THE PREGALACTIC COSMIC GRAVITATIONAL WAVE BACKGROUND

RICHARD A. MATZNER
Department of Physics and Center for Relativity
University of Texas at Austin

ABSTRACT

An outline is given estimating the expected gravitational wave background, based on plausible pregalactic sources. Some cosmologically significant limits can be put on incoherent gravitational wave background arising from pregalactic cosmic evolution. The spectral region of cosmically generated and cosmically limited radiation is, at long periods, $P > 1$ year, in contrast to more recent cosmological sources, which have $P \sim 10^{0} - 10^{-3}$.

I. INTRODUCTION

This is a review paper on sources of the pregalactic cosmic gravitational radiation background and on some of the techniques that are available to study this background as well as recently developed improvements. The paper is structured first (§II) to analyze incoherent, very early (primordial) sources, which have frequencies now $\sim 10^{10}$Hz, down to $\sim 10^{-9}$Hz. Limits on radiation density, in various wavelengths due to knowledge of early cosmic evolution are given in §III. The results of §II–III appear in Fig. 1. Figure 2 repeats Fig. 1 but also shows the expected upper limit on the background from events occurring at low redshift due to discrete sources. In all cases we will express backgrounds in terms of the logarithmic spectral flux: νF_ν where F_ν (ergs/cm^2/sec/Hz) is spectral flux. By an accident of numerics, normal cgs units of this flux correspond to interesting cosmological energy densities. For instance:

$$\nu F_\nu \sim 6 \times 10^2 \text{ergs/cm}^2\text{/sec} \tag{I.1}$$

corresponds to an energy density $\sim 2 \times 10^{-29}$gm/cm^3, which is approximately $\rho_{closure}$, the critical mass density needed to recollapse the universe, assuming a Hubble constant $H_0 \sim$ 100km/sec/Mpc. Most primordial sources and all current detectors have sensitivities comparable (within a few orders of magnitude) to this value (see Figs. 1 and 2). An idea of the difficulty of detection of gravitational radiation is to compare this flux to some everyday electromagnetic radiation fluxes. Noon sunlight $\simeq 10^6$ergs/cm^2/sec; full moonlight $\simeq$ 1 erg/cm^2/sec $\simeq 10^{-2}\rho_{closure}$. Electromagnetic radiation at this level can, of course, be detected with no instrumentation at all.

II. SOURCES

a) Stochastic Background Sources

1) PRIMORDIAL BACKGROUND RADIATION

The most primordial source one can imagine for gravitational radiation is the Big Bang, the formation of the universe itself. By analogy to the cosmic microwave electromagnetic wave scattering (called the decoupling epoch; this probably occurred at redshift $z \sim 1{,}000$), there should also be a low temperature gravitational radiation microwave background. The gravitational interaction becomes as strong as the electromagnetic only at energies near the Planck energy $\sim 10^{19}$GeV $\sim 10^{31}$K, which, according to classical Big Bang models, occurs at about 10^{-43} sec after the Big Bang. The gravitons would have been in thermal equilibrium then and would have shared their energy with other forms (modes) of energy present then. While the physics of that instant is very uncertain; many models predict only a few (10 to 100) total modes then. In that case, microwave gravitons of ~1K are expected (Matzner, 1969). The energy density associated with 1K microwave gravitational radiation is $\sim 8 \times 10^{-36}$gm/cm^3 $\sim 8 \times 10^{-15}$ergs/cm^3, centered at the associated wavelength of a few centimeters. Both these features put it in a very unfavorable regime for detection by any current technique. This radiation is ~2 orders of magnitude lower in density than the microwave radiation background and thus represents Ω_{gw} (thermal gravitons) $= \rho$ (thermal gravitons)$/\rho_{closure} \approx 10^{-6}$. Ω_γ is similarly defined for the electromagnetic microwave background, $\Omega_\gamma \sim 10^{-4.5}$.

