asymmetrisch. Relativ zum optischen Zentrum kann in der NO-Hälfte der Galaxie HI bis zu einer Distanz von 10 Bogenminuten, in der S-W-Hälfte dagegen bis zu 14 Bogenminuten nachgewiesen werden. Der Unterschied der Masse von Neutralem Wasserstoff in den beiden Hälften der Galaxie beträgt etwa 30 %.

Im Anschluß wird über den aktuellen Stand der Modellrechnungen zur HI-Verteilung in M 33 berichtet. Die 21-cm-Durchmusterung der Galaxie M 33 wurde ebenfalls in Nancay ausgeführt.

P. Kafka (Max-Planck-Institut für Physik und Astrophysik München): Discussion of Possible Sources of Gravitational Radiation.

WEBER (1969) reported the detection of gravitational radiation on a high level of significance. Radiation seems to arrive in pulses of duration less than 0.4 sec. The frequency of observation was 1660 Hz. The energy arriving over the pulse in a bandwidth $\Delta\omega \approx 0.1$ was of the order of 10^4 erg cm^{-2}. Hence, if a flat spectrum is assumed up to a cut-off at or beyond the frequency of observation, the total energy per cm^2 in each pulse was $>10^9$ ergs. A source at distance D (kiloparsecs) must have emitted

$$E > 10^{53} \times D^2 \text{ ergs.} \tag{1}$$

Whereas the observation of about one such pulse per century or even per year might be expected at the present state of knowledge, WEBER's observations indicate a number of about hundred per year. This poses severe problems.

A strong pulse of gravitational radiation is expected only when a configuration of mass m comes close to its Schwarzschild radius $r_s = 2\ \mathrm{Gm/c^2} \approx 3\ \mathrm{m/m_\odot}$ km, and its quadrupole and/or higher moments change rapidly. A critical surface of approximate extent r_s will exist in any relativistic theory of gravitation (cf. TRAUTMAN, 1965), also for asymmetric configurations.

The following situations are possible sources for pulses of gravitational radiation: (1) Gravitational collapse of a rotating star towards a neutron star. In this case a pulse at roughly 1 kHz, lasting about 1 sec, with a total energy of the order of 10^{52} ergs ($\lesssim 1/2$ % of the stellar rest-mass energy) is expected, according to recent work at Caltech (cf. BURKE and THORNE, 1969). It is due to vibrational modes excited in the collapse.

(2) Hypothetical transitions in the state of a neutron star in which asymmetric vibrations may be excited. Similar processes have been proposed as a possible cause for the sudden decrease in the period of the pulsar PSR 0833–45 between February 24th and March 3rd 1969. Such "neutron-star-quakes" might emit a gravitational pulse similar to that in case (1) but with a smaller total energy.

(3) Asymmetric collapse towards a "black hole" (as a collapsing object is called in the state where gravitational redshift and capture make all types of radiation fade away for a distant observer, and only the stationary gravitational field remains). In such events one can expect a pulse of gravitational radiation. Its duration will be roughly $\tau \gtrsim r_s/c \approx 10^{-5}\ m/m_\odot$ [sec], the high-frequency cut-off will lie near $\nu \approx \tau^{-1}$, and the total energy may nearly reach the order of $mc^2 \approx 10^{54.3}\ m/m_\odot$ [ergs].

(4) Swallowing of a mass m by a black hole of much larger mass M. In this case the time scale will be roughly R_s/c, where R_s is the Schwarzschild radius corresponding to M. The total energy in the pulse is supposed to be less than $(m/M)mc^2$ (cf. ZELDOVICH and NOVIKOV, 1965).

(5) Close passage or fusion of two black holes of comparable masses. In this case the time scale and total energy of the pulse will again be of the order r_s/c and mc^2, respectively.

Instead of thinking about such "extreme" sources one might speculate that the whole universe could be filled with gravitational radiation – perhaps ab initio. The pseudo mass density corresponding to Weber's observations would be larger than 10^{-28} g cm^{-3}. Hence, matter would only be a small distubance in a wildly behaving vacuum metric. Apart from the fact that one would hardly expect sharp pulses, this possibility is ruled out because such a high pseudo-density would lead either to an age of the universe less than 3×10^9 years or to a very small spherical space in which the antipole would be seen at a redshift less than $z \approx 0.15$ (cf. KAFKA, 1969, hence called paper I).

