Radiative Feedback from the First Objects and the End of the Cosmological Dark Age

Zoltan Haiman
Princeton University

Abstract. In hierarchical models of structure formation, an early cosmic UV background (UVB) is produced by the small ($T_{\rm vir} \lesssim 10^4$K) halos that collapse before cosmological reionization. If the sources in the first collapsed halos are stars, then their UV flux below 13.6 eV photo–dissociates the molecular hydrogen H_2 in subsequently collapsing halos and causes a pause in the cosmic star–formation history. The buildup of the UVB, and reionization is delayed until larger halos ($T_{\rm vir} \gtrsim 10^4$K) collapse. In contrast, if the small halos host mini–quasars with hard spectra extending to ∼1keV, then their X–rays balance the effects of the UVB, the negative feedback does not occur, and reionization can be caused early on by the small halos.

Keywords: cosmology:theory – galaxies:formation –molecular processes

1. Introduction

Recent progress in high redshift observations has made it possible to estimate the global star–formation history of the universe to redshifts as high as $z \sim 5$ (Madau et al. 1996; Steidel et al. 1999). We do know, however, that some stellar activity must have taken place even at $z > 5$. The presence of heavy elements observed in the high redshift Lyα forest, as well as the reionization of the intergalactic medium (IGM), require sources of metals and ionizing photons in addition to the currently known population of galaxies and quasars. Such ultra–high redshift objects are indeed expected in the current best–fit cosmological cold dark matter (CDM) models, which predict that the first virialized halos appear at redshifts as high as $z \sim 30$. It is natural to identify these small halos as the sites where the first stars or massive black holes are born, forming the first generation of "mini–galaxies" or "mini–quasars".

Because of the low virial temperatures ($T < 10^4$K) of the first halos, the presence or absence of H_2 molecules inside them determines whether they can form any stars or quasars, before larger halos dominate the collapsed baryonic fraction. As a consequence, the H_2 abundance determines when the "dark age" ends: if there is sufficient H_2 inside the first small halos, the dark age ends earlier; if H_2 is absent, it ends at the later redshift when the larger scales collapse.

In this contribution, we study the H_2 abundance inside halos collapsing in a ΛCDM cosmology, by quantifying the radiative feedback of the first collapsed halos on their H_2 abundance, as the early UVB is established in Press–Schechter models. The main questions we address is: *Could the first collapsed dark halos, with masses near the Jeans mass, contribute to the early UVB, and to the reionization of the universe?* For a more detailed report on this work, we refer the reader to Haiman, Abel & Rees (1999).

2. Radiative Transfer of the Soft UV Background

In hierarchical models of structure formation, small halos appear at high redshift, and larger halos form later, with the total fraction of collapsed baryons monotonically increasing with time. The radiation output associated with the collapsed halos gradually builds up a cosmic UV background. Photons in the 11.18–13.6eV range can travel to a large fraction of the Hubble length across the IGM, and photo–dissociate molecular H_2 both in the IGM and inside other collapsed halos (Field et al. 1966). In order to assess the molecular fraction inside collapsed halos, it is necessary to quantify the spectrum of the UVB in this wavelength band.

Consider an observer at redshift $z_{\rm obs}$, measuring the UVB at the local frequency $\nu_{\rm obs}$, where $11.18{\rm eV} < h\nu_{\rm obs} < 13.6{\rm eV}$. The photons collected at the frequency $\nu_{\rm obs}$ are arriving from sources located at $z_{\rm s} > z_{\rm obs}$, and have redshifted their original frequency $\nu_{\rm s} > \nu_{\rm obs}$. If during its travel, the photon's frequency equals that of an atomic Lyman line, it is absorbed by the neutral IGM (e.g. $\tau_{{\rm Ly}\alpha} \sim 10^6$ at $z \sim 20$). In effect, a "dark screen" blocks the view of all sources at redshifts above $z_{\rm max}$, defined as $(1+z_{\rm max})/(1+z_{\rm obs}) = \nu_{\rm i}/\nu_{\rm obs}$, where $\nu_{\rm i}$ is the frequency of the Lyman line closest to $\nu_{\rm obs}$. The processing of the early UVB by the neutral IGM leads to a characteristic spectral shape, resembling a "sawtooth". The resulting spectrum[1] is shown in a specific model (described below) in Figure 1.

