COSMOLOGICAL AND ENVIRONMENTAL INFLUENCES ON HOT GAS OBSERVED IN ELLIPTICAL GALAXIES

WILLIAM G. MATHEWS and FABRIZIO BRIGHENTI

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ABSTRACT

The X-ray emission from hot gas in bright elliptical galaxies often extends far beyond the radius of the stellar system. This “circumgalactic” gas accounts for most or all of the large spread in X-ray luminosity \( L_X \) among elliptical galaxies having similar optical luminosities \( L_B \). We have developed gasdynamical models describing the evolution of gas within and around elliptical galaxies beginning with an overdensity perturbation in a simple flat cosmology. At some early time, we form the stellar galaxy and release supernova energy, conserving dark and baryonic matter. We follow the subsequent evolution of intergalactic and interstellar gas to the present time. These models confirm that hot gas density and temperature distributions currently observed in massive, group-dominant elliptical galaxies can be understood as a combination of intergalactic gas that has flowed into the galaxy group over time and gas lost from galactic stars. Furthermore, if the hot gas and dark matter halos are subject to differential tidal truncations or mass exchanges between group members, then the observed correlation between \( L_X/L_B \) and the relative sizes of galactic X-ray images can be understood. The distribution and physical properties of hot interstellar gas observed in massive elliptical galaxies today are sensitive to the cosmic baryon fraction, the time of maximum star formation, and the amount of “feedback” energy delivered to the gas by Type II supernovae at the epoch of galaxy formation.

Subject headings: cooling flows — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation — X-rays: galaxies

For many years, X-ray observers have noticed that the X-ray luminosities of elliptical galaxies span a huge range for galaxies of similar optical luminosity \( L_B \) (Fabbiano 1989; Eskridge, Fabbiano, & Kim 1995). Attempts to find correlations between \( L_X/L_B \) and other galactic parameters had been largely unsuccessful. However, in a recent compilation of ROSAT data, Mathews & Brighenti (1998) discovered that \( L_X/L_B \) correlates strongly with the size of the X-ray image \( r_{ex}/r_e \), where \( r_{ex} \) is the projected radius that contains half the total \( L_X \) and \( r_e \) is the optical half-light radius. A correlation between \( L_X/L_B \) and \( r_{ex}/r_e \) was suspected because the hot gas in well-resolved, X-ray–luminous elliptical galaxies often extends far beyond the optical images where it could be rather stochastically influenced by tidal mass exchanges.

The very extended X-ray halos around many bright elliptical galaxies also indicate that most of this gas is unlikely to have been ejected by old galactic stars during their post–main-sequence evolution. Furthermore, the average gas temperature in bright elliptical galaxies exceeds the equivalent stellar temperature \( T_\star \) by \( \sim 1.5 \) (Davis & White 1996), suggesting again that the hot gas is in virial equilibrium in the more massive and more extended dark halos surrounding the galaxies. Using detailed hydrodynamic models, Brighenti & Mathews (1998a) showed that the extended hot gas density and temperature profiles in X-ray–bright elliptical galaxies can be understood only if most of the hot interstellar gas is very old, dating from the epoch of galaxy formation, and has not come solely from mass loss from galactic stars.

In this Letter, we combine these two lines of inquiry. First, using a simple cosmological model, we show that the additional “circumgalactic” gas required to account for the large values of \( L_X/L_B \) can result quite naturally from secondary infalling intergalactic gas that has accumulated in the outer dark halo over a Hubble time. Second, we demonstrate that the correlation between \( L_X/L_B \) and \( r_{ex}/r_e \) can indeed be generated by tidal truncations of these same models.

For a fully self-consistent model of the global evolution of gas in elliptical galaxies, it is necessary to begin with a galaxy-group–sized perturbation in an expanding universe, to allow for the formation of the stellar elliptical galaxy, and to include the release of supernova energy that accompanies early star formation. For simplicity, we consider here a localized density perturbation in a simple flat cosmology with various baryonic fractions \( \Omega_B/\Omega \). After a few gigayears, when enough baryonic matter has accumulated to create the giant elliptical galaxy, we construct the stellar galaxy with a de Vaucouleurs profile and simultaneously release the energy from Type II supernovae. By forming the galaxy in this instantaneous fashion, we circumvent the dynamically complex merging processes that must have occurred (e.g., Merritt 1985). After the stellar system is formed, baryonic and dark matter continue to flow into the galactic perturbation. The baryonic matter shocks and compresses to approximately the virial temperature in the halo, \( T \sim 10^7 \) K, similar to the interstellar gas temperatures observed today. With this simple model, we conserve baryonic and dark matter and properly allow for the influence of supernova energy. We study the subsequent gasdynamical evolution of the intergalactic and interstellar gas in detail, allowing for stellar mass loss and Type Ia supernovae. The objective in this calculation is to reproduce the density and temperature profiles observed in the hot gas within and around bright elliptical galaxies today. A more detailed discussion of our hydrodynamical models may be found in Brighenti & Mathews (1998b).

