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Gravitational wave signals from the collapse of the first stars

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ABSTRACT

We study the gravitational wave emission from the first stars, which are assumed to be very massive objects (VMOs). We take into account various feedback (both radiative and stellar) effects regulating the collapse of objects in the early Universe and thus derive the VMO initial mass function and formation rate. If the final fate of VMOs is to collapse, leaving very massive black hole remnants, then the gravitational waves emitted during each collapse would be seen as a stochastic background. The predicted spectral strain amplitude in a critical density cold dark matter (CDM) universe peaks in the frequency range $\nu \approx 5 \times 10^{-4}$–$5 \times 10^{-3}$ Hz, where it has a value in the range $\approx 10^{-20}$–$10^{-19}\,\mathrm{Hz}^{-1/2}$, and might be detected by the *Laser Interferometer Space Antenna* (*LISA*). The expected emission rate is roughly 4000 event yr^{-1}, resulting in a stationary discrete sequence of bursts, i.e. a shot-noise signal.

Key words: gravitation – waves – galaxies: formation – intergalactic medium – cosmology: theory.

1 INTRODUCTION

Hierarchical models of cosmic structure formation predict that the first collapsed luminous objects (often referred to as Population III) should form at redshift $z \approx 30$, and have a total (i.e. dark+baryonic) mass $M \approx 10^6\,\mathrm{M}_\odot$ (Couchman & Rees 1986; Ciardi & Ferrara 1997; Haiman, Rees & Loeb 1997; Tegmark et al. 1997; Ferrara 1998; Nishi & Susa 1999; Ciardi et al. 2000, hereafter CFGJ). These properties are typically derived by requiring that the cooling time, t_c, of the gas is shorter than the Hubble time, t_H, at the formation epoch, but as we will see later (see CFGJ for a thorough discussion) several feedback effects could modify this conclusion. Particularly important is the correct treatment of the molecular hydrogen formation/destruction network, this molecule being the only efficient coolant for objects close to the above mass-scale.

As the collapse proceeds, the gas density increases and the first stars are likely to be formed. However, the final product of such star formation activity is presently quite unknown. This uncertainty largely depends on our persisting ignorance of the fragmentation process and on its relationship with the thermodynamical conditions of the gas. Ultimately, this prevents firm conclusions on the mass spectrum or the initial mass function (IMF) of the formed stars to be drawn. In the last two decades this problem has been tackled intermittently (Silk 1977; Kashlinsky & Rees 1983; Palla, Salpeter & Stahler 1983; Carr, Bond & Arnett 1984; Carr 1994; Uehara et al. 1996; Omukai & Nishi 1998). These studies, however, could not converge to the same conclusion on the typical mass range of newly formed stars in the first protogalactic objects. Roughly speaking, two possibilities have been proposed: either (i) very massive objects (VMOs), i.e. single stars with mass in the range 10^2–$10^5\,\mathrm{M}_\odot$ (or even larger) could be formed, or (ii) a more common stellar cluster, slightly biased towards low-mass stars, would emerge (or some combination of the two involving low-mass star coalescence to form a VMO). Early studies (Fricke 1973; El Eid, Fricke & Ober 1983; Ober, El Eid & Fricke 1983; Bond, Arnett & Carr 1984) of the physics of VMOs were left almost unfollowed in the literature, probably because observational evidence of the VMO hypothesis were lacking in the local Universe. The field has recently been rejuvenated by observations, such as the Pistol Star (Figer et al. 1998), a VMO with mass $\simeq 250\,\mathrm{M}_\odot$ and about 1 Myr old, and calculations (collected in the review by Larson 1998) indicating that at earlier times the IMF was top-heavy and that VMOs could be a plausible outcome of the process. This possibility would bear tremendously important consequences for the reionization and metal enrichment of the intergalactic medium, as well as for galaxy formation and the nature of the dark matter.

We propose here a test of the VMO hypothesis based on the detection of the gravitational waves (GWs) emitted during the collapse into very massive black holes in the late phases of their evolution. The extreme assumption is made that the stellar

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population of Population III objects is entirely comprised of VMOs with masses proportional to their parent objects. This allows us to estimate an upper limit to the cumulative GW signal from VMOs, and to compare it with forthcoming experimental apparatus (*LISA*). This proposal is an ideal development of the original suggestions made by Thorne (1978), Carr et al. (1984) and Bond & Carr (1984), and are made possible by an improved understanding of structure formation, properties of early objects and their GW-emission mechanisms. The method adopted here presents some similarities to the one outlined in Ferrari, Matarrese & Schneider (1999), although that work concentrated on the stochastic GW background produced by the core-collapse of standard supernovae at relatively low redshift.

