論文の内容の要旨

Optical and thermal study of molecular thin layers on cryogenic mirrors in next-generation gravitational wave telescopes

(次世代重力波望遠鏡における低温鏡への分子吸着薄膜層形成による光学的および熱的影響)

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Detections of the gravitational waves (GWs) opened the new window, and have been bringing physically and astronomically important information. From now on, precise measurement of the signal and accurate sky localization are important for the multi-messenger astronomy with the broadband electromagnetic waves and the neutrino observations.

KAGRA is the Japanese GW telescope which is aiming the precise measurement by adapting the cryogenic mirrors for the first time in the world to reduce the thermal noise that limits the most sensitive frequencies. For the more precise measurement, the next generation GW telescopes such as Einstein telescope in Europe and Cosmic Explorer in the U.S also plan to adapt cryogenic mirrors with their 10 km scale baseline. The development of the cryogenic system adaptable in the GW telescope is important not only to complete KAGRA but also to improve the sensitivity of the future detectors. The material properties at the cryogenic temperature and the low vibration refrigerator have been measured and developed for this purpose. However, the interaction between the cryogenic mirrors and the vacuum residual gasses have never studied except for a few experimental expectations, though it is a well known phenomenon.

When the molecules hit the cryogenic surface, they reduce their kinetic energy and are caught up by the potential near the surface. In a cryogenic GW detector, the molecules that are transported from the long beam duct

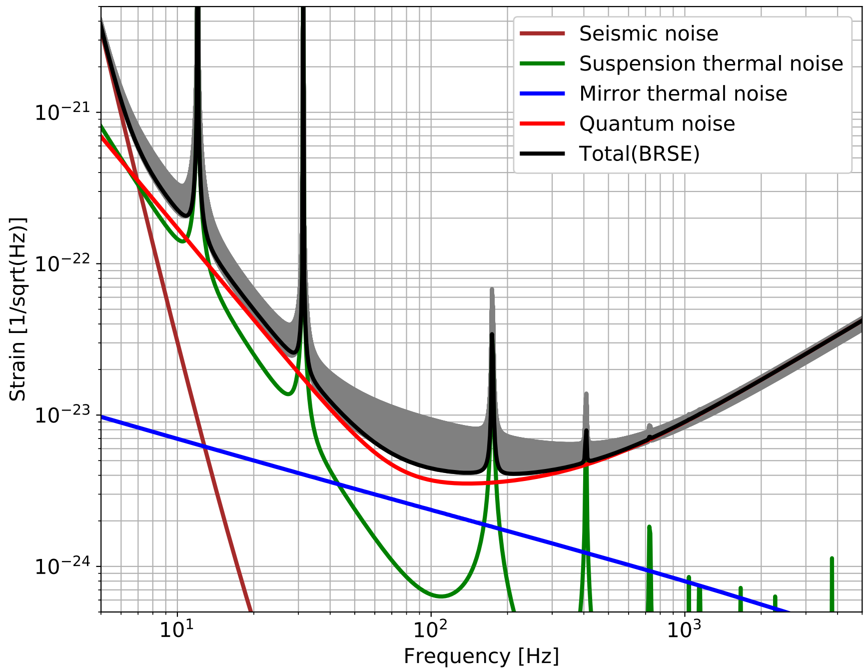

Figure 1: KAGRA sensitivity with the molecular layer. As a result of the molecular layer formation, the quantum noise, the Brownian noise and suspension thermal noise are modified. Within the thickness of 2.5μm, the sensitivity moves inside the gray area.

hit the surface of the cryogenic mirrors, and finally, many molecules form the molecular layer on the surface. The frequency of the molecular injection to the cryogenic mirror was evaluated by adopting the KAGRA cryogenic and vacuum system into the vacuum engineering theory. As a result, it was revealed that even if KAGRA achieve the target vacuum pressure of 1×10^{-7} Pa, the water molecular layer grow about 150 nm during one year of operation. The KAGRA vacuum system is not finalized and the vacuum pressure is worse than the designed value by a factor of 10. Utilizing the situation, the molecular incident frequency was experimentally and numerically evaluated, and we confirmed that these two evaluation is well consistent.

When there is the growing molecular layer on the top of the mirror, it works as the optical coating. As a result of the interference of the reflected light from the top of the molecular layer and the coating, the reflectivity of the mirror is changed. Further, the optical absorption inside the molecular layer increases the temperature of the system. Within the molecular layer thickness of 2.5 μm, if the molecular layer grows on four cryogenic test mass in the cryogenic GWD, the sensitivity changes in the gray area as shown in Fig.(1). The detection of the GWs from the 1.4 $M_\odot$ is estimated to decreases by 84%.

KAGRA doesn't have the system to remove the molecular layer, and it takes 1 month for one thermal cycle. To solve the situation, the thermal desorption system using the CO_2 laser was suggested and tested in the laboratory. The study indicates that 13.5 W of the laser power is enough to increase the temperature of the cryogenic mirror in KAGRA to desorb the adsorbed molecular layer. The temperature of the cryogenic mirror get 180 K after 30 hours. Because the temperature of the mirror returns to the nominal cryogenic temperature after 30 hours as shown in Fig.(2), the system shortens the observation dead time from 1.5 months to 60 hours.

Through the dissertation, we discuss the formation, effects, and countermeasures of the molecular layers in the cryogenic GWD first in the world.

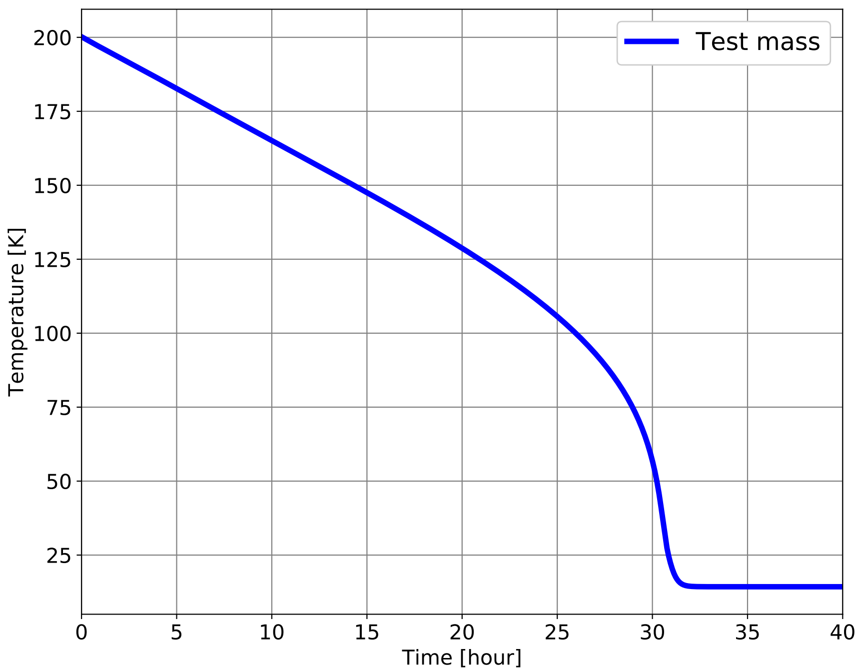

Figure 2: Cooling time after the heating to remove the molecular layer.