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A Constraint on Astrophysical Sources of Gravity Waves

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A CONSTRAINT ON ASTROPHYSICAL SOURCES OF GRAVITY WAVES

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ABSTRACT

A refined search has been conducted for pulses of microwave emission arriving at the times Weber reports pulses of gravitational radiation. Two radiometers 100 km apart tracked both the galactic center and the Crab Nebula. The low upper limit set on the microwave flux imposes an interesting constraint on possible models for the source of the events observed by Weber.

I. INTRODUCTION

For several years, Weber (1969, 1970*a*, *b*) has been gathering data which indicate the existence of gravitational radiation from a celestial source. The source appears to lie in the general direction of the galactic center. However, Weber's cylindrical detectors have an angular resolution of 70° and an axially symmetric antenna pattern, so that the source need not necessarily be precisely at the galactic center, although very recent arguments due to Misner (1971) indicate that this may in fact be true.

Weber's events are short pulses, of duration 20 s or less. He is currently detecting about two events per day; the detectable events, however, may represent only a fraction of the actual number of events (Weber 1970*b*). The characteristic energy flux required for a detectable event is

$$E_g \approx 3 \times 10^5 \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$$

at his operating frequency of 1660 Hz.

In the past two years, a number of attempts have been made to detect other kinds of emission which might accompany bursts of gravitational radiation. Charman *et al.* (1970, 1971) and one of us (Partridge 1971) have searched for electromagnetic emission; Bahcall and Davis (1971) and Reines *et al.* (1971) have looked for neutrinos. In each case, limits on the energy flux may be set which are lower than the energy flux of gravity waves, E_g.

In this Letter, we report the results of a more refined search for microwave pulses associated with gravitational-wave events. Two microwave radiometers, spaced 100 km apart, were used in the search. One was located at Bell Telephone Laboratories, Crawford Hill, Holmdel, N.J., and the other at Haverford College, Haverford, Pa. Operating the two instruments in coincidence enabled us largely to eliminate local sources of interference which, especially at Haverford, produced frequent spurious signals. In addition, the large collecting area of the Bell Labs antenna resulted in a large increase in sensitivity over the earlier work of Partridge (1971).

Measurements were made at the two sites for approximately three months, from 1970 December to 1971 March. The results are discussed in § III below, and are then compared in § IV with the data obtained by Weber in the same time interval.

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II. APPARATUS

a) *Bell Laboratories*

Here the 20-foot (6 m) horn reflector antenna on Crawford Hill was used to make the observations at a frequency of 16 GHz. The antenna and its properties at lower frequencies have been described elsewhere (Crawford, Hogg, and Hunt 1961; Hogg and Wilson 1965). At 16 GHz the gain of the antenna was measured to be 57.6 dB, corresponding to an aperture efficiency of 44.4 percent (Wrixon, Gott, and Penzias 1971). From pattern measurements the half-power beamwidth was found to be about 12 minutes of arc. Out to angles of about 2° from the beam center, the antenna response was not less than 40 dB below the measured on-axis gain. The pointing accuracy of the antenna is better than 1 minute of arc.

A radiometer switched the input of a mixer between the antenna and a room-temperature termination. A balanced Schottky-barrier diode mixer with a broad-band input circuit was directly connected to transistor IF amplifiers. At the output of the receiver the signal was displayed on a chart recorder with a $0^{s}.5$ time constant. The IF bandwidth was about 200 MHz, and the double-sideband noise temperature of the receiver was 1200° K. The receiver was calibrated by using matched waveguide terminations at room and liquid-nitrogen temperatures, and the rms receiver noise was found to be 0.1° K, in good agreement with theory.

For the purposes of the experiment an "event" was taken to be a sudden increase of antenna temperature to more than 5 times the rms noise, that is, more than 0.5° K. From the calibration, this corresponds to a flux density of 9.6×10^{-22} ergs cm^{-2} s^{-1} Hz^{-1} at the beam center, or more than 9.6×10^{-18} ergs cm^{-2} s^{-1} Hz^{-1} from any point within 2° of the beam axis.

Timing of the events could be determined from the chart records to better than ± 1 min for data taken in December. For the later January and February data, the timing accuracy was improved to ± 10 s.

b) *Haverford College*

The apparatus and experimental techniques used at Haverford were the same as used for the preliminary study reported by Partridge (1971). The operating frequency was 19 GHz, and the full width of the beam at half-maximum was $\sim 12°$. For this series of observations, however, the integration time employed was longer. For the early runs in December an effective integration time of $0^{s}.45$ was employed: the corresponding rms noise level σ was 1.5° K antenna temperature. For the remainder, the integration time was set at 3 s, and σ was reduced to $\sim 0.5°$ K.

Unfortunately, in a semiurban environment, IF interference at 30 MHz was a severe problem. Despite all efforts to shield the instrument, interference was clearly present in about 20 percent of the data. The largest contributors were two ham radio operators a few blocks away, who operated intermittently. This IF interference produced spurious output signals of both signs. In principle, this made it possible to distinguish most of the interference signals from single pulses of microwave radiation falling on the main antenna. In fact, we simply rejected all data showing possible interference.

The remaining data, nominally interference-free, were examined for sudden increases of antenna temperature exceeding $3\frac{1}{2}$ times the rms noise. A lower threshold was used at Haverford because of the poorer sensitivity of the instrument. This threshold corresponds to about 5.3° K or $\sim 3 \times 10^{-17}$ ergs cm^{-2} s^{-1} Hz^{-1} for the early data taken with a $0^{s}.45$ integration time, and to 1.7° K or $\sim 10^{-17}$ ergs cm^{-2} s^{-1} Hz^{-1} with a 3-s integration time. The timing accuracy for all the Haverford data was ± 10 s.

