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ASTRONOMY AND ASTROPHYSICS

Final Result of the Munich-Frascati Gravitational Radiation Experiment

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Summary. Within 580 days of usable common observation time between July 1973 and February 1976, this Weber-type coincidence experiment had set the lowest upper limits to the rates of gravitational wave pulses. We report the total result up to the dismantling of the detectors. We also describe a re-evaluation of our data using Weber's preferred algorithm for two months in 1974 during which Weber communicated to have found a particularly significant effect in his own experiment. Finally, we confront the negative results with the far aims of gravitational pulse astronomy.

Key words: gravitational wave astronomy — supernova rates

Introduction

In 1971, groups at the Max Planck Institute for Physics and Astrophysics in Munich and at the ESRIN Institute in Frascati near Rome had started independently a repetition of Weber's gravitational wave experiment (Weber, 1969–1974, Weber et al., 1973). Very soon, first results (Kafka, 1972, 1973) were in conflict with Weber's. Later the Frascati group was incorporated into the Munich institute and a long-term coincidence experiment was run. Between July 1973 and January 1975 we collected common data for 350 days. Then the Frascati detector was moved to Garching (10 km from the Munich site) and common data were collected for another 230 days. In March 1976 the detectors were dismantled and the experiment stopped.

The aim had been to verify or to exclude the existence of gravitational wave pulses of the kind proposed by Weber as an explanation for his own results. Although the non-existence became obvious a long time ago, it still seems appropriate to publish our final negative result, because our experiment was as similar to Weber's as possible, whereas all other coincidence experiments deviated in one way or the other (Braginsky et al., 1974; Douglass et al., 1975; Drever et al., 1973; Hough et al., 1975; Levine and Garwin, 1974; Hirakawa and Narihara, 1975). Moreover, we think we have set the lowest upper limits obtained by Weber-type experiments over a reasonably long period of observation.

The Frascati detector has been described by Bramanti and Maischberger (1972), Bramanti et al. (1973) and Maischberger (1973), the Munich detector by Billing and Winkler (1976), the principles of data evaluation (as developed by Meyer and Kafka) in Kafka (1973). Results of the first 150 days were given in Billing et al. (1975) and discussed in some detail in Kafka (1974). A very detailed description of the theory and practice of signal detection and many other aspects of Weber-type experiments, as well as the results of 350 days (up to the moving of the Frascati detector) were presented in Kafka (1975).

Here it remains to report the total result, including the last year, and to describe some tests with data from two periods in 1974 for which Weber had communicated a significant positive result (Lee et al., 1976, Weber, 1977).

Finally, we will state the upper limits achieved within our 580 days of total useful observation time and compare them with future aims of gravitational pulse astronomy.

The Raw Data

At both stations a Weber-type aluminium cylinder was observed in its fundamental oscillatory mode, which has a damping time of the order of a minute. We were searching for relatively faster changes in the state. The state vector in the "co-rotating phase plane" of the oscillator was tape-recorded at time intervals of 0.1 s after smoothing over this interval. Instead of amplitude and phase, two Cartesian coordinates x and y were used. To avoid expenditure, the relative phase between the stations was not observed. The reference oscillators defining the co-rotating frames were controlled to an

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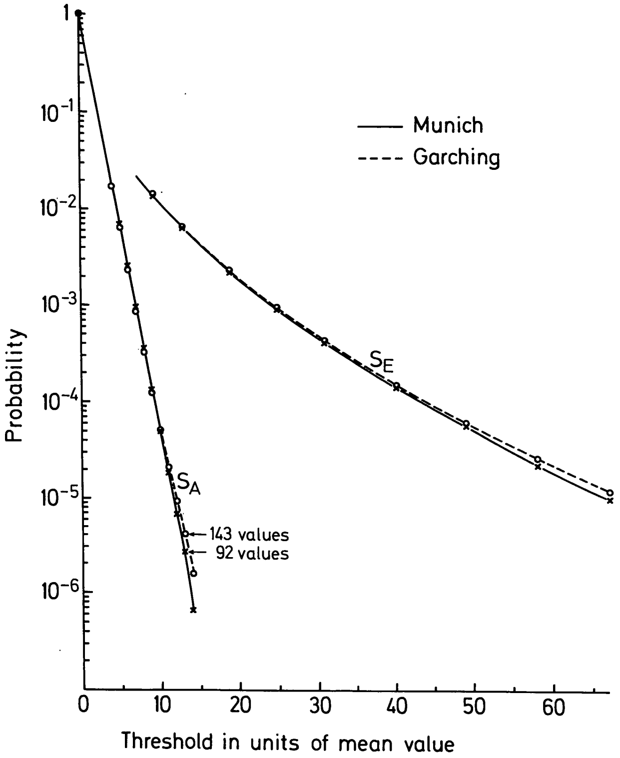