2) GRAVITATIONAL RADIATION ENHANCEMENT IN VERY HIGH ENERGY (GRAND UNIFIED THEORY) PHASE TRANSITION

Here the energy is not as high as that associated with the production of gravitons but is a "mere" $T_{GUT} \sim 10^{14}$ to 10^{17}GeV. The behavior of the universe as it evolves through these temperature ranges ($\sim 10^{-42}$ to 10^{-40} seconds after the Big Bang) acts parametrically to pump up the gravitational wave amplitude of very long wavelengths. This is essentially an "overshoot" phenomenon, as the equation of state changes in a phase transition. If the universe, as predicted in many field theories, undergoes a period of inflation with reheating temperatures in the 10^{17}GeV range, then the enhanced radiation may turn out to be detectable. The wavelengths in question are 0.1 to 1 present horizon sizes, periods of billions of years. Radiation of this wavelength acts like large-scale distortions of the universe and is detectable in distortions of the electro-magnetic microwave background radiation. The present limits ($\sim 5 \times 10^{-5}$) in quadrupole $(\Delta T/T)_q$ (Wilkinson, 1987) put limits on the parameters of the model, and tighter limits would force the model away from $T_{GUT} \sim 10^{19}$GeV to one with typical transition energy at *smaller* values of T_{GUT} ($\Omega_{gw}/\Omega_\gamma \sim (\Delta T/T)_q^2 \sim \frac{(T_{GUT})^4}{(T_{Pl})^4}$, (Veryaskin, Rubakov, and Sazhin, 1983). In general, for small amplitude, one finds $\rho_{gw} \sim \rho_\gamma (\Delta T/T)^2$ for horizon scale waves (Misner, 1968).

3) GRAVITATIONAL RADIATION ENHANCEMENT IN HIGH ENERGY (QUARK-HADRON) PHASE TRANSITIONS

Korotun (1980), studies the effect on primordial wave spectrum of the parametric amplification that occurs during the possible phase transitions occurring in the early universe due to string interactions. The process is the same as that described in §II.2 just above; during the phase transition the universe deviates from a simple (fractional) power of t expansion function, and this leads to enhancement of gravitational wave creation. However, the net effect on gravitational waves decreases with decreasing energy scale, with

$$\frac{\Omega_{gw}}{\Omega_\gamma} \sim \left(\frac{T^*}{T_{Pl}}\right)^4 \qquad \text{(II.1)}$$

where $T*$ is the characteristic temperature associated with these processes. The range of these processes is $T \sim 10^{14}$GeV (maximum) for baryon synthesis (which gives $\Omega_{gw}/\Omega_\gamma \sim 10^{-20}$) and lower in temperature for other processes, which give uninterestingly small values of Ω_{gw} (Korotun, 1980).

4) GRAVITATIONAL RADIATION FROM ACOUSTIC NOISE IN STRONGLY FIRST ORDER PHASE TRANSITION

Hogan (1986) estimates the gravitational radiation produced by the random noise from random nucleation in cosmological phase transitions. He finds: $\Omega_{gw}/\Omega_\gamma \sim \delta^2(R_nH)^3v_s^6$ where v_s^2 (~1/3 for most situations) is the square of the sound speed, R_n is the typical nucleation separation, and δ is the fractional supercooling $\delta = \delta T/T_{\text{transition}}$, which we take here to be $\delta \sim 1$. While this spectrum is formally flat, we expect strong damping at high frequency, $\Omega_{gw}/\Omega_\gamma \sim \nu^{-1}$ (or faster) for $\nu \gg R_n^{-1}$. A second effect of phase transitions arises because of the pressure disturbances caused by different equations of state in different locations. For $\nu \sim H$ (then), $\Omega_{gw}/\Omega_\gamma$ is comparable to that found above, but for smaller ν ($\nu < H^{-1}$), the spectrum of the fall-off is $\propto \nu^3$. The nucleation length R_n can be perhaps generously estimated (Kajantie and Kurki-Suonio, 1986; Kurki-Suonio, 1988) as $R_nH \lesssim 10^{-2}$ (then). Thus $\Omega_{gw}/\Omega_{rad} \lesssim 10^{-7.5}$ or $\Omega_{gw} \sim 10^{-12}$ peak.

Hogan makes the important point that astronomically accessible gravitational wave frequencies (~10^2 Hz to ~10^{-9} Hz) correspond to possible phenomena of this type at strong interaction (or higher energies): 10^9 GeV $\leftrightarrow$ 10^2 Hz; 100 GeV (the possible temperature of the electroweak phase transition) $\leftrightarrow$ $10^{-4.5}$ Hz; 100 MeV (the quark-hadron transition) $\leftrightarrow$ 10^{-8} Hz.

