GRAVITATIONAL WAVES AND A SEARCH FOR ASSOCIATED MICROWAVE ELECTROMAGNETIC RADIATION

Submitted for an Award for Essays on Gravitation, April 1970, by

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SUMMARY

We discuss astronomical sources which might produce the pulses of gravitational waves reported by Weber(3). A fraction of the energy emitted by such sources may emerge as electromagnetic radiation. We are now searching for electromagnetic pulses associated with the reported gravitational events. We observe the galactic center at a favorable microwave frequency, 19 GHz. The directional sensitivity of Weber's detector (given below) is a maximum during our observing period, allowing a direct comparison between our data and his. If positive correlations are found, the propagation velocity of gravitational waves can be determined to one part in 10^{11} relative to c.

In the very first days of General Relativity, Einstein$^{(1)}$ showed that the geometry of space time can undulate and carry energy by gravitational waves.

In 1922 A. S. Eddington$^{(2)}$ raised questions about both the existence and propagation of such waves ("merely sinuosity in the coordinate system propagating with the speed of thought"!). Happily in the intervening years much more has been learned in this field and today no one would seriously doubt the existence of gravitational radiation.

J. Weber$^{(3)}$ in the late 1950's was the first to launch a realistic effort to detect gravitational waves. He considered a large class of possible detectors varying enormously in size and resonant frequency. Particularly promising possibilities were observations of the quadrupole vibration of the earth (with a period of 54 minutes), of the moon (period of 15 minutes), and of a five-foot aluminum cylinder (with a resonant frequency of 1660 Hz). Some advantages of the last mentioned detector are:

i) It is a convenient size, which facilitates isolation from external noise.

ii) Coincidences between identical but widely separated detectors (three at College Park, Maryland, and one at Argonne) may be studied.

iii) The angular distribution of sources may be found since the directional sensitivity of the detector is known. For a cylinder aligned east-west and exposed to a randomly polarized source located at hour angle H and declination δ, the response function is

$$E = E_o[(\cos^2 H - \sin^2\delta \sin^2 H)^2 + (\sin\delta \sin 2 H)^2] \quad (1)$$

where E_o is the maximum response (see Fig. 1).

Weber has recently reported significant coincidences between his detectors. Moreover, a directional effect in the distribution of the sources, with a maximum in the direction of the center of the galaxy seems to be present (5). The energy involved in each event has been estimated to be of the order of 10^4 ergs/cm^2 sec at his detector(3). If the events originate at the galactic center, a power of $\sim 10^{50}$ ergs/sec is implied. We propose in the following some possible sources:

i) Pulsating neutron stars(6). The expected period lies between 0.1 and 1.0 milliseconds, the power emission is $10^{52} \langle (\delta R/R)^2 \rangle$ erg/sec. where $\langle (\delta R/R)^2 \rangle$ is the average square amplitude of the pulsational mode, and the length of the pulse is $\sim$ 1 sec.

ii) Rotating, non-axially symmetric neutron stars(7). For a frequency $\sim$ 1660 Hz, the total energy emission $\approx 10^{50}$ ergs, and the length of the pulse $\approx$ 10 sec. for a bandwidth of 0.01 Hz. We take the eccentricity of the neutron star to be $\sim 10^{-4}$.

iii) Non-rotating (Schwarzschild) black holes. If a particle of mass m falls into a black hole of mass M, it will emit a burst of gravitational waves(4) of frequency c^3/GM (to obtain 1660 Hz, $M \approx 120\, M_\odot$), of energy $\sim \alpha m^2 c^2/M$ with $\alpha = 0.057$, and of length $\sim GM/c^3$ sec.

iv) Rotating (Kerr) black holes. Approximately the same as case (iii), but with $\alpha = 0.42$!

Clearly, a measurement of the length of the pulses could help in discriminating between these different possibilities.

We would like now to emphasize a different point, one which may be of paramount importance. If indeed such enormous releases of gravitational radiation take place, it is highly likely that electromagnetic radiation will also be emitted. For instance, the accretion of matter by a collapsed object, and very likely the process of gravitational collapse itself, will produce a broad spectrum of electromagnetic radiation(4).