Fig. 1. Single-detector noise during a period of 42 days in 1975. For Munich (×) and Garching (0) the probability (=relative frequency) is shown to find the signal functions S_A and S_E above certain thresholds. Apart from rare non-thermal disturbances in Garching, the thermal character is confirmed (exponential law=straight line for S_A)

accuracy which allowed phase drifts only over many minutes (Billing and Winkler, 1976). It would have been far more difficult and unreliable to achieve a comparable stability by temperature control. Therefore, Weber's (1975) critical remarks about a "lack of significant temperature control in Munich" were totally irrelevant.

The (x, y)-data were digitalized with 8 bits per value and written in blocks of one minute, each block starting with the value of Central European Time. There was no interaction between the two stations, except at rare occasions by telephone, when artificial excitation was used simultaneously for gauging purposes and checks of the clock system. The Frascati/Garching tapes were sent to Munich where all the tapes are still being stored.

The Filtering Algorithms

Weber had reported (at least up to 1974) that his cylinders showed simultaneous excitations with a coincidence width of the order of a few tenths of a second or less. Therefore, we optimized the evaluation for short pulses of gravitational radiation. Given the statistics of the pure noise output of the detectors, the optimal filtering procedure can be derived for any assumed kind of signal (Kafka, 1975). Applying this numerical filtering to the output data one constructs a function of time (we called it a "signal function"), in which real signals of the assumed kind would be most significantly detectable. With our detectors, and for pulses shorter than a few tenths of a second, an excellent approximation of the optimal signal function, to be constructed from our raw data $x(t)$ and $y(t)$, turned out to be

$$S_A \equiv (x^+ - x^-)^2 + (y^+ - y^-)^2 \quad (1)$$

where all symbols refer to a moment t and, with $n>0$:

$$x^\pm(t) \equiv \mu\Delta t \sum_n x(t \pm n\cdot\Delta t)e^{-n\mu\Delta t}$$

$$y^\pm(t) \equiv \mu\Delta t \sum_n y(t \pm n\cdot\Delta t)e^{-n\mu\Delta t}$$

with $\Delta t = 0.1$ s = interval between our data points. This procedure means: measure the jump in the (x, y)-plane between the averaged future and past neighbourhoods of each point x, y. The time constant μ in this averaging was calculated from the known properties of the thermal noise. For the Munich and Frascati detectors it was $1/\mu \approx 0.3$ s and 0.1 s respectively.

Weber had used a different evaluation scheme. In our experiment this could be simulated by constructing another signal function S_E from the (x, y)-data, namely

$$S_E \equiv (E^+ - E^-)^2 \quad (2)$$

with

$$E^\pm = \mu\Delta t \sum_n E(t \pm n\Delta t)e^{-n\mu\Delta t}$$

This corresponds to observing the squared jump in the "energy" $E \equiv x^2 + y^2$. Of course, contrary to (1), the use of μ in (2) is not justified by any theory of optimization, since (2) is always far from optimal. The statistical behaviour of the two signal functions S_A and S_E is shown in Figure 1 where, for an arbitrary section of time (≈ 42 days), it was counted how often the values of the signal functions were above certain thresholds, measured in units of the mean values during this period.