5) COSMIC STRINGS

Cosmic strings are possible "topological singularities" that arose in the very high temperature early epochs of the universe. For parameters appropriate to the formation of clusters of galaxies, the associated energy is ~10^{14} GeV; the linear mass density of a string is ~10^{22} gm/cm. These objects, if formed into loops ~1 kpc on a side, have masses that can act to seed structure formation. Vachaspati and Vilenkin (1985; also Hogan and Rees, 1984) have investigated the expected gravitational radiation background in a universe in which strings contributed the seeds for the observed structure. Their analysis takes into account that cosmic string loops can be said to form when the age of the universe, t_u, reaches L/c, where L is the loop size, and we call t_i the formation time of the strings. Before that time, the loops cannot be subject to causal forces and cannot oscillate. After this time, they act as massive oscillating gravitational radiators. Following Hogan and Rees (1984), one estimates that the gravitational energy wave produced by the strings equals the horizon crossing energy fluctuations $(\frac{\delta\rho}{\rho})_{hc}$ produced by the string distribution and is essentially produced at their decay time t_{dec}. The birth time $t_i = L/c$, and the strings radiate at a constant rate $G\mu^2\gamma$, so the time of their decay is $t_{dec} = t_i/(G\mu^2\gamma)$. Because the gravitational and electromagnetic background radiation redshift the same way, one finds

$$\nu \frac{d\rho_{gw}}{d\nu} \simeq \Omega_\gamma \left(\frac{\delta\rho}{\rho}\right)_{hc} \left(\frac{1 + z_i}{1 + z_{dec}}\right). \quad \text{(II.2)}$$

The latter factor gives the relative enhancement due to the fact that the radiation background decays away as the strings evolve. This formula holds for strings that decay prior to the present epoch; otherwise the quantity z_{dec} must be replaced by the present: z (now) = 0. Now $(\delta\rho/\rho)_{hc} \simeq 2\pi G\mu$. If z_{dec} lies within the radiation-dominated epoch, then $(1 + z_i)/(1 + z_{dec}) = (t_{dec}/t_i)^{1/2} = (G\mu^2\gamma)^{-1/2}$, and the resulting spectrum is flat:

$$\nu \frac{d\rho_{gw}}{d\nu} \simeq \Omega_\gamma \gamma^{-1/2} (G\mu)^{1/2} \simeq (10^{-8} \text{ to } 10^{-7})\, \Omega_\gamma . \quad \text{(II.3)}$$

This holds for loops small enough that the decay occurs before the transition to matter-dominated expansion. For larger loops, which produce lower frequencies, two effects enter. The time dependence of the redshift factor changes, $(1 + z) \propto t^{2/3}$, which gives an enhancement for lower frequencies until the decay time reaches the present. Strings whose decay time exceeds the present have not had time to decay completely, and so the spectrum falls off for very long period waves. With the parameters $G\mu \sim 10^{-6}$, $\gamma \sim 10^2$ found in a numerical survey by Vachaspati and Velinkin, the spectrum rises for periods longer than about 10 years, peaking about a factor of 100 higher than its high frequency value (*i.e.*, at $\Omega_{gw} \sim 10^{-6}$ to 10^{-5}) for period $\sim 10^3$ years and then decreasing as P^{-1} for longer periods (see Fig. 1). The short period (high frequency) cut-off of the spectrum is $\sim 10^{-11}$ seconds, *i.e.*, comparable to the thermal gravitons in frequency, although not in energy density. In Fig. 1, I also plot the gravitational wave spectrum from cosmic strings evaluated at $t = 1$ second. This is relevant to comparison to the nucleosynthesis limit (§III.a below).

6) GRAVITATIONAL WAVE PERTURBATION IN EQUIPARTITION WITH DENSITY FLUCTUATIONS

Assuming that the gravitational wave perturbation density is comparable to the fluctuations leading to galaxy formation in standard (noncosmic-string) models, Zel'dovich and Novikov,1970, obtain a long-period, gravitational wave density that is

$$\Omega_{gw} = \varepsilon^2 \Omega_\gamma \quad \text{(II.4)}$$

where ε is the density contrast that leads to eventual galaxy formation: $\varepsilon^2 \lesssim 10^{-4}$.

7) QUASARS: "LATE" COSMOLOGICAL SOURCES

An estimate may be made for the gravitational wave density from the cosmic population of quasi-stellar objects. We present an estimate here based on one plausible model for quasars: quasars as $10^{10} M_\odot$ black holes, driven by accretion.

$M = 10^{10} M_\odot$ means the natural gravitational period associated with these black holes is $\sim 10^5$ seconds. The lifetime T of typical quasars has been variously estimated at 10^6 years.

An upper limit on the mass accretion rate is

$$\dot{M} \sim M/T \sim 10^4\ M_{\odot}/\text{year}. \qquad \text{(II.5)}$$

Assume an (unrealistically generous) efficiency of conversion to gravitational radiation:

$$\varepsilon \sim 0.1\,. \qquad \text{(II.6)}$$

Then

$$L \simeq 10^{50}\ \text{ergs/sec}\,. \qquad \text{(II.7)}$$

All quasars are at cosmological distances, $R \sim 10^{28}$ cm. A (perhaps low) estimate of the number of quasars is ~1,000.

