10-1982

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Repository Citation

Boughn, Stephen. "Observations with a Low-Temperature, Resonant Mass, Gravitational Radiation Detector" (with W. M. Fairbank, R. P. Giffard, J. N. Hollenhorst, E. R. Mapoles, M. S. McAshan, P. F. Michelson, H. J. Paik, and R. C. Taber), Ap. J. Letters 261, L19 (1982).

THE ASTROPHYSICAL JOURNAL, 261:L19–L22, 1982 October 1

OBSERVATIONS WITH A LOW-TEMPERATURE, RESONANT MASS, GRAVITATIONAL RADIATION DETECTOR

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Received 1982 March 25; accepted 1982 May 18

ABSTRACT

The noise level at the output of a highly sensitive antenna has been used to establish a new observational upper limit on the flux of 1 kHz gravity wave bursts.

Subject heading: gravitation

I. INTRODUCTION

Since Joseph Weber's pioneering attempts to detect gravitational radiation, and the subsequent program of observations with room-temperature, resonant-mass antennas (see recent reviews by Tyson and Giffard 1978 and Shaviv and Rosen 1975), there has been a steady effort to develop various kinds of improved detectors. One way to obtain greater sensitivity is to operate the antenna at a lower temperature, thus reducing its Brownian motion noise. If the temperature is low enough, one can also use the properties of superconductors to build Josephson effect parametric amplifiers and low-noise electrical circuits. Several experimental groups have been working for a number of years to solve the technical problems involved, and some preliminary results have already been published (Boughn *et al.* 1977; Amaldi *et al.* 1977; Davis and Richard 1980; Blair and Mann 1981). We have now operated a detector at a temperature near 4.2 K for more than 1 year. In terms of the gravitational pulse intensity required to equal the output noise power, this detector is between two and three orders of magnitude more sensitive than any other known to us. The rms noise level corresponds to a dimensionless antenna strain of 10^{-18}. In this *Letter*, we discuss the detector and its calibration and present the results of observations of the output signals over a total of 74 days. The results place a new upper limit on the distribution of gravitational wave pulses which may presently be reaching the Earth.

II. DETECTOR

In its present form (Giffard *et al.* 1978), the detector consists of a 4.8×10^6 g cylindrical aluminum antenna maintained at about 4.3 K. The free fundamental longitudinal mode of oscillation has a frequency of 841.66 Hz and a maximum observed Q-value of 5×10^6. A resonant superconducting transducer (Paik 1976) converts the mechanical motion of one end of the antenna into an electrical signal which is amplified by a Josephson-effect device (Hollenhorst and Giffard 1979). The amplifier output is fed to a digital filter which closely approximates the characteristics of the optimal filter required to maximize the sensitivity for short-duration gravitational signals (Michelson and Taber 1981). The output of the filter with a known delay resulting from signal processing is recorded on magnetic tape at a rate of eight samples per second together with timing information derived from WWVB.

The magnitude of signals and the calibration pulses are conventionally referred to the energy E_e which they would impart to a noise-free antenna which was initially at rest. The equivalent energy E_e of a gravitational wave burst with a spectral energy flux density, $F_g(\omega_a)$, which is assumed to be uniform over the antenna bandwidth centered at ω_a may be written $E_e = \sigma(\theta, 2\phi)\ F_g(\omega_a)$, where $\sigma(\theta, 2\phi)$ is an integrated polarization and direction-dependent cross section which may be readily calculated from the properties of the antenna (Misner, Thorne, and Wheeler 1973; Weinberg 1972). For statistical analysis, $\sigma(\theta, 2\phi)$ is generally replaced by its value $\bar{\sigma}$ averaged over all polarizations, ϕ, and source directions, θ. For our antenna, the value of $\bar{\sigma}$ appropriate for spin-two tensor gravitational waves is 4×10^{-21} cm^2 Hz.

For calibration, a known force pulse is applied to the antenna by a small piezoelectric test transducer attached to the end of the antenna away from the main transducer. The equivalent energy of the pulse is given by $E_e = |M_c(\omega_a)|^2/2m_e$, where $|M_c(\omega_a)|$ is the amplitude of the Fourier transform of the calibration pulse at the antenna frequency and m_e is the antenna equivalent mass. To illuminate comparisons with thermal noise, the

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equivalent energy for a pulse is conventionally expressed as an equivalent temperature, $T_e = E_B/k_B$.