For purely thermal noise the probability to find the signal function (normalized with its long-term mean value) above a value S_A at an arbitrary instant of time, will be given by

$$W(>S_A) = e^{-S_A}, \quad (3)$$

whereas for S_E it is mathematically less simple. In many different ways it had been established (Billing et al., 1975, Billing and Winkler, 1976, Kafka, 1974, 1975) that the noise of the detectors was due to the known thermal sources (cylinder, transducers and amplifier), except for rare disturbances occuring mainly in the Frascati detector, which was situated in busy laboratories, especially after its transport to Garching. This is also obvious from Figure 1.

The signal function S_A guaranteed nearly optimal detectability for all events lasting less than a few tenths of a second. Even for "almost all" other kinds of signals

Table 1. Total counts of coincidences at two typical pairs of thresholds $(S_1;S_2)$. N_0 is the observed number of coincidences at zero time delay. $\bar{N}$ and ΔN are the observed mean and r.m.s. values for the 23 counts at time delays $\tau \geqq 1$ s and $\tau=0$. n_τ is the average number of data points above threshold in a coincidence peak (i.e. the peak width). $\langle N \rangle$ and $\langle \Delta N \rangle$ are the theoretical expectation values of $\bar{N}$ and ΔN.

$S_1;S_2$	N_0	$\bar{N} \pm \Delta N$	n_τ	$\langle N \rangle \pm \langle \Delta N \rangle$
5; 4	60900	60928 ± 273	1.2	60714 ± 270
11; 8	2	2.7 ± 1.6	1	2.8 ± 1.7

it would have been superior to the S_E-algorithm. Therefore, the latter was only applied to the data of a few periods, e.g. those for which Weber has reported particularly conspicuous results with his preferred algorithm. Our and Weber's algorithms were compared in Kafka (1975). (See also Pizzella, 1976, who, however, does not seem to have been aware how easily a beat between the oscillating cylinder and the reference oscillator could be avoided by control of the latter. Thus, he remarked unjustly that Weber's algorithm would be superior.)

The sensitivity of our detectors for short pulses can be characterized by the pulse strength (i.e. the spectral density in "Gravitational Pulse Units", 1 GPU$=10^5$ erg/(cm^2 Hz)) which corresponds to the long-term mean value of the signal function S_A in the thermal noise. In Munich this was 5 GPU for a pulse duration below about half a second, in Frascati/Garching 6 GPU below about 0.2 s. (We refer to pulses of optimal direction and polarization.) Details can be found in Kafka (1975). For a homogeneous evaluation it was very helpful that the sensitivities remained constant within a few percent during the whole observation time.

Counts of Coincidences

Like Weber, we had searched for "coincidences", i.e. simultaneously high values of the signal functions of both detectors. Between July 1973 and February 1976 we had collected 580.4 days of common data which were not spoilt by breakdowns or significant local disturbances. For these data the signal-functions S_A were computed, and recorded (at least if the values were above certain thresholds), after normalization with long-term mean values. Then the two tapes were compared by the computer at the same instant of time as well as at 20 relative time shifts up to ± 1 s in steps of 0.1 s, and at 20 more time shifts up to ± 300 s in steps of 30 s. Coincidences (or delayed coincidences respectively) were registered at many different pairs of thresholds $(S_1;S_2)$, the lowest being $S_1=5$ in Munich and $S_2=4$ in Frascati (to take care of the somewhat different sensitivities). Since the noises are independent, one predicts from Equation (3) the probability exp-(S_1+S_2) for events above a threshold pair $(S_1;S_2)$. Multiplied