Thus the flux from quasars in the octave centered at $\nu \sim 10^{-5}$ Hz is

$$\nu F_\nu \sim 1000 \times 10^{50}/4\pi(10^{28})^2 \sim 8 \times 10^{-5}\text{erg/cm}^2\text{/sec}. \qquad \text{(II.8)}$$

This is marked as Q10 in Fig. 2. Other candidate models for quasars are also marked in Fig. 2: Q1, quasars as supermassive pulsars; Q2, quasars as sites of rapid stellar collapse; and Q4, quasars as relativistic star clusters (Q1, Q2, and Q4 from Rosi and Zimmerman, 1976).

b) "Recent" Cosmological Sources, SN1987a

The classical catastrophic source for gravitational radiation is supernova collapse. The gravitational flux from SN1987A can be estimated in the following way. The supernova may have converted $0.01M_{\odot}$ to gravitational radiation (a generous efficiency of ~0.05%). The timescale is fixed by the total mass: $20M_{\odot}$ means a typical timescale ~10^{-3} to 10^{-2} second.

Then one has

$$\nu F_\nu(1987\text{a}) \sim (10^5\text{ergs})/(10^{-2}\text{sec})/4\pi/(63\text{kpc})^2 \simeq 10^6\text{ergs/cm}^2\text{/sec}\,. \qquad \text{(II.9)}$$

This is shown as 87a on Fig. 2. More conservative estimates of backgrounds from supernovae (Rosi and Zimmerman, 1976) are labeled SN in that figure.

III. LIMITS ON THE GRAVITATIONAL RADIATION BACKGROUND DENSITY

In using cosmological limits, one must be aware of the obvious fact that early universe limits only limit waves produced before the epoch at which the limit is imposed. A number of the following points have been made by Carr (1980).

a) Cosmic Nucleosynthesis

The observed light element abundances are remarkably accurately modeled by the "standard model:" a homogeneous, isotropic universe with three neutrino flavors and a present baryon density $\rho_b \sim 2 \times 10^{-31}$ gm/cm^3. Deviations in the parameters of only ~10% from standard values lead to discrepancies with observations, and despite some effort (*e.g.*, Matzner and Rothman, 1984) no deviation has been found that does not have an unmistakable signature different from the standard model results. In particular, the expansion rate at nucleosynthesis cannot be substantially perturbed as it would be if the gravitational radiation energy density then exceeded ~10% of the photon density (the dominant energy density) then. This gives different limits, depending on the wavelength of the gravitational radiation, in particular whether the wavelength was less than or greater than ~3 × 10^5 km (*i.e.*, 1 second) at the beginning of nucleosynthesis, $T \sim 10^{10}$ K. This size corresponds to waves of 3 × 10^{15} km (periods ~100 years) now. Waves of shorter wavelength redshift exactly as the photon radiation, so we have the *nucleosynthesis limit*,

$$\Omega_{gw}(\nu) \lesssim 10^{-1}\Omega_\gamma \simeq 10^{-6} \text{ for } \nu \gtrsim (100 \text{ years})^{-1} . \qquad \text{(III.1)}$$

Wavelengths that exceeded the horizon size but did not dominate the energy density redshift like $(1 + z)^5$ (rather than the $(1 + z)^4$ redshifting of the photons) (Misner, 1968). Thus one has

$$\Omega_{gw}(\nu) \lesssim \Omega_\gamma \left(\frac{z_h(\nu)}{10^{10}}\right)$$

where z_h is the redshift of the epoch when the wavelength finally fell within the horizon

$$z_h \sim 10^{18}\text{sec}/P_{now} \simeq ((\text{size of the universe})/\text{wavelength}) .$$

Hence

$$\Omega_{gw}(\nu) \lesssim (10^8 \text{ sec} \cdot \nu_{now})\Omega_\gamma \quad \left\{ \begin{array}{l} \nu_{now} \lesssim 10^{-10} \text{ Hz} \\ P_{now} \gtrsim 100 \text{ years} \end{array} \right. . \qquad \text{(III.2)}$$

These limits are reflected in Fig. 2. Both Eqs. (III.1) and (III.2) refer to waves that are present at the time of nucleosynthesis. Hence, in Fig. 2 the *dotted* cosmic string curve, giving waves produced by cosmic strings prior to t_u = 1 second, is the relevant one, so there is no conflict between cosmic string prediction and nucleosynthesis time.

