THE TEMPERATURE OF HOT GAS HALOS OF EARLY-TYPE GALAXIES

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ABSTRACT

Recently, the temperature $T$ and the luminosity $L_X$ of the hot gas halos of early-type galaxies have been derived, with unprecedented accuracy, from Chandra data for a sample of 30 galaxies, covering a wider range of galactic luminosity (and central velocity dispersion $\sigma_c$) than before. This work investigates the origin of the observed temperatures by examining the relationship between them and the galaxy structure, the gas heating due to Type Ia supernovae (SNe Ia) and the gravitational potential, and the dynamical status of the gas flow. In galaxies with $\sigma_c < 200$ km s$^{-1}$, the $T$'s are close to a fiducial average temperature of gas in outflow; at $200 < \sigma_c$ (km s$^{-1}$) $< 250$, the $T$'s are generally lower than this and unrelated to $\sigma_c$, which requires a more complex gas flow status; at larger $\sigma_c$, the $T$'s may increase as $\sigma_c^2$, as expected for infall heating, though heating from SNe Ia, that is independent of $\sigma_c$, should be dominant. All observed $T$'s are larger than the virial temperature, by up to ~0.5 keV. The additional heating can be provided in the X-ray brightest galaxies by SNe Ia and infall heating, with an SN Ia energy input even lower than in standard assumptions; in the X-ray fainter ones it can be provided by SNe Ia, whose energy input would be required to be close to the full standard value at the largest $\sigma_c$. This same energy input, though, would produce temperatures larger than observed at low $\sigma_c$ if entirely thermalized. The values of the observed $T$'s increase from outflows to inflows; the gas is relatively hotter in outflows, however, if the $T$'s are rescaled by the virial temperature. For $200 < \sigma_c$ (km s$^{-1}$) $< 250$, lower $L_X$ values tend to correspond to lower $T$'s, a result that deserves further investigation.

Key words: galaxies: elliptical and lenticular, cD – galaxies: fundamental parameters – galaxies: ISM – galaxies: kinematics and dynamics – X-rays: galaxies – X-rays: ISM

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1. INTRODUCTION

The advent of the Chandra X-ray Observatory, with its unprecedented subarcsecond resolution, allowed researchers to study better than ever before the main contributors to the total X-ray emission of early-type galaxies (hereafter ETGs): low-mass X-ray binaries (LMXBs; Fabbiano 2006), a population of weak sources such as late-type stellar coronae, cataclysmic variables, coronally active binaries (Pellegrini & Fabbiano 1994; Revnivtsev et al. 2008), the nuclear emission due to a supermassive black hole (MBH; e.g., Gallo et al. 2010; Pellegrini 2010), and a hot interstellar medium (ISM) with a temperature of a few million degrees. After careful subtraction of the stellar (resolved and unresolved) and nuclear emissions, the properties of the hot ISM could be characterized with unprecedented accuracy. Recently, this was done for a sample of 30 normal (non-cD) ETGs observed with Chandra to a depth that ensured the detection of bright LMXBs (Boroson et al. 2011, hereafter BKF). This is the first X-ray sample of ETGs covering a wide range of galactic luminosity, central velocity dispersion $\sigma_c$, and hot gas emission $L_X$; the X-ray properties of the hot gas (e.g., the luminosity $L_X$ and the average temperature $T$) were derived in a homogeneous way, using a complete and accurate procedure to subtract all kinds of nongaseous emissions (nucleus, detected and undetected LMXBs, and unresolved weak stellar sources). This approach resulted in a larger fraction of hot gas-poor galaxies than in previous samples, with $L_X$ extending down to much lower values than before ($\sim$10$^{38}$ erg s$^{-1}$) and showing a variation of up to ~ three orders of magnitude at the same galactic luminosity (see also David et al. 2006; Diehl & Statler 2007; Memola et al. 2009).

Such a wide variation, even larger than found previously, had been linked to the origin and evolution of the hot ISM, and provided evidence for the effectiveness of an internal heating mechanism (e.g., from Type Ia supernovae, hereafter SNe Ia) to regulate gas evolution and produce very different content of the gas in ETGs in the present epoch (Loewenstein & Mathews 1987; David et al. 1990; Ciotti et al. 1991). The action of external agents (gas stripping, confinement, accretion) to reduce or enhance the hot gas content was also invoked (e.g., White & Sarazin 1991; Brown & Bregman 2000; Sun et al. 2007).

