Gamma-Rays from Large Scale Structure Formation and the Warm-Hot Intergalactic Medium: Cosmic Baryometry with Gamma-Rays

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Abstract. It is shown that inverse Compton gamma-rays from electrons accelerated in large scale structure formation shocks can be crucially affected by non-gravitational effects such as radiative cooling and galaxy formation, with corresponding uncertainties by an order of magnitude in either the gamma-ray source counts or the extragalactic background contribution. However, this also implies that such gamma-rays may in the near future provide us with valuable information about the fraction of cosmic baryons in different forms, particularly the warm-hot intergalactic medium where the majority of the baryons in the universe are believed to reside. We address this problem in a simple way through semi-analytic modeling of structure formation shocks which self-consistently treats merger and accretion shocks.

INTRODUCTION

The majority of the baryons in the universe today are believed to reside in a warm-hot intergalactic medium (WHIM) at temperatures $T \sim 10^5 - 10^7$ K, as a result of shock heating during the hierarchical buildup of large scale structure in the universe [2, 3]. They are often referred to as ‘missing baryons’, since quantitative measurements of the WHIM through direct observations are still lacking, hampered by heavy Galactic obscuration in the relevant extreme UV to soft X-ray bands (notwithstanding important but fragmentary information from absorption lines that probe only selected lines of sight [17]). Current indirect estimates of the cosmic fraction of baryons in the WHIM $f_{WH}$ range from ~20 to ~70 % [5, 6, 24]. In view of the significance of elucidating this fundamental component of the universe, dedicated satellite missions such as the Diffuse Intergalactic Oxygen Surveyor [18] and the Missing Baryon Explorer [4] are being planned in order to detect emission lines from the WHIM and directly constrain $f_{WH}$.

On the other hand, the same large scale structure formation (SF) shocks that create the WHIM may give rise to GeV-TeV gamma-ray emission through nonthermal electron acceleration and inverse Compton upscattering of the cosmic microwave background. Such gamma-rays may be observable either as a contribution to the cosmic gamma-ray background (CGB) [14] or as individual sources [28]. This interesting possibility has spawned a number of studies using numerical simulations [12, 15] or semi-analytic
methods [9, 10], although most such works had limited their scope to treating purely gravitational effects. In reality, the global hydrodynamical evolution of intergalactic gas and the associated gamma-ray emission can be crucially affected by non-gravitational effects such as radiative cooling (with consequent star formation and feedback) and photoionization heating.

By considering such non-gravitational effects in a simplified way, we show here that there should be a nontrivial connection between SF gamma-rays and the baryonic fraction in the WHIM. The problem is addressed through semi-analytic modeling of SF shocks based on Monte Carlo merger trees with multiple mergers [22], which allows a self-consistent treatment of major and minor merger shocks as well as diffuse accretion shocks. The full details can be found in a forthcoming paper (Inoue and Nagashima, in prep.).

**FORMULATION**

An important point in considering nonthermal effects due to SF shocks is that such shocks can be either strong or weak, with Mach numbers \( M \) ranging from very large ones (\( \gg 1 \)) for minor mergers between systems with large mass ratios or accretion of relatively cold gas onto a large object, to values as low as \( \sim 1.5-3 \) in the case of major mergers between virialized objects of comparable masses [1, 20, 26]. This implies that the spectral index of shock accelerated particles \( p \) can be either the strong shock limit of \( p \approx 2 \) or much steeper with \( p > 2 \), leading to considerably different effects at high energies [8]. Thus it is imperative to account for the distribution of shock Mach numbers appropriately.

One way to address this problem is through full-scale cosmological hydrodynamical simulations [12, 15, 20]. Here we opt for a semi-analytic approach based on the extended Press-Schechter (PS) formalism of structure formation [13], which gives a simple yet reasonably accurate description of the hierarchical gravitational growth of dark matter halos. In particular, we employ the multiple merger tree algorithm of Somerville & Kolatt [22], which accurately reproduces the total and conditional halo mass functions and also accounts for diffuse accretion. At each time step in the merger tree, we also employ an accurate mass function derived from very high resolution N-body simulation results [30]. Note that the semi-analytic model of Gabici & Blasi (GB03) [8, 9, 10] is built on the simpler binary merger tree algorithm of Lacey & Cole [13], which cannot treat accretion and is known to produce self-inconsistent results when the merger tree is extended to high redshifts [22]. (Nevertheless, it is found that the differences are not very large at low redshifts, and our results below for SF gamma-rays are in basic agreement with [8, 10] when appropriate comparisons are made.)