At the present time, only about a dozen bright, nearby elliptical galaxies have been spatially resolved in soft X-rays. For these galaxies, the X-ray surface brightness and projected spectral variation can be inverted to determine the electron density \( n(r) \) and temperature \( T(r) \) profiles with physical radius.

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1 UCO/Lick Bulletin No. 1378.
2 University of California Observatories/Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064; matthews@lick.ucsc.edu.
3 Dipartimento di Astronomia, Università di Bologna, via Zamboni 33, Bologna 40126, Italy; brighenti@asbbo3.bo.astro.it.
Assuming an approximate hydrostatic equilibrium, the density and temperature gradients can be used to determine the total internal mass \(M(r)\) (Brighenti & Mathews 1997). As a guide in evaluating the success of the models we discuss here, we choose NGC 4472, a typical bright E2 elliptical galaxy in Virgo that is the dominant elliptical in a local galaxy subgroup. Data for NGC 4472 are available from the Einstein HRI (Trinchieri, Fabiano, & Canizares 1986) and the ROSAT HRI and PSPC (Irwin & Sarazin 1996). The interstellar gas density profile for NGC 4472 has been determined out to almost 17\(r_e \approx 150\) kpc (at a distance of 17 Mpc). NGC 4472 appears to be colliding with a small dwarf galaxy and interacting with more extended Virgo intercluster gas (Irwin & Sarazin 1996; Irwin, Frayer, & Sarazin 1997). This may explain the azimuthal asymmetry in the X-ray image beyond ~3.5 kpc. In spite of this undesirable asymmetry, in these times of pre-AXAF resolution, NGC 4472 is one of the few normal bright elliptical galaxies in which the stellar component is clearly seen in the mass profile determined from X-ray observations; this is useful for our models to accurately evaluate the stellar potential, the gas contributed by stellar mass loss, etc. The X-ray profile in NGC 4469 is also sensitive to the stellar potential, and its X-ray properties are similar to those of NGC 4472 (Brighenti & Mathews 1997). On balance, we adopt the X-ray profile in NGC 4472 as generally representative of other X-ray–bright elliptical galaxies.

The total mass distribution for NGC 4472 found by Brighenti & Mathews (1997) can be fit quite well with a de Vaucouleurs stellar core out to \(\sim r_e\) and a Navarro-Frenk-White halo beyond (Navarro, Frenk, & White 1996, hereafter NFW). In making these fits, we use a total stellar mass of \(M_\star = 7.26 \times 10^{11} M_\odot\), which is based on \(L_{\odot} = 7.89 \times 10^{10} L_{\odot,\odot}\), and the mass-to-light ratio \(M_\star/L_\odot = 9.20\) of van der Marel (1991); this \(M_\star/L_\odot\) is in fact verified by the X-ray image of NGC 4472 (Brighenti & Mathews 1997). For the one-parameter NFW halo, we use a virial mass of \(M_\nu = 4 \times 10^{13} M_\odot\), which corresponds to a NFW concentration parameter of \(c = 10.47\). The total mass distribution, stars plus dark halo, agrees very well with the X-ray–determined \(M(r)\) but is slightly too massive near \(r_e\), suggesting that the dark halo may be less centrally peaked than NFW predict.

