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Search for gravitational radiation from the Crab pulsar

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The result of a search for the gravitational radiation from the Crab pulsar, at 60.2 Hz, is presented. A 400-kg aluminum quadrupole antenna, $Q = 4500$, is thermally tuned tracking the pulsar frequency. Correlating the 420 h of recorded antenna output with the timing of the optical pulses, we have obtained an upper limit for the energy flux of the gravitational radiation: $S < 14$ W/m^2.

I. INTRODUCTION

There have been various estimates on the emission from astrophysical sources, such as binary star systems,[1] rotating and vibrating stars,[2] of gravitational radiation (GR) of continuous wave form. Although the expected energy fluxes of GR at the earth based on these estimates are well below the sensitivity of present-day detectors, it is worthwhile trying to detect the fluxes or to establish their upper limits since the estimates involve several assumptions that could be wrong, and since a different format of experiment is used in a search for these sources as compared with those employed in a search for burst events.[3-9]

PSR 0532, the pulsar in the Crab nebula, is one of the most promising objects in this respect because of its short period (0.033 sec) and the relatively small distance (1–2 kiloparsec) from the solar system. There are thorough records of the optical[10,11] and radio[12,13] observations on this pulsar which narrow down the frequency band to look for. The estimated energy flux S of GR ranges from 10^{-10} to 10^{-19} W/m^2, depending on models of the pulsar.[14,15] There have been several experimental works, a geophysical strain measurement using a laser interferometer,[16] seismometer observations,[17] and a laboratory experiment using a laser interferometer,[18] setting an upper limit of the energy flux,[16] $S < 10^6$ W/m^2. In the following we report on the result of a search for GR from the Crab pulsar performed with a resonant antenna at $\omega/2\pi = 60.2$ Hz, twice the pulsar rotation frequency. The experiment distinguishes itself from the previous ones in two respects: the use of a tunable resonant antenna which tracks the pulsar frequency and the extended period of the correlation integration.

II. EXPERIMENTAL

The antenna used in this experiment is an aluminum quadrupole with mass $M = 400$ kg (Fig. 1), of a similar type as those used in our previous experiments.[6] The size of the cuts on each side is so determined that the frequency of the fundamental B_{1g} vibration mode is slightly over 60.2 Hz. Figure 2 shows the tuning curve of this mode obtained from a scale model study. The antenna is tuned more precisely with small weights mounted at the four corners. The resonant frequency of the antenna is measured by incorporating the antenna in a feedback oscillation loop together with an amplifier of a proper phase shift. The tracking of the antenna resonance after the expected arrival frequency of GR (Fig. 3) is effected by enclosing

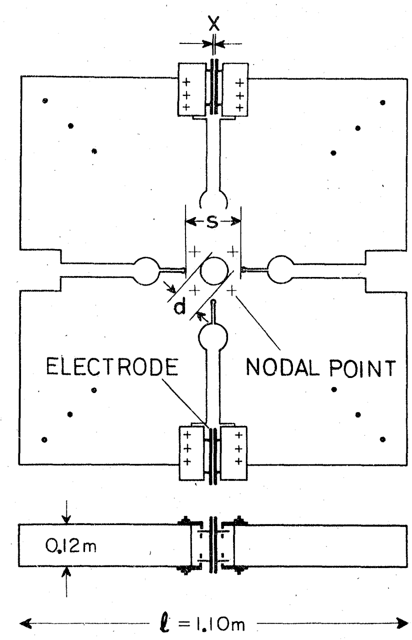

FIG. 1. 400-kg quadrupole antenna for gravitational radiation (GR) at 60.2 Hz. Machined from a square aluminum plate $l = 1.10$ m, it has cuts on each side, $s = 0.14$ m, $d = 0.08$ m. Four electrode plates are mounted in the cuts to form a pair of capacitors.