To provide some discrimination against local noise, a second filter chain has been arranged to record the antenna vibrations at the frequency of the second longitudinal mode of the antenna. Since this mode cannot be easily excited by a tidal force,[6] simultaneous excitation of the fundamental and second harmonic modes is a strong indication of local noise. The output of the second harmonic channel was therefore used to provide veto information.

III. CALIBRATION

The recorded data consist of filtered sample pairs of the synchronously detected output of the antenna. The ith sample of the squared envelope (Whalen 1971) of the filter output is ε_i.

In the presence of Gaussian noise, the probability distribution, $P(\varepsilon)$, of the squared envelope values is an exponential given by

$$P(\varepsilon) = \langle \varepsilon_i \rangle^{-1} \exp(-\varepsilon/\langle \varepsilon_i \rangle), \qquad (1)$$

where $\langle \varepsilon_i \rangle$ is the mean squared envelope output.

In the absence of noise, a signal pulse would lead to a peak output $\varepsilon_{\max}$ whose value would be proportional to the equivalent temperature T_e of the pulse. In practice, noise is present and the values of $\varepsilon_{\max}$ resulting from pulses of a given strength display a Rician distribution (Whalen 1971).

In order to calibrate the antenna, a number of force pulses of various intensities were applied to the antenna with the test transducer at known times. The test transducer had previously been calibrated so that the equivalent temperature of each pulse was known to better than 4%. The output data were examined at the appropriate times, and the values of $\varepsilon_{\max}$ tabulated. For large enough calibration pulses, $\varepsilon_{\max} \gg \langle \varepsilon_i \rangle$, the output calibration factor S_c of the detector is defined by $S_c = \langle \varepsilon_{\max} \rangle / T_e$, where $\langle \varepsilon_{\max} \rangle$ is the average of the values obtained with pulses of effective energy T_e.

Using this method, the calibration factor was determined periodically during observations. The measurements were in good agreement with the value calculated using the known parameters of the detector. Using the measured calibration factor, the mean square noise output in the absence of signals may be expressed in terms of a noise temperature $T_n = \langle \varepsilon_i \rangle / S_c$, where $\langle \varepsilon_i \rangle$ is the average value observed in the absence of signals, obtained either from the average mean square output or the slope of the distribution as shown by equation (1). The values obtained from the slope were usually in the 20 ± 1 mK range, although values as high as 60 mK were sometimes obtained by averaging the mean output in the presence of strong disturbances. Figure 1 shows the distributions of values $\varepsilon_{\max}$ obtained from 100 test pulses of effective energy $E_e = k_B \times 50$ mK. The dashed line shows the Rician distribution expected in the presence of noise corresponding to the measured noise temperature of 20.6 mK. Data such as these show that the effect of noise on the signals is well understood. The noise temperatures typically measured are in agreement with detailed calculations[7] given elsewhere (Michelson and Taber 1981).

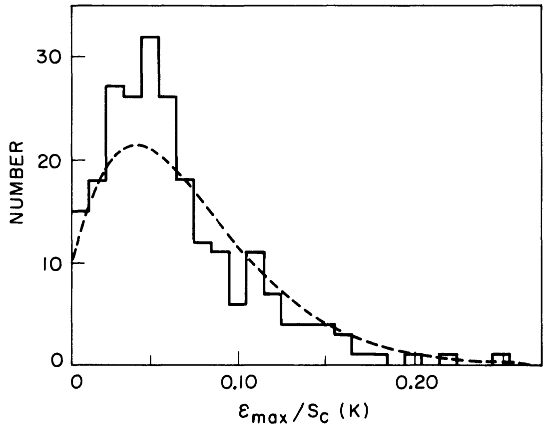

FIG. 1.—Distribution of the squared envelope of the output in the presence of calibration pulses. The solid line is the binned distribution obtained by applying 100 test pulses of effective energy $E_e = k_B \times 50$ mK. The dashed line is the Rician distribution expected in the presence of noise corresponding to the measured noise temperature of 20.6 mK.