The directional effect observed by Weber suggests that a search for electromagnetic pulses would be most likely to succeed in the direction of the galactic center. To find coincidences between gravitational and electromagnetic events, it is also desirable to work at approximately the same longitude as Maryland (or 180° away), so that the observations are made when Weber's apparatus is maximally responsive (see equation 1 or Figure 1).

The microwave region of the spectrum has several advantages for a ground-based experiment. For wavelengths greater than one centimeter, absorption and scattering by the earth's atmosphere are negligible. At centimeter wavelengths the galaxy is virtually transparent, and its non-thermal emission is lower than at longer wavelengths. The most important advantage of working at relatively high radio frequencies is, however, that the time delay caused by dispersion by interstellar plasma is small, since it varies as ν^{-2}. For frequencies above 10 GHz, this time delay is of the order of milliseconds. Thus the time delay between the arrival of a pulse of gravitational radiation (for which the dispersion is negligible) and the arrival of any associated electromagnetic radiation is small. However, this estimate should be treated with some reserve, for it may be that the free electron density at the galactic center is radically different from its average value in the galactic plane. This uncertainty re-inforces the desirability of working at new ¶

high frequencies.

Since late March, we have been observing the region of the galactic center with a microwave radiometer operated at 19 GHz (see Figures 2 and 3). Since it is not certain exactly where Weber's events originate, we chose an instrument of low angular resolution: the half-power beamwidth is about 10°. With a simple mounting we can track the galactic center to within 1° over a time span of five hours. It is important to note that Princeton's location, at about the same longitude as College Park, Maryland, ensures that our measurements are made at a time when Weber's instrument is maximally sensitive to gravitational waves from the galactic center.

Now let us estimate the sensitivity of the instrument. The minimum detectable flux density for a Dicke-switched radiometer is(8)

$$S_m = \frac{2\,k}{A_e}\,\frac{2\sqrt{2}\,T_s}{\sqrt{\Delta\nu\,t}} \qquad (2)$$

where k is Boltzmann's constant and t is the integration time. Other parameters for our instrument are:(9) A_e, the effective aperture, 80 cm^2; T_s, the system noise temperature, $\sim$ $2000^{\circ}K$; and $\Delta\nu$, the predetection bandwidth, 10^7 Hz. With t = 1 sec., $S_m = 6.2 \times 10^{-18}$ erg/cm^2 sec Hz. A comparison with the minimum detectable flux for Weber's detector, $\sim 10^4$ erg/cm^2 for a single pulse, shows how much easier the detection of electromagnetic radiation is.

If we now assume that the electromagnetic pulses originate at the center of the galaxy, we can estimate the energy per unit frequency interval that an event must have to be detected:

$$E_m = 2(4\pi R^2)S_m$$

where R is the distance to the center and the factor 2 appears because our instrument is sensitive to one polarization only. $E_m \approx 10^{29}$ erg/Hz for a one second pulse.

The fraction of the total energy falling in a one Hertz band at 19 GHz is determined by the spectrum of the emitted radiation, which we have no way of predicting. If we assume it is flat from some low frequency to a cut-off frequency ν_c, and that the total electromagnetic power equals the gravitational power of 10^{50} ergs, then the energy emitted per Hertz is greater than E_m for $\nu_c < 10^{21}$ Hz. Suppose the radiation is emitted by the synchrotron mechanism. Then as long as the cut-off frequency lies above 19 GHz, and the spectral index is negative, the energy per Hertz exceeds E_m.

At present the observed instrumental sensitivity in clear weather, and for $t = 1\frac{1}{2}$ seconds, is 1.5° to 2.0°K antenna temperature, corresponding to a flux density of 5 to 7×10^{-18} ergs/cm^2 Hz. We search for pulses of microwave radiation which exceed three times this value and record the times at which they occur. Timing measurements are now accurate to ± 10 seconds; this value will soon be improved to ± 1 second.

In the near future, when we have acquired sufficient data, we intend to compare our results with those of Weber for the same period. If significant correlations are found, our observations should help to strengthen Weber's argument that his events are pulses of gravitational radiation originating at the center of our galaxy. Additional information about the nature of the violent events which produce the gravitational waves could emerge from a study of the associated electromagnetic emission. Moreover, the observation of coincidences between gravitational and electromagnetic pulses would allow us to determine the ratio of the velocity of gravitational waves to the velocity of light to one part in 10^{11}, assuming a coincidence gate of ten seconds.

