The Astrophysical Journal, 608:L45–L48, 2004 June 10

THE FIRST STELLAR BINARY BLACK HOLES: THE STRONGEST GRAVITATIONAL WAVE BURST SOURCES

Krzysztof Belczynski,[1,2] Tomasz Bulik,[3] and Bronislaw Rudak[3]
Received 2004 March 15; accepted 2004 April 26; published 2004 May 10

ABSTRACT

The evolution of the first populations of massive metal-free and metal-poor binary stars is followed. Such stars may form with large initial masses and evolve without significant mass loss. Stellar evolution at low metallicity may lead to the formation of intermediate-mass black holes (∼100–500 $M_{\odot}$) in the early universe, in contrast to the much lower mass black holes (∼10 $M_{\odot}$) formed at present. Following the assumption that some of these Population III stars have formed in binaries, we present the physical properties of the first stellar binary black holes. We find that a significant fraction of such binary black holes coalesce within the Hubble time. We point out that a burst of gravitational waves from the final coalescences and the following ringdown of these binary black hole mergers can be observed in the interferometric detectors. We estimate that the advanced Laser Interferometer Gravitational-Wave Observatory detection rate of such mergers ranges from several to a thousand events per year with a high signal-to-noise ratio ($\gtrsim 10$) for a number of evolutionary models. We also identify assumptions that preclude the formation of massive binary black holes and point out what could be learned from the lack of detection of their mergers.

Subject headings: binaries: close — black hole physics — gravitational waves

1. INTRODUCTION

The properties of Population III stars have stirred up a lot of interest in recent years. It has been realized that zero-metallicity stars with masses up to several hundred solar masses are stable (Baraffe et al. 2001). Heger & Woosley (2002) estimated black hole (BH) masses formed in the evolution of high-mass metal-free stars. For initial masses above 40 $M_{\odot}$, the remnant is a BH with the mass essentially the same as the progenitor with the exception of stars with initial masses between 140 and 260 $M_{\odot}$, which undergo pair instability supernova (SN) explosions and leave no remnant at all. Numerical simulations (Bromm et al. 1999, 2002; Omukai & Palla 2003) indicate that the initial mass function (IMF) of Population III stars is top-heavy and might be bimodal with the high-mass peak around 100 $M_{\odot}$ (Larson 1998; Nakamura & Umemura 2001; Chabrier 2003). Although it is generally accepted that reionization and early metal enrichment were due to the first very massive stars, it was demonstrated that the first stellar population with a Salpeter-like IMF reaching only 140 $M_{\odot}$ may account for the most recent observations as well (Tumlinson et al. 2004).

Recent studies of the collapse of a metal-free gas cloud (Ripamonti & Abel 2004) seem to preclude fragmentation and formation of binary systems. However, the small (<1%) binary fraction in the metal-free population cannot be excluded even in the most recent three-dimensional simulations (T. Abel 2004, private communication). Once the very first (metal-free) stars evolved and ended their lives, the surrounding gas was heated up by energetic UV photons and enriched with metals. The conditions for the formation of the next generation of stars were changed. In particular, it was demonstrated (Bromm & Loeb 2003) that for metallicities $Z \gtrsim 10^{-3.5}\ Z_{\odot}$, found in the intergalactic medium at redshifts of ∼5 (Songaila 2001), the fragmentation is efficient. In the epoch between the formation of the very first metal-free stars and the later epoch of metal-rich star formation, there was a period when stars slightly enriched with metals may have existed (Mackey et al. 2003). Evolution at very low metallicity may also lead to the formation of massive BHs (Heger et al. 2003). In our study, we allow for the possibility of low-level binary formation for metal-poor and metal-free early stellar populations. Wyithe & Loeb (2003) considered the hierarchical buildup of supermassive BHs by mergers of single massive BHs (the end products of Population III single stars) and studied the expected Laser Interferometer Gravitational-Wave Observatory (LIGO) detection rate. Here we *assume* a small binary fraction for Population III stars and investigate their subsequent evolution. There is a possibility (noted already by Wyithe & Loeb 2003) that the first binary stars formed massive BH-BH systems. We explore the formation of these BH-BH binaries and point out that tight systems coalesce and may be observable in gravitational waves by the interferometric detectors.