3. H_2-Cooling in the Presence of the UV Background

3.1. The H_2 Abundance in Collapsed Clouds

The radiative efficiency of a gas cloud by collisional excitations of H_2 molecules depends on the gas temperature, density, and H_2 abundance.

[1] We find that the overall effect of intergalactic molecular absorption is negligible.

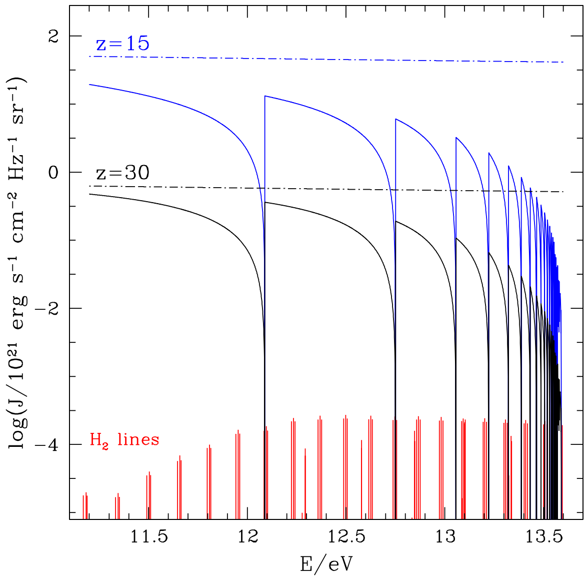

Figure 1. The spectrum of the UV background at redshifts $z = 30$ and $z = 15$ in the cosmological model of Figure 4. The solid lines show the spectrum after absorption by neutral H in the high–redshift IGM; the dashed lines show the spectrum without this absorption. For reference, at the bottom of the figure we show the location of the 76 LW lines of H_2.

To characterize the central condensation of collapsed halos, we adopt the density profiles of truncated isothermal spheres (TIS, Shapiro et al. 1999). We assume that the TIS is composed of the nine species H, H^-, H^+, He, He^+, He^{++}, H_2, H_2^+, and e^-, with the initial abundances given by their post–recombination values (Anninos and Norman 1996). We solve the subsequent time evolution of the chemical abundances, as a function of radius throughout the cloud, assuming that the cloud is illuminated by the external UVB. The UVB flux is assumed to be a sawtooth–modulated power law below 13.6eV, with index -1, and to be zero above 13.6eV. The initial conditions are further specified by the virial temperature $T_{\rm vir}$, and collapse redshift $z_{\rm coll}$ of the TIS, and the amplitude of the UVB, J_{21}.

The evolution of $x_{\rm H_2}$ at the core radius $r = r_0$ of the TIS is shown by the middle solid curves in Figure 2 for various J_{21}. For comparison, in this figure we also show the evolution of $x_{\rm H_2}$ in the same shell under less intense ($J_{21} = 0$ or 10^{-2}) or stronger ($J_{21} = 10^{-1}$ or $10^{-0.5}$) UV backgrounds. In the absence of any UVB, the H_2 fraction rises continuously,

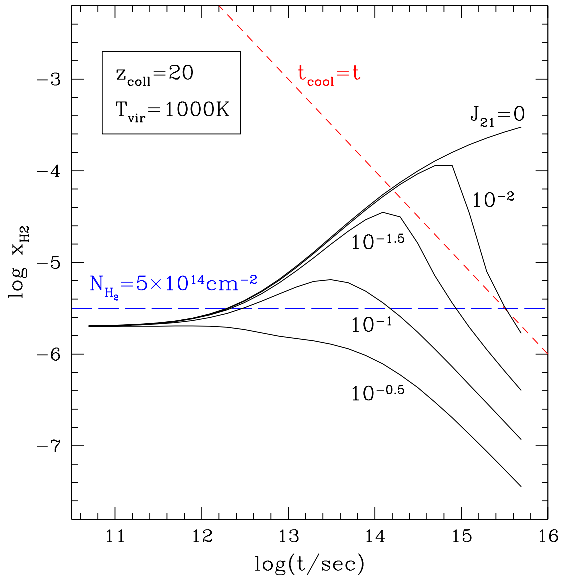

Figure 2. Evolution of the H_2 abundance in the core of a truncated isothermal sphere with $T_{\rm vir} = 10^3$K, $z_{\rm coll} = 20$, in the presence of various UV background fluxes (solid lines). Also shown is the H_2 abundance at which the cooling time equals the time elapsed since the collapse of the cloud (short dashed line); and the H_2 abundance at which the LW lines would become self–shielding (at an integrated H_2 column density of 5×10^{14} cm^{-2}, long dashed line).