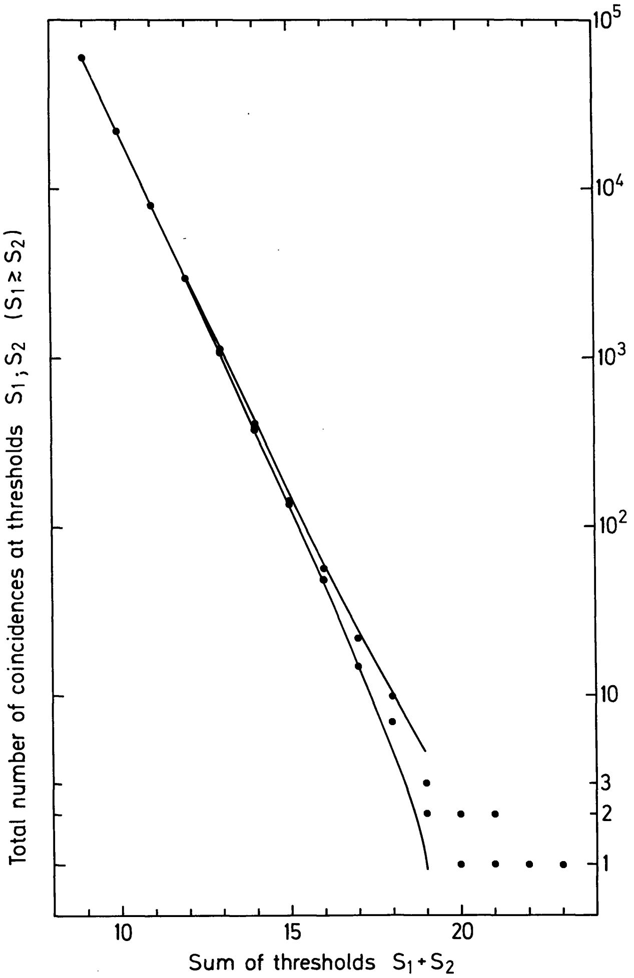

Fig. 2. Total counts of coincidences within the 580.4 days of usable data, using the signal functions S_A (optimal for short pulses). Thresholds S_1 and S_2 are for Munich and Frascati/Garching respectively. At each value of the sum S_1+S_2 the counts are plotted for the two pairs of integer thresholds nearest $S_1=S_2$, but with $S_1>S_2$ (because of the higher sensitivity in Munich). The prediction for thermal noise is the straight line $N\sim$exp-(S_1+S_2). The lines drawn are $N \pm \sqrt{N}$

with the total number of data points in 580.4 days, this gives the expected number $\langle N \rangle$ of coincidences. The expected fluctuation is $\sqrt{\langle N \rangle}$ at pairs of high thresholds where the average duration of a coincidence is just one data point. At lower thresholds the expected fluctuation is larger by a factor $\sqrt{n_\tau}$, n_τ being the average number of data points per "coincidence-peak". (The peaks are the independent events in the signal function S_A.) But even at our lowest pair (5; 4) we had only $n_\tau \approx 1.2$ which meant only 10% increase over $\sqrt{\langle N \rangle}$ in the expected fluctuation. The lines in Figure 2 represent the values $\langle N \rangle \pm \sqrt{\langle N \rangle}$ as functions of S_1+S_2. The figure also shows the observed counts at zero time-delay, for each value of S_1+S_2 at two pairs of thresholds with $S_1 \approx S_2$ but $S_1<S_2$. We see that the total count agrees excellently with the prediction from the statistics of thermal noise.