2 THE FIRST STARS

The gas in a forming galaxy is initially virialized in the potential well of the parent dark matter halo and ignition of star formation is possible only if the gas can efficiently cool and lose pressure support. For a plasma of primordial composition at temperature $T < 10^4$ K, the typical virial temperature of the early bound structures, molecular hydrogen is the only efficient coolant. Thus, a minimum H_2 fraction $f_{H_2}^{\min} \approx 5 \times 10^{-4}$ is required for the gas to cool (Tegmark et al. 1997). As this value is typically more than 100 times the intergalactic relic H_2 abundance, it is necessary to study in detail the H_2 formation efficiency during the collapse phase. The condition $f_{H_2} > f_{H_2}^{\min}$ is only met by relatively large haloes, implying that for each virialization redshift there will exist some critical redshift dependent mass, $M_{\rm crit}$, such that only protogalaxies with total mass $M > M_{\rm crit}$ can eventually form stars. We can then associate each Population III object with $M > M_{\rm crit}$ with a corresponding baryonic collapsed mass $M_{\rm b} = \Omega_{\rm b} M$. Throughout the paper we adopt a value of the baryon density parameter $\Omega_{\rm b} = 0.06$.

However, this is only half of the story. In fact, photons from the first stars with energies in the Lyman–Werner band and above the Lyman limit, respectively, can photodissociate H_2 molecules and ionize H and He atoms in the surrounding IGM. This is the so-called *radiative feedback* that suppresses the formation of objects more massive than $M_{\rm crit}$ but with mass below $M_{\rm sh}$. The latter mass-scale corresponds to the minimum total mass required for an object to self-shield from an external flux of intensity $J_{s,0}$ at the Lyman limit. The dissociating flux is the sum of two separate contributions: the first arises from the background radiation produced by all luminous sources at a given redshift; the second comes instead from the direct flux of neighbouring objects. The relative importance of the two depends on the cosmic epoch. The detailed calculation of $M_{\rm sh}$ is rather complicated but it is fully described in CFGJ, hence we do not repeat it here. Protogalaxies with virial temperatures $T_{\rm vir} \gtrsim T_{\rm H} = 10^4$ K, corresponding to a mass $M_{\rm H} = 4.4 \times 10^9\,{\rm M}_\odot \times (1 + z_{\rm vir})^{-1.5}\,h^{-1}$ where $z_{\rm vir}$ is the redshift of virialization, for which cooling via Lyα-line radiation is possible, are not affected by the radiative feedback and are assumed to form stars unimpeded. These results are graphically shown in Fig. 1. For example, at $z \approx 15$ it is $6 \times 10^6\,{\rm M}_\odot \approx M_{\rm crit} < M_{\rm sh} < M_{\rm H} \approx 10^8\,{\rm M}_\odot$, depending on the value of $J_{s,0}$.

However, these results should be applied with a caveat to the situation presently analysed in which the luminosity in the early universe – and hence the radiative feedback – is dominated by VMOs rather than by standard stars with a Salpeter IMF, as assumed by CFGJ. The main problem is that the emission spectrum of VMOs in not known (although it is currently under investigation; Chiosi, private communication) and therefore the feedback effect cannot be calculated entirely self-consistently. To alleviate the problem we note that CFGJ concluded that the results are poorly sensitive to the exact form of the spectrum as long as it is of a soft, stellar type.

