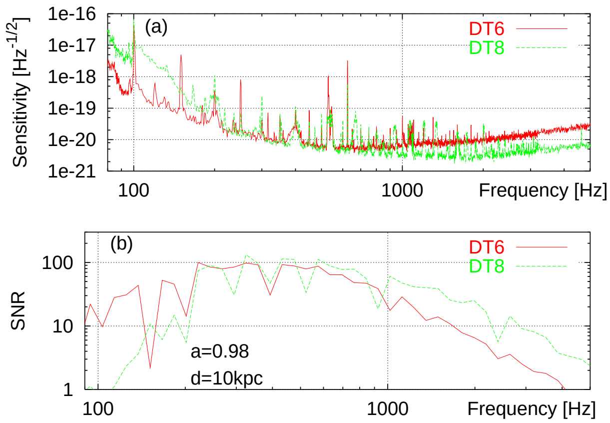

Fig. 1. (a) Strain sensitivity of TAMA300 in DT6 and DT8, (b) Expected SNRs for ringdown events of a fixed Kerr parameter $a = 0.98$, at $d = 10$kpc away from the detector.

3.4. Template Constructions

The matched-filter analysis requires a large number of templates with different parameter values to find the "best" waveforms to reproduce the observed signals. We employ an efficient template construction method developed by Nakano [4], which enables to cover the parameter space with a fewer templates and small SNR losses due to the template spacings. We define the search parameter volume from the investigation of the detector sensitivity and the expected SNRs described in the previous section, as $f_c = 100 \sim 2500\text{Hz}, Q = 2 \sim 20$. The total number of templates used amounts to 478.

3.5. Detection Efficiency for Galactic Ringdown Events

We have performed a simulation study to evaluate the detection efficiencies for Galactic BH ringdown events. The randomly generated ringdown signals are injected into the TAMA300 data, filtered with the preselected template bank, and examined the SNRs. We generate 500 events in this simulation, for each of all the DT6 data chunks. The spatial distribution of the sources is assumed as $\mathrm{d}N \propto Re^{-R^2/R_0^2}e^{-|z|/h_z}\mathrm{d}R\mathrm{d}z$ in the Galacto-centoric coordinates (R, z), where $R_0 = 4.8$kpc, and $h_z = 1$kpc. The signal parameters are uniformly sampled in the (f_c, Q) plane within the ranges defined above. The antenna pattern of the detector and the orientation in the celestial sphere in the observation period are also considered. Figure 2. shows the search templates used and the detection efficiency with SNR ≥ 6 as a function of the ringdown frequency f_c. This demonstrates that we can detect the Galactic BH ringdown events of frequencies $< 1500\text{Hz}(\sim 20M_\odot)$ with the detection probability of $> 90\%$.

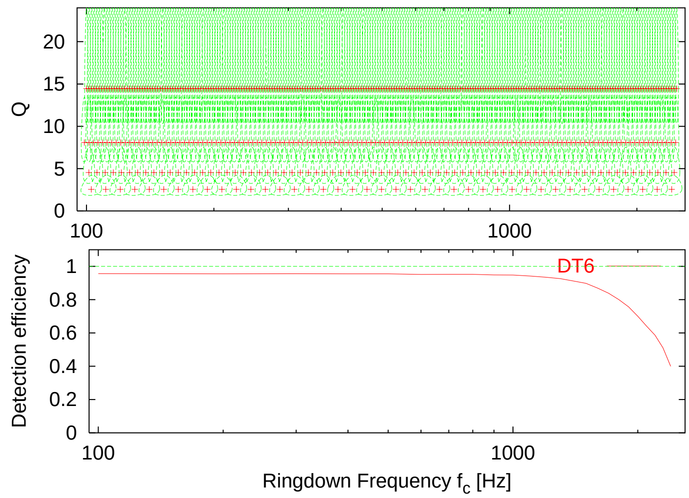

Fig. 2. Top: the template space. the crosses are the templates, and dashed lines denote the tilings with the maximal SNR losses of 2%. Below: the detection efficiency for Galactic ringdown events with SNR > 6, for DT6 data.

4. Summary

We have described the current status of the TAMA300 data analysis for black hole ringdown detection. The detector sensitivities at the time of the observation in 2001 and 2003 give expected signal-to-noise ratios (SNRs) of ~ 100 for ringdown events of BH masses $\sim 50M_\odot$ at 10kpc away. By considering the location of the site and SNR losses due to the finite template spacings in the matched-filtering analysis, the detection probability for the Galactic ringdown events is evaluated as $\sim 90\%$ for events of $> 20M_\odot$.

An elaborated study on vetoing techniques is required to distinguish the "true" ringdown signals from spurious ones attributed to the detector noise fluctuations. We will report this effort together in the conference.

1. Chandrasekhar S. and Detweiler S., *Proc.R.Soc.Lond.*, **A344**, 411 (1975), Leaver E.W., *Proc.R.Soc.Lond.*, **A402**, 285 (1985)
2. Echeverria F., *Phys.Rev.D*, **40**, 3194 (1989)
3. Flanagan E.E. and Hughes S.A., *Phys.Rev.D*, **57**, 4535 (1998)
4. Nakano H. *et al.*, in preparation
5. Regge T. and Wheeler J.A., *Phys.Rev.*, **108**, 1063 (1957), Teukolsky S.A., *Phys.Rev.Lett.*, **21**, 1114 (1972)
6. Tatsumi D., and Tsunesada Y., *et al.*, in this conference