IV. ANALYSIS OF OBSERVATIONS

The data reported here were recorded in 1981 during the period from 244,627 MJD to 244,730 MJD. The record is not continuous and many of the data correspond to the local night-time period or to weekends. The remaining time during the observation period was used for detector development and calibration.

The recorded data have now been carefully analyzed for evidence of impulsive tidal excitations lasting less than the detector resolution time. The detector is optimized for such events, and energy flux arguments suggest that wide-band gravitational events strong enough to be detectable have to be very brief (Smarr 1979). The data could, of course, be analyzed in other ways.

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[6] The cross section of the second harmonic mode is 10^{-6} smaller than the cross section of the fundamental mode. The cross section is not exactly zero because the presence of the transducer breaks the symmetry of the mode.

[7] The measured mean energy of the antenna-transducer mode, $k_B \times 5.5$ K, was used in the noise temperature calculations. The thermal temperature of the antenna was 4.3 K. A discussion of possible explanations of this difference is beyond the scope of this *Letter*.

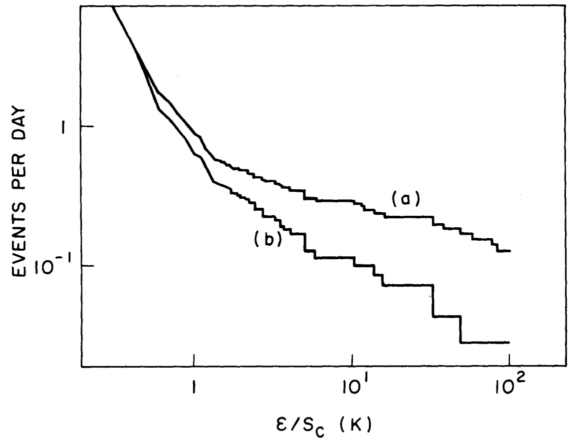

FIG. 2.—(a) Cumulative distribution of all isolated events with peak values exceeding 250 mK. (b) Cumulative distribution after removal of events coincident with significant excitation of the second harmonic of the antenna.

During the period of observations, data were recorded for an aggregate of 73.7 days. Below $\varepsilon_i = S_c \times 150$ mK, the distribution of the recorded samples is well expressed by equation (1) with a slope corresponding to $\langle \varepsilon_i \rangle = S_c \times 20$ mK. At higher energies, more samples were recorded than are predicted by equation (1), showing that the detector was affected by one or more nonstationary or non-Gaussian processes.

Curve a in Figure 2 shows the cumulative distribution of all isolated events which have peak values of ε_i exceeding 250 mK and which do not coincide with known local disturbances. There are 547 such events, a number which is significantly in excess of the 30 expected on the basis of equation (1) when the oversampling of the data is taken into account. Of the 547 events, 40 were coincident with significant excitation of the second harmonic of the antenna, and thus are almost certainly not tidal excitations. The cumulative distribution of the remaining events is shown in Figure 2 as curve b.

TABLE 1

EVENTS IN 1981 WITH MAGNITUDE GREATER THAN 10 K[a]

Magnitude ε/S_c (K)	Time (UT)
14.0	$023^d07^h21^m47^s.3$
33.1	056 09 00 13.9
32.8	056 19 36 29.4
210.0	076 08 19 07.0
49.2	078 04 57 34.8
10.4	098 00 43 22.8
108.0	102 17 35 22.1
15.8	104 14 32 30.5

[a] The detector is located at 37°30′ latitude and 122°10′ longitude. The axis of the antenna is horizontal and oriented along true north.

The time evolution of the envelope during each of the eight largest events, which correspond to effective energies in excess of $k_B \times 10$ K, was examined in detail. The duration at half-amplitude of each event was found to be close to the 0.8 s value characterizing the calculated impulse response of the complete detector, and thus each one qualifies as an impulsive event of duration less than 0.2 s. This analysis was inappropriate for smaller events because their waveforms were significantly affected by background noise.

Table 1 is a list of the times and magnitudes of all the events with effective energies in excess of $k_B \times 10$ K that were not coincident with significant excitation of the second harmonic of the antenna.