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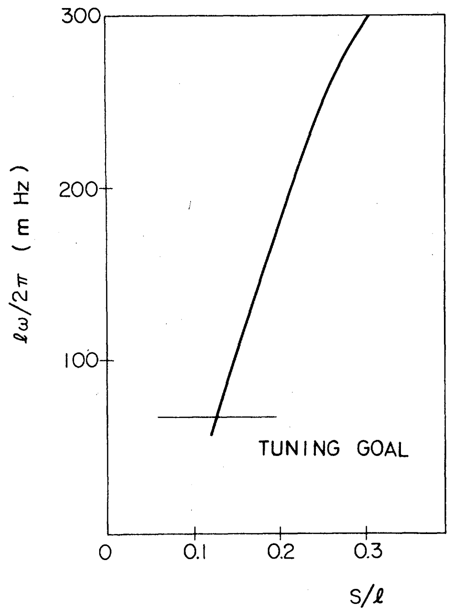

FIG. 2. The resonant frequency, $\omega/2\pi$, of a square quadrupole antenna varies with the size of cuts on each side. The cut is specified by a distance s (Fig. 1). The product $l\omega/2\pi$ is given as a function of a nondimensional parameter s/l, $d/l = 0.073$.

the antenna within a thermal shield of a controlled temperature. The temperature coefficient of the antenna frequency is -0.014 Hz/K, while the thermal time constant of the antenna in vacuum is 60 h. The resultant tracking accuracy is ± 0.003 Hz. Equipped with two capacitors and supported at the four nodal points, the antenna has a loaded quality factor $Q = 4500$, an effective area[6] $A_G = 0.40$ m^2, and a reduced mass $\mu = 78$ kg in reference to the electrode distance x indicated in Fig. 1. Two capacitors are connected in parallel to form an

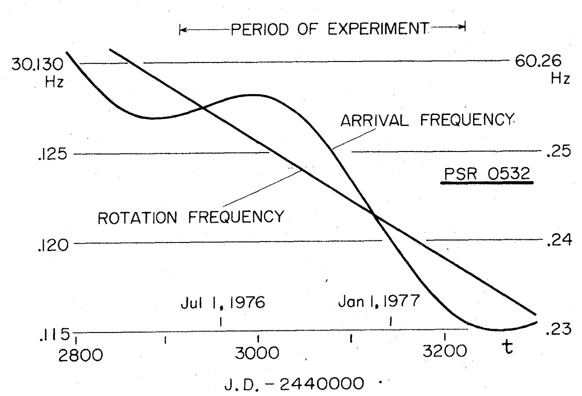

FIG. 3. The rotation frequency ($d\phi/dt \sim 30.1$ Hz) of the Crab pulsar slows down 0.04% annually. The arrival frequencies of the optical pulse ($d\psi/dt \sim 30.1$ Hz) and the expected GR ($2d\psi/dt \sim 60.2$ Hz) show, in addition, a Doppler shift of maximum $\pm 0.01\%$.

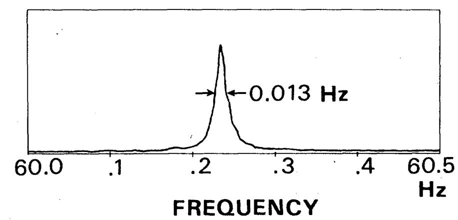

FIG. 4. Power spectrum of the antenna signal of a typical three-hour run, obtained by an autocorrelation analysis with a Bartlett filter.

electrostatic transducer circuit of capacity $C = 3700$ pF and electric field $E = 2.1 \times 10^6$ V/m, with an electromechanical coupling coefficient[6] $\beta = CE^2/\mu\omega^2 = 1.4 \times 10^{-3}$. After amplification, 148 db within 2 Hz bandwidth, the signal $v(t)$ is sampled and converted into 12 bits digital code every $\Delta t = 1$ sec and recorded onto perforated paper tape. At temperature $T = 300$ K, the antenna Brownian motion has a root-mean-square (rms) amplitude $a = (kT/\mu)^{1/2}/\omega = 1.9 \times 10^{-14}$ m in the electrode distance x around its equilibrium value, while the wide-band noise of the transducer plus amplifier system is 30 nV at the amplifier input, equivalent to an rms amplitude $w = 1.5 \times 10^{-14}$ m in x. Figure 4 illustrates the power spectrum of the signal obtained from the taped record $v(t_i)$ by an autocorrelation analysis. The Brownian motion of the antenna is recognized in the bandwidth $\omega/2\pi Q = 0.013$ Hz. The power spectra are conveniently utilized to check the frequency tracking of the antenna during the experiment.