and reaches 10^{-3} in a Hubble time (top curve); when a flux is turned on and increased (bottom 4 solid curves), the H_2 fraction is continuously suppressed. By performing similar calculations for clouds with virial temperatures and collapse redshifts in the ranges $10^2 < T_{\rm vir} < 10^4$K and $5 < z_{\rm coll} < 50$, we have found that the evolution shown in Figure 2 remains qualitatively the same in all cases. However, the level of flux required at which the H_2 molecules are photo–dissociation depends on the values of both $z_{\rm coll}$ and $T_{\rm vir}$.

3.2. The H_2 Abundance and Criterion for Star Formation

In order for a cloud to fragment into stars, or continue collapsing to form a central black hole, it is necessary for the gas to radiate efficiently. Here we adopt a criterion for star formation, as follows. For a given combination of $z_{\rm coll}$, $T_{\rm vir}$, and J_{21}, the cloud is assumed to be able to cool if, at any time during its evolution, the cooling time in the core becomes shorter than the "present time", defined as the time elapsed

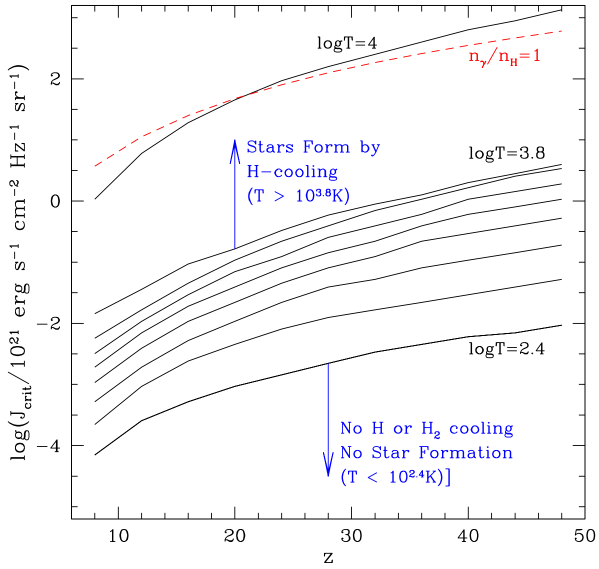

Figure 3. The critical flux above which star formation in a halo with virial temperature $T_{\rm vir}$ and collapse redshift $z_{\rm coll}$ is prevented. Halos smaller than $T_{\rm vir} \approx 10^{2.4}$K cannot cool even in the absence of any flux. Halos larger than $T_{\rm vir} \approx 10^{3.8}$K can cool via atomic H, irrespective of the H_2 abundance. For reference, the dashed curve show the flux corresponding to one ionizing photon per H atom, the minimum flux necessary to reionize the universe.

since the formation of the cloud at $z_{\rm coll}$. We assume this to be both a necessary and a sufficient criterion. This definition explicitly takes into account the behaviour of the H_2 fraction shown in Figure 2, especially the fact that the H_2 fraction in the core first rises and then declines again.

3.3. The Minimum Flux for Negative Feedback

Given a collapsed cloud with $z_{\rm coll}$ and $T_{\rm vir}$, what is the critical value of the background flux, $J_{\rm crit}$ so that star–formation in this collapsed cloud is suppressed? In the example shown in Figure 2, $(z_{\rm coll}, T_{\rm vir}) = (20, 10^3{\rm K})$, $J_{\rm crit}$ can be read off directly from Figure 2, $J_{\rm crit} = 10^{-1.5}$. In order to be able to investigate the evolution of the UVB in the Press–Schechter models, we have repeated the same calculation for a grid of values for $5 < z_{\rm coll} < 50$, and $2 < \log(T_{\rm vir}/{\rm K}) < 4$. For each pair of values, we have found the critical flux for preventing star formation, $J_{\rm crit}$.