Note that the frequencies of the radiometers were about the same. Thus differences in the arrival times at the two sites due to dispersion delay of the signals may be safely ignored, unless the column density of electrons in the direction of the galactic center is very large (see § IV below).

III. CORRELATION BETWEEN BELL LABORATORIES AND HAVERFORD DATA

Both radiometers were run on clear nights and on nights with light, uniform cloud cover. A total of 18 runs, each of about 5 hours duration, was obtained on the galactic center. We also made 17 somewhat shorter runs on the Crab Nebula, another conceivable source of gravitational radiation. In general, the Bell Labs runs were longer (with a tighter beam, the galactic center could be tracked to a lower elevation), and the Haverford runs more frequent (the Haverford instrument was easier to operate).

Since the Bell Labs instrument was far more sensitive, and since the Bell Labs data were freer of local interference, these data were regarded as primary. The times of arrival of all pulses exceeding the 5 σ threshold were determined, and then compared with the Haverford data. Analysis of the two sets of data was carried out independently. In examining the data for correlations, a coincidence time interval Δt was used which was equal to twice the sum of the estimated timing uncertainties at the two sites. That is, for the December data $\Delta t = 2$ min 20 sec, and for the later data $\Delta t = 40$ sec.

While both instruments were tracking the galactic center, 23 events exceeding 5 σ were recorded at Bell Labs. The events range in amplitude from 47 σ down to the selected threshold of 5 σ. The distribution is very clearly non-Gaussian. Of these 23 events, only *one*, on December 18, at 13:52 EST, coincided within the interval Δt with an event recorded at Haverford.

Next, we ask whether one out of 23 events is statistically significant. The accidental rate is given by the usual expression

$$A = r_{\rm BL} r_{\rm H} t \Delta t \, , \qquad (1)$$

where $r_{\rm BL}$ is the rate at which events were recorded at Bell Labs, $r_{\rm H}$ is the corresponding rate at Haverford, Δt is the coincidence interval, and t is the total elapsed time of the joint runs. For simplicity, we set $t r_{\rm BL} = N_{\rm BL}$, the number of events actually observed at Bell Labs during our joint observations. For the data taken in December, $\Delta t = 2.33$ min, $r_{\rm H}$ was found to be 0.031 min^{-1}, and $N_{\rm BL}$ was 6. For the later data, $\Delta t = 0.67$ min, $r_{\rm H} = 0.0075$ min^{-1}, and $N_{\rm BL} = 17$. Combining these values, we find $A = \frac{1}{2}$. Although the statistics are not good, we conclude that the single observed coincidence is likely to be accidental.

Finally, for the runs on the Crab Nebula, 10 events were recorded at Bell Labs while both instruments were on, ranging in amplitude up to 52 σ. We assume that the event rate $r_{\rm BL}$ was somewhat lower for these runs because they were made at night, when there was less interference. None of these 10 events occurred within the coincidence time limits of a Haverford event. The calculated accidental rate was again about $\frac{1}{2}$.

IV. COMPARISON WITH GRAVITATIONAL-WAVE DATA

Professor Weber has very kindly supplied us with a list of arrival times for gravitational events recorded by him in the interval 1970 December–1971 February. During the time intervals in which our radiometers were running, he observed 21 events. If we adopt as before a coincidence time interval of 2 $(\Delta t_{\rm BL} + \Delta t_{\rm W})$, where $\Delta t_{\rm W}$ is Weber's timing uncertainty of ± 10 s, we find that none of his events coincide with a significant event recorded at Bell Labs. A direct inspection of the analog chart records allows a limit of

$$E_{\rm em} \lesssim 10^{-21} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$$

to be placed on the microwave flux at the times Weber's events arrived. That is, $E_{\rm em}/E_g \lesssim 3 \times 10^{-27}$. Note that this ratio does *not* take into account the unknown bandwidths, spectra, or pulse widths of either the gravitational radiation or any possible microwave emission[1] (Partridge 1971).

[1] Experiments at a different frequency with greater sensitivity and shorter time constants are now in progress.

This result is consistent with earlier work: very little pulsed radio-wavelength energy accompanies the pulses observed by Weber, *if* the source is located in or near either the galactic center or the Crab Nebula. We feel that our results set a strong and interesting constraint on possible theories for the origin of Weber's events.

Finally, we wish to consider the possibility that the electromagnetic pulses are so delayed by passage through ionized interstellar gas that the coincidence with the gravitational pulses is lost. We have used a computer to search for delays of up to 2 hours between microwave and gravitational events,[2] using both the present data and the earlier data of Partridge (1971). No statistically significant results emerged: the number of coincidences between our data and Weber's remained approximately equal to the expected number of accidentals.

At the lower frequency employed in the experiment, 16 GHz, a dispersion delay of 2 hours in the electromagnetic signal would require a column density of electrons, $\int n_e dl$, of 1.4×10^{27} cm^{-2}. This figure may be compared with a recent estimate of the hydrogen column density to the galactic center obtained from X-ray observations: $\int n_{\rm H} dl = 6.3 \times 10^{22}$ cm^{-2} (Kellogg *et al.* 1971).

We wish to thank the Gravity Research Group of Princeton University for the loan of some equipment, Dr. Charles Misner for permission to cite unpublished research, and Dr. R. W. Wilson for assistance. Keeping both radiometers running both night and day would have been impossible without the consistent help of A. W. Norris at Crawford Hill and Blair Hines ('74) at Haverford.

Without the data provided by Professor Joseph Weber, this experiment would have lost much of its meaning; we are extremely grateful to him for providing us with a list of his arrival times.

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[2] In both senses: $-2^{\rm h} \leq t_g - t_{\rm em} \leq +2^{\rm h}$.