2. EVOLUTIONARY MODEL

A simple model of the evolution of Population III stars was constructed. Lacking the observational input, we used a set of recent calculations for metal-free and metal-poor single stars and then combined them with the basic binary evolutionary prescriptions. Using the numerical calculations of stellar tracks for Population III stars (Baraffe et al. 2001; Marigo et al. 2001; Schaerer 2002), we obtained the evolutionary timescales and radial expansion histories of such stars as a function of their initial mass. After the core hydrogen exhaustion, we calculate the He core mass for a given star using the approximate empirical formula of Heger & Woosley (2002). Once a star has finished its nuclear evolution, we follow the work of Heger et al. (2003) to decide on the core collapse outcome. Depending on the initial star mass, the low-metallicity massive star may either collapse directly and form a BH (without an accompanying SN explosion) or be entirely disrupted (no remnant left) in a pair instability SN (stars within an initial mass range of 140–260 $M_{\odot}$). In the former case, the total mass of a collapsing star forms a BH, and we assume that there is no natal kick associated with direct BH formation. The pulsational pair instability is also taken into account as it may remove part of the star envelope just prior to

[1] Department of Physics and Astronomy, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208; belczynski@northwestern.edu.
[2] Lindheimer Postdoctoral Fellow.
[3] Nicolaus Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland; bulik@camk.edu.pl, bronek@ncac.torun.pl.

TABLE 1
BH-BH Formation Channels

Channel	Evolutionary Sequence[a]	Efficiency
bhbh01	BH1 BH2	0.67
bhbh02	MT1 BH1 CE2 BH2	0.15
bhbh03	MT1 BH1 MT2 BH2	0.07
bhbh04	BH1 MT2 BH2	0.05
bhbh05	All others	0.06

[a] BH1/BH2: first/second BH formation. CE: Common envelope. MT: Nonconservative RLOF, where 1 or 2 denotes the donor, either primary or secondary, respectively.

the collapse (Heger et al. 2003). We assume that half of the envelope is lost for the stars with initial mass 100–140 $M_\odot$.

The orbit of each binary is assumed to be circular, and the orbital separation is drawn from a distribution flat in logarithm. The minimum orbital separation is chosen such that the components do not fill their Roche lobes at the zero-age main sequence, with the maximum value of 10^6 $R_\odot$. Since little is known about the shape of the IMF of Population III stars, we adopt a power-law shape with $\alpha = -2$ exponent and draw the primary (initially more massive component) mass from such a distribution in the range of 100–500 $M_\odot$. The secondary mass is obtained through the mass ratio (secondary/primary), which is drawn from a flat distribution. Radial expansion of the components is followed and may lead to the Roche lobe overflow (RLOF). For unevolved (main sequence) donors, we assume that the RLOF will always lead to the component merger, thus terminating further evolution and aborting potential BH-BH formation. For evolved donors, we check whether the RLOF may lead to dynamical instability. If the donor mass is larger than twice the accretor mass ($q_{crit} = 2$), we apply the standard common envelope (CE) prescription (Webbink 1984) with 100% efficiency of in-spiral orbital energy conversion into the envelope ejection. Otherwise, we use the nonconservative evolution with half of the transferred material leaving the system with the angular momentum specific to a given binary (Belczynski et al. 2002). Unevolved stars are rejuvenated by accretion and may reach larger radii than their initial mass would have suggested, while the evolved stars are allowed only to increase their mass. Once a BH-BH binary is formed, the orbit decay time due to gravitational wave emission is calculated.

3. RESULTS

3.1. *Formation and Properties of a BH-BH Population*

A large set ($N_{tot} = 10^6$) of Population III binaries, described in § 2, is evolved. Evolution leads to efficient formation of BH-BH systems (38%), despite the fact that a significant fraction of binaries cease to exist when one of the components is disrupted in a pair instability SN (46%) or components merge in an RLOF event (16%). Major evolutionary channels along with BH-BH formation efficiencies are listed in Table 1. Most of the progenitor systems form on wide orbits and never interact (channel bhbh01). Systems formed on the tight orbits interact twice, as first the primary then the secondary overfill their Roche lobes (bhbh02, bhbh03). Systems formed on the intermediate orbits interact only once; depending on the maximum component radii and the mass ratio, RLOF is initiated by either the secondary (bhbh04) or the primary (within bhbh05).