The antenna rests horizontally, with the plane of capacitors normal to the meridian, on a vibration-isolation stack in a vacuum tank located on the University of Tokyo campus. The expected intensity curve[6] for unpolarized GR from the Crab pulsar received with this antenna is shown in Fig. 5. It has two peaks of $f = 3.6$ db and 0 db every side-

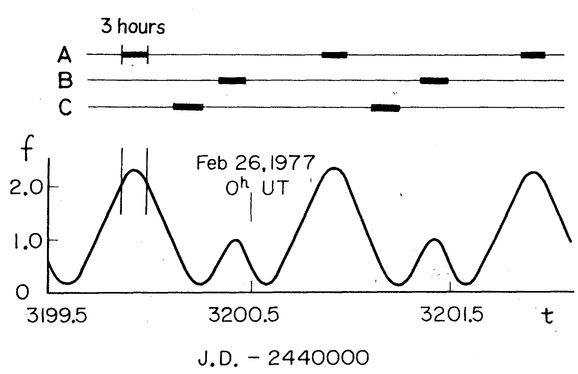

FIG. 5. Expected intensity variation of Crab GR signal received by the quadrupole antenna at the University of Tokyo ($+9^h 19^m.1$, $+35°43'$). Three series of observation runs, A, B, and C, were made.

real day. During May 1976–March 1977, a series of 140 runs of observations, A, were made covering the central peak. Also, an additional two series of runs, B and C, were made for the side peak and for one of the valleys between the peaks. A unit run lasted three hours, recording $n = 10\,800$ words. The timing pulse for the sampling was obtained from a quartz oscillator which was monitored against the standard broadcast JJY. The accuracy of the timing was kept within ±0.05 msec throughout the experiment. In the east part of Japan including the Tokyo area, the power line frequency is 50 Hz. This eliminates the troubles expected in a similar experiment performed in a 60-Hz area. It might be worthwhile to note that in a high-sensitivity work such as this one, we have to prepare against the infiltration of noise at 59.94 Hz, the vertical sweep frequency of network TV.

III. RESULTS

The first step of the processing of the taped data is the calculation of the sum of n vectors for the Ith run,

$$\left(\sum v(t_i)\cos 4\pi\psi(t_i),\quad \sum v(t_i)\sin 4\pi\psi(t_i)\right) = (C(I), S(I)) = \vec{V}(I)\,, \tag{1}$$

where $\psi(t_i)$ is the phase (in Hz sec) at t_i of the Crab electromagnetic pulse arriving at the antenna. In our analysis we used the polynomial

$$\begin{aligned}\phi(t) &= \phi_0 + \nu_0(t-t_0) + \tfrac{1}{2}\nu_1(t-t_0)^2 + \tfrac{1}{6}\nu_2(t-t_0)^3\,,\\ \phi_0 &= -0.355 \text{ Hz sec}\,,\\ \nu_0 &= 30.122\,428\,853\,7 \text{ Hz}\,,\\ \nu_1 &= -3.830\,147\,29\times 10^{-10} \text{ Hz/sec}\,,\\ \nu_2 &= 1.225\times 10^{-20} \text{ Hz/sec}^2\,,\\ t_0 &= \text{Julian day } 2\,443\,100.5\,,\end{aligned} \tag{2}$$

representing the barycentric arriving phase of Crab pulses, obtained by Lohsen[11] at Hamburg based on his optical observations of 1975–77. The polynomial is checked against the polynomials obtained from the complementary observation in the radio frequency band by Gullahorn, Isaacman, Rankin, and Payne[13] at Arecibo. The phase $\psi(t_i)$ at our antenna is calculated from the above polynomial for $\phi(t)$ through a program based on the Ephemeris and including the earth diurnal motion and the motion of the sun around the barycenter of the solar system. If the antenna signal $v(t)$ contained a possible coherent component $u\cos[4\pi\psi(t) + \alpha]$, the vector $\vec{V}(I)$ should consist of two parts, the coherent component

$$((nu/2)\cos\alpha, -(nu/2)\sin\alpha) = (C_0, S_0)\,, \tag{3}$$

and a random component representing the Brownian motion and the wide-band noise. The distribution of $\vec{V}(I) = (C,S)$ is therefore given by a normal form

$$\frac{1}{\pi b^2}\exp\left(-\frac{(C-C_0)^2 + (S-S_0)^2}{b^2}\right) dC\, dS\,, \tag{4}$$

$b^2 = n[(2Q/\omega\Delta t)a^2 + w^2]$, where the contribution of the wide-band noise to b^2 is less than 3%. The second step of the analysis is the summation of the vectors $\vec{V}(I)$. A phase shift $(1/2\pi)\tan^{-1}(2Q\Delta\omega/\omega)$ Hz sec is added here for each vector, in connection with the daily tracking error $\Delta\omega/2\pi$ of the antenna frequency. Figure 6 shows the accumulation of vectors obtained from the observation of series A through the entire period of the experiment. During the first few weeks we noticed by surprise, a growth of the sum toward one direction. However,

