The History of Cosmic Baryons: X-ray emission vs. Star Formation Rate

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ABSTRACT

Using current models of structure and star formation based on hierarchical clustering, we connect the cosmic star formation rate (SFR) to the X-ray emission properties of groups and clusters of galaxies. We show that when the baryons cool down from a hot phase to condense into stars with a SFR flat for \( z \geq 2 \), then such hot phase yields deep X-ray source counts (at fluxes \( F = 10^{-15} \) erg/cm\(^2\) s in the energy band 0.5-2 keV) about 5 times larger than in the case of a SFR peaked at \( z \approx 1.5 \). We also discuss the effect of the SFR on the shape and evolution of the X-ray \( L - T \) relation.
1. Introduction

In current models of galaxy formation the SFR of the Universe is tightly related to the amount of cold and hot gas ($m_c$ and $m_h$, respectively) contained in the dark matter (DM) halos where the galaxies are located. As a consequence, we expect the history of the SFR to be related to the X-ray properties of groups and clusters of galaxies, since these host most of the hot baryons emitting by thermal bremsstrahlung luminosities $L \sim 10^{44}$ erg/s. In particular, the process of star formation is expected to affect the X-ray properties of small galactic systems, since the “stellar” temperature $kT_* = E_* m_H/3 m_h \sim 0.2$ keV ($E_*$ being the Supernova energy) which measures the thermal energy provided by the Supernovae (SN) is close to the virial temperature $kT \approx G M / 10 R \propto M^{2/3}$ of small galaxy groups (DM masses $M \sim 10^{13} M_\odot$). Thus, in X-rays the connection with the SFR should show up mainly at faint luminosities.

Since the behaviour of the cosmic SFR at $z > 2$ is still plagued by observational uncertainties in the optical bands, we explore here the above connection with the X-ray data, and show that such observations are within the reach of forthcoming X-ray observatories like AXAF. These observations can discriminate between a declining SFR for $z > 2$ (as initially proposed (Madau et al. 1996) and a flat SFR for $z > 2$ (as indicated by recent observations; see, e.g., Pettini 1997; Meurer et al. 1997). The result may have relevant implications for all sides of the current theories of galaxy formation, including the cosmogony of DM halos. In fact in these theories the SFR is strongly coupled to the dynamical history of the DM halos, whose hierarchical growth is thought to proceed through merging and accretion events.

2. Star Formation Models

The baryonic processes inside dynamically evolving DM halos are usually treated using semi-analytic models (SAM) in the framework of hierarchical clustering (for a comprehensive account see Somerville & Primack 1998). According to the SAMs, the baryons gravitationally bound to a DM halo are assumed to be exchanged among three phases: the cold phase produced by radiative cooling; the resulting condensed phase into stars; the hot phase constituted by gas preheated by SN explosions and further raised to the virial temperature of the potential well. Besides, a fraction of the hot gas may be expelled by SN winds; this depends on the key parameter $\epsilon_o$, defining the fraction of SN energy going into kinetic energy. The SAMs also include coalescence of baryons following halo merging and the luminosity-colour evolution due to rise and fall of successive star generations. In the end, the statistics of the baryonic phases are related to the statistics of the DM halos, usually characterized in terms of their circular velocity $v_c$.

We developed an analytic version of the SAMs (based on the Extended Press & Schechter Theory, see Lacey & Cole 1993), to describe the above baryonic phases and the exchanges among them (we refer to Menci & Cavaliere 1999 for an extended description of the model and of its results). The parametrizations we adopt are the same as in the SAMs. The star formation time scale and the SN feedback are related to $v_c$ by scaling laws depending on a set of four global parameters which, as described in Cole et al. 1994, are related to the detailed parameter $\epsilon_o$. We focus on two particular sets of parameters. The first (Model A) is characterized by a relatively large value of $\epsilon_o = 0.1$. With this, the SN winds are effective in expelling hot gas from small halos. Correspondingly, the resulting SFR we find (see fig. 1) is peaked at $z \approx 1.5$ and then declines considerably for larger $z$. The second set (Model B) is characterized by a small $\epsilon_o = 0.01$; in this case the SN are not effective in expelling baryons from the halos, but they heat them to somewhat larger temperatures compared with model A.

3. X-ray Observables Related to SFR

The different conditions described by Models A and B lead to different amounts and physical states for the hot baryons which are contained in the DM potential wells and emit in X-rays. The X-ray luminosity of groups or clusters may be written in the form (Cavaliere, Menci & Tozzi 1998)

$$L \propto \rho^{1/2}(z) \left( \frac{m_h}{M} \right)^2 I(M, z) G^2(M) T^2(M) .$$

Here the normalization is adjusted (as usually) so as to match the height of the observed local $L - T$ relation at $T = 4$ keV; $\rho(z)$ is the DM density of the halo; the shape factor $I$ describes the internal ICM distribution. In addition, $G$ denotes the density jump across the shock induced by the infalling gas, averaged over the merging histories, that is, over the probabil-
ity to merge clumps $M'$ onto $M$; $G$ is governed by $T/T'$, where $T'$ is the temperature of infalling gas. The overall effect of $G^2$ is to depress the $L - T$ relation at the scale of groups, bending it down from the self-similar behaviour $L \propto T^2$, which applies to very rich clusters Ponman et al. (1996).

The different amounts of hot baryons retained in small halos in Model A and Model B affect the $z$-evolution of the $L - T$ relation (see fig. 2); the considerable increase with $z$ at the faint end of $L$ found in Model B reflects the larger amount of emitting baryons in the smaller halos, which dominate the statistics at $z > 1$. In addition, the larger amount of expelled diffuse baryons marking Model A, together with the corresponding lower SN-induced temperature, make the shocks more effective in this case. Correspondingly, the factor $G^2$ in eq. 1 is more effective in bending down the $L - T$ relation from its self-similar shape.

Such effects of different SFR on the X-ray emission at the groups scale interestingly affect the deep source counts, as shown in fig. 3. Note that at fluxes $F \approx 10^{-15}$ erg/s cm$^2$ (reachable, e.g., by AXAF) a flat SFR implies counts larger by a factor $\gtrsim 5$ with respect to a SFR declining for $z > 2$.

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FIGURE CAPTIONS

Fig. 1.— The SF histories in Model A (left panel) and model B (right panel). Critical Universe with $H_0 = 50$ km/s Mpc and tilted CDM spectrum of perturbations.

Fig. 2.— The $L - T$ correlation at $z = 0$ (solid line) and $z = 1$ (dashed) in Model A (left) and Model B (right). The data are taken from Ponman et al. (1996) and Markevitch (1998).

Fig. 3.— The X-ray source counts in the energy band 0.5-2 keV for the SFRs derived from Model A (solid line) and from Model B (dashed line). The assumed cosmological/cosmogonical parameters are as given for fig. 1. The shaded region corresponds to the ROSAT cluster counts observed by Rosati et a. (1998).