For their kind help and suggestions, we thank John A. Wheeler, Joseph Weber, and Martin Rees.

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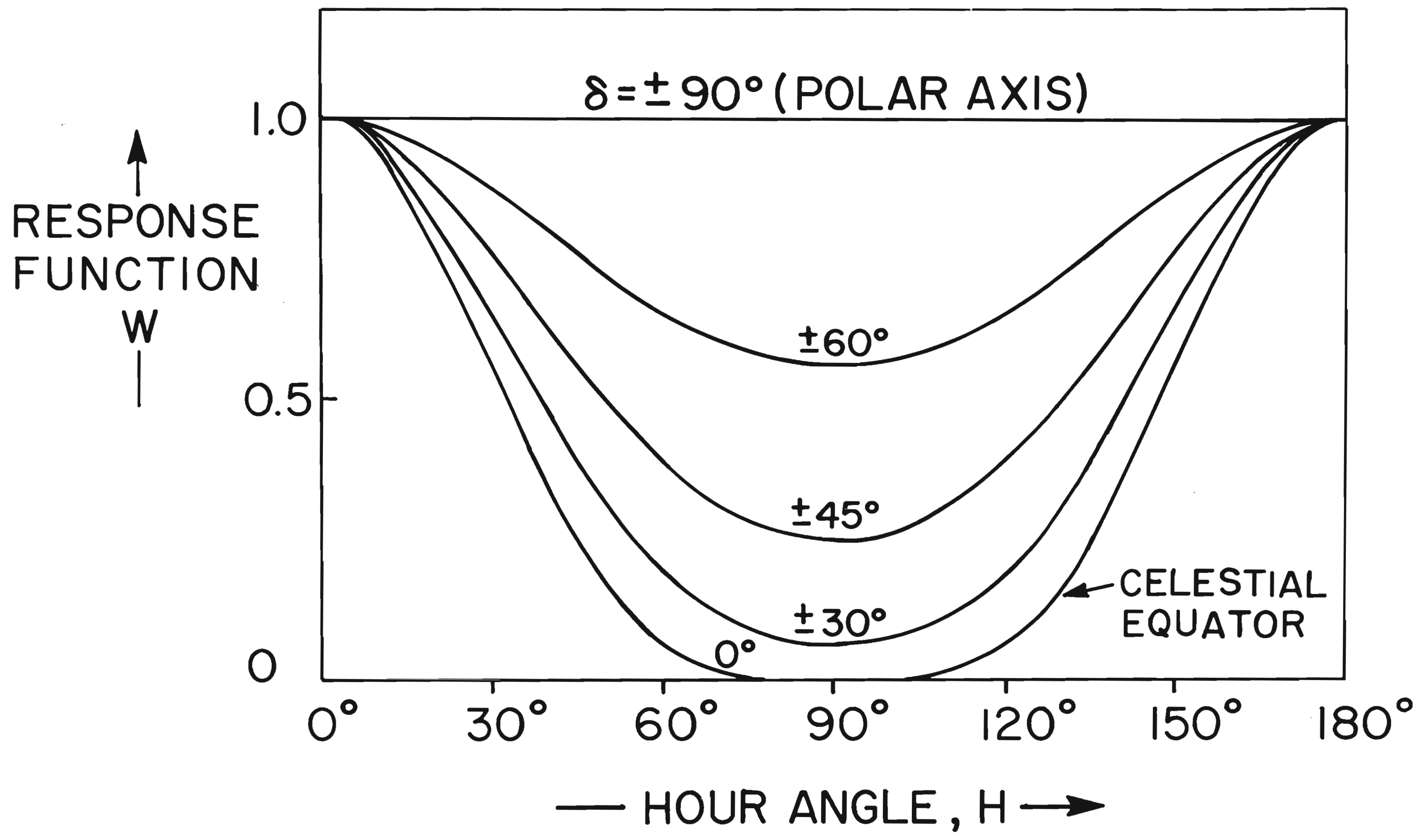
FIGURE CAPTIONS

Figure 1. A plot of the expected theoretical response of Weber's detector for randomly polarized sources (see equation 1).

Figure 2. A block diagram of the apparatus. The main horn is directed at the galactic center. The reference horn scans a random area of the sky near the zenith. Some elements, such as an isolator and a frequency meter, have been omitted.