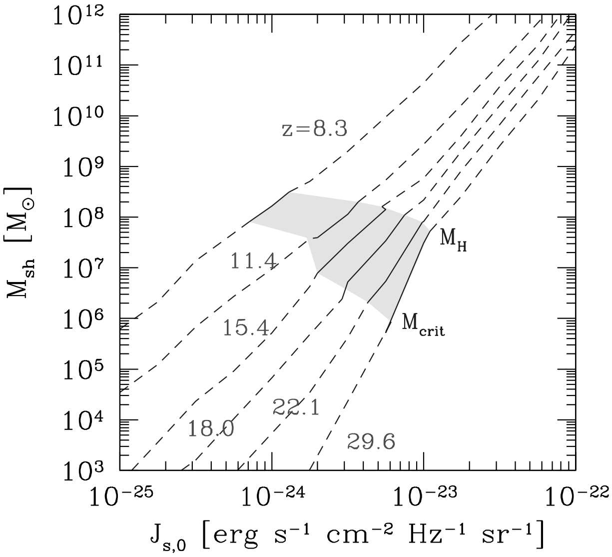

Figure 1. Minimum total mass for self-shielding from an external incident flux with intensity $J_{s,0}$ at the Lyman limit. The curves are for different redshifts: from top to bottom $z = 8.3$, 11.4, 15.4, 18.0, 22.1 and 29.6. Radiative feedback works in the shaded area delimited by the mass scales $M_{\rm H}$ and $M_{\rm crit}$ (see text).

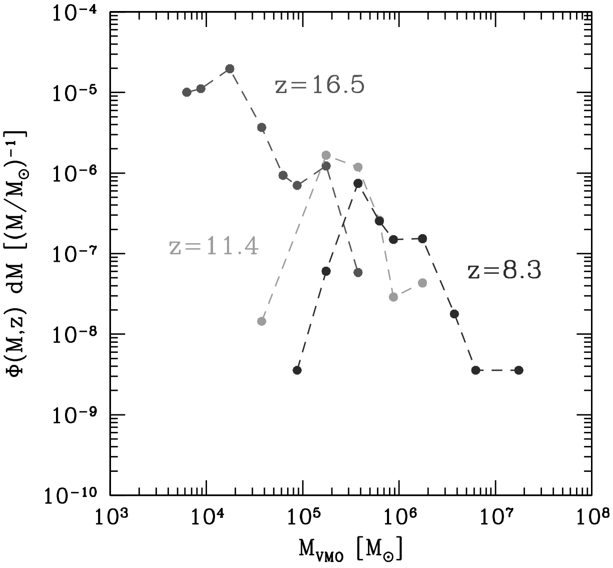

Figure 2. VMO initial mass function evolution at three different redshifts $z = 16.5$, 11.4 and 8.3.

In Fig. 2 we show the evolution of the VMO initial mass function, $\Phi(M, z)$, deduced from the simulations by CFGJ in which all the above effects have been included, for three different redshifts. These results have been obtained for a critical density cold dark matter (CDM) model ($\Omega_0 = 1$ and $h = 0.5$, with $\sigma_8 = 0.6$ at $z = 0$); as a consequence, all the results presented here refer to the same cosmological model. The mass of the VMO is determined here as $M_{\rm VMO} = f_{\rm b\star}M_{\rm b}$, with a baryon-to-star efficiency conversion $f_{\rm b\star} = 0.012$. As expected, the mass distribution shifts towards larger masses with time, but smaller masses cannot form because of the collapse conditions imposed. Together with the VMO IMF, we can directly calculate their formation rate from the curves given in fig. 11 of CFGJ, which we do not repeat here.

A great deal of uncertainty obviously remains on the upper mass limit of VMOs. As the mass of the parent Population III object becomes larger, it is increasingly difficult for the gas to collapse preventing fragmentation into lower mass stars (see, however, Silk & Rees 1998). Nevertheless, conditions could be suitable for the steady growth of a massive star through collisions with other intermediate mass stars. There is now a substantial amount of theoretical work on this subject, mostly on the formation of relatively massive stars ($M > 100\,{\rm M}_\odot$) in the local Universe and neglecting the effects of a massive dark matter halo as the one in which Population III objects are embedded (Bonnell, Bate & Zinnecker 1998; Portegies Zwart et al. 1999). The central VMO in the Population III cluster is then 'rejuvenated' by each new collision, and its lifetime is extended considerably as a consequence. When does this VMO mass build-up process come to an end? The usual argument based on the idea that radiation pressure from the VMO finally removes the gas producing the cluster expansion, with a consequent decrease in the stellar collision rate, is probably not appropriate in this context as the gravitational field (dominated by the dark halo) would only be very weakly affected. Also, radiation pressure might have been much less important in the absence of heavy elements.