With this new characterization of the hot gas, BKF revisited the relationships between fundamental properties of the hot gas and those of the host galaxy, such as the $L_X - T$, $L_X - \sigma_c$, and $T - \sigma_c$ relations, where $\sigma_c$ is a representative measure of the depth of the galactic potential well (Eskridge et al. 1995; O’Sullivan et al. 2001, 2003). $L_X$ correlates positively with $T$ and $\sigma_c$, though with a wide variation at fixed $\sigma_c$ and $T$. Interestingly, the best-fit relation $L_X \propto T^{4.5}$, close to that already known for X-ray-luminous ETGs (O’Sullivan et al. 2003), is still moderately strong among ETGs with low $T$ and $L_X$; also, in the $L_X - \sigma_c$ relation, ETGs with $kT > 0.4$ keV have the brightest X-rays (with one exception), while those with $kT < 0.3$ keV have the faintest X-rays. The least gas-rich ETGs are then the coolest ones, which seems contrary to the expectations that low $L_X$ ETGs lose their ISM in an outflow (e.g., David et al. 1990; Ciotti et al. 1991) and that the hotter the gas, the stronger the outflow (BKF). On average, $T$ increases with $\sigma_c$, and most ETGs lie above a rough estimate of the virial gas temperature ($T_v = \mu m_p \sigma_c^2 / k$), suggesting the presence of additional heating. ETGs with a moderate to high gas content ($L_X > 5 \times 10^{39}$ erg s$^{-1}$) follow a trend roughly parallel to that of $T_v$; instead, ETGs with little hot gas ($L_X < 5 \times 10^{39}$ erg s$^{-1}$) have similar $\sigma_c$ temperatures ranging from 160 to 250 km s$^{-1}$. 
This lack of correlation was attributed to different dynamical states of the hot ISM in gas-poor and gas-rich ETGs, though a full explanation of this aspect remained to be found (BKF).

This work takes advantage of the new, accurate measurements of the hot gas properties and of the fundamental relations \( L_X - \sigma \) and \( T - \sigma \), derived down to galaxy masses and X-ray luminosities smaller than ever before (BKF), to investigate the relationships among \( T \), galaxy structure, internal gas heating mechanisms (SNe Ia and those linked to the gravitational potential), and the dynamical status of the gas flow. A few characteristic temperatures are introduced that depend on the nature of the gas heating sources and galaxy structure, and are relevant for various gas-flow phases; these characteristic temperatures are then compared with the observed \( T \) values. In doing so, galaxy mass models are built according to the most recent understanding of the ETGs’ structures, such as their stellar mass profile and dark matter content and distribution, as indicated by detailed modeling of optical observations and the main scaling laws (e.g., Cappellari et al. 2006; Weijmans et al. 2009; Auger et al. 2010; Napolitano et al. 2010; Shen & Gebhardt 2010). This paper aims to address the following questions: can the gas heating sources above account for the observed \( T \)'s? How are the various input energy sources of the gas used in different flow phases? Is there any relation between \( T \) and the flow phase?

I present the sources of mass and heating for the hot ISM in Section 2, the conditions for the gas to escape from the galaxy in Section 3, the galaxy mass models in Section 4, the comparison between observed and predicted temperatures in Section 5, the relation between gas temperature and flow status in Section 6, and the conclusions in Section 7.

2. SOURCES OF MASS AND HEATING FOR THE HOT GAS

2.1. Gas Mass

In ETGs, the hot gas comes from stellar mass losses produced by evolved stars, mainly during the red giant, asymptotic giant branch, and planetary nebula phases, and by SNe Ia that are the only ones observed in an old stellar population (e.g., Cappellaro et al. 1999). The first, more quiescent, type of losses originates from ejecta that initially have the velocity of the parent star, then individually interact with the mass lost from other stars or with the hot ISM and mix with it (Mathews 1990; Parriott & Bregman 2008).

For a galaxy of total stellar mass \( M_\ast \), the evolution of the stellar mass-loss rate \( \dot{M}_\text{st} \) (c) can be calculated using single-burst stellar population synthesis models (Maraston 2005) for Salpeter and Kroupa initial mass functions (IMFs), assuming, for example, solar abundance. Doing so at an age of 12 Gyr, a rate of \( \dot{M}_\ast = B \times 10^{-11} L_B/(L_\ast) M_\odot \text{yr}^{-1} \) is recovered, where \( L_B \) is the galactic B-band luminosity at an age of 12 Gyr, and \( B = 1.8 \) or \( B = 1.9 \) for the Salpeter or Kroupa IMF (see also Pellegrini 2011). This value is in reasonable agreement with the average derived for nine local ETGs from Infrared Space Observatory data (Athey et al. 2002) of \( \dot{M}_\ast = 7.8 \times 10^{-12} L_B/(L_\ast) M_\odot \text{yr}^{-1} \), an estimate based on individual observed values that vary by a factor of \( \sim 10 \) and were attributed to different ages and metallicities.