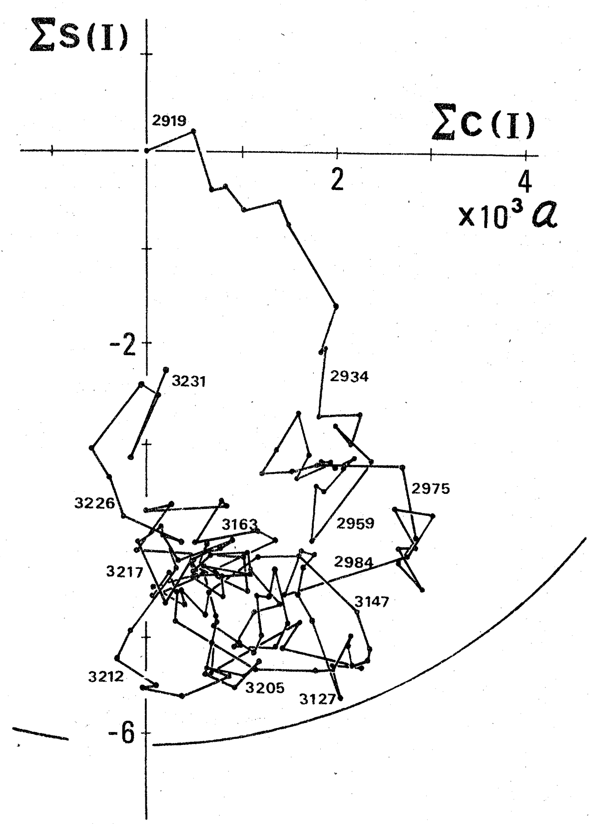

FIG. 6. Successive summation of the daily signal vectors $\vec{V}(I) = (C(I), S(I))$ of series A. Total number of vectors $K = 140$. Date of observation is designated by Julian day $-2440\,000$. The segment of circle shows the rms expected distance of a random walk.

TABLE I. Estimated coherent component (C_0, S_0) [Eq. (3)], contained in the three series of antenna output.

Series	C_0	S_0
A	$(1\pm 30)a$	$(-16\pm 30)a$
B	$(-28\pm 35)a$	$(59\pm 35)a$
C	$(-16\pm 31)a$	$(-6\pm 31)a$

the growth did not continue further with the increasing number of runs, and the final outcome turned out to be

$$\sum C(I) = 0.21\times 10^3 a\,,$$
$$\sum S(I) = -2.24\times 10^3 a\,, \tag{5}$$

which is the sum of 140 $(=K)$ vectors with the rms length $b = 510a$. Considering the possibility of unexpected slips of the assumed phase of the pulsar, the nature of the vector series $\vec{V}(I)$ is checked by an autocorrelation analysis, and the taped data themselves were examined with other sets of the phase factor ψ corresponding to slightly offset pulsar frequencies. No significantly different consequences were found in these analyses. From the vector sum obtained above, we estimate the size of the coherent component (C_0, S_0) contained in the taped record of series A,

$$C_0 = \frac{1}{K}\sum C(I) \pm \frac{b}{(2K)^{1/2}} = (1\pm 30)a$$
$$S_0 = \frac{1}{K}\sum S(I) \pm \frac{b}{(2K)^{1/2}} = (-16\pm 30)a\,, \tag{6}$$
$$C_0{}^2 + S_0{}^2 < 2.1\times 10^3 a^2\,.$$

The errors represent the statistical standard deviation. The records of series B and C were processed identically. Table I compares the results of estimation on the coherent components contained in the three series A, B, and C, respectively.

The GR flux S arriving at the antenna is obtained from the formula for the equilibrium energy of the antenna at resonance,[19]

$$E = \tfrac{1}{2}\mu u^2\omega^2$$
$$= \frac{2\mu}{n^2}(C_0{}^2 + S_0{}^2)\omega^2$$
$$= \frac{2\pi G}{5c^3} M Q^2 A_G f S\gamma\,. \tag{7}$$

Using C_0 and S_0 given by (6) and assuming the polarization factor $\gamma = \frac{1}{2}$, we have an upper limit of GR flux from the Crab pulsar

$$S < 14\ \mathrm{W/m^2}$$

determined in this experiment, which is nearly 10^5 times lower than the previous value.

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