b) Effects On Galaxy Foundation

Since galaxies must form in the expanding universe, they must be somehow gravitationally effective at $z \sim 10^3$ in order for the observed structure to have formed by now. Carr (1980) shows that this requires $\Omega_{gw} < \Omega_m^2 \sim 10^{-4}$ where Ω_m is the ratio of baryon matter to closure density; this is a limit somewhat weaker than the nucleosynthesis limit but which may apply if the nucleosynthesis argument is somehow evaded.

c) Limits from Solar System Observations

Other upper limits on gravitational wave energy density can be obtained from the long-term effects of gravitational waves on the orbits of the moon or of the planets. For the moon, Carr (1980) finds $\Omega_{gw} \lesssim 4$ for periods $P_0 \sim 10^6$ seconds; for the planets, similar effects hold. Mashhoon (1978) finds that the effect on the phase of the moon's orbit could be more sensitive than is its semimajor axis to incident gravitational radiation.

Some very weak limits on the gravitational background can also be found by considering terrestrial and solar oscillation. Boughn and Kuhn (1984) report $\Omega_{gw}(4 \times 10^{-4}\ \mathrm{Hz}) \lesssim 10^2$ from solar oscillations, and similarly $\Omega_{gw}(2 \times 10^{-3} - 2 \times 10^{-2}\ \mathrm{Hz}) \lesssim 10^2$ from earth oscillations. They suggest that both earth and solar mode observations may improve by orders of magnitude and may in the future provide real limits on the density of gravitational radiation in these frequency bands.

d) Limits on the Gravitational Background from Distortions and Polarization of the Electromagnetic Microwave Background

Gravitational waves introduce anisotropy in the cosmic microwave background because the associated metric variation affects the overall redshift between source and observer. For wavelengths shorter than the horizon, the amplitude h scales as R^{-1} so the dominant effect on the microwave radiation comes from the earliest post-collisional part of the microwave photon evolution. The earliest point that the microwave background samples is thus the "decoupling epoch," which occurs at $z \sim 1{,}000$ in most models of the microwave temperature (although there have been suggestions that "late" reheating of the intergalactic in standard gas could mean that the last scattering was much more recent. Only if the decoupling redshift $\sim 1{,}000$ do we obtain any usable limits from the microwave backgrounds). Gravitational radiation imprints a signature $\Delta T/T \sim h$, where h is the amplitude of the wave perturbation. For waves comparable to the size of the horizon now, the effect of waves is like that of uniform anisotropy: quadrupole $\Delta T/T$. Current upper limits on the quadrupole temperature anisotropy are $\sim 5 \times 10^{-5}$ (Lubin, Epstein, and Smoot, 1983; Fixsen, Cheng, and Wilkinson, 1983), which gives an energy content in these waves

$$\Omega_{gw} \lesssim 2.5 \times 10^{-9} \Omega_\gamma . \tag{III.3}$$

Waves produced at decoupling might be expected to have wavelengths comparable to the horizon size at decoupling. This corresponds to angular scales minutes to degree. The limits on $\Delta T/T$ on the angular scale 10 arcminutes to 1° is $\sim 8 \times 10^{-5}$ (Wilkinson, 1987) with a somewhat tighter limit at 4.5 arcseconds $\sim 2 \times 10^{-5}$ (Uson and Wilkinson, 1984). These give

$$\Omega_{gw} \lesssim 4 \times 10^{-10} \Omega_\gamma \text{ for } P \sim 3 \times 10^8 \text{ years} . \tag{III.4}$$