In Figure 1, we present the distribution of the coalescence times for the BH-BH populations. A significant fraction of BH-BH systems (0.17) coalesces within the Hubble time (15 Gyr).

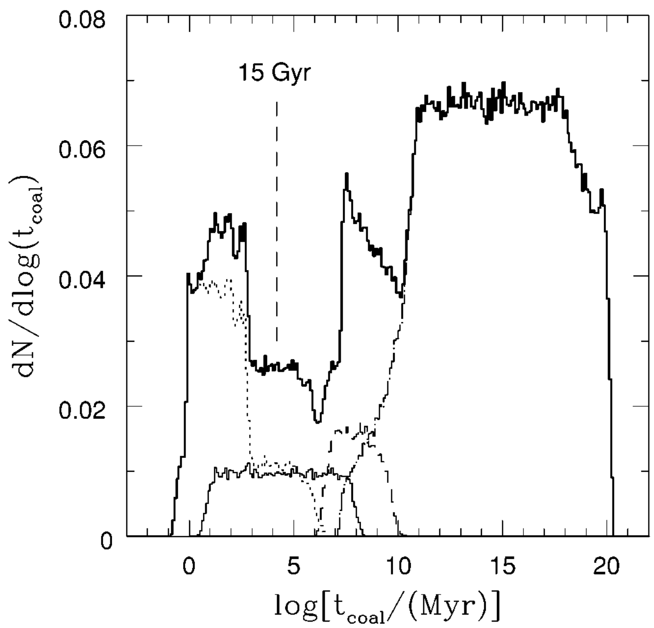

Fig. 1.—Distribution of BH-BH coalescence times (*thick solid line*) normalized to unity. In addition, main subpopulations, which have evolved to the BH-BH stage along different evolutionary channels, are presented with thin lines: bhbh01 (*long-dash– dotted line*), bhbh02 (*dotted line*), bhbh03 (*solid line*), and bhbh04 (*short -dashed line*). Note that the subpopulation of systems formed along bhbh05 channels with $\log t_{coal} \sim 3$–10 is not shown. For the definition of channels, see Table 1.

Binaries with short and intermediate initial periods interact and tend to either form tight BH-BH systems or merge in RLOF. Various subpopulations of BH-BH systems are shown in Figure 1. The stronger (CE in the case of bhbh02 as compared to nonconservative mass transfer) or more frequent interactions (two interactions in bhbh03 vs. one in bhbh04) lead to a shorter coalescence time for the BH-BH binary. Large coalescence times are found for systems that never interacted and basically remained on the unchanged wide orbits throughout the evolution (bhbh01). Systems with large coalescence times dominate the population, since they have formed without interactions (wide orbits) and avoided the possibility of a component merger in RLOF events. Binary BHs found in our calculation cover a wide range of masses: 50–500 and 40–620 $M_\odot$ for the first and the second BH formed in a system, respectively. The total mass of BH-BH binaries spans the wide range $M = 100$–$1000\ M_\odot$, with most of the systems forming with $M = 100$–$200\ M_\odot$. The distribution of masses of the remaining population peaks at $M = 350\ M_\odot$ and has a tail extending up to $M = 1000\ M_\odot$.

3.2. *Observability in Gravitational Waves*

The signal-to-noise ratio (S/N) from each phase of a coalescence (in-spiral, merger, and ringdown) in the interferometers has been calculated by Flanagan & Hughes (1998). The typical total mass of a BH binary in the population considered is quite large and reaches above a few hundred solar masses. The in-spiral signal for such massive binaries is very low since it falls outside the maximum sensitivity range. However, the merger and ringdown signals for the advanced LIGO detector peak for the redshifted total masses at 100–2000 $M_\odot$.

We calculate the observed coalescence rates following the formalism in Bulik et al. (2004; see also Bulik & Belczynski 2003). We estimate the comoving rate of Population III star formation R_{sfr} that satisfies the following: (1) the formation of