In our hydrodynamical model for the evolution of the intergalactic and interstellar gas, we adopt a very simple flat cosmology with \(\Omega = 1\) and \(H = 50\) km s\(^{-1}\) Mpc\(^{-1}\), corresponding to a current universal age of \(t_u = 13\) Gyr. Primordial nucleosynthesis restricts the baryonic mass fraction to a narrow range, \(\Omega_b/(H/50)^2 \approx 0.05 \pm 0.01\) (Walker et al. 1991). We assume that both baryonic and dark matter converge toward the proto-4472 galaxy perturbation as described by the self-similar solution of Bertschinger (1985). In this model, all flow parameters depend on a single similarity variable \(\Lambda = r/r_\nu(t)\), where \(r_\nu(t) \approx t^{0.9}\) is the turnaround radius where the cosmic flow velocity vanishes at time \(t\).

Before we form the galaxy at time \(t_u\), the cold baryonic gas within \(r_\nu(t_u)\) flows exactly with the dark matter until it encounters an accretion shock. The time-dependent dark matter potential is described by an outer Bertschinger flow, similar to that into a central singularity, and an inner stationary NFW halo characterized by parameters that fit \(M(r)\) for NGC 4472. At each time, the NFW and Bertschinger mass distributions are matched at some radius \(r(r)\) that conserves the total mass of dark matter. Outside both \(r(r)\) and the accretion shock, the mass flux in the baryonic component at a fixed radius varies as \(\rho u \propto r^{-1.3}\), so most of the halo gas is accumulated at early times. The accretion shock forms at a very large radius, \(r_a \approx 1\) Mpc for \(t \geq 6\) Gyr. Within the accretion shock, a cooling flow is established and the gas velocity is very subsonic.

At some time \(t\), when a sufficient number of baryons has collected in the center of the flow, we form the de Vaucouleurs stellar mass distribution \(M_\nu(r)\) matching NGC 4472. This is done by reducing the gas density within the accretion shock radius \(r_a(t_u)\), lowering its mass by \(M_\nu\). Also at this time, the remaining gas in \(r < r_a(t_u)\) is heated by the Type II supernova (SNI) energy from massive stars, \(m > 8 M_\odot\). We assume a Salpeter power-law initial mass function (IMF) from \(m_1 = 0.08\) to \(m_2 = 100 M_\odot\), for \(\eta_{SN} = 6.81 \times 10^{-5}\) SNI are produced per \(M_\odot\) of stars formed, each of energy \(E_{SN} = 10^{51}\) ergs. The amount of SNI energy received by the hot gas depends on both the uncertain IMF-dependent value \(\eta_{SN}\) and the efficiency with which this energy is transferred to the hot gas and not lost by radiation. For this reason, we adopt \(\eta_{ad} E_{SN} M_\nu\), with \(\eta_{ad} = 6.81 \times 10^{-3}\) as a reference energy that can be adjusted as needed.

After time \(t_u\), the stars lose mass as described by \(\alpha(t) = 4.7 \times 10^{-20} [t/(t_u)]^{-1.1} s^{-1}\), where \(t_u = 13\) Gyr is the current time, \(t = t_u - t\), and \(s = 1.26\). We assume that the gas is heated after \(t\) by Type Ia supernovae, each of energy \(E_{SN} = 10^{51}\) ergs, in supernova units) of \(\eta_{SN}(t) = 0.03\) supernovae per 100 yr per \(10^{10} L_{R,\odot}\),

The gasdynamical equations we solve are

\[
\frac{\partial \rho}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \rho u \right) = \alpha \rho_{\nu}.
\]

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} \right) = -\frac{\partial P}{\partial r} - \rho \frac{GM_{\text{tot}}(r, t)}{r^2} - \alpha \rho_{u},
\]

\[
\frac{dE}{dt} = -\frac{P}{\rho} \frac{dP}{dr} - \frac{\rho^2 A}{m_p^2} + \alpha_{\nu} \left( E_{\nu} - \frac{P}{\rho} + \frac{u^2}{2} \right),
\]

where \(E = 3kT/2 m_p\) is the specific thermal energy, \(\mu = 0.62\) is the molecular weight, and \(m_p\) the proton mass. \(M_{\text{tot}}(r, t)\) is the total mass of stars, dark matter, and hot gas within radius \(r\). The mean injection energy of gas from stars is \(\epsilon_{\nu} = 3kT_s/2 m_p\), where \(T_s = (\alpha_\nu T_{\text{std}} + \alpha_{\nu\text{ex}} T_{\text{ex}})/\alpha_\nu\) and \(\alpha_\nu = \alpha_\nu + \alpha_{\nu\text{ex}}\), \(\Lambda(T)\) is the coefficient for optically thin radiative cooling. These equations are described more fully by Brighenti & Mathews (1998a). We solve them numerically using a spherical one-dimensional Eulerian hydrocode (ZEUS) with logarithmic spatial zoning.