What are the possible fates of VMOs? The answer depends essentially on their mass. Here we are interested in objects with $10^3\,{\rm M}_\odot \lesssim M \lesssim 10^7\,{\rm M}_\odot$, i.e. the span of the IMF in Fig. 2. Stars more massive than about $100\,{\rm M}_\odot$ are pair-production unstable (Fowler & Hoyle 1964). This process may lead to (Portinari, Chiosi & Bressan 1998) (i) violent pulsation instability with, finally, iron core instability, (ii) complete thermonuclear explosion or (iii) collapse to a black hole. Case (iii), the one of interest here, occurs for masses $M \gtrsim 200\,{\rm M}_\odot$ (but rotation might increase this value; Glatzel, El Eid & Fricke 1985). At higher masses ($M \gtrsim 10^5\,{\rm M}_\odot$) the evolution depends on the metallicity Z (Fricke 1973; Fuller, Woosley & Weaver 1986): if $Z \lesssim 0.005$ the star collapses to a black hole as a result of post-Newtonian instabilities without ignition of the hydrogen burning; for higher metallicities it explodes as it could generate nuclear energy more rapidly from the β-limited cycle. The former case appears to be appropriate here, as the metallicity level produced by reionization is only $Z \approx 6\times10^{-6}$ (CFGJ) and is likely to be even smaller if the nucleosynthetic products are swallowed by black holes. These conclusions are based on the detailed simulations by Fuller et al. (1986) that extend up to stellar masses $M = 10^6\,{\rm M}_\odot$. It must be pointed out that if some fraction of dark matter is present (at the level of about 0.1–1 per cent of the VMO central density), the onset of post-Newtonian instability can be delayed and the hydrogen burning ignited; however, this *favours* the collapse to a black hole rather than the explosion, as shown by McLaughlin & Fuller (1996). Above $10^6\,{\rm M}_\odot$ the study is tremendously complicated by the necessity of taking into account general relativity effects that can influence the stability and evolution of the stars. Little is know about these supermassive objects (SMOs) although promising investigations are underway (Baumgarte & Shapiro 1999; Baumgarte, Shapiro & Shibata 2000). In order not to add additional uncertainty sources to our calculation *our main results are limited to VMOs with* $M \leqslant 10^6\,{\rm M}_\odot$. However, because of the interesting nature of these objects, based on the preliminary findings of Baumgarte & Shapiro (1999), we will also separately discuss the GW signal produced by the largest objects present in the derived IMF.

3 GW EMISSION FROM VERY MASSIVE BLACK HOLE (VMBH) COLLAPSE

The properties of the gravitational radiation emitted during the stellar collapse to a black hole have been extensively investigated during the past 20 years (see Ferrari & Palomba 1998 for a recent review). The gravitational energy is released in a short initial broad-band burst with efficiency $\epsilon_{\rm g}$ so that the total gravitational energy emitted is $\epsilon_{\rm g}M_{\rm B}c^2$, where $M_{\rm B}$ is the mass of the newly formed hole (Thorne 1986). The values of $\epsilon_{\rm g}$ found both in pertubative approaches and in fully numerical simulations came out quite low. For an axisymmetric collapse, the efficiency is less than $\sim 7\times10^{-4}$ (Stark & Piran 1985). However, if the star is rotating sufficiently rapidly to undergo a dynamical bar mode instability prior to forming the black hole, then the energy released in gravitational waves can be substantially higher (Smith, Houser & Centrella 1995). Therefore, the collapse of a VMO promises to be a very interesting source for gravitational wave detection.

For the sake of simplicity, we assume that the gravitational energy released during each collapse, $\Delta E_{\rm g} = \epsilon_{\rm g}M_{\rm B}c^2$, is emitted in a broad-band burst centred at a frequency $\nu_0 = c/10R_{\rm g}$, which corresponds to a wavelength of order 10 times the Schwarzschild radius, $R_{\rm g} = 2\ G\ M_{\rm B}/c^2$, associated with the hole (Thorne 1978; Carr et al. 1984). The spectrum of gravitational waves emitted during the collapse can be approximated to a Lorenzian,

$$\frac{{\rm d}E}{{\rm d}\nu} = \frac{\Delta E_{\rm g}}{\nu_0\mathcal{N}}\frac{\nu^2}{(\nu-\nu_0)^2+\Gamma^2}, \tag{1}$$