V. DISCUSSION OF DATA

The data shown in curve b of Figure 2 demonstrate that, during the observation period, the detector was being excited by pulses with non-Gaussian statistics. The absence of corresponding veto signals shows that the pulses contained only modest power at the second harmonic frequency of 1680 Hz. The veto was applied only when the filtered output of the second harmonic mode indicated an impulsive excitation in excess of 10 K.

Apart from gravitational radiation, the detector is known to be vulnerable to a number of external disturbances. Some parts of the antenna and its supports are very highly stressed, and it is probable that occasional spontaneous acoustic emission takes place. Intense power-line transients can affect the low-signal level electronics and even excite the antenna indirectly. Heavy electrical machinery which operates intermittently in the same building as the antenna constitutes a possible source of noise. Although earthquakes which produce easily perceptible ground motion are known to disturb the antenna, there is no significant correlation between the excess events and local seismic records. We estimate that the local event rate was not significantly affected by acoustic noise, cosmic-ray showers, or electromagnetic waves in the kilohertz band.

Optimistic current estimates of the gravitational radiation emitted from highly anisotropic gravitational collapses of solar mass objects suggest a maximum flux of about 2.5×10^3 ergs cm^{-2} (Thorne 1980) from an event at the galactic center. With optimum direction and polarization, this would cause an excitation with $T_e \sim 0.1$ K. The rate of such events is not predicted to exceed 0.1 per year.

Without coincidence operation with another detector of comparable sensitivity, it is not possible to draw positive conclusions from the data. The event distribution shown in Figure 2 does, however, constitute a

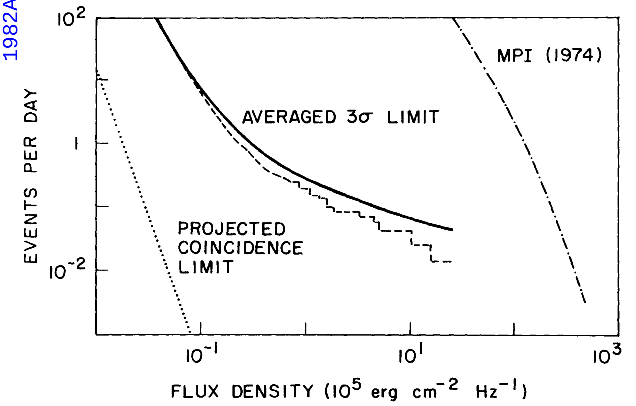

FIG. 3.—Logarithmic plot of upper limits on the rate and strength of gravitational wave pulses which were reaching the Earth during the observations. The solid line is the smoothed 3 σ limit averaged over polarization and direction determined from the observations which are shown as the dashed line. The dot-dashed curve is the upper limit determined by the Munich-Frascati coincidence experiment when their result is averaged over polarization and direction (Billing *et al.* 1975). The dotted line is the upper limit that could be achieved by a coincidence experiment involving two 4.8×10^6 g detectors with overall noise temperatures $T_n = 20$ mK.

measured upper limit on the distribution of gravitational wave pulses reaching the detector at the time of the experiments. Figure 3 shows a smoothed estimate at the 3 σ confidence level based on the observed event rate. Figure 3 also shows an upper limit previously estimated by Kafka and Schnupp (1978) based on the coincidence experiments of Billing *et al.* (1975).

The data have not yet been studied for coincidence with the outputs of other gravitational wave antennas or detectors of other forms of radiation. We have, however, estimated the accidental coincidence rate which we could expect if we could operate in coincidence with another detector of similar sensitivity. The dotted curve in Figure 3 shows that substantially improved sensitivity could be obtained.

VI. CONCLUSION

The data from about 74 days of operation have been used to place a new observational upper limit on the distribution of wide-band gravitational wave pulses which reach the Earth during a typical period.

The detector at Stanford is the product of a cooperation with Louisiana State University, the aim of which is the construction of detectors at both places. Coincidence operation of these two systems and of others of comparable sensitivity now under construction in several parts of the world will result in observations of greatly increased sensitivity.

We wish to thank W. O. Hamilton and his group at L. S. U. for their continuing contributions to the joint endeavor. In particular we acknowledge the work of P. B. Pipes and T. P. Bernat in the construction of the apparatus. We also thank J. R. Bond and R. V. Wagoner for their comments. This work has been supported by the National Science Foundation under grant PHY 80-14184.

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