If pulses as observed by WEBER are produced by mechanisms of types (1) to (5), the sources have to be situated in our galaxy. This follows from the condition that the high-frequency cut-off must not lie much lower than 1660 Hz, which gives an upper limit for the total energy E and, hence, for the distance D: 1660 Hz $< \tau^{-1} \approx$ $\approx 10^5\, m_\odot/m$ gives roughly $m < 100\, m_\odot$ and $E < mc^2 < 10^{56.3}$ erg. The inequality (1) says $D^2 < 10^{-53}\, E$ (in kpc and ergs). Hence, $D < 40$ kpc. It is easily seen that for all mechanisms considered the observed activity of 100 events per year has to be rather a transient than a steady-state phenomenon.

Let us first try the possibilities (1) to (3), involving neutron stars or collapse of more massive stars. To be optimistic, let us assume that each source emits n pulses of energy $E \approx mc^2/n$, before it dies in a black hole. If the pulses observed come from sources up to distance D kpc, we have from (1)

$$D < 4\sqrt{m/m_\odot} \cdot 1/\sqrt{n} \qquad [\text{kpc}]\,. \tag{2}$$

A frequency of $f \approx 100$ pulses per year in a volume $4\pi/3\, D^3$ means that

$$p \approx f/(n \cdot 4\pi\, D^3/3) > \sqrt{n}\, (m/m_\odot)^{-3/2}\ \text{kpc}^{-3}\ \text{years}^{-1} \tag{3}$$

is the number of sources dying every year per kpc^3.

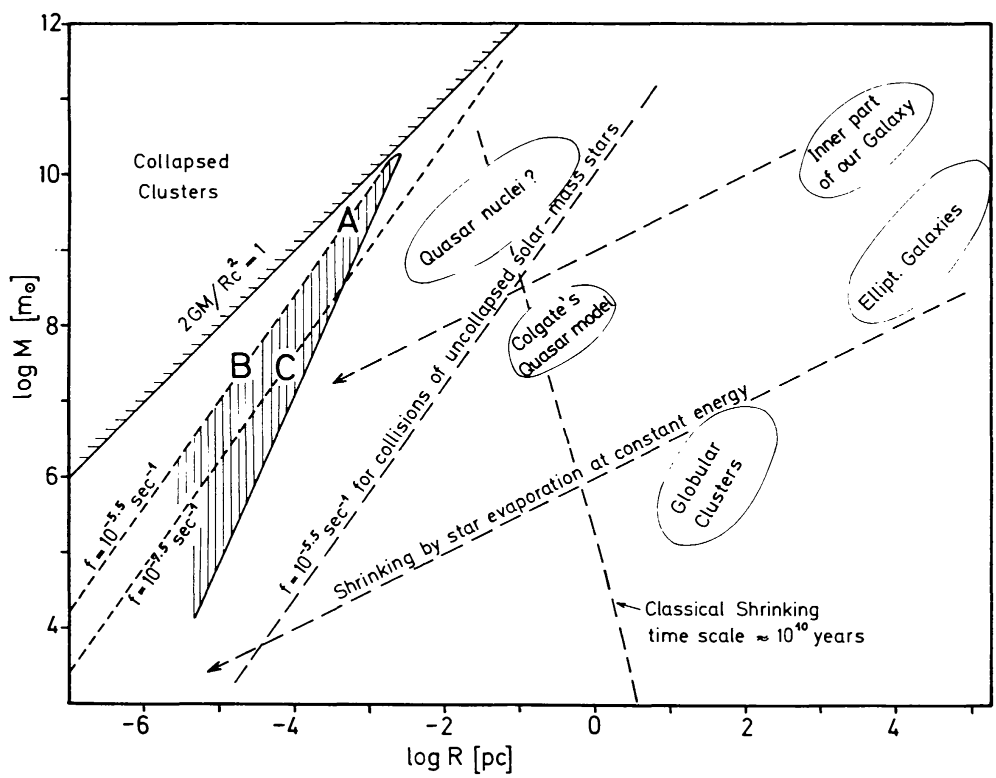
In a steady-state process these sources would have to be replaced at the same rate. However, the rate at which stars more massive than the white-dwarf limit ($\approx 1.5\, m_\odot$) leave the main sequence is estimated to be of the order of 10^{-3} kpc^{-3} years^{-1} (cf. SALPETER, 1955; ZELDOVICH and NOVIKOV, 1965). This value is too small compared with equation (3). It is seen that a hypothetical stepwise collapse makes the discrepancy larger.