where $\Gamma = (2\pi\Delta t)^{-1}$ and $\Delta t = 1/\nu_0$ is the typical duration of the burst, $\nu_0\mathcal{N}$ is the normalization,

$$\nu_0\mathcal{N} = \int_0^{\nu_{\rm max}/\nu_0}{\rm d}\tilde\nu\,\frac{\tilde\nu^2}{(1-\tilde\nu)^2+0.03},$$

with $\tilde\nu = \nu/\nu_0$ and $\nu_{\rm max} = c/R_{\rm g}$, the maximum frequency emitted by the source. While the available theoretical waveforms are too uncertain to warrant a more elaborate analysis, this crude approximation highlights well the main features and assumptions of the model.

The average gravitational flux emitted by a source at a distance r can be easily shown to be

$$\left\langle\frac{{\rm d}E}{{\rm d}\Sigma\,{\rm d}\nu}\right\rangle = \frac{1}{4\pi r^2}\int{\rm d}\Omega\left[\frac{{\rm d}E}{{\rm d}\Omega\,{\rm d}\nu}\right] = \frac{1}{4\pi r^2}\frac{{\rm d}E}{{\rm d}\nu}. \tag{2}$$

For sources at cosmological distances, the above expression can be immediately generalized to

$$\left\langle\frac{{\rm d}E}{{\rm d}\Sigma\,{\rm d}\nu}\right\rangle = \frac{(1+z)^2}{4\pi d_{\rm L}(z)^2}\frac{{\rm d}E_{\rm e}[\nu(1+z)]}{{\rm d}\nu_{\rm e}}, \tag{3}$$

where $\nu = \nu_e(1+z)^{-1}$ is the redshifted emission frequency $\nu_{\rm e}$, and $d_{\rm L}(z)$ is the luminosity distance to the source.

4 PREDICTIONS AND IMPLICATIONS

If the final fate of VMOs is to collapse, leaving VMBH remnants, then the overall effect of the gravitational waves emitted during each collapse would be observed today as a stochastic background. The signal produced by these events can be computed integrating the gravitational signal contributed by each source over the differential source formation rate,

$$\frac{\mathrm{d}E}{\mathrm{d}\Sigma\,\mathrm{d}\nu\,\mathrm{d}t}(\nu) = \int\!\!\int \mathrm{d}z\,\mathrm{d}M\Phi(M,z)\frac{\dot{\rho}(z)}{(1+z)}\left\langle\frac{\mathrm{d}E}{\mathrm{d}\Sigma\,\mathrm{d}\nu}\right\rangle\frac{\mathrm{d}V}{\mathrm{d}z}, \qquad (4)$$

where $\dot{\rho}(z)/(1+z)$ is the VMO cosmic formation rate per comoving volume obtained from the CFGJ simulations.

The spectral energy density allows the evaluation of the corresponding spectral strain amplitude,

$$S_{\mathrm{h}}(\nu) = \frac{2G}{\pi c^3}\frac{1}{\nu^2}\frac{\mathrm{d}E}{\mathrm{d}\Sigma\,\mathrm{d}\nu\,\mathrm{d}t}(\nu). \qquad (5)$$

Clearly, the relevant parameters that determine the amplitude and the location of the signal are the efficiency, ϵ_{g}, and the fraction of the initial mass that participates in the collapse, $\phi_{\mathrm{B}} = M_{\mathrm{B}}/M$. The value of ϕ_{B}, as well as its dependence on M, is very uncertain. For an axisymmetric collapse, only about 10 per cent of the initial stellar mass collapses to the final black hole (Stark & Piran 1985). However, Baumgarte & Shapiro (1999) suggest that for $M \gtrsim 10^6\,\mathrm{M}_{\odot}$ only a few percent of the initial mass is left outside of the black hole, most likely in the form of a disc. Thus, it is not unreasonable to assume that ϕ_{B} may vary in the range 0.1–0.9 (see also Carr et al. 1984).

The stochastic background signal predicted by our model is shown in Fig. 3 for $\epsilon_{\mathrm{g}} = 10^{-4}$ and $\phi_{\mathrm{B}} = 0.1$. There we compare the spectral energy density produced by pre-galactic VMBHs to the more recent contribution from core-collapse SNe at $z < 6$ (see Ferrari et al. 1999). Owing to their larger masses, the gravitational signal from the birth of VMBHs falls at much shorter wavelengths than that produced by core-collapse SNe.