The resulting $J_{\rm crit} = J_{\rm crit}(z_{\rm coll}, T_{\rm vir})$ are shown in Figure 3. In general, the higher the density (or $z_{\rm coll}$) or temperature, the higher the flux needs to be to prevent star formation. Note that for temperatures below $\log(T_{\rm vir}/{\rm K}) < 2.4$, H_2 cooling is inefficient even in the absence of any flux. On the other hand, for $\log(T_{\rm vir}/{\rm K}) > 3.8$, cooling from neutral H always dominates over H_2 cooling, i.e. stars can form irrespective of the H_2 abundance.

The values of $J_{\rm crit}$ shown in Figure 3 are relatively low. For reference, the dashed curve in this figure shows the value of $J_{\rm crit}$ that corresponds to one ionizing photon per hydrogen atom, i.e. the minimum flux necessary to reionize the universe. *Since the values of the flux necessary to prevent star–formation are 2–4 orders of magnitude below this minimum reionizing flux, a negative feedback necessarily turns on prior to reionization.*

4. H_2–Feedback and the Buildup of the Cosmic UV Background

In this section, we put together the results of the previous sections to compute the redshift evolution of the UV background, the intergalactic H_2 fraction, and the mass–scale (expressed by the critical virial temperature $T_{\rm crit}[z]$) of the H_2 feedback. Note that the evolution of $T_{\rm crit}(z)$ and the UVB amplitude, $J_{21}(z)$ are coupled together. We assume that each halo (provided it satisfies the star formation criterion) has a constant star formation rate for $t_{\rm on}$ years, during which it turns a total fraction ϵ of its baryonic mass into stars with a Scalo IMF. We do not attempt to summarize all the relevant uncertainties here (instead, see Haiman & Loeb 1997), and view $t_{\rm on}$ and ϵ as representative parameters in the simplest possible model. Within this model, we start from a high redshift ($z = 200$), and take small redshift steps towards z=0, computing the background flux is obtained by summing the flux of all sources that are within the imaginary redshift screen at $z_{\rm max}$ as discussed in § 2.1, and satisfy the star formation criterion of § 3.2. Once the flux is obtained, we find the critical virial temperature numerically for the new flux J_{21} and redshift, using the information contained in Figure 3.

5. Results

Our main results are shown in a model with $(t_{\rm on},\epsilon) = (10^7\ {\rm yr}, 10\%)$ in Figure 4. The figure shows the evolution of the total ionizing flux produced by all sources at 13.6 eV ($J_{\rm ion}$) and the average flux in the LW

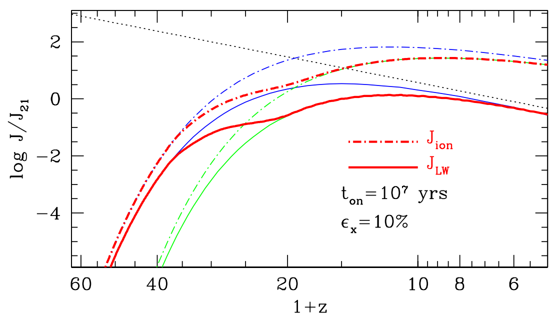

Figure 4. Evolution of the background flux J at 13.6eV (dot–dashed lines) and the average flux in the LW bands (solid lines). In both cases, the bottom and top curve assume a constant $T_{\rm crit} = 10^{3.8}K$, and $10^{2.4}K$, respectively, and bracket our actual coupled solution, shown by the thick middle curve. The diagonal dotted line shows the minimum flux for reionization, corresponding to one photon per hydrogen atom.

bands, (J_{rmLW}) The three solid curves show the evolution of $J_{\rm LW}$ in our model with feedback (middle curve), assuming that the critical virial temperature is fixed at $T_{\rm vir} = 10^{2.4}$K (upper curve), and at $T_{\rm vir} = 10^{3.8}$K (lower curve). These curves demonstrate that initially the small halos are allowed to form stars, there is no feedback, and the flux builds up as in the constant $T_{\rm vir} = 10^{2.4}$K case. At redshift $z \approx 35$, the feedback starts to be noticeable, as the flux builds up to $J_{\rm LW} \approx 10^{-2}$, and $T_{\rm crit}$ rises above $10^{2.4}$K. By redshift $z = 20$, $T_{\rm crit}$ reaches $10^{3.8}$K. The dot–dashed lines show the evolution of the ionizing flux, $J_{\rm ion}$; and the dotted line shows the minimum flux required for reionization (corresponding to one photon per hydrogen atom). As the figure shows, reionization in this model occurs at $z \sim 15$, and at this redshift the contribution from the small halos to $J_{\rm ion}$ is only $\sim$10%.