The total mass-loss rate of a stellar population \( \dot{M} \) is given by the sum \( \dot{M} = \dot{M}_\ast + \dot{M}_{\text{SN}} \), where \( \dot{M}_{\text{SN}} \) is the rate of mass loss via SNe Ia events for the entire galaxy. \( \dot{M}_{\text{SN}} \) is given by \( \dot{M}_{\text{SN}} = \dot{M}_{\text{SN}} R_{\text{SN}} \), where \( \dot{M}_{\text{SN}} = 1.4 M_\odot \) is the mass ejected by one event and \( R_{\text{SN}} \) is the explosion rate. \( R_{\text{SN}} \) has been determined to be \( R_{\text{SN}} = 0.16 (H_0/70)^2 \times 10^{-12} L_B/(L_\ast) \text{yr}^{-1} \), where \( H_0 \) is the Hubble constant in units of km s\(^{-1}\) Mpc\(^{-1}\) (Cappellaro et al. 1999). More recent measurements of the observed rates of supernovae in the local universe (Li et al. 2011) give an SNe Ia rate in ETGs consistent with that of Cappellaro et al. (1999). For \( H_0 = 70 \text{ km s}^{-1}\text{ Mpc}^{-1} \), one obtains \( \dot{M}_{\text{SN}} = 2.2 \times 10^{-11} L_B/(L_\ast) M_\odot \text{yr}^{-1} \), which is \( \sim 80 \) times smaller than the \( M_\ast \) derived above for an age of 12 Gyr; therefore, the main source of mass for the hot gas is provided by \( \dot{M}_\ast \). A reasonable assumption is that the gas is shed by stars with a radial dependence that follows that of the stellar distribution, so that the density profile of the injected gas is \( \rho_{\text{gas}}(r) \propto \rho_\ast(r) \), where \( \rho_\ast(r) \) is the stellar density profile. This assumption is adopted hereafter, and the characteristic temperatures presented below apply to a gas distribution following \( \rho_{\text{gas}}(r) \propto \rho_\ast(r) \) (but see also Section 5).

2.2. Heating from Stellar Motions and Supernovae

The material lost by stars is ejected at a velocity of a few tens of km s\(^{-1}\) and at a temperature of \( \lesssim 10^5 \) K (Parriott & Bregman 2008); it is subsequently heated to high, X-ray emitting temperatures by the thermalization of the stellar velocity dispersion as it collides with the mass lost from other stars or with ambient hot gas and is shocked. Another source of heating of stellar mass losses is provided by the thermalization of the kinetic energy of SNe Ia events. The internal energy given by these heating processes to the unit mass of injected gas is \( 3kT_{\text{inj}}/2\mu m_p \) (where \( k \) is the Boltzmann constant, \( m_p \) is the proton mass, and \( \mu m_p \) is the mean particle mass, with \( \mu = 0.62 \) for solar abundance); \( T_{\text{inj}} \) is determined by the heating from thermalization of the motions of the gas-losing stars (\( T_{\text{star}} \)) and of the velocity of the SNe Ia ejecta (\( T_{\text{SN}} \)), and is written as (e.g., Gisler 1976; White & Chevalier 1983)

\[
T_{\text{inj}} = T_{\text{star}} + T_{\text{SN}} = \frac{M_\ast T_{\text{star}} + \dot{M}_{\text{SN}} T_{\text{SN}}}{M}.
\]

Here, \( T_{\text{inj}} \) is the equivalent temperature of the stellar motions (see below) and \( T_{\text{SN}} = 2\mu m_p E_{\text{SN}}/(3kM_{\text{SN}}) \) is the equivalent temperature of the kinetic energy \( E_{\text{SN}} \) of the SNe Ia ejecta, with \( E_{\text{SN}} = 10^{51} \text{ erg} \) for one event (e.g., Larson 1974). \( T_{\text{inj}} \) can be calculated by assuming that a factor \( f \) of \( E_{\text{SN}} \) is turned into heat; \( f < 1 \), since radiative energy losses from expanding supernova remnants may be important, and values down to \( f = 0.1 \) have been adopted (Larson 1974; Chevalier 1974). A value of \( f = 0.85 \) should not be too wrong for the hot, diluted ISM of ETGs (e.g., Tang & Wang 2005). In this way, \( T_{\text{SN}} = (f/0.85) \times 10^9 \text{ K} \). By approximating \( M \approx M_\ast \) and using the estimates of Section 2.1 for \( M_{\text{SN}} \) and \( M_\ast \) (for a Kroupa IMF) in the present epoch, one obtains \( T_{\text{SN}} \approx 1.7(f/0.85) \times 10^9 \text{ K} \).