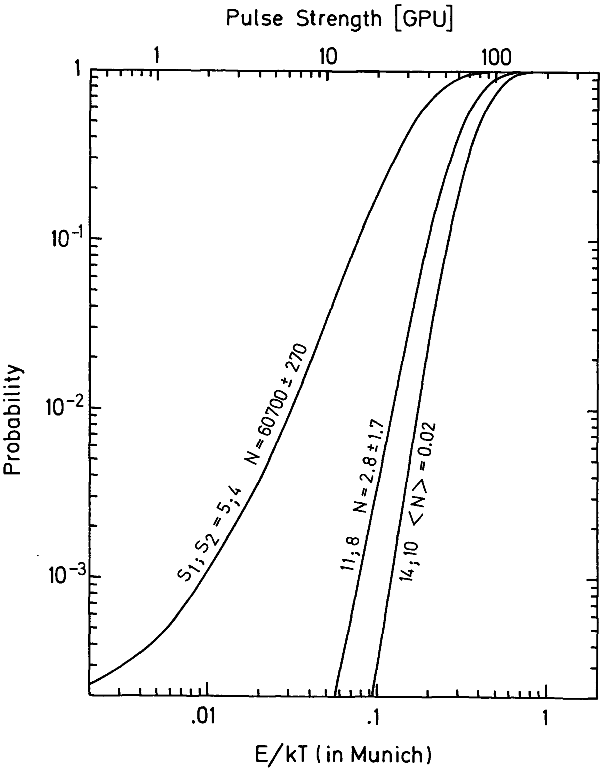

Fig. 3. Detection Probability in Coincidence at 3 pairs of thresholds $S_1; S_2$ (for our optimized algorithm S_A) as a function of pulse strength. (1 GPU $= 10^5$ erg/cm^2 · Hz. The lower scale is in terms of the energy to which the pulse would excite the Munich cylinder from rest, measured in units of the mean thermal energy kT.) Also shown are the observed average N of coincidences in 580.4 days and its fluctuation over 23 independent time delays. (At $S_1; S_2 = 14; 10$ no coincidence was observed and the expectation value was only $\langle N \rangle \approx 0.02$.) Dividing the statistical fluctuations by the detection probability one obtains upper limits to the detectable pulse rate as a function of pulse strength (cf. Table 2).

At the 40 time delays different from zero, and at other pairs of thresholds, the result was similar: Deviations of the total number of coincidences from the expectation value were nowhere significant.

The most important result is, of course, that we did not find any significant excess at zero time delay. At no thresholds did the total number of coincidences at zero delay deviate significantly from the average over the 22 counts with delays $\geqq 1$ s. Instead of drawing many insignificant histograms, we present two examples of this negative result in Table 1.

Our strongest "event", i.e. the highest coincidence near zero time delay, just crossed the thresholds (13; 10) and should occur once in about 20 comparable experiments. In fact, a similar one appeared at a time delay of 3 min. In spite of the negligible significance of our strongest event, let us state its arrival time: 1975, November 25th, 18 h 49 min 25.0 s Central European Time. Had it been caused by a pulse of gravitational radiation (with most favourable direction and polarization), its strength would have been about 60 GPU $= 6\ 10^6$ erg/(cm^2 Hz).

Table 2. Upper limits to the average annual rate of gravitational pulses of various strengths. The values of the rates are rounded and would have produced significances between 2 and 3σ within our 580 days of observation. If one prefers confidence limits $> 99.9\%$ for the exclusion of such pulses one should increase the numbers given for the rates by about a factor 2

Pulse strength [GPU]	Rate [year^{-1}]
$\geqq$ 1	$< 10^6$
$\geqq$ 10	$< 10^4$
$\geqq$ 20	$< 10^3$
$\geqq$ 50	< 10
$\geqq$100	< 0.63

In order to increase the significance of the search for highly variable pulse rates, we also studied the fluctuations of coincidence rates. They could be understood as mainly due to statistical uncertainties in the determination of long-term mean values and the corresponding normalization of the signal function. On time-scales between days and months, the fluctuations did not reveal any special feature at zero time delay as compared with the 40 different time delays. Scanning our whole data, we could, of course, find periods of a few days, for which at some pair of thresholds the number of coincidences was up to more than 3 standard deviations higher than the average over the various time delays. However, the same was true for arbitrary delays, and zero delay did not seem to be distinguished in any obvious way. However, one should not forget: If one searches long enough in our finite sample of data, one must find some complicated property which distinguishes zero delay significantly from the others. (Again this is true for an arbitrary delay, but with a different property.)

Counts with respect to position in the sky (sidereal time) were not done, since Weber had stopped claiming significance for the galactic center. Anyway, the upper limits to the pulse rates of a point source would only have been roughly a factor two lower than for a distribution over the whole sky.

Treatment of Disturbed Data

In both stations there occurred technical breakdowns, mainly of the recording system, which usually led to a loss of data for at least several days. In addition, there were occasional local disturbances found in the data, sometimes due to highly non-thermal excitation of one of the cylinders (recognisable from the slow decay of the energy), but mostly from electromagnetic influences on the amplifying system without previous or subsequent mechanical excitation. Although such events could spoil the statistics of a single detector (see Fig. 1), they were in general too rare to influence the coincidence statistics. Therefore, data containing isolated and not too extreme disturbances were kept in the common evaluation even if a non-gravitational origin was clearly obvious. Sometimes, however, the Frascati detector (especially in Garching) produced "electric spikes" quite frequently during a period of up to several hours. Such data would already have influenced the coincidence-statistics at low thresholds. Because of the local character of the disturbances we excluded such periods from the overall evaluation. To counter the suspicion that thereby we just might have left out "the real signals" (of a mysterious kind), we did a separate analysis for these data. Of course, the result did not show thermal statistics in this case, but again no distinction of small over large time-delay was detectable.