Although in Figure 4 we show the results only in one model, we have found that different choices for $t_{\rm on}$ and ϵ would yield similar conclusions: the H_2 feedback suppresses star formation inside the small halos, and that the contribution of the small halos to the reionizing flux is always below 10%. If reionization occurs late, then the H_2 feedback makes little difference to the overall ionizing flux: the contribution from small halos to the reionizing flux is then small in any case, since by this late time, the collapsed baryon fraction, as well as the UV background, is dominated by the large halos even in the absence of the H_2 feedback. Note that there is a preliminary indication from 3–D simulations that the efficiency in small halos might be unusually small (< 1%, Abel et al. 1998). If the star formation efficiency in the small halos were intrinsically indeed much smaller than in the large halos, then the contribution to the flux from the small halos would be small, regardless of the H_2–feedback.

It is not surprising that the H_2 feedback generically occurs in any model that satisfies the reionization constraint by $z = 5$. This is because, as we have shown in § 3.3, the suppression of the H_2 abundance and star formation inside clouds with the relevant range of densities and temperatures requires a UV flux that is only a fraction $10^{-2} - 10^{-4}$ of the minimum flux level required for reionization (one photon per hydrogen atom). As the UVB builds up to the reionizing level, it must necessarily first reach the level at which the H_2 feedback sets in.

6. Early Mini–Quasars and the Effects of X–rays

So far, we have assumed that the early sources have "stellar" spectra, and have simply truncated the observed flux above 13.6 eV. An alternative possibility is that a halo collapsing at high redshift forms a central black hole, and turns into a "mini–quasar", with a hard spectrum extending into the X-ray regime (Haiman & Loeb 1998). If the spectra of the early sources have a non–negligible contribution at these frequencies, they would establish an early X–ray background (XRB), and change the chemistry qualitatively. The X–rays provide additional free electrons, both by direct photo–ionization of H and He, as well as indirectly, by collisional ionization of H by the fast photo–electrons. The resulting extra free electrons catalyze the formation of H^-, and therefore tend to increase the H_2 abundance. At sufficiently high densities, a positive feedback is expected when the UV and X–ray backgrounds together illuminate a collapsed halo.

We have recomputed the evolution of the H_2 profiles in the TIS models, with a power law flux extending to 10 keV (although suppressed above 13.6eV by the neutral IGM). We have also introduced a multiplicative factor above 13.6eV, $\epsilon_{\rm x}$, to characterize the ratio of X–ray to UV flux: for pure stellar sources, $\epsilon_{\rm x} = 0$; for typical quasar spectra (Elvis et al.), $\epsilon_{\rm x} \sim 1$. Values of $\epsilon_{\rm x}$ in–between 0 and 1 could describe either miniquasars with softer spectra, or a mixed population of stars and mini–quasars.

In Figure 5, analogously to Figure 2, we show the evolution of the H_2 fraction of a TIS with $z_{\rm coll} = 30$ and $T_{\rm vir} = 10^3$K, illuminated by a flux with $J_{21} = 0.1$ and $\epsilon_{\rm x} = 0, 0.1$, and 1, corresponding to increasing amounts of X–ray contribution. As in the example shown in Figure 2, in the absence of any flux the H_2 fraction rises continuously, in this case to