The injection temperature \( T_{\text{inj}} \) is then the sum of two parts: one (\( T_{\text{SN}} \)) is independent of the position within the galaxy where the gas is injected (i.e., independent of the radius in spherical symmetry) and is also constant from galaxy to galaxy (for a fixed IMF, age of the stellar population, and SNe Ia rate); however, for each ETG it can evolve with time if \( M_{\text{SN}} \) and \( M_\ast \) evolve differently with time (Ciotti et al. 1991). The other part (\( T_{\text{star}} \)) is basically independent of time but has a radial dependence and changes with galaxy structure, i.e., with the total mass and its distribution. An average \( T_{\text{star}} \) is obtained by calculating the mass-weighted gas temperature gained by the thermalization of the \( \text{gas} \).
stellar random motions \( \langle T \rangle \):

\[
\langle T \rangle = \frac{1}{M_*} \int_0^\infty 4\pi r^2 \rho_*(r) \sigma^2(r) \, dr,
\]

where \( \sigma(r) \) is the one-dimensional velocity dispersion of the stars. The integral term in Equation (2) is the same one that gives the kinetic energy associated with the stellar random motions \( E_{\text{kin}} = \frac{1}{2} \int 4\pi r^2 \rho_*(r) \sigma^2(r) \, dr \) and enters the virial theorem for the stellar component; the mass-weighted temperature in Equation (2) is then often called “gas virial temperature.” For a galaxy mass model made of stars and dark matter, characterized by \( R = M_*/M_* \), where \( M_0 \) is the total dark mass and \( \beta = r_0/r_s \), with \( r_0 \) and \( r_s \) being the scale radii of the two mass distributions, \( \langle T \rangle \) can be expressed using the central velocity dispersion \( \sigma_c \) as \( \langle T \rangle = \mu m_p \sigma^2_c / k \) (e.g., Ciotti & Pellegrini 1992).

The function \( \Omega \) increases slightly for larger \( R \) and for lower \( \beta \), that is, for a larger amount of gravitating mass or a higher mass concentration, but \( \Omega \) is always \(<1\), since \( \sigma(r) \) has in general a negative radial gradient (e.g., Section 4 and Figure 1). \( \langle T \rangle \) is then proportional to \( \sigma^2_c \), and a simplified version of the virial temperature in Equation (2) that is often used is \( T = \mu m_p \sigma^2_c / k \); \( T_\sigma \), of course, overestimates the true \( \langle T \rangle \).

The mass-averaged injection temperature is finally given by

\[
\langle T_{\text{inj}} \rangle = \langle T \rangle + 1.7(f/0.85) \times 10^7 \text{ K},
\]

where, in general, the second term dominates, as is shown in Section 5 below.

### 2.3. Heating during Infall

In the case of mass losses flowing to the galactic center, the gas can be heated due to infall in the galactic potential and adiabatic compression; this process is sometimes referred to as “gravitational heating.” The average change in gravitational energy per unit of gas mass flowing in through the galactic potential down to the galactic center is

\[
E_{\text{grav}}^+ = \frac{1}{M_*} \int_0^\infty 4\pi r^2 \rho_*(r) [\phi(r) - \phi(0)] \, dr
\]

for galaxy mass distributions with a finite value of \( \phi(0) \) (see also Ciotti et al. 1991). One can define the temperature equivalent to the energy in Equation (4) as \( \langle T_{\text{grav}}^+ \rangle = 2 \mu m_p E_{\text{grav}}^+ / 3k \). As \( \langle T \rangle \), \( \langle T_{\text{grav}}^+ \rangle \) is also \( \propto \sigma^2_c \) and increases with larger \( R \) and smaller \( \beta \), which, for infalling gas, can be understood as a larger gas heating by compression during infall for a larger dark matter amount or for more concentrated dark matter.