Our basic assumptions are as follows. (1) The adopted cosmological parameters are \( \Omega_m=0.3, \Omega_\Lambda=0.7, \Omega_b=0.044 \) and \( h=0.7 \). The normalization and spectral index of primordial fluctuations are respectively \( \sigma_8=0.9 \) and \( n=1 \). (2) At each step, a multiple merger event between more than two halos is pictured as an ensemble of binary mergers with the primary (i.e. most massive) progenitor. Associated with each binary pair are two shocks propagating within them. Mass below a certain mass scale (see
An interesting connection can be made between our principal parameters \( V_{\text{acc}} \), \( V_{\text{cut}} \), \( f_{\text{GF}} \), and the present-day diffuse fraction of baryons in the universe in different forms. Following [3] in dividing cosmic baryons into four phases, diffuse \((T < 10^5 \text{ K})\), condensed (stars and cold gas), warm-hot \((10^5 < T < 10^7 \text{ K})\), and hot \((T > 10^7 \text{ K})\), these respectively relate in our picture to systems with velocity dispersion \( V < V_{\text{acc}} \), a fraction \( f_{\text{GF}} \) of \( V_{\text{acc}} < V < V_{\text{cut}} \), the rest \( 1 - f_{\text{GF}} \) of \( V_{\text{acc}} < V < V_{\text{cut}} \) plus a part of \( V > V_{\text{cut}} \) with \( T < 10^7 \text{ K} \), and the remainder of \( V > V_{\text{cut}} \) with \( T > 10^7 \text{ K} \). If we take our fiducial values \( V_{\text{acc}} = 40 \text{ km/s} \) and \( V_{\text{cut}} = 200 \text{ km/s} \), there is a one to one relation between \( f_{\text{GF}} \) and \( f_{\text{cond}} \), the baryon fraction condensed into stars and cold gas. This relation can be quantitatively evaluated using the semi-analytic galaxy formation model of [16]. In turn, \( f_{\text{cond}} \) can be
related to $f_{WH}$ by subtracting the baryon fractions in the diffuse and hot phases. For example, cosmological simulations including radiative cooling and galaxy formation [3] indicate a range $f_{\text{cond}} \simeq 0.2 - 0.4$ and $f_{WH} \simeq 0.2 - 0.4$ at $z = 0$, which corresponds to $f_{GF} \simeq 0.6 - 0.9$. Alternatively, a recent observational census [5] suggests $f_{\text{cond}} \simeq 0.1$ and $f_{WH} \simeq 0.4$, which is consistent with $f_{GF} \simeq 0.4$.

A further non-gravitational effect that might be important is feedback (pre-)heating by supernovae-driven winds or AGN outflows, as indicated by the observed X-ray scaling relations of groups and clusters (21 and references therein). Since the details of such processes are highly uncertain at present, we defer a consideration of these effects to future work (see 27 for an early, crude discussion).

One important caveat is in order concerning our formulation. In the PS picture, all the dark matter in the universe is described as being bound inside spherically virialized halos of some mass. This is a fairly good approximation, as many comparisons with N-body simulations demonstrate (e.g. 30 and references therein.) However, the same cannot be said about the gas component. In fact, we have explicitly assumed the fraction of gas with $V < V_{\text{acc}}$ to be in diffuse form outside bound halos due to photoionization heating. It is less clear how much of the WHIM, particularly the gas with $V_{\text{acc}} < V < V_{\text{cut}}$, can be considered to be inside or outside bound objects. Although hydrodynamical simulations indicate that a large part of the WHIM arises through shock heating by gravitational infall onto filamentary or sheet-like structures [2, 3], much of the gas in such structures may actually be interpreted as residing inside sufficiently small halos if seen at high enough resolution. Since the essential driving force of WHIM evolution is the gravity of the dark matter, most of which is indeed in bound form, we have chosen to describe the WHIM as gas inside bound haloes with the corresponding range of virial temperatures which do not condense into stars. Just how good such a description (or some alternative, e.g. 7) may be can only be judged through future comparisons with detailed numerical simulations.

**RESULTS AND DISCUSSION**

Figure 1 shows our results of the SF shock contribution to the CGB for different values of $V_{\text{acc}}, V_{\text{cut}}$ and $f_{GF}$. To be compared are CGB data from COMPTEL [29] and EGRET, including both the old Sreekumar et al. (1998; S98) [23] and new Strong, Moskalenko & Reimer (2004; SMR04) [25] determinations.

We first take $V_{\text{acc}} = V_{\text{cut}} = 20$ km/s, corresponding closest to the situations treated in numerical simulations, where the sole non-gravitational effect is a temperature floor of $T = 10^4$ K [12, 15]. The result accounts for almost all of the S98 CGB, and in fact exceeds the new SMR04 CGB, indicating either that this case does not represent reality or that $\xi_\nu$ is significantly less than the fiducial value 0.05. Although this is in more agreement with the result of [15] than of [12], here we reserve a quantitative judgement, given the approximate nature of our formulation.