If we think of collapses concentrated near the galactic center, each pulse means emission of more than $m_\odot c^2$. Then all the stars will be used up in less than 10^9 years.

Apart from these difficulties it seems quite improbable that collapses towards neutron stars or black holes do not produce supernova-like phenomena. The frequency of supernova, however is less than 10^{-6} kpc^{-3} year^{-1} (which may indicate the efficiency of mass-loss mechanisms in stellar post-mainsequence evolution).

As a steady state is not possible with this type of source, one might think about an "accident": could a neutron star be so close to us that it produced the pulses observed? If it was formed t years ago and radiated ≈ 100 t pulses, each with an energy $E \lesssim 10^{54}/100$ t ergs, its distance must be less than $1/\sqrt{10\,t}$ kpc. For $t \approx 1000$ years, e. g., this would mean that one of the closest stars would have to be a neutron star, collapsing in an extremely hypothetical way step by step towards a black hole. This seems rather absurd.

The possibility (4) – swallowing of meteorites or planets by a black hole – is ruled out by similar arguments: Our moon, for instance, with $m \approx 10^{26}$ g, falling into a black hole, would emit much less than 10^{47} ergs (probably only a fraction $m/M < 10^{-7}$). Hence $D <$ lpc would be needed. If one thinks, on the other hand, of a very massive black hole sitting near the galactic center and eating stars at the required rate, it turns out that it would have to be surrounded by a cluster so dense that stars would collide.



Now we are left with the last mechanism: "Mutual swallowing" or close passage of two black holes. It is clear that this will never happen in our neighbourhood. In paper I, I have discussed relativistic clusters of black holes which might produce the radiation observed in collisions. For shortness (and for fun) I called them "gravars". The conditions under which in a cluster of collapsed stars collisions at distances of the order of the Schwarzschild radius arise frequently enough, can be seen in the diagram (taken from paper I).

M is the total mass of a cluster, R a typical value of its radial extent. In the shaded region there are drawn the straight lines along which a cluster produces 100 or 1 strong pulses per year ($f = 10^{-5.5}$, resp. $10^{-7.5}$ sec^{-1}). The right hand border of the shaded area corresponds to clusters which emit $100/n$ pulses per year, such that $n \cdot M \approx 10^{10.5}\ m_\odot$.

It is clear that a cluster of stars can reach the gravar state only after collapse of the individual stars. Let us assume that about 10^9 solar masses might be involved in gravars today and that about 1 % of this rest mass went into electromagnetic radiation and fast particles in their formation. Then the nucleus of our galaxy must have been a quasar some time ago liberating more than 10^{61} ergs. This is not too unreasonable. A problem may, however, arise from the short lifetime of the gravars.

Let us draw the following highly speculative picture: The core of a galaxy may become so dense that stellar collisions set in (cf. GOLD, 1967, COLGATE, 1967). They will lead partly to fusion, partly to the production of a dense interstellar medium. Massive stars produced by fusion ($\approx 50\ m_\odot$ in Colgate's quasar model) will evolve rapidly and suffer collapse towards black holes. The quasar stadium of the cluster will be finished only after all stars are either collapsed or destroyed, or have left the cluster. The optical flashes of quasars might be immediately associated with the collapses and with collisions of black holes with stars. (Perhaps a process of the latter kind, which has not yet been examined, could lead to light curves dropping even more steeply than they rise, as observed in quasars on time scales of days or even hours (cf. HUNTER and LÜ, 1969). After these processes are finished, the black holes will re-swallow most of the dense interstellar matter. This may lead to additional energy loss of the cluster through braking and radiation. The radiation of gas falling into a black hole has been discussed by SALPETER (1964) and recently by LYNDEN-BELL (1969); the latter places a very massive black hole in the center of a galaxy and tries to derive the infrared activity of the nucleus from the accretion process. If the quasar which died in this black hole was a cluster, it must have passed the "gravar" region before it finally collapsed.