When photon scattering occurs in an anisotropic medium, polarization of the scattered photon occurs. A photon scattered at right angles must be polarized orthogonally to the plane of its trajectory. If we consider viewing a distant thermal source, then horizontally polarized photons are all those that scattered from a horizontal orbit toward us. A gravitational wave induces an anisotropic shear $\sigma = \dot{h} = (h/P)$ in the transverse dimensions of a system. This shear leads to a differential redshift, $\Delta T/T \sim \sigma t_c$, where t_c is the mean time between collisions (assumed less than P; if $t_c \gtrsim P$ then the effect saturates). This means that vertically travelling photons pick up a different redshift between their last two collisions than do horizontally traveling photons. There is thus a net polarization induced in the radiation that reaches us. (h is a tensor that has principal axes. For "horizontal" and "vertical" above, one should strictly say "the projection on the sky of one of the principal axes;" "the projection on the sky of the other vertical axis.") Unlike the temperature fluctuations, which are diminished or destroyed by scattering, the production of polarization demands it. Since decoupling in most models is a gradual process, occurring over a factor ~2 in redshift, we expect polarization $p \sim (h/P)P \sim h \sim \Delta T/T$ (actual model calculations typically give $p \sim 0.3\Delta T/T$) induced in the microwave background from gravitational radiation. If the period P is small compared to the age of the universe at decoupling, t_{ud}, then we see the superposition of many oppositely polarized regions; so the minimum scale on which this effect can be relevant is roughly the horizon size at decoupling, and larger. Polarization limits are, in fact, comparable to temperature anisotropy limits ($p \lesssim 6 \times 10^{-5}$; Lubin and Smoot, 1981, so these results provide an upper bound on the present-day wave density consistent with the temperature anisotropic limits given above. (For essentially homogeneous waves, one calculates (with $t_c \sim t_{ud}$ at scattering) first that $(\Delta T/T)$ quadrupole now $\sim(\dot{\beta} t_{ud})$. Again taking $t_c \sim t_{ud}$, we find $p \sim \Delta T/T$ consistent with the gravitational wave discussion above.)

Sunyaev, 1974 has studied the distortions in the microwave background due to the dissipation of density fluctuations in the early universe. (These would be equal to gravitational wave background under the equipartition hypothesis of Zel'dovich and Novikov, 1970). He finds the limit $\Omega_{gw} \lesssim 10^{-6.5}$ for waves of period 10^{12} sec $< P_0 < 10^{15}$ sec.

IV. CONCLUSION

As can be seen from Figs. 1 and 2, certain possible early cosmology sources can be excluded by cosmologically based limits. In particular, it seems that parametric amplification at temperatures greater than ~5 × 10^{16} GeV conflicts with the quadrupole anisotropy upper limit. The small scale microwave anisotropy also puts limits on the acoustic noise-induced gravitational waves arising from the QCD (quark-hadron) phase transition. (In both these cases we assume that the microwave decoupling temperature is $T \sim 3{,}000$ K ($z_{decoupling} \sim 1{,}000$).) The cosmological sources and cosmological limits) apply at longer periods than do the typical "more recent" sources and observational limits (Fig. 2). However, it is notable that as pulsar timing increases in accuracy and in length of time observed, very interesting limits on cosmological features ($P \gtrsim 10$ years) will emerge. The timing data on PSR 1937+2 1 (Rawley, Taylor, Davis, and Allen, 1987) is, for instance, very close to limiting the cosmic string-produced gravitational radiation.

Present day detectors are being supplemented by systems in process or proposed that can substantially improve sensitivity.

Allen Anderson (1987, and this volume) has described an earth orbital interferometer design. This design could reach $\Omega_{gw} \sim 10^{-5}$ at $\sim 10^{-2}$ Hz. Michaelson, 1987, has investigated the sensitivity of coincidence between cryogenic "Weber bar" detectors, which could limit $\Omega_{gw} \lesssim 10^{-7}$ for ~200 Hz; and between interferometric detectors with ~1,000 km separation, which could give sensitivities $\Omega_{gw} \sim 10^{-12}$ at 50 Hz. Even better sensitivities at ~1 to ~50 Hz could be obtained by orbiting interferometers.

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SOURCES

1° K thermal gravitons: (Last equilibrium at ~10^{31} K) gravitational equivalent of the 2.7 K background radiation (Matzner 1969).

PA19: Parametric amplification of long wavelength radiation from overshoot due to phase transition at Planck epoch ~ 10^{31} K ~ 10^{19} GeV (Veryaskin, Rubakov, and Sazhin 1983).

PA17: Parametric amplification in Grand Unified Theory (GUT) phase transitions at ~10^{17} GeV (Korotun 1980).

EW: Gravitational waves generated by acoustic noise arising in the electroweak phase transition (~100 GeV) (Hogan 1986).

QCD: Gravitational waves generated by acoustic noise arising in the quark-hadron phase transition (~100 MeV) (Hogan 1986).

GALEQ: Gravitational waves produced by primordial fluctuations in an adiabatic collapse scenario for galaxy formation, assuming equipartition between density fluctuations and gravitational radiation (Zel'dovich and Novikov 1970).