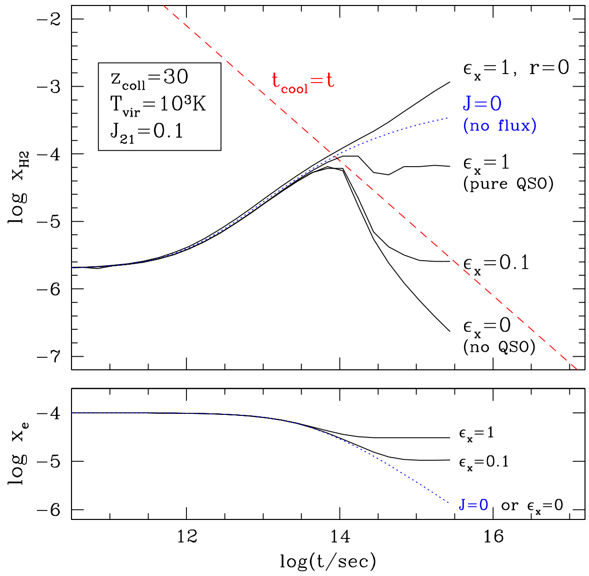

Figure 5. Effect of X–rays on the evolution of the H_2 abundance, as in Figure 2, except that $z_{\rm coll} = 30$, and $J_{21} = 0.1$, and we have added an X–ray contribution to the background flux. The curve labeled J=0 shows the evolution of the H_2 abundance in the absence of any flux. The label $\epsilon_{\rm x}$ on the other curves is a measure of the X–ray/UV flux ratio, where $\epsilon_{\rm x} = 0$ corresponds to a pure stellar spectrum with no X–rays, and $\epsilon_{\rm x} = 1$ corresponds to a pure "mini–quasar" spectrum with a spectral index of -1. The bottom panel shows the evolution of the free electron fraction in each case.

$\sim 10^{-3.5}$ (dotted curve). If the UVB is turned on, the final H_2 fraction is suppressed to $\sim 10^{-7}$ (bottom solid curve). However, if increasing amounts of X–rays are also added (solid curves, second and third from the bottom), then the H_2–suppression (relative to the dotted curve) is less pronounced.

By experimenting with different combinations of $z_{\rm coll}$ and $T_{\rm vir}$, we have found that the situation shown in Figure 5 is typical of collapsed clouds with $5 < z_{\rm coll} < 50$ and $10^{2.4}{\rm K} < T_{\rm vir} < 10^4{\rm K}$. Generally, a $\sim 10\%$ contribution by X–rays to the flux is sufficient to keep the H_2 fraction high enough to allow star formation, and hence to eliminate the negative feedback caused by the UV background. We therefore expect that if the early background had a non–negligible contribution from "mini–quasars" with hard spectra, extending to $\sim$ 1 keV, then the negative H_2 feedback described here would not occur.

7. Conclusions

We have examined the build–up of the UV background in hierarchical models, based on the Press–Schechter formalism, and its effect on star formation inside small halos that collapse prior to reionization. We have found that the contribution to the reionizing flux from small ($T_{\rm vir} \lesssim 10^4$K) halos is limited to be less than $\sim$10% percent in any of a large range of hierarchical models, either because of the negative feedback on the H_2 abundance, or else because the star formation efficiency in small halos is intrinsically small. However, we have shown that the negative feedback would be turned into a positive one if there was a significant ($\gtrsim$ 10%) contribution to the early UV background from "mini–quasars" with hard spectra extending to the X–rays (upto $\sim$1keV). The evolution of the early small halos is therefore distinctly different in stellar and mini–quasar models: this may help shed light on the question of what type of sources were responsible for ending the "dark age", and reionized the Universe.

Acknowledgements

I thank my collaborators Tom Abel and Martin Rees with whom the work described here was carried out. Support for this work was provided by NASA through a Hubble Fellowship grant, awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS 5-26555.

References

Abel, T., Bryan, G. L., & Norman, M. L. 1998, in Proc. of the MPA/ESO Conference "Evolution of LSS: from Recombination to Garching", Garching, Germany, Aug. 1998, astro-ph/9810215
Anninos, P., Zhang, Y., Abel, T., Norman, M. L. 1997, New Ast., 2, 209
Elvis, M., et al. 1994, ApJS, 95, 1
Field, G. B., Somerville, W. B., and Dressler, K. 1966, ARA&A 4, 207
Haiman, Z., Abel, T., & Rees, M. J. 1999, ApJ, submitted, astro-ph/9903336
Haiman, Z., & Loeb, A. 1997, ApJ, 483, 21
Haiman, Z., & Loeb, A. 1998, ApJ, 503, 505
Haiman, Z., Abel, T., & Rees, M. J. 1999, ApJ, submitted
Madau, P., et al. 1996, MNRAS, 283, 1388
Miralda-Escudé, J., Haehnelt, M., & Rees, M. J. 1999, ApJ, submitted
Press, W. H., & Schechter, P. L. 1974, ApJ, 181, 425
Shapiro, P. R., Iliev, I., & Raga, A. C. 1999, MNRAS, 307, 203