Not all of \( E_{\text{grav}}^+ \) can be available for heating, though. If the inflow remains quasi-hydrostatic, then, according to the virial theorem, the energy radiated away is roughly one-half of the change in the gravitational potential energy, and the part available for the heating of the gas is the remaining half (i.e., ~0.5\( E_{\text{grav}}^+ \)). Actually, the energy available for heating will be much less than this. Inflows are caused by the radiative losses produced by the accumulation of stellar mass return, which makes the cooling time less than the galactic age; in the central regions, within a radius of \(~1\ kpc\), the cooling time can be as short as \(<10^8\ yr\), even shorter than the infall time (e.g., Sarazin & White 1988; Pellegrini 2011). In these conditions, the gas departs from a slow inflow, becomes very dense and supersonic close to the center, and cools rapidly down to low temperatures, so that \( >0.5 E_{\text{grav}}^+ \) is radiated away or goes into the kinetic energy of condensations (Sarazin & Ashe 1989). Furthermore, there is a possibility that not all the gas is hot when it reaches the galactic central regions if thermal instabilities develop and produce drop-outs from the flow; if gas cools and condenses out of the flow at large radii, then \( E_{\text{grav}}^+ \) can be much lower than in the definition above, and heating from infall in the gravitational potential is “lost” (Sarazin & Ashe 1989). In conclusion, without precise knowledge of how to compute \( E_{\text{grav}}^+ \) (which depends on the radius at which the injected gas drops below X-ray-emitting temperatures) and about what fraction of \( E_{\text{grav}}^+ \) is radiated or goes into the kinetic energy of the condensations, \( \langle T_{\text{grav}}^+ \rangle \) remains a reference value. A more direct use can instead be made
of the analogous temperature for escape \(T_{\text{grav}}^−\), introduced in Section 3.

2.4. Heating from a Central MBH

Because of the presence of a central MBH in ETGs, another potential source of gas heating could be provided by nuclear accretion. This subject has recently been studied intensely, through both observations and modeling, and it appears that the energy provided by accretion is of the order of that needed to cyclically offset the cooling of the inflowing gas in the central regions of gas-rich ETGs (e.g., Birzan et al. 2004; Million et al. 2010; Pellegrini et al. 2011). Therefore, the central MBH is believed to be a heat source that balances the radiative losses of the gas, acting mostly in the central cooling region. In gas-poor ETGs, the nuclear accretion energy is far lower due to the very small mass accretion rate, if present (Pellegrini et al. 2007), and the absorption of the energy output from accretion is likely not efficient. Given the role of the MBH outlined above, possible energy input from the MBH will not be considered as a source of global heating of gas.

3. CONDITIONS FOR ESCAPE

Another characteristic temperature for comparison with observed \(T\) values is the temperature with which the gas can escape from the galaxy. Assuming that the flow is stationary and adiabatic, the Bernoulli constant on each streamline along which the gas flows out of the galaxy must be positive. The Bernoulli equation with the minimum energy for escape is written as

\[
H(r) + v^2(r)/2 + \phi(r) = 0, \quad H = \frac{\gamma k T}{\mu m_p} = \frac{c_s^2}{\gamma - 1},
\]

where \(H\) is the enthalpy per unit gas mass, \(\gamma\) is the ratio of specific heats, \(c_s\) is the sound velocity, and \(v\) is the flow velocity. Integrating over galaxy volume and gas-mass averaging, this condition becomes

\[
\int_0^\infty 4\pi r^2 \rho_s(r) H(r) dr + \frac{1}{2} \int_0^\infty 4\pi r^2 \rho_s(r) v^2(r) dr = M_\star E_{\text{grav}}^−,
\]

where the escape energy

\[
E_{\text{grav}}^− = -\frac{1}{M_\star} \int_0^\infty 4\pi r^2 \rho_s(r) \phi(r) dr.
\]

is the average energy required to remove a unit of gas mass from the galaxy. \(E_{\text{grav}}^−\) gives a minimum energy requirement, since energy losses from cooling may be present, but these are not important for outflows that typically have a low density (e.g., Section 5.3). The escape temperature equivalent to \(E_{\text{grav}}^−\) is \(T_{\text{grav}}^−\) = \(2\mu m_p E_{\text{grav}}^−/3k\). The condition for the minimum energy for escape can then be translated into a condition for the injection temperature of the gas \(T_{\text{inj}}\) to be larger than \(T_{\text{grav}}^−\). In the simple case that \(\phi(r)\) is due only to one (stellar) mass component, from \(T_{\text{inj}} = 2\mu m_p E_{\text{kin}}/3k M_\star\) and the virial theorem (Section 2), one derives that \(T_{\text{grav}}^− = 4T_s\). The estimates of \(E_{\text{grav}}^−\) in Equation (6) and \(T_{\text{grav}}^−\) are calculated below for a general mass model (e.g., made by the superposition of stars and dark matter with different radial distributions). In previous works, the sufficient condition for the existence of a galactic wind was that the injection temperature exceeded an “escape temperature,” defined as \(T_e\) (White & Chevalier 1983) or “twice the equivalent dark halo temperature” (Loewenstein & Mathews 1987), and that the radiative cooling time in the central part of the galaxy was longer than the time required to flow out of this region. These conditions are similar to imposing that \(T_{\text{inj}}\) exceeds \(T_{\text{grav}}^−\), as derived above.