Resulting Limits to Rate and Strength of Arriving Pulses

From the theory of the signal function S_A, which was fully confirmed by experiments with series of artificial pulses (Kafka 1974, 1975; Billing et al. 1975), one knows the probability distribution of S_A in the presence of a pulse of given strength for each detector. This allows to calculate "optimal pairs of thresholds", at which gravitational pulses of given strength would be most significantly detected in coincidence. Hence, the negative result of our counts sets upper limits to the number of pulses stronger than a given value which might have arrived during our observation time. Details concerning detectability were discussed in Kafka (1975), but the essential information can be extracted from Figure 3, where the detection probability above three pairs of thresholds is shown as a function of pulse strength. Our lowest pair $(S_1; S_2) = (5; 4)$ is not far from optimal for pulses weaker than 10 GPU. For stronger pulses, the optimal pair almost "jumps" to values so high that "accidentals" occur very rarely. Since the peaks in the signal functions are already quite narrow above (5;4), the influence of peak-width is negligible, and the upper limit to the detectable rate at a given pulse strength is roughly given by some multiple of the standard deviation of the rate of accidentals, divided by the detection probability, both at the optimal pair of thresholds. In this way one can construct from Figure 3 the upper limits to the rate per year shown in Table 2.

Comparison with Some of Weber's Results

For a few periods, Weber's group (Lee et al., 1976) had reported particularly significant coincidence counts in their own experiment. Of these, only for the two periods from May 21 to June 25 and from August 3 to October 17, 1974 we had overlapping data from both stations. Within the first period we had 25.7 days between May 21 and June 15, within the second period 41.2 days between August 3 and October 17.

Table 3. Our results during two periods for which J. Weber's group had reported significant results. Evaluation with our (S_A) and Weber's (S_E) preferred algorithms. For several pairs of thresholds there are given: N_0 = number of coincidences at zero time delay, $\bar{N}$ = average over 22 delays $\geqq 1$ s, ΔN = observed r.m.s. fluctuation around $\bar{N}$.

25.7 days between May 21 and June 15, 1974:

S_A-coincidences			S_E-coincidences		
N_0	$\bar{N}$	ΔN	N_0	$\bar{N}$	ΔN
2650	2665	46	5011	4912	113
330	360	18	1383	1345	49
33	50	9	436	435	24
4	7	3	135	154	14
			53	60	8
			26	23	6

41.2 days between August 3 and October 17, 1974:

S_A-coincidences			S_E-coincidences		
N_0	$\bar{N}$	ΔN	N_0	$\bar{N}$	ΔN
4112	4239	80	6587	6667	142
559	583	21	459	477	28
84	79	7	55	57	8
14	11	3	5	9	3

After Weber had again stressed the reliability and significance of his results (Weber, 1977), we decided to re-evaluate our data for the two overlapping periods. We applied both the signal functions S_A and S_E. As stated above, the latter was a reasonable approximation to Weber's preferred algorithm, which (according to Lee et al., 1976) had led to highly significant time-delay histograms for the two periods, whereas an algorithm similar to our S_A was reported to have been rather unsuccessful. One of us had predicted (Kafka, 1974, 1975) that the S_E-algorithm could be superior to S_A only if the unknown signals excited the cylinders relatively slowly to high values of the energy: In this case no significant "jump in the phase-plane" would appear in S_A, but for about the damping time a high rate of noise peaks would be observed in S_E (because of its non-linearity). This would also increase the rate of coincidences above the mean, but the peak-width in the time-delay histogram would be of the order of the damping time, i.e. about half a minute in our experiment and perhaps a bit shorter in Weber's. Actually, this predicted feature became more and more obvious in Weber's results (Lee et al., 1976). (We proposed to study directly the correlation between the energies of the cylinders, because the S_E-algorithm does not seem to be its most specific indicator.)