In Figure 1 we illustrate the results of several gasdynamical calculations at time \(t_u = 13\) Gyr using \(t_0 = 2\) Gyr, \(\eta_{SN} = \eta_{ad}\), and \(\Omega_b = 0.05\) or 0.06. Considering the relative simplicity of our model, the agreement with both the temperature and density distributions observed in NGC 4472 is excellent. The positive gas temperature gradient within \(r \sim (3-5) r_a\) kpc observed in NGC 4472 and other bright elliptical galaxies (Brighenti & Mathews 1997) occurs as hot inflowing halo gas mixes with the slightly cooler gas at \(\sim T_s\), that characterizes the gas ejected from stars orbiting within a few \(r\). The apparent sensitivity of our results to \(\Omega_b\) is of considerable interest. However, we emphasize that the influence of the parameters \(\Omega_b, \eta_{ad}\), and \(t_u\) is degenerate. For example, solutions with \(\Omega_b\) decreased by ~0.01
are similar to those with $\eta_{\text{HII}}$ increased by $\sim 2$ or with $t_*$ decreased by $\sim 1$ Gyr. This degeneracy can be removed with more detailed models that include the abundance of iron and other elements produced in supernovae (Renzini 1998). Nevertheless, the $\Omega_b = 0$ solution shown in Figure 1, for which the only source of gas since $t_*$ is stellar mass loss, is clearly inadequate. We conclude that cosmic inflow of gas is essential in understanding the properties of hot gas observed in giant elliptical galaxies today. Moreover, this extended “circumgalactic” gas is sensitive to important cosmological parameters and to the details of SNII energy release during the epoch of galaxy formation; solutions with little or no SNII energy provide very poor fits in Figure 1.

In Figure 2 we show the current distribution of the baryon fraction $f_b = \Omega_b/\Omega$ with radius for the $\Omega_0 = 0.05$, $\eta_{\text{HII}} = \eta_{\text{rad}}$ solution. The baryonic cavitation around the galaxy is a relic of the SNII energy released at $t_*$ when gas was pushed out of the central parts of the flow. This suggests that determinations of $f_b$ based on X-ray observations in the range $100-300$ kpc could either underestimate or overestimate the true cosmic value of $\Omega_b$. Obviously, the variation of $f_b(r)$ in $r \approx 300$ kpc

![Figure 1](image1.png)

**Figure 1.—**Gas density (upper panel) and temperature (lower panel) of several models at $t = 13$ Gyr compared with observations of NGC 4472. Solid line: $\Omega_0 = 0.05$, $t_0 = 2$ Gyr, $\eta_{\text{HII}} = \eta_{\text{rad}}$; long-dashed line: $\Omega_0 = 0.06$, $t_0 = 2$ Gyr, $\eta_{\text{HII}} = \eta_{\text{rad}}$; short-dashed line: $\Omega_0 = 0.05$, $t_0 = 2$ Gyr, $\eta_{\text{HII}} = 0$, $t_0 = 9$ Gyr, $r_0 = 400$ kpc; dash-dotted line: $\Omega_0 = 0.00$, $t_0 = 2$ Gyr, $\eta_{\text{HII}} = 0$. Filled circles are Einstein HRI gas density observations from Trinchieri, Fabbiano, & Canizares (1986); open circles are ROSAT density and temperature observations from Irwin & Sarazin (1996).

![Figure 2](image2.png)

**Figure 2.—**Solid line: Variation of the baryon fraction $f_b$ at time $t = 13$ Gyr. Dashed line: The baryonic contribution of the gas alone. The model parameters are $\Omega_0 = 0.05$, $t_0 = 2$ Gyr, and $\eta_{\text{rad}} = \eta_{\text{rad}}$. At very large radii, the baryonic fraction approaches $\Omega_b = 0.05$.

shown in Figure 2 cannot be relevant to NGC 4472 because of the gravitational influence of the Virgo cluster.