In our diagram the quasar stage may lie near the broken line where the collision rate of normal stars is of the order of 100 per year. From this line to the shaded region the evolution will be governed mainly by "stellar evaporation" (star loss) and partly by accretion. Perhaps the accretion process becomes unimportant before the final state is reached. (Hence, Lynden-Bell's model should also be discussed for a cluster of black holes instead of a single very massive one.)

The time scales of star loss and of possible evolution of a dense core in clusters seem to be still controversial in stellar dynamics. As the "classical" evaporation time scale is too long to permit shrinking of a cluster into the quasar state within the age of the galaxy, one has either to connect the phenomenon with the very origin of the galaxy, or to believe that the core of a cluster can shrink much faster (as suggested by various authors). For the post-quasar evolution the classical time scale will be 10^9 to 10^{10} years. For a long time up to this order (but perhaps considerably less) the quasar remnant will remain seemingly-dead, until it finally begins to radiate more and more gravitational waves. This energy loss makes the cluster shrink faster and faster. Moreover, in many or most of the close encounters the two colliding black holes will fuse which is also likely to accelerate the shrinking of the cluster. If not for some unknown reason star loss takes over in the last moments, the cluster must reach the line where $2\,GM/Rc^2 = 3$. At this value of 3 times the Schwarzschild radius there lies the last stable circular orbit around a point mass, according to the General Theory of Relativity. Approximately the same value for the onset of general relativistic instability in clusters has been found in computations of FACKERELL, IPSER and THORNE (1969). At this stage the redshift will be ≈ 0.4 from the center and ≈ 0.25 from the "surface" of the gravar. Finally, after a time of several R_s/c, the gravar forms a single black hole, perhaps after throwing out a few members at nearly relativistic velocities. For a cluster of 10^9 solar masses the relativistic collapse takes only about a day (several times 10^{-5} sec per solar mass).

The probability to observe one or several gravars in our own galaxy depends critically on the time scales of evolution in the shaded area of the diagram and at its right hand side. A rough estimate for the remaining life time τ of a gravar with total mass M and individual masses m, at a radius such that the collision frequency is f, will be $\tau \leq M/fm$. Lines of constant τ are parallel to the right-hand border line of the shaded area. Along this line $\tau \leq (m_\odot/m) \cdot 10^{8.5}$ years, at point "B", e. g., it is 1000 times less.

A gravar at point "A" is already excluded by relativistic instability (if this sets in at $R \approx 3 \cdot R_s$). The largest single cluster which could produce 100 pulses per year would have $\approx 10^9$ solar masses and a residual life time $\tau \leq (m_\odot/m)\, 10^{6.5}$ years, i. e. perhaps 10^5 years.

Hence, a single gravar fitting Weber's observations would be a very accidental phenomenon. The remaining life time can be larger only proportional to the total mass of the quasar remnant. For more than $10^9\, m_\odot$ this has to be split in subclusters in order to avoid relativistic instability at the present collision rate. Instead of a single point in the upper part of the shaded region, one can think of a cloud of points crossing the lower part from right to left. A quasar remnant of $\leq 10^{10}\, m_\odot$, divided in many smaller clusters, might yield effective gravars for a few million years, The number of pulses per year might be expected to fluctuate considerable in this case (on time scales ranging from days to centuries, depending on the mass range of the "cloud"). If a gravar of $M \approx 10^5\, m_\odot$, for instance, arrives at the line at which it alone produces 100 pulses per year, τ is only of the order of a few years. Hence, in some years the number of pulses might grow steadily, until relativistic instability cuts off the "left-most" gravar and leaves only the background activity of the less evolved gravars. (The final collapse of a cluster of $10^5\, m_\odot$ would probably emit a pulse at a frequency ≈ 1 Hz. Perhaps this pulse could be detectable in the light travel time from earth to moon, which is of the order of a second. If a growth of gravar activity were observed, an improved laser experiment should watch the distance of the moon!* As a maximum of the fluctuating number of pulses is approached, one would also expect an increasing average pulse energy, due to the fusion process, which may increase the mass of individual black holes.

Some other properties of expected pulse distribution, spectra, etc. have been discussed shortly in paper I.

Conclusion

All possibilities to explain the large number of events observed by Weber seem rather unlikely and demand more or less "accidental" sources. Still the least accidental ones seem to be relativistic clusters of black holes, which might be remnants of a quasar in the nucleus of our galaxy.

*) The corresponding "bump" in the moon's orbit will be smaller than 0.1 mm!