In spite of their great distances, pre-galactic VMOs produce a background signal that adds, as a confusion noise component, to the *LISA* sensitivity curve in the range 10^{-3}–10^{-2} Hz (see Fig. 4) for the parameters assumed in the model. Thus, we expect that *LISA* will be able to place an upper limit on the intensity of the Population III background signal in this frequency range.

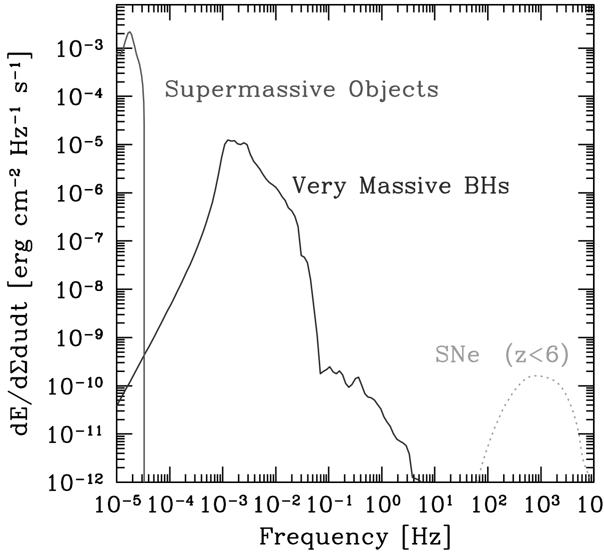

Figure 3. Stochastic background signal produced by the VMBHs remnants of Population III stars and by core-collapse SNe leaving black hole remnants at $z < 6$. The background signal produced by VMBHs is computed assuming $\epsilon_{\mathrm{g}} = 10^{-4}$ and $\phi_{\mathrm{B}} = 0.1$ (see text). Also shown is the contribution from the collapse of supermassive ($M \gtrsim 10^6\,\mathrm{M}_{\odot}$) objects.

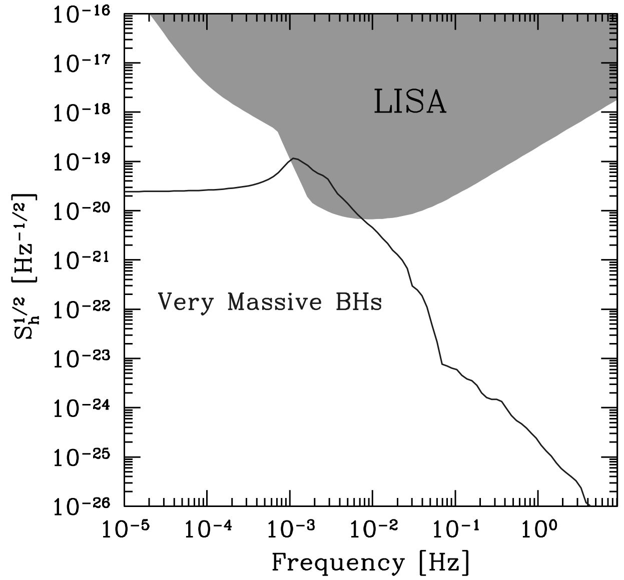

Figure 4. The spectral strain amplitude of the Population III stars signal (assuming $\epsilon_{\mathrm{g}} = 10^{-4}$ and $\phi_{\mathrm{B}} = 0.1$) is compared to the sensitivity curve of the *LISA* space interferometer. The *LISA* sensitivity curve accounts for both the instrumental noise component and for the confusion noise component arising from double white dwarfs binaries (Bender & Hils 1997).

4.1 Contribution from supermassive objects

In Fig. 3 we also show a crude estimate of the signal produced by VMOs with masses $\gtrsim 10^6\,\mathrm{M}_{\odot}$, which undergo a dynamical bar instability before the final implosion. This possibility has been recently discussed by Baumgarte & Shapiro (1999). They investigated the secular evolution of supermassive stars (SMSs) with masses $\gtrsim 10^6\,\mathrm{M}_{\odot}$ up to the onset of the instability. The gravitational efficiency of the collapse, as well as the detailed waveforms of the resulting signal, can be definitely assessed only with a numerical three-dimensional hydrodynamics simulation in general relativity (Baumgarte et al. 2000). However, based on simple arguments, these authors suggest that the collapsing star may form a non-axisymmetric bar before it forms a black hole.

