Search for gravitational radiation from the Crab pulsar

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The result of a revised search for the gravitational radiation from the Crab pulsar at 60.2 Hz is presented. Cold damping was applied to a 1400-kg aluminum quadrupole antenna at room temperature. The resulting antenna system had a bandwidth increased to 0.012 Hz and a noise temperature reduced to 24 K. From the taped record of 621 h of observation, we have obtained an upper limit for the energy flux of the radiation in one of the polarization components: $S_{G+} < 0.08$ W/m^2.

I. INTRODUCTION

Gravitational radiation (GR) of the continuous waveform has been studied by several authors, both experimentally[1,2] and theoretically.[3,4] For an experimental work using a resonant antenna, the Crab pulsar, PSR 0531+21, along with the Vela pulsar, PSR 0833−45, seems to be the most promising source of GR of this kind because of its large rotational frequency and the small distance from us. Hirakawa, Tsubono, and Fujimoto (hereafter denoted as HTF)[2] obtained an upper limit $S_G < 14$ W/m^2 for the energy flux of GR from the Crab pulsar at 60.2 Hz using a resonant quadrupole antenna of mass 400 kg. In the following we report on the result of another search for this radiation with a room-temperature antenna of mass 1400 kg and quality factor 65 000. The larger mass and the larger quality factor of the antenna resulted in an improvement of sensitivity by two orders of magnitude compared to that of HTF. The GR signal frequency shifts 0.025 Hz in a year due to the spin-down of the pulsar and the Doppler effect of the earth's motion around the sun. It is difficult to keep this signal at the center of the antenna resonance which has a width less than 10^{-3} Hz. Therefore, we applied the method of cold damping to the antenna, increasing the bandwidth of resonance and decreasing the noise temperature.

II. PRINCIPLE OF COLD DAMPING

A dynamical system resonating at frequency $\omega/2\pi$ has a thermal energy kT contained in the bandwidth $\omega/2\pi Q$. One can reduce the quality factor Q by loading the system with a resistor of a noise temperature T_R through a passive transducer. The quality factor Q_e and the noise temperature T_e of the resulting system are given by

$$\frac{1}{Q_e} = \frac{1}{Q} + \frac{1}{Q_R} , \qquad \frac{T_e}{Q_e} = \frac{T}{Q} + \frac{T_R}{Q_R} . \tag{1}$$

Therefore, if T_R is low enough, it is possible to increase the bandwidth of the system without much reducing its significant quantity, the quality factor divided by the noise temperature. This principle has been demonstrated by use of a resistor held in a helium cryostat[5] and also by use of an artificial cold resistor consisting of an electronic negative feedback circuit.[6] Although the cold damping does not improve the sensitivity of an antenna, it provides a practical advantage for tracking frequency shifts and phase changes of a signal with high-Q antennas.

III. EXPERIMENTAL

The quadrupole antenna[7] used in this experiment is made of an aluminum 5052 alloy plate, $1.65 \times 1.65 \times 0.19$ m^3 (Fig. 1). It has a mass of 1400 kg and a reduced mass of 300 kg at 60 Hz. After mounting a pair of electrodes at a distance of 40 μm to form a capacitor of 3600 pF, we obtained $Q = 65\,000$ with no electrical loading. The electrodes are connected to a 180 V dc supply and coupled to an artificial cold resistor, $R = 6.3$ MΩ and $T_R = 3.0$ K, made of a negative feedback circuit (Fig. 2). The resulting quality factor $Q_e = 4600$ and the noise temperature $T_e = 24$ K of the system, determined from the analysis of the Brownian motion, agree with Eq. (1). Figure 3 shows the power spectra of the antenna output before and after the application of the cold damping. In a vacuum tank of a controlled temperature, ± 0.1 K, the frequency drift of the antenna was less than $\pm 1 \times 10^{-3}$ Hz. Thus with the antenna bandwidth increased to 0.012 Hz, it was possible to track the GR signal

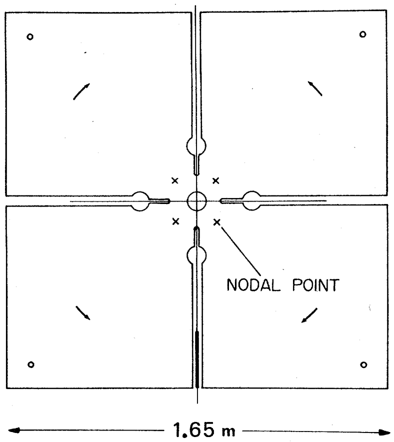

FIG. 1. The aluminum antenna of mass 1400 kg for gravitational radiation at 60.2 Hz. Supported horizontally at the four nodal points, it vibrates in a quadrupole mode B_{1g}.

by a thermal tuning, -1×10^{-2} Hz/K, of the antenna resonance.