In principle, the gas can escape with different combinations of \(v\) and \(T\), and the observed \(T\) should be close\(^2\) to that entering \(H\) in Equation (5). There are two extreme cases for the value of the flow velocity \(v\) with respect to \(c_s\) (i.e., to the temperature). One is when the material is brought to infinity, keeping a subsonic velocity, and the minimum energy requirement becomes \(H \approx -\phi\); neglecting the kinetic term in Equation (5), one then obtains a characteristic gas-mass-averaged subsonic escape temperature:

\[
(T_{\text{esc}}^−) = \frac{2\mu m_p}{5k M_\star} \int_0^\infty 4\pi r^2 \rho_s(r) \phi(r) dr = \frac{3}{5} (T_{\text{grav}}^−). \tag{7}
\]

In the general case, \(H \approx -\phi\) gives for \(T\) a larger requirement than when \(v\) is not neglected; the partition of the gas energy between enthalpy and kinetic energy also can vary with radius within a galaxy. All this means that \(T_{\text{esc}}^−\) represents a fiducial upper limit to the observed temperatures of outflowing gas: if the kinetic energy of the flow is important, then the actual gas temperature will be lower (the stronger the outflow, with respect to \(c_s\), the cooler the gas). In the opposite extreme case, in which the temperature’s contribution to the gas energy is minor and that of velocity is dominant, the Bernoulli equation reduces to \(v_{\text{esc}}^2/2 + \phi = 0\); this gives the usual escape velocity of a unit of mass from a potential well: \(v_{\text{esc}}(r) = \sqrt{2(\phi(r))}\).

Finally, \(T_{\text{grav}}^−\) and \(T_{\text{esc}}^−\) have the same dependence as \(T_s\) on \(\sigma^2_\text{e}, R_c, \text{and } \beta\). For the representative galaxy mass models used here (Section 4, Figure 2), \(E_{\text{grav}}^− = (1.7–2.3) E_{\text{grav}}^−\), because \(\leq 0.5 E_{\text{grav}}^−\) can be converted into heat, the corresponding temperature gained by infall is \(T_{\text{inf}} \lesssim (T_{\text{grav}}^−)/2\).

4. GALAXY MASS MODELS

In this work, the exact values of \(T_s\), \(T_{\text{esc}}^−\), and \(T_{\text{grav}}^−\) are calculated as a function of \(\sigma_\text{e}\) for a series of representative three-component galaxy mass models, which are made via the superposition of a stellar distribution and a dark matter halo, to which a central MBH is added. The stellar density profile is given by the deprojection of a Sérsic law with index \(n = 4\) or 5, as appropriate for ETGs of the luminosities considered in this work (e.g., Kormendy et al. 2009). The mass of the MBH is \(M_{\text{BH}} = 10^5 M_\odot\), in agreement with the Magorrian et al. (1998) relation. The dark halo has the Navarro et al. (1997; Navarro–Frenk–White, NFW) profile \([\rho_h \propto (r/r_h)(1 + r/r_h)^2]\), where \(r_h\) is the scale radius, and the profile is truncated at large radii: \(M_\Phi\) is the total mass. For each \(\sigma_\text{e}\), the defining parameters of the stellar mass model were chosen according to the observational constraints that \(L_\star\) must follow the Faber–Jackson relation and that \(L_\star, \sigma_\text{e}\), and the effective radius \(R_e\) must lie on the fundamental plane of ETGs (e.g., Bernardi et al. 2003). The free parameters defining dark matter were chosen in agreement with the results from dynamical modeling of the observed motions of stars, planetary nebulae, and globular clusters at small and large radii; these indicate that dark matter begins to be dynamically important at \(2–3 R_e\) (e.g., Saglia et al. 1992; Cappellari et al. 2006; Weijmans et al. 2009; Shen & Gebhardt 2010). This requires