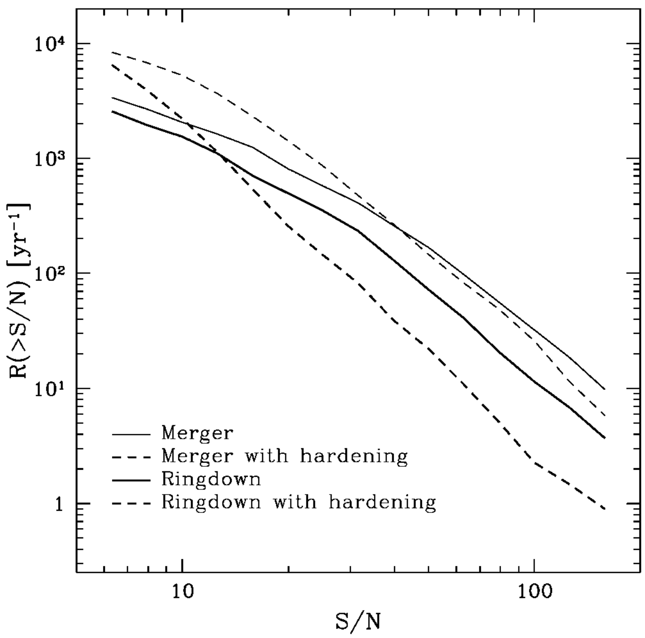

FIG. 2.—Expected observed coalescence rate of Population III BH-BH binaries as a function of S/N for the advanced LIGO detector. The thick lines correspond to the detection of the ringdown signal and the thin lines to the detection of the merger (burst) signal. Solid lines are for isolated orbital decay of BH-BH systems, while dashed lines represent the case when binaries are hardened in a dense environment (see text for details).

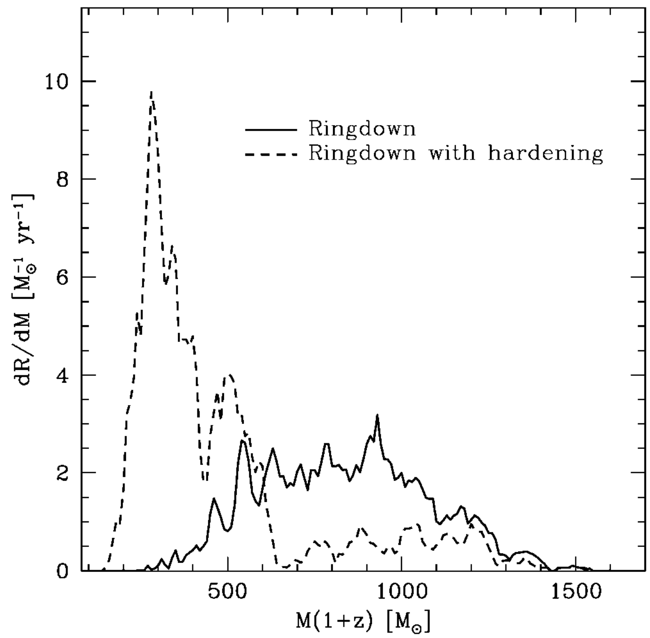

FIG. 3.—Differential rate as a function of observed (redshifted) total mass of a BH-BH system. In this calculation, we required a detection with high S/N (>10).

Population III stars occurs at a constant rate at redshifts z from 30 to 10, and (2) $f_{\rm mass} = 10^{-3}$ of baryonic matter goes into the Population III stars (Madau & Rees 2001). We adopt a flat cosmology with density parameter of matter $\Omega_m = 0.3$, density parameter of cosmological constant $\Omega_\Lambda = 0.7$, and Hubble constant $H_0 = 100\ h$ km s^{-1} Mpc^{-1}, with $h = 0.65$. We obtain $R_{\rm sfr} \simeq 1.4 \times 10^{-2}\ M_\odot$ Mpc^{-3} yr^{-1}. We assume that the binary fraction in Population III stars is $f_b = 10\%$ and that the IMF below 100 $M_\odot$ is flat and extends down to 1 $M_\odot$. We calculate the differential merger rate as a function of redshift $df_{\rm coal}(z)/dM$, taking into account the delay between formation and coalescence due to gravitational in-spiral. The differential coalescence rate per unit observed mass is

$$\frac{dR}{dM_{\rm obs}} = \int_0^{z_{\rm max}} \frac{df_{\rm coal}(z)}{dM} \frac{1}{1+z} \frac{dV}{dz}\, dz, \qquad (1)$$

where $M_{\rm obs} = M(1+z)$ is the observed (redshifted) total mass, $z_{\rm max}$ is the maximum redshift out to which a binary is observable, and dV/dz is the comoving volume element. The maximum redshift $z_{\rm max}$ is estimated using the S/N values estimated by Flanagan & Hughes (1998) for the advanced LIGO detector.