Supported horizontally, the antenna is located in the Hongo Campus, University of Tokyo, with two of its sides parallel to the meridian. We define a reference coordinate system in which the YZ plane contains the polar axis and the Z axis points to the source. Figure 4 shows the expected daily modulation of the amplitude, a_+ and $a_\times$, of each polarization component of the Crab GR received by our antenna. The + component, at which the present experiment is aimed, is the vibration of the space metric in the X and Y directions, while the × component is at 45° to it. Sampled every 1 sec ($=\Delta t$), the antenna output was taped for 6 h a day from August 1978 to January 1979, accumulating 2.2×10^6 ($=N$) words of record. Except for several improvements in the hardware, the sampling system was similar to that of HTF.

IV. DATA ANALYSIS AND RESULTS

From the recorded series of the antenna output $v(t_i)$, two consecutive sums

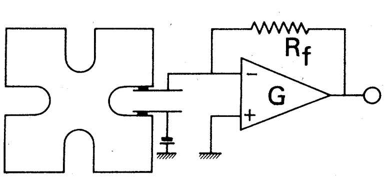

FIG. 2. Schematic of the transducer circuit with a feedback resistor $R_f=1.2$ GΩ and an amplifier of voltage gain $G=185$. The apparent impedance of the artificial cold load presented to the antenna is $R=R_f/(1+G)$ $=6.3$ MΩ, with a noise temperature $T_R=3.0$ K at 60 Hz. The coupling coefficient between the antenna and the load was $\beta=1.7\times10^{-3}$.

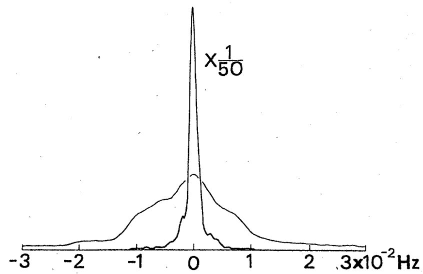

FIG. 3. Power spectra of the antenna output before and after the cold damping was applied. The narrow spectrum ($Q_e=58\,000$ and $T_e=300$ K), shown here with its height reduced by a factor of 50, was obtained with a transducer having a room-temperature input impedance of $R=700$ MΩ. The broad spectrum (Q_e $=4600$ and $T_e=24$ K) was obtained with a circuit given in Fig. 2.

$$C_+ + iS_+ = \sum a_+(t_i)p(s)v(t_i)\exp[i4\pi\psi(t_i)]\,,$$
$$C_\times + iS_\times = \sum a_\times(t_i)p(s)v(t_i)\exp[i4\pi\psi(t_i)] \qquad (2)$$

were calculated. The antenna dynamic impedance, $p(s)=s+iQ_e(1-s^2)$ with $s=\omega/\omega_A$, corrects the tracking error between the antenna frequency ω_A and the signal frequency ω. The expected arrival phase $4\pi\psi$ (rad) of GR at the antenna was calculated from a polynomial, giving the barycentric arrival phase $2\pi\phi$ of the Crab optical pulses. The coefficients of the polynomial were determined by Lohsen[8] at Hamburg on the basis of his observation of the pulsar in this season and were communicated to us.

The antenna output v gives the sum of the transducer displacement x and the equivalent displacement x_N representing the noise in the transducer and following circuits of a bandwidth $\Delta f=4.7$ Hz. The coordinate x is related to the generalized force acting on the antenna, which consists of a force

$$F_G = F_{G+}a_+(t)\cos(4\pi\psi+\alpha_+) + F_{G\times}a_\times(t)\cos(4\pi\psi+\alpha_\times) \qquad (3)$$

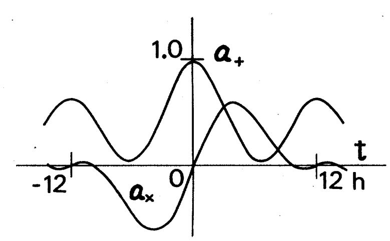

FIG. 4. Expected daily modulation of the amplitude of two polarization components, + and ×, of the Crab GR received by our antenna. a_+ and $a_\times$ are normalized so that for a fictional source at zenith, $a_+^2+a_\times^2=1$.