\(^2\) For example, one recalls two approximations made here with respect to the case of real ETGs: the total gas profile may be different from that of the stars, and the flow has a time-continuous distributed mass and energy input. The first of these points will be further discussed in Section 5.
that $\beta = r_h/R_e > 1$ and $R = M_b/M_* = 3$ or 5 (the latter value corresponds to the baryon-to-total-mass ratio of the Wilkinson Microwave Anisotropy Probe; Komatsu et al. 2009). By numerically solving the Jeans equations for the three mass components in the isotropic orbits case (e.g., Binney & Tremaine 1987), these choices produce $M_*, M_b$, and $R_e$ (the dark-to-luminous mass ratio within $R_e$). Reasonable values of $M_*/L_B = (4-10) M_*/L_B(\odot)$ and $R_e = 0.2-1.0$ are obtained. The main properties of a few representative mass models are shown in Figure 1.

For a consistent comparison between observed $T$'s and the characteristic temperatures derived for the mass models, the central stellar velocity dispersion $\sigma_c$ must be the same for observed ETGs and models. Typically, for nearby well-observed ETGs, the value of $\sigma_c$ is that of the projected and luminosity-weighted average within an aperture of radius $R_e/8$. Therefore, when defining a mass model, the chosen value of $\sigma_c$ was assigned to this quantity. Finally, streaming motions such as stellar rotation were not considered in these models (possible heating from these motions is discussed by Ciotti & Pellegrini 1996).

5. DISCUSSION

I investigate here the relationship between the observed $T$'s and those expected from the various sources of heating (stellar motions, gravitational potential, SNe Ia) or during the escape of the hot gas. To illustrate this, Figure 2 shows the run with $\sigma_c$ of the various temperatures defined in Sections 2.2, 2.3, and 3, together with the distribution of the observed $T$ values from BKF (Section 1). For the BKF sample, the value of $\sigma_c$ is the luminosity-weighted average within $R_e/8$, taken from SAURON studies for 12 ETGs (Kuntschner et al. 2010); for the remaining cases, $\sigma_c$ is taken from the references in the Hyperleda catalog (see Table 1).

The temperatures defined in Sections 2.2, 2.3, and 3 are mass-weighted averages, which are required when discussing energetic aspects of the gas (e.g., the energy required for escape as measured by $\langle T_{esc} \rangle$ compared with the input energy from SNe Ia). When a direct comparison is made with observed $T$'s, it must be noted that the latter coincide with mass-weighted averages only if the entire ISM has one temperature value; if the gas is multi-phase, or its temperature profile has a gradient, a single $T$ value measured from the spectrum of the integrated emission will be close to an emission-weighted average (e.g., Ciotti & Pellegrini 2008; Kim 2011). This means that, since the densest region is the central one, the measured $T$'s tend to be closer to the central values than the mass-weighted ones. The temperature profiles observed with Chandra change continuously in shape as the emission-weighted average $T$ decreases from $\lesssim 1$ keV to $\sim 0.3$ keV; they switch from a flat central profile that increases outside of $\sim 0.5 R_e$ to a quasi-isothermal profile to a profile with a negative gradient (Diehl & Statler 2008; Nagino & Matsushita 2009). Therefore, the lowest observed $T$'s, presumably associated with the last category, may be larger than mass-weighted values; intermediate $T$'s may be the closest to mass-weighted averages; and the largest observed $T$'s may be lower than mass-weighted averages. Another aspect to recall is that the temperatures defined in Sections 2.2, 2.3, and 3 refer to a gas distribution with $\rho_{gas} \propto \rho_c$; this is appropriate for continuously injected gas (e.g., for $\langle T_{inh} \rangle$), but it may be less accurate when comparing observed $T$'s with $\langle T_{esc} \rangle$ or when...
discussing the energetics of the entire gas content of an ETG by means of \( \langle T^+ \rangle \) and \( \langle T^- \rangle \), since the bulk of the hot ISM may have a different distribution from that of the stars. For example, the observed X-ray brightness profile of gas-rich ETGs was found to follow the optical profile, which was taken as evidence that, roughly, \( \rho_{\text{gas}} \propto \rho_{\text{stellar velocity dispersion}} \) (e.g., Sarazin & White 1988; Fabbiano 1989). For gas-poor ETGs hosting galactic winds, modeling shows that the profile \( \rho_{\text{gas}}(r) \) again will be shallower than \( \rho_{\text{stellar}}(r) \), though not as much as in the previous case (see, e.g., White & Chevalier 1983). If \( \rho_{\text{gas}} \) has a flatter radial profile than \( \rho_{\text{stellar}} \), then it is easy to show that its mass-weighted \( \langle T^+ \rangle \) will be larger than that derived using Equation (4), and its mass-weighted \( \langle T^- \rangle \) will be lower than derived using Equations (6) and (7). In conclusion, the comparison of observed \( T^+ \)s with mass-weighted expectations is the best that can currently be done in a general analysis such as the present work, albeit with the warnings above. Note, however, that all arguments and conclusions below remain valid or are strengthened when taking into account the above considerations about observed \( T^+ \)s or about the modifications to \( \langle T^- \rangle \), \( \langle T^+ \rangle \), and \( \langle T^- \rangle \).