Numerical simulations of the dynamical bar mode instability in compact stellar cores with a stiff equation of state ($n < 1.5$) have shown that a burst of gravitational radiation is emitted with an efficiency ϵ_{g} ranging between 10^{-4} and 10^{-2}, depending on the initial equatorial radius of the bar R_{eq} and on the polytropic index (Houser & Centrella 1996). The burst is centred at a frequency $\sim 2\nu_{\mathrm{bar}}$, where ν_{bar} is the rotation frequency of the bar,

$$\nu_{\mathrm{bar}} = \frac{1}{2\pi}\left(\frac{GM}{R_{\mathrm{eq}}^3}\right)^{1/2}.$$

The width of the gravitational burst sensitively depends on the polytropic index: stiffer models undergo several episodes of bar formation and recontraction, emitting a sequence of bursts of decreasing amplitude. The structure of SMSs with $M \gtrsim 10^6\,\mathrm{M}_\odot$ is that of an $n = 3$ polytrope (Baumgarte & Shapiro 1999) and it is reasonable to assume that the radiation emitted would be concentrated in a single burst of width $\sim 2\nu_{\rm bar}$. Following Baumgarte & Shapiro (1999), we assume

$$R_{\rm eq} \sim 1.5 R_{\rm pol} \qquad \text{and} \qquad R_{\rm pol} \sim \frac{15\,GM}{c^2},$$

where $R_{\rm pol}$ is the polar radius at the onset of the bar instability. With these parameters, we model the spectrum emitted by a VMO with $M > 10^6\,\mathrm{M}_\odot$ using equations (1) and (3) with an efficiency $\epsilon_{\rm g} = 10^{-4}$ and $\phi_{\rm B} = 0.1$.

As it can be seen from Fig. 3, these objects produce a significant signal at frequencies $<10^{-4}$ Hz, too small to be detectable with *LISA*.

4.2 Rates and duty cycle

The rate of VMBH formation is shown in Fig. 5 as a function of redshift. The total number of VMBHs formed per unit time is $N_{\rm VMBH} \sim 4000\,\mathrm{event\,yr^{-1}}$. The ratio of the duration of each burst to the separation between successive bursts, i.e. the duty cycle, given by

$$\frac{\mathrm{d}DC(z)}{\mathrm{d}z} = \frac{\dot{\rho}(z)}{(1+z)} \frac{\mathrm{d}V}{\mathrm{d}z} \frac{(1+z)}{\nu_0} \int \mathrm{d}M \Phi(M, z), \tag{6}$$

is also shown in Fig. 5 as a function of z. It is clear that the overlap condition, $DC > 1$, is not satisfied even if we consider all VMOs out to the farthest z. Thus we find, contrary to previous claims (Carr et al. 1984), that VMBHs originating from Population III stars do not generate an overlapping background but rather a stationary discrete sequence of bursts, i.e. a shot-noise signal (see also Ferrari et al. 1999).

Thus, although a stochastic background at comparable frequencies and amplitude might have been generated in the very early universe, it would still be possible to disentangle any Population III gravitational signature through this peculiar shot-noise character.

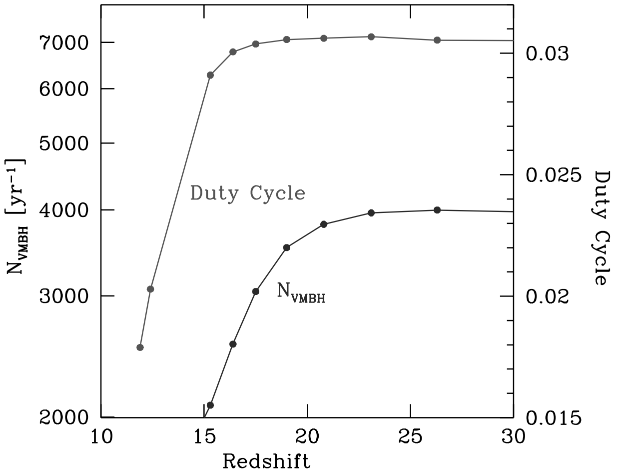

Figure 5. Rate of VMBH formation and duty cycle of the gravitational-wave signal produced by VMBH collapses as a function of redshift.