Cosmic Strings: Spectrum produced by cosmic strings with dimensionless mass parameter per unit length $G\mu/c^2 \sim 10^6$ (appropriate to galaxy function). The break at period ~ P ~ 1 year is due to those that decay just at transition to matter domination in universe evolution. The peak near P = 300 years arises from the longest strings to have completely decayed by now. The P^{-1} fall-off at long periods arises because large cosmic strings have not yet completely radiated away. It must be understood that limits apply only to radiation produced prior to when the limiting mechanism is effective. See §III.A for a discussion of the apparent contradiction between the cosmic string and galaxy equilibrium production schemes and the nucleosynthesis limit. The dotted line shows the wave spectrum due to cosmic strings at the time t ~ 1 sec when nucleosynthesis begins.

BOUNDS

Qμ: The quadrupole microwave background limits very long wavelength radiation present prior to the redshift z of last scattering (decoupling) of the radiation. The strong limit here assumes that redshift was $z \sim 1{,}000$ (Carr, 1980, and references therein).

SSm: Small scale microwave limits waves with a scale comparable to the horizon size at last scattering, here assumed to be $z_d \sim 1{,}000$. Notice that this appears to put limits on QCD noise-generated, gravitational radiation. However, both Qμ and SSμ become much weaker if $z_d < 1{,}000$, as can be the case in some reionization scenarios (Carr, 1980, and references therein).

GALFORM: Galaxies must be gravitationally effective at $z \sim 1{,}000$ in order to condense. If the gravitational wave background is too large at that time, it prevents their formation (Carr, 1980).

NUC: A limit from cosmic nucleosynthesis. For periods P shorter than ~100 years, these are waves that were shorter than the horizon scale during nucleosynthesis and that scale with the background radiation.

S74: Limit on maximum density fluctuations and associated equipartition gravitational waves, based on limits on distortion of 2.7 K microwave background from dissipation of these fluctuations (Sunyaev, 1974).

RECENT COSMOLOGICAL SOURCES

Q1: Quasars as Supermassive Pulsars (Rosi and Zimmerman, (1976)

BIN: Late evolution in spiraling binaries (binaries consisting of stellar remnants, *i.e.*, black holes, neutron stars, white dwarfs) (Rosi and Zimmerman, 1976).

BINF: Main sequence binaries (Rosi and Zimmerman, 1976).

Q10: Quasars as supermassive black holes; see §II.a-7.

SMBH: Supermassive black hole binaries ($10^2 - 10^5\ M_\odot$)(Bond and Carr, 1984).

BHIII: Early black hole collapse from supermassive Population III stars (Rosi and Zimmerman, 1976).

BH: Black hole collapse from galactic stellar populations (Rosi and Zimmerman, 1976).

Q2: Quasars as sites of rapid stellar collapse (Rosi and Zimmerman, 1976).

Q4: Quasars as relativistic star clusters (Rose and Zimmerman, 1976).

87a: Peak flux from very optimistic estimate of supernova SN1987A (pulse length $\sim 10^{-2}$ seconds); see §II.b).

SN: Background due to galactic and extragalactic supernovae (Rosi and Zimmerman, 1976).

OBSERVATIONS (BOUNDS)

RTDA: Timing of Millisecond Pulsar PSR 1937+21 (Rawley, Taylor, Davis, and Allen, 1987).

RT: Timing of Pulsar PSR 1237+25 (Romani and Taylor, 1983).

P10: Pioneer 10 tracking data (Anderson and Mashhoon, 1985).

VI: Voyager I tracking data (Hellings, Callahan, Anderson, and Moffet, 1981).

S: Solar oscillation excitation limit (Boughn and Kuhn, 1984).

E: Earth oscillation excitation limit (Boughn and Kuhn, 1984).

L: Limit from lunar orbit constancy (Carr, 1980).