Formerly, we had applied Weber's algorithm to a few periods during which there appeared a (spuriously significant) peak in one of our own histograms (for S_A) near zero time-delay. (Compare e.g. the results of two

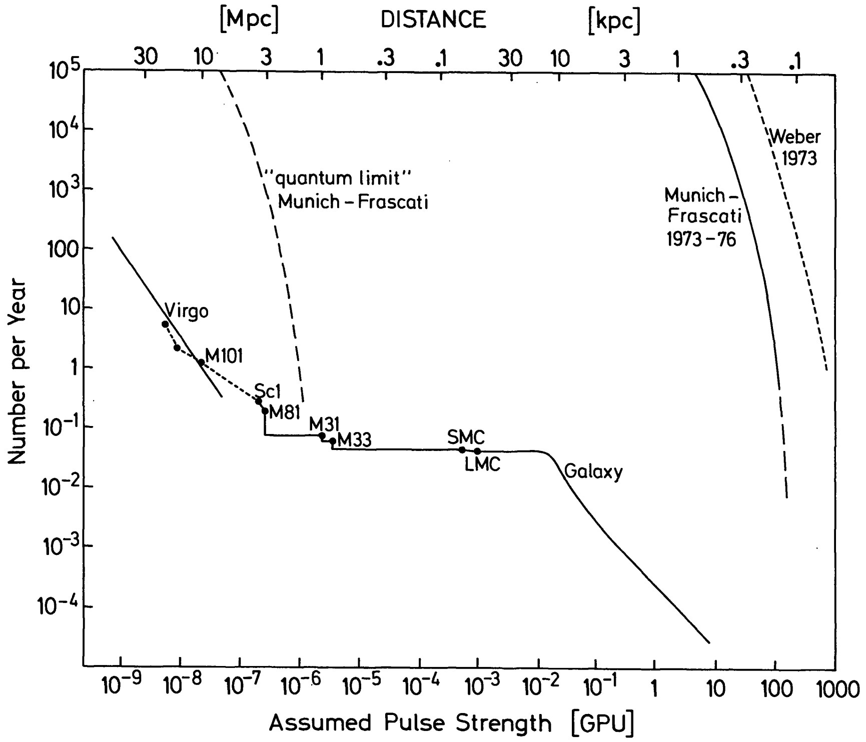

Fig. 4. Gravitational Pulse Astronomy: The state of the art and the aims. As a function of pulse strength (spectral density in GPU) our upper limits to the annual rates from Table 2 are drawn. The broken line, marked "Weber 1973", is from the estimate in Kafka (1975). If all noise could be suppressed to the level defined by the uncertainty principle, the upper limits would be shifted to 10^{-8} times weaker pulses (line marked "Quantum Limit"). Assuming a rather arbitrary standard pulse, containing 1% of a solar Mc^2 in a band-width of 1 kHz, one can draw the distance scale at the top. With respect to this, Talbot's (1976) estimate of supernova rates in the neighbouring galaxies has been drawn. Inside our galaxy, the curve has been constructed from the mass distribution in the disk

weeks in March 1974, described in Kafka, 1974). In these cases the delay histograms produced with S_E-coincidences never showed significant features.

Also with the two periods taken from Weber's communications the result was negative. Table 3 contains the corresponding counts at a few typical pairs of thresholds of the signal functions S_A and S_E. Instead of showing many histograms, we only give the count N_0 at zero time-delay, the observed average $\bar{N}$ over the 22 delays $\geqq 1$ s, and its observed r.m.s. fluctuation ΔN. For the narrow and independent peaks in S_A the fluctuation is well represented by $\Delta N \approx \sqrt{\bar{N}}$. For the S_E-coincidences ΔN is larger because peaks in S_E are not fully independent events. (Their rate rises steeply with the energy and, therefore, the long damping time appears in the autocorrelation of S_E.)