We present the expected rates for the advanced LIGO detector as a function of the value of the S/N threshold as solid lines in Figure 2. The curves for the merger and ringdown phases are similar because of the similarity of the dependence of S/N on the masses of the system in the two cases. Population III BH-BH binaries might have populated dense stellar environments in young galaxies. If this was the case, their coalescence times could have been significantly shortened owing to the additional orbital decay by three-body interactions. We estimate the observed coalescence rates in the alternative model in which we allow for additional orbital decay due to the dynamical hardening through simple orbital shrinkage for all BH-BH binaries. Orbits are tightened by a factor of 10, causing the decrease of the coalescence times by $\sim 10^4$. The corresponding rates are shown in Figure 2. Hardening does not have a strong impact on the observed rates because of two opposing effects. On one hand, the tight binaries merge at higher redshifts and their detectability drops. On the other, the large population of wide noncoalescing binaries is shifted to shorter coalescence times, and in particular some may add to the predicted detection rate when hardening is included.

The redshifted total mass of the system is the principal quantity that can be inferred from the observation of a ringdown signal. In Figure 3, we present the observed rate as a function of the redshifted total mass, requiring a detection with S/N = 10. The typical redshifted total mass lies between 600 and 1000 $M_\odot$. In the case of the alternative model with hardening included, the typical value shifts down to $\approx 300\ M_\odot$. This is due to the fact that originally long-lived binaries contain lighter BHs. A merger signal calculation leads to similar results.

4. DISCUSSION

The principal result of the calculations is presented in Figure 2. The expected coalescence rate of Population III intermediate-mass BH-BH binaries is high for our standard model calculation. We predict that the advanced LIGO detector should observe more than a thousand strong (S/N $\gtrsim$ 10) events per year. What are the uncertainties of this prediction?

In our calculation, we have assumed that Population III stars were formed at redshifts z from 30 to 10 out of $f_{\rm mass} = 10^{-3}$ of the baryon mass contained in the universe and that the binary fraction of the initial population was $f_b = 10\%$. The exact length and duration of the Population III star formation era does not affect the rate calculation. However, the rate scales linearly with $f_{\rm mass}$ and f_b. And if our assumption on the initial nonzero binarity was relaxed, we would not predict formation of *any* BH-BH systems. However, even for a very low binarity of $f_b = 0.01\%$–0.1% we still expect several detections per year in our standard model calculation. The IMF of Population III stars is another unknown. Numerical investigations show that the IMF leans toward massive stars. We have assumed a rather steep IMF ($\alpha = -2$) for the most massive stars (over 100 $M_\odot$). The change of this part of the IMF does not significantly alter the detection rate. Further steepening of the IMF ($\alpha = -3$) decreases the expected rate by half, while a flatter IMF assumption ($\alpha = -1$) increases the expected rate by a factor of 2. Note that we maintain a flat IMF between 1 and 100 $M_\odot$ and that the maximum mass of the Population III stars was fixed to 500 $M_\odot$. If an alternative IMF without very massive stars ($\gtrsim$140 $M_\odot$) was used, as proposed by Tumlinson et al. (2004), the formation of BH-BH binaries with a high total mass is aborted, and detections with S/N $\gtrsim$ 10 are not expected. The estimate of the lifetime of the BH binaries can be strongly affected if the binaries are hardened by interactions in dense stellar environments. Our simulations show that a large number of BH binaries should be formed, with the lifetimes in excess of the Hubble time. Interactions in dense systems may significantly shorten their lifetimes. We demonstrated above that hardening does not affect strongly the expected rate. Another possibility arises that the interactions disrupt some BH-BH binaries. This would deplete the population of wide systems. Neither of the two effects, unless operating on extremely short timescales, can much affect systems with the shortest coalescence timescales. Therefore, a combination of the two effects may constrain the mergers of Population III BH-BH binaries to large redshifts. In order to estimate the S/N for the advanced LIGO detector, we have used the formulae of Flanagan & Hughes (1998). The predicted values of the S/N may change when more realistic noise curves and binary gravitational wave form templates are known. Because of the large masses of the binaries considered in this work, the changes in the low-frequency range are most important. The typical ringdown frequency is $\nu_{\rm qnr} \approx 90(300\, M_\odot/M)$ Hz, so the rate is most sensitive in the low-frequency region. Had we used the more recent advanced LIGO detector noise curves (Shoemaker 2003), our rates would drop by a factor of ~2.