For this and all other cases discussed here, the end result is dominated by minor merger shocks, with accretion shocks amounting to at most 1% of the S98 CGB. Keeping $V_{\text{acc}} = V_{\text{cut}}$ (i.e. no condensation into stars), a larger value decreases the merger
component and hence the total CGB, while slightly increasing the accretion component; for smaller values, vice-versa. Taking $f_{GF} = 1$ (complete condensation in the cooling regime) with $V_{acc} = 40$ km/s fixed, varying $V_{cut}$ has a dramatic effect, with the CGB being suppressed by more than an order of magnitude as $V_{cut} = 200$ km/s is approached. This can be understood as removing larger and larger galaxy-scale objects, which can potentially produce strong shocks in minor mergers with cluster-scale objects. Our fiducial set of $V_{acc} = 40$ km/s, $V_{cut} = 200$ km/s leads to $\sim 10\%$ of the S98 CGB, consistent with the results of GB03.

Obviously, when condensation occurs only for a fraction $f_{GF}$ of objects in the cooling regime, the reduction is less, and one gets a CGB somewhere between 10 to 100% of the S98 CGB. Recalling the above-mentioned connection between $f_{GF}$ and $f_{cond}$, the current uncertainty in $f_{cond} \simeq 0.1 - 0.4$ allows a range $f_{GF} = 0.4 - 0.9$, and the CGB due to SF shocks cannot be reliably predicted to within an order of magnitude. However, this points to an interesting possibility of constraining $f_{cond}$ and hence $f_{WH}$ if the SF shock contribution to the CGB can be observationally determined. In practice, this requires removing other contributions (e.g. blazars) to the CGB with good precision, which may not be an easy task.

A more promising way to constrain $f_{WH}$ with gamma-rays may be through the

**FIGURE 1.** Cosmic gamma-ray background for different values of $V_{acc}$, $V_{cut}$ and $f_{GF}$ as indicated in the legend, compared with COMPTEL and EGRET (both S98 and SMR04) data.
statistics of source counts. Figure 2 displays the cumulative source counts due to SF shocks at energies > 100 MeV and > 10 GeV, for fixed fiducial values of $V_{\text{acc}}$ and $V_{\text{cut}}$ and different $f_{GF}$. Again, differences of an order of magnitude can be seen, depending on how much minor merger shocks are suppressed. For $f_{GF} = 0.9$ ($f_{\text{cond}} \approx 0.25$, $f_{WH} \approx 0.25$), $\sim 100$ and $\sim 10$ sources should be observable by GLAST at >100 MeV and >10 GeV, respectively, while none exists above the EGRET sensitivity at >100 MeV. For $f_{GF} = 0.4$ ($f_{\text{cond}} \approx 0.1$, $f_{WH} \approx 0.4$), the respective numbers are $\sim 600$ and $\sim 30$ at >100 MeV and >10 GeV for GLAST, whereas a few are expected for EGRET. The fact that EGRET actually saw no emission associated with clusters [19] may point to either $f_{GF} > 0.4$ or $\xi_e < 0.05$. This underlies the need for the electron injection efficiency to be pinned down, preferably through detailed observations of individual sources where the kinetic energy can be estimated independently. Once this is done, SF gamma-rays may provide an indirect but very valuable probe of the unknown fraction of baryons in the WHIM. In fact, a close connection between SF gamma-rays and the WHIM is not surprising at all, as they both arise from the same large-scale shocks. However, the quantitative correspondence is a nontrivial one involving the reduction of strong, minor merger shocks by condensation into stars.

To summarize, we have investigated inverse Compton gamma-rays from large scale

![Figure 2](image-url)
SF shocks including non-gravitational effects with a self-consistent semi-analytic formulation. Radiative cooling and galaxy formation were shown to have crucial impact, with the predicted CGB contribution and gamma-ray source counts uncertain by an order of magnitude depending on the fraction of baryons condensing into stars. This in turn implies that SF gamma-rays may serve as an indirect ‘baryometer’ of the universe and probe the ‘missing’ fraction of baryons in the WHIM, which is very difficult to measure directly.

The present work is an example of nonthermal phenomena due to SF shocks where semi-analytic, PS-based methods can be applied effectively, allowing the exploration of physical effects in a simple way which is not always the case with numerical simulations. However, in view of the numerous approximations in our formulation, further studies with simulations are warranted, both to confirm the qualitative trends found here and to make predictions that are quantitatively more robust. The effects of feedback (pre-heating), which have not been treated here, may also be potentially important and need to be investigated further.

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