The thresholds for the counts in Table 3 were not accurately measured in terms of the long-term mean values. For the S_A-evaluation, they were roughly (5;4), (6;5), (7;6) and (8;7). For the S_E-evaluation the thresholds were chosen nearly equally in both detectors. (Their values in terms of the mean values can be found from the counts N_0 and the total number of data points for each period in Table 3, and from the square of the probability given by the S_E-curve in Figure 1.)

These results do not give the slightest hint of a simultaneous influence on both detectors. If the significant observations reported by Weber's group for these two periods had been due to gravitational radiation of any kind, they should have shown even more significantly in our experiment.

We do not have an explanation for Weber's observations, but we never lost an old suspicion (Kafka, 1973, 1974, 1975) that Weber's analogue detector, having reacted to an accidental coincidence (discovered over the telephone line), might have been able to feed energy into the Maryland cylinder. This could have been sufficient to cause significant (but wide and perhaps somewhat asymmetric) peaks in his time delay histograms.

Confrontation with the Aims of Gravitational Pulse Astronomy

The most interesting aim of gravitational wave astronomy will be the observation of stellar collapse. While the observation of "weak" radiation, e.g. from close binaries, will be helpful for a confirmation of Einstein's theory (and a check of the approximation methods to solve its equations), the "strong" radiation from final collapse will contain fascinating additional information about the behaviour of matter at extreme densities, unobtainable in any other way. So far, supernovae are the only known events which may be connected with collapse towards neutron stars and black holes. Hoping that rotation is usually not damped out before the final stages of stellar evolution, one may expect of the order of 1% of a solar mass to go into gravitational radiation around 1 kHz in a bandwidth of about 1 kHz (Lattimer and Schramm, 1976; Clark and Eardley, 1977; Endal and Sofia, 1977; Kafka, 1977). Although the wave trains might last several seconds, with the frequency sweeping from below 100 Hz to a few kHz, and the amplitude slowly increasing, they would act on a Weber-type resonator like short pulses. For an (isotropic) source near the center of our galaxy the observed spectral density would then be about $0.01\ M_\odot c^2/[4\pi \cdot (8\ \text{kpc})^2 \cdot 1\ \text{kHz}] = 2500\ \text{erg}/(\text{cm}^2\ \text{Hz}) = 2.5 \cdot 10^{-2}$ GPU. In Figure 4 we plot a recent estimate of supernova rate (Talbot, 1976) versus distance and the observed strength of this assumed pulse. Unfortunately these rates are lower than one would have estimated just using the number of galaxies, neglecting type. Inside our galaxy we have modified Talbot's curve according to a rough model of mass distribution in the disk (Allen, 1973). In the upper right-hand corner we have drawn the line representing the upper limits from the Munich-Frascati experiment, as given in Table 2, and our estimate (Kafka, 1974, 1975) of corresponding limits with Weber's sensitivity in 1973. Obviously, we would have been able to detect our standard event ($1\%\ M_\odot$ in 1 kHz) only from a distance less than 100 pc, where it may occur only about once every million years. In the figure, we have also shifted the line representing the Munich-Frascati limit towards 10^8 times weaker pulses, i.e. 10^4 times larger distance. From this distance our standard pulse would excite a Weber-cylinder so weakly, that the square of the classically calculated jump in the phase plane would be as small as Planck's quantum. For pulses below this "quantum limit", the uncertainty principle will forbid the application of our optimal algorithm (Braginsky, 1975; Giffard, 1976; Kafka, 1977). Because of the difficulties possibly arising from this problem and because one would certainly like to measure more details than just the spectral density of pulses, the Munich group decided not to continue with (low temperature/high quality) Weber-type experiments, but rather with a Weiss-Forward type experiment, i.e. a laser-lighted Michelson interferometer (Moss et al., 1971; Weiss, 1972; Winkler, 1976, 1977). This can, in principle, measure directly the time-dependence of geometry under the action of gravitational waves. (For a simple-minded discussion of a possible observation of the collapse of a fissioning stellar core see Kafka, 1977.) It is hoped that the many new antennae, being developed now and during the next decade, will be able to detect a few gravitational collapse events per year, and thus provide most valuable information on extreme states of matter and final stages of stellar evolution which will otherwise remain hidden.

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