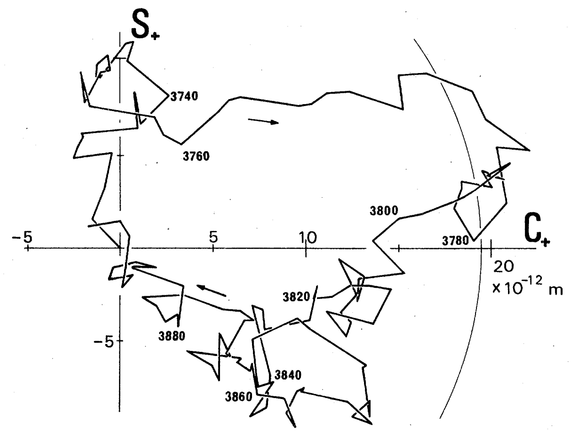

FIG. 5. Growth of the series $C_+ + iS_+$ during the observation period, from August 10, 1978 to January 19, 1979 (JD 244 3730–3892). The circle shows the rms expected distance of a random walk.

of the GR field, a noise force connected with the mechanical dissipation in the antenna, and an electromechanical back reaction through the transducer.[4] It can be shown that the sum $C_+ + iS_+$ consists of a signal term

$$N\langle a_+^2\rangle(F_{G+}Q_e/2\mu\omega^2)(\sin\alpha_+ + i\cos\alpha_+) \tag{4}$$

and a noise term which is distributed in the complex plane with a variance

$$N\langle a_+^2\rangle 2Q_e kT_n/\mu\omega^3\Delta t\,, \tag{5}$$

provided the average $\langle a_+ a_\times\rangle$ vanishes. In theory, the apparent noise temperature T_n of the antenna is given by $T_e + T_w$, where T_w (=0.8 K) is the wide-band noise in the transducer and circuit,

$$T_w = (\mu\omega^3/2Q_e k)\langle|p^2|\rangle\langle x_N(\nu)^2\rangle\Delta f\Delta t\,, \tag{6}$$

with $\langle x_N^2(\nu)\rangle$ representing the power spectrum density of x_N at frequency $\nu = 60$ Hz. In practice, however, occasional excitations of the antenna by environmental noise resulted in $T_n = 33$ K. Figure 5 shows the growth of the series $C_+ + iS_+$ in the summation process. Table I summarizes the several quantities obtained in our analysis.

From this result we estimate the size of the + component of the force

$$\begin{aligned}(F_{G+}/\mu\omega^2)\cos\alpha_+ &= (3.4\pm 39.9)\times 10^{-22}\ \text{m}\,,\\ (F_{G+}/\mu\omega^2)\sin\alpha_+ &= (-5.0\pm 39.9)\times 10^{-22}\ \text{m}\,,\end{aligned} \tag{7}$$

TABLE I. Quantities obtained in the course of the analysis.

$C_+ + iS_+$	$(-1.77 + i\,1.18)\times 10^{-12}$ m
$C_\times + iS_\times$	$(\ 0.99 - i\,3.90)\times 10^{-12}$ m
$\langle a_+^2\rangle$	0.678
$\langle a_\times^2\rangle$	0.027
$\langle a_+ a_\times\rangle$	0.018

where the errors represent the statistical standard deviation. This gives an upper limit of GR from the Crab pulsar in the + polarization,

$$h_+ < 8.4\times 10^{-21}\,, \tag{8}$$

for the root-mean-square amplitude of the nondimensional element of the metric tensor, or

$$S_{G+} < 0.08\ \text{W/m}^2 \tag{9}$$

for the energy flux. Considering a possible frequency difference, if any, between GR and optical pulses, we have also surveyed the recorded antenna output searching for a coherent component with a frequency offset up to $\pm 7\times 10^{-5}$ Hz. There is no component of a significant magnitude giving an upper limit larger than 0.5 W/m^2 in the frequency range examined.

The upper limit given by (9) is more than 10^2 times smaller than that of HTF and is close to the lowest value attainable with resonant antennas operating at a room temperature. The maximum flux of GR, on the other hand, which could be expected from the Crab pulsar as deduced from its spin-down is $\sim 10^{-9}$ W/m^2.

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