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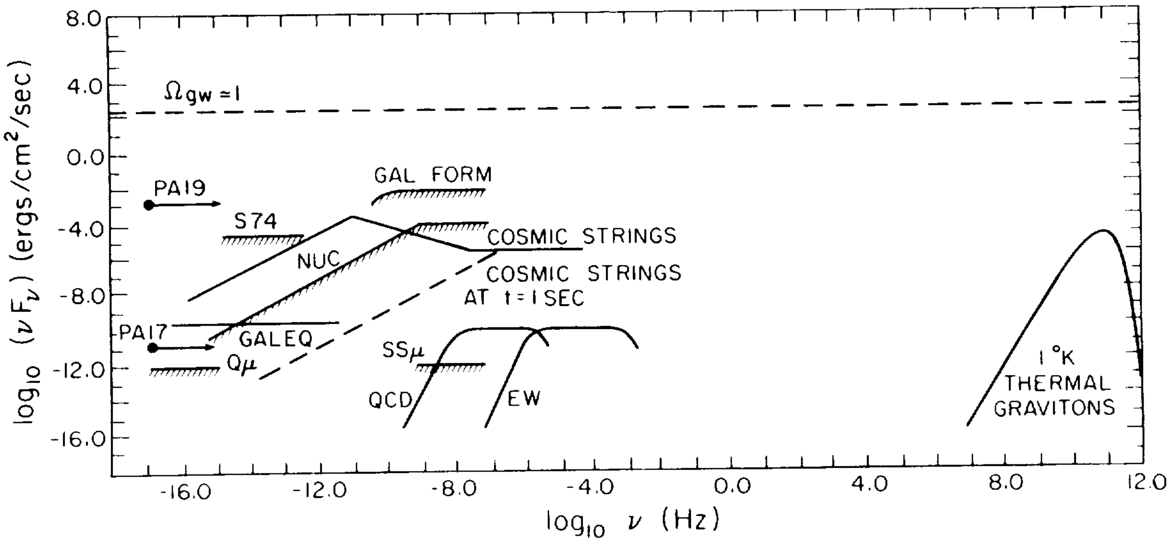

FIG. 1.— Logarithmic spectral flux for pregalactic sources of radiation and some inferred limits on their densities. Closure density $\rho_{closure} \sim 2 \times 10^{-29}$ gm/cm^3 (corresponding to $H_0 \sim 100$ km/sec/Mpc is at $\sim 6 \times 10^2$ ergs/cm^2/sec, shown here as a dotted line, so ordinary units have a significance on such a scale. For comparison, noon sunlight $\sim 10^6$ ergs/cm^2/sec, full moonlight ~ 1 erg/cm^2/sec, the 2.7 K microwave radiation $\sim 10^{-3}$ ergs/cm^2/sec. The waves appearing here are theoretical estimates for high energy, early cosmology processes; several indirect limits from cosmological observations are also indicated.

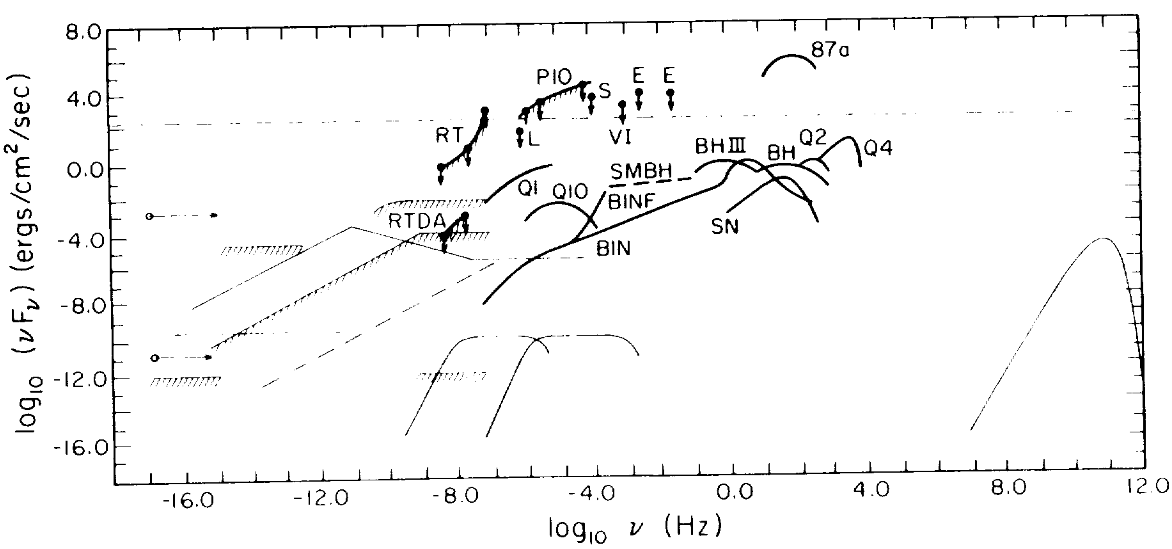

FIG 2.— Repeats Fig. 1, but includes a number of possible sources and indicates limits obtained from nonlaboratory-scale experiments (*i.e.*, including "Weber" bar and LASER detectors). It is expected that the new generation of cryogenic cooled bars and ground-based and space-based interferometers will provide sensitivity first in the dominant peak of the expected spectrum at ~ 100 Hz of Ω_{gw} 10^{-2} to 10^{-3}. Later such devices have the potential to be 5 to 7 orders more sensitive than the expected background limit in the 0.1-100 Hz range.