5 SUMMARY AND DISCUSSION

We have investigated the gravitational wave emission from the collapse of very massive objects formed in the early universe. The presence of such objects would bear tremendously important consequences for the intergalactic medium reionization, the generation of the first metals and for their contribution to the dark matter in the Universe.

The predicted spectral strain amplitude in a critical density CDM universe peaks in the frequency range $\nu \approx 5 \times 10^{-4}$–$5 \times 10^{-3}$ Hz where it has a value in the range $\approx 10^{-20}$–$10^{-19}\,\mathrm{Hz}^{-1/2}$, which is above the *LISA* sensitivity curve. The expected emission event rate is roughly $4000\,\mathrm{event\,yr^{-1}}$, resulting in a stationary, discrete sequence of bursts, i.e. a shot-noise signal. The issue of the actual detectability of our signal by *LISA* is more complex as cross-correlation techniques, which would be needed to disentangle a stochastic background from the noise, cannot be applied here (see e.g. Flanagan & Hughes 1998). So, any background would actually add as a confusion limited noise component to the *LISA* instrumental noise. In this sense *LISA* will place an upper limit to the amplitude of our signal. On the other hand, the predicted stochastic background has a shot-noise structure, similar to the background produced in the high frequency bandwidth by the core-collapse to black holes in standard supernovae at $z \lesssim 6$ (Ferrari et al. 1999, see Fig. 3).

Thus, standard detection techniques, which have been developed for continuous stochastic signals, can be applied only if the integration time of the antenna is much longer than the typical separation between two successive bursts (of the order of a few hours for the present study).

Specific techniques should be investigated in order to assess how far the shot-noise structure can be exploited to help the detection or, at least, to distinguish the signal from the instrumental noise or from continuous backgrounds contributing in the same band.

Our underlying assumption, that down to $z \approx 10$ fragmentation in collapsing cosmological objects is inhibited by the absence of metals (and therefore only very massive stars are formed), is clearly strong and at present untestable, but not an unreasonable one. The motivation behind this assumption is that it allows us to estimate an upper limit to the expected gravitational wave emission from this population of astrophysical objects. The growth of the metallicity level in the Universe not only favours fragmentation of the gas but also quenches the formation of VMBHs as these objects tend to explode, as discussed in Section 2. For these reasons the GW contribution from collapsing VMOs can only come from redshifts higher than approximately 10.

Some details of the calculation are uncertain, as for example the exact shape of the GW emission spectrum from a collapsing VMO. However, a different choice of the spectrum (i.e. the one suggested by Stark & Piran 1985) produces only a slight difference in the integrated spectral energy distribution. Indeed, the expected signal could be even higher than that predicted here if the conversion efficiency of the total gravitational energy into GWs is higher than the value 10^{-4} used here, as suggested by some previous studies (the amplitude of the GW signal is $\propto \epsilon_{\rm g}$).

According to our predictions, detecting a GW signal from VMOs will become possible with the new class of GW detectors such as *LISA*. This would enable direct testing of epochs and objects that would otherwise be difficult to reach with other instruments, at best not in the near-future. This experiment could also provide stringent limits to the cosmic star formation history at redshifts $z > 10$ and allow us to investigate the physics and properties of the first stars in the Universe. The remnants of such primordial objects could still be present in the haloes of galaxies like our own (for an excellent review see Carr 1994). The type of BH remnants discussed here are interesting dark matter candidates (see also Nakamura et al. 1997; Ioka, Tanaka & Nakamura 1999): gravitational lensing effects measured from the line-to-continuum variation of quasars suggest that the lensing objects in the intervening galaxies have a mass in the range 3×10^4–$3 \times 10^7\,\mathrm{M}_\odot$ (Subramanian & Chitre 1987). However, the upper end of this interval might be constrained to be $\lesssim 10^6\,\mathrm{M}_\odot$ by either dynamical (heating of disc stars; Lacey & Ostriker 1985) or luminosity (accretion of gas in the haloes of galaxies; Ipser & Price 1977; Hegyi, Kolb & Olive 1986) constraints. Interestingly enough, this interval appears not only to well match the predicted VMO IMF (see Fig. 2), but also to provide a GW signal that might be detectable by *LISA*.

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