As a further confirmation of the overall success of our models, we compare in Figure 3 the locus of truncated models with observed elliptical galaxies in the $(L_{X}/L_{B}, r_*/r_0)$-plane. The large circle, cross, and square at the right are the current loci of untruncated models with $\Omega_0 = 0.04, 0.05,$ and $0.06$; we have made these models somewhat more gas rich than NGC 4472 by reducing $\eta_{\text{HII}}$. When these models are truncated at time $t_n = 9$ Gyr, the current position of the galaxy at time $t_0 = 13$ Gyr moves progressively along the observed sequence of el-

![Figure 3](image3.png)

**Figure 3.—**A plot of the $(L_{X}/L_{B}, r_*/r_0)$-plane showing the correlation among observed elliptical galaxies taken from Mathews & Brighenti (1998). The large circle, cross, and square at the right are the loci of untruncated, gas-rich models at $t_0$ with the following parameters: $(\Omega_0, t_0, \eta_{\text{HII}}) = (0.04, 3, 0.1), (0.05, 2, 0.3)$, and $(0.06, 2, 1)$, respectively. The smaller symbols that extend from the untruncated solution toward the lower left show the current $(t = t_0)$ loci of models truncated at time $t_n = 9$ Gyr at five decreasing truncation radii: $r_n = 500, 400, 300, 200,$ and $100$ kpc. As $r_n$ decreases, the current locus in the $(L_{X}/L_{B}, r_*/r_0)$-plane moves from the untruncated solution almost exactly through the observed correlation. The filled square at the lower left is the locus of NGC 4472 if stellar mass loss creates all of the interstellar gas (the $\Omega_b = 0$ solution).
elliptical galaxies as the truncation radius $r_t$ decreases from 500 to 100 kpc. At the time of truncation, all gas and dark matter is removed at $r > r_t$, causing a rarefaction wave to propagate into the galactic interstellar medium; the cosmic inflow is stopped after $t_t$, and a new equilibrium is established in a sound crossing time $\sim 1$ Gyr. These results are insensitive to the time $t_t$ when the truncation occurred as long as $t_t \geq 6$ Gyr. This insensitivity to $t_t$ arises from the rather small changes in the gas flow variables within the accretion shock until the present time, the large radius of the accretion shock at early times ($r_{sh} \approx 400$ kpc at $t = 4$ Gyr), and the declining rate of intergalactic gas accumulation with time. The density and temperature profiles at $t_t$ for the truncation solution that best matches NGC 4472 ($\Omega_b = 0.05$, $r_c = 400$ kpc) are shown in Figure 1. This suggests that NGC 4472 may have been tidally truncated in the past. Finally, we expect that purely gaseous truncations produced by ram pressure stripping in dense clusters would also reduce both $L_x/L_B$ and $r_c/L_B$ (Sakelliou & Merrifield 1998).

We summarize our main conclusions:

1. The extended "circumgalactic" hot gas surrounding massive elliptical galaxies can be understood as a natural consequence of inflowing intergalactic gas over the Hubble time. This gas cannot have been produced by mass loss from stars within the elliptical galaxy itself.

2. Gas provided by stellar mass loss virializes to a relatively lower temperature $\sim T_c$ and, when mixed with hotter gas flowing in from the outer halo, creates the positive gas temperature gradients commonly observed within $\sim 3r_c$ (Brighenti & Matthews 1997).

3. Currently observed hot gas density and temperature profiles are sensitive to $\Omega_b$, to the time of galaxy formation, and to the total "feedback" energy released by Type II supernovae as galactic stars formed.

4. Because of the SNII-driven outflow just after the time of galaxy formation, the cosmic baryonic fraction $\Omega_b/\Omega$ cannot be accurately measured from X-ray observations or dynamical arguments within several hundred kpc.

5. The fraction of hot gas currently within $\sim r_c$ that comes from stellar mass loss is strongly dependent on $\Omega_b$ and the SNII energy. This must be considered in interpreting the abundance of iron and other elements in the hot gas.

6. The enormous range in $L_x/L_B$ among elliptical galaxies is due in large part to the differential truncation of the outer halos. The truncation could be caused by massive nearby group member galaxies or by another nearby group or cluster. It is likely that NGC 4472 has been truncated, perhaps by nearby group companions or by the Virgo cluster. If the wide range in $L_x/L_B$ were due to Type Ia supernova-driven galactic winds, as is often suggested, the correlation between $L_x/L_B$ and $r_c/L_B$ would be difficult to explain and the hot gas iron abundance would depend on $L_x/L_B$.

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