Figure 3. The instrument *in situ* on the roof of Jadwin Hall.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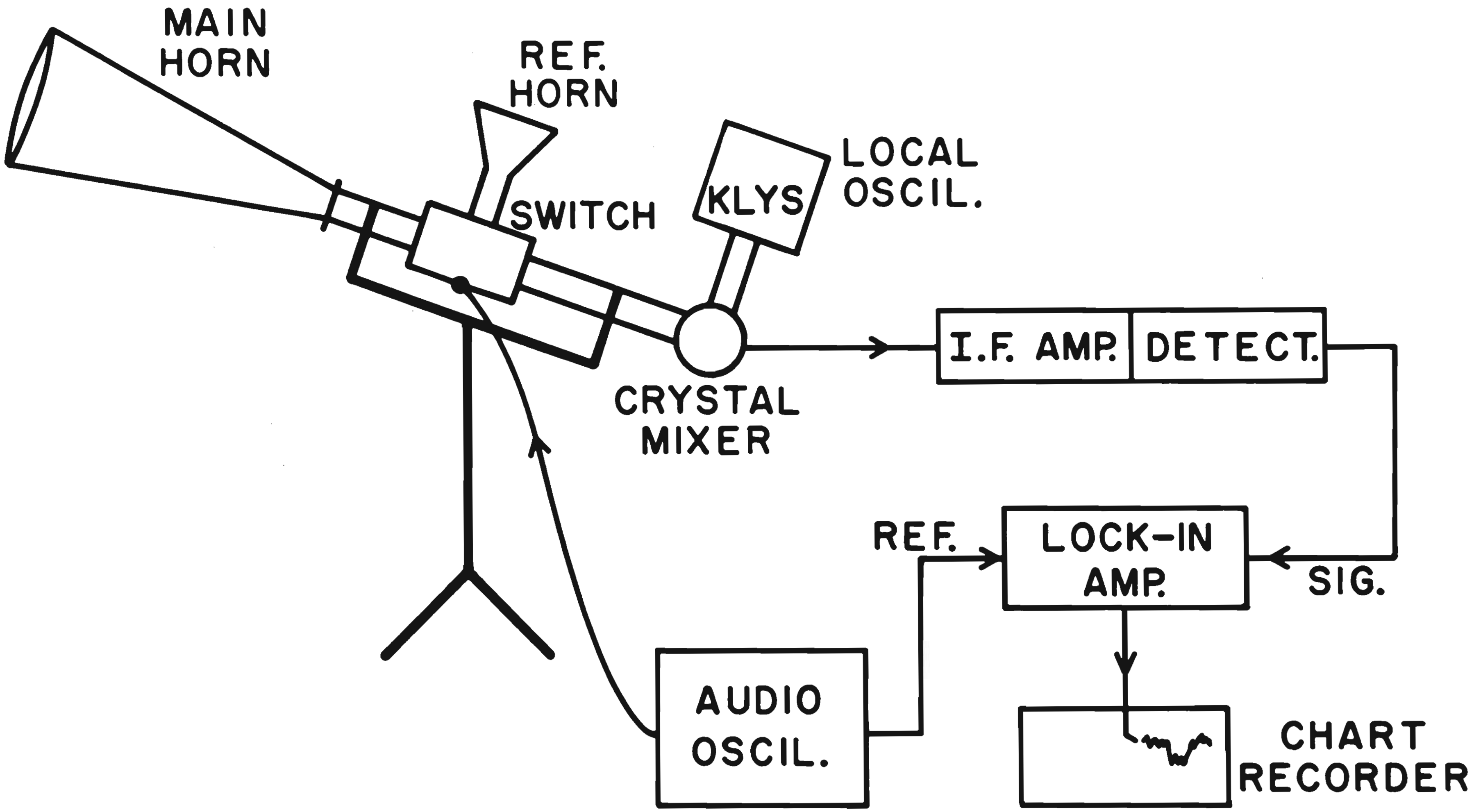
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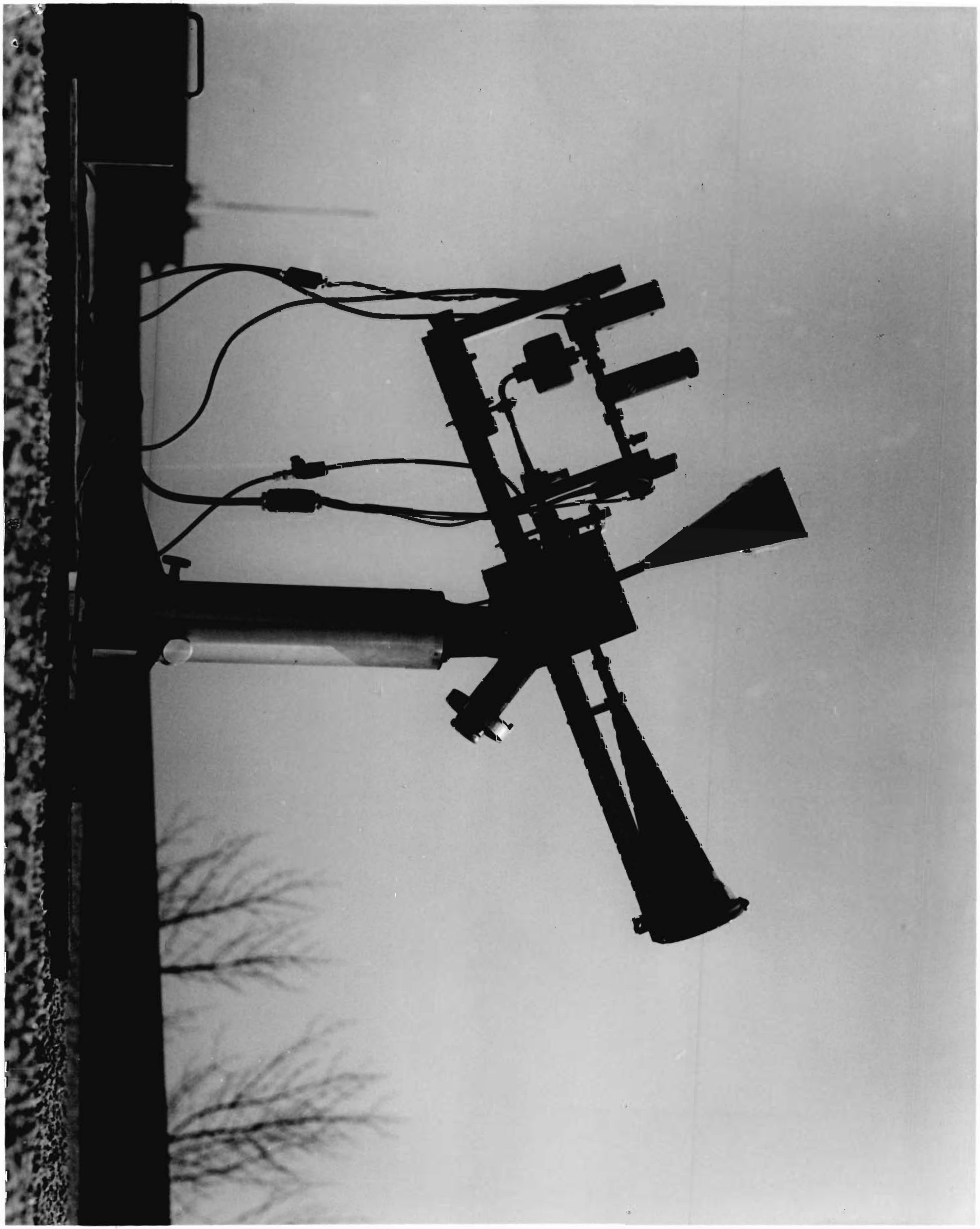

BIOGRAPHICAL SKETCH OF R. B. PARTRIDGE

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Remo Ruffini was born in La Brigue (in Italy until 1945, now in France) in 1942. He attended Rome University where he obtained his doctorate degree in 1966. Since 1968 he has been a member of the Institute for Advanced Study of Princeton, N. J. and Assistant Professor (on leave of absence) at the University of Rome. His research in the last four years ha~~ve~~s been in the theory of gravitation and General Relativity with particular interest in gravitational collapse, equations of state at supranuclear density and gravitational radiation. He is a member of Professor John A. Wheeler's "Gravity Group".