The influence of the evolutionary model assumptions on detection rate was tested. We changed the CE efficiency (increase/decrease by a factor of 2), altered the evolution through stable RLOF phases from conservative to fully nonconservative cases, changed the specific angular momentum of the matter leaving the system during RLOF (increase/decrease by a factor of 2), and varied the critical mass ratio over which the dynamical instability develops (from $q_{\rm crit} = 2$ in the standard model to $q_{\rm crit} = 1$–3). We have also allowed for asymmetry in the remnant formation and calculated the model in which all BHs receive a natal kick drawn from a Gaussian distribution with $\sigma = 200$ km s^{-1}. The detection rate was decreased at most by a factor of 3 in the above models, and it does not depend strongly on the binary evolution.

There is one more potential limiting factor in the formation of coalescing BH-BH binaries. We have used the distribution of the initial binary separations characteristic of young stellar populations, which is skewed toward shorter periods (i.e., flat in logarithm). This distribution does not have to be representative of the first stellar populations. If the first binaries were formed predominantly on wide orbits, and the components did not interact through RLOF phases, coalescing massive BH-BH binaries would not have formed.

In summary, in our calculations we have shown the consequences of the assumption of a small nonzero binarity in the first stellar populations. The formation of massive coalescing BH-BH binaries, which may potentially be detected with ground-based interferometric gravitational wave detectors during the ringdown and merger phases, seems to be a possible outcome. Although the results are burdened with high uncertainties, the predicted detection rates for the advanced LIGO detector are very high. The possibility of the existence of this new class of candidate sources and their potential high detection rates call for further study of the formation and evolution of the first stellar populations. Coalescences of intermediate-mass BHs can be the primary targets for the LIGO burst search, provided that accurate templates are available. Turning the argument around, we may learn something about the first stars in the case of a nondetection. In particular, this may indicate that either (1) no binaries were formed or (2) there were no massive stars ($\gtrsim$140 $M_\odot$) in the first stellar populations.

We thank S. Hughes, E. Flanagan, R. Taam, A. Gürkan, T. Abel, A. Loeb, V. Kalogera, and the referee for useful comments and the Northwestern University Astro Theory Group for their hospitality. We acknowledge the support of grant PBZ-KBN-054/P03/2001.

REFERENCES

Baraffe, I., Heger, A., & Woosley, S. E. 2001, ApJ, 550, 890
Belczynski, K., Kalogera, V., & Bulik, T. 2002, ApJ, 572, 407
Bromm, V., Coppi, P. S., & Larson, R. B. 1999, ApJ, 527, L5
———. 2002, ApJ, 564, 23
Bromm, V., & Loeb, A. 2003, Nature, 425, 812
Bulik, T., & Belczynski, K. 2003, ApJ, 589, L37
Bulik, T., Belczynski, K., & Rudak, B. 2004, A&A, 415, 407
Chabrier, G. 2003, PASP, 115, 763
Flanagan, É. É., & Hughes, S. A. 1998, Phys. Rev. D, 57, 4535
Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288
Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532
Larson, R. B. 1998, MNRAS, 301, 569
Mackey, J., Bromm, V., & Hernquist, L. 2003, ApJ, 586, 1
Madau, P., & Rees, M. J. 2001, ApJ, 551, L27
Marigo, P., Girardi, L., Chiosi, C., & Wood, P. R. 2001, A&A, 371, 152
Nakamura, F., & Umemura, M. 2001, ApJ, 548, 19
Omukai, K., & Palla, F. 2003, ApJ, 589, 677
Ripamonti, E., & Abel, T. 2004, MNRAS, 348, 1019
Schaerer, D. 2002, A&A, 382, 28
Shoemaker, D. 2003, Classical Quantum Gravity, 20, S11
Songaila, A. 2001, ApJ, 561, L153
Tumlinson, J., Venkatesan, A., & Shull, J. M. 2004, ApJ, submitted (astro-ph/0401376)
Webbink, R. F. 1984, ApJ, 277, 355
Wyithe, S., & Loeb, A. 2003, ApJL, submitted (astro-ph/0312080)