### 5.1. Observed and Predicted Temperatures in the \( T - \sigma_c \) Plane

In the left panel of Figure 2, the observed \( T^+ \)s are compared with approximate estimates of the stellar temperature \( T_{\text{stellar}} \), \( T_{\text{inj}} \), and the escape temperature \( T_E \) (Section 3). The gas luminosity is also indicated with different colors; the \( L_X \) values are grouped in three ranges and have a roughly equal number of ETGs in each range. This grouping gives an indication of the gas flow status, based on previous works: a galactic wind leaving the galaxy at supersonic velocity has \( L_X < 10^{38} \text{ erg s}^{-1} \) (e.g., Mathews & Baker 1971; Trinchieri et al. 2008); global subsonic outflows and partial winds can reach \( L_X \sim 10^{40} \text{ erg s}^{-1} \) (Ciotti et al. 1991; Pellegrini & Ciotti 1998); and a central inflow becomes increasingly more important in ETGs of increasingly large \( L_X \). Magenta ETGs \( (10^{38} \text{ erg s}^{-1} < L_X < 1.5 \times 10^{39} \text{ erg s}^{-1}) \) should then host winds, subsonic outflows, and partial winds with a very small inflowing region of radius \( < 100 \) pc; cyan ETGs \( (1.5 \times 10^{39} \text{ erg s}^{-1} < L_X < 1.2 \times 10^{40} \text{ erg s}^{-1}) \) should host subsonic outflows and partial winds with an increasingly large inflowing region (of radius up to a few hundred pc); and black ETGs are hot-gas-rich and mostly inflowing. The best fit found for X-ray bright ETGs is also shown in the left panel (O’Sullivan et al. 2003) and gives a good representation of the distribution of observed \( T^+ \)s down to a range of low temperatures and gas contents never before explored. The slope of the fit \( (T \propto \sigma_c^{1.79}) \)

| Name          | \( kT \) (keV) | \( 1\sigma \) Error | \( L_X \) (\(10^{40} \text{ erg s}^{-1} \)) | \( \sigma_c \) (km s\(^{-1}\)) | Ref.           |
|---------------|--------------|---------------------|---------------------------------|--------------------------|----------------|
| NGC 720       | 0.54         | −0.01; +0.01        | 5.06                            | 241                      | Binney et al. (1990) |
| NGC 921       | 0.15         | −0.05; +0.05        | 2.13 \times 10^{-3}             | 200                      | Kuntschner et al. (2010) |
| NGC1023       | 0.32         | −0.01; +0.02        | 6.25 \times 10^{-2}             | 204                      | Kuntschner et al. (2010) |
| NGC1052       | 0.34         | −0.02; +0.02        | 4.37 \times 10^{-1}             | 215                      | Binney et al. (1990) |
| NGC1316       | 0.60         | −0.01; +0.01        | 5.35                            | 230                      | D’Onofrio et al. (1995) |
| NGC1427       | 0.38         | −0.11; +0.26        | 5.94 \times 10^{-2}             | 171                      | D’Onofrio et al. (1995) |
| NGC1549       | 0.35         | −0.04; +0.04        | 3.08 \times 10^{-1}             | 210                      | Longo et al. (1994) |
| NGC2434       | 0.52         | −0.05; +0.04        | 7.56 \times 10^{-1}             | 205                      | Longo et al. (1994) |
| NGC2768       | 0.34         | −0.01; +0.01        | 1.26                            | 205                      | Kuntschner et al. (2010) |
| NGC3115       | 0.44         | −0.10; +0.16        | 2.51 \times 10^{-2}             | 239                      | Fisher (1997) |
| NGC3377       | 0.22         | −0.07; +0.12        | 1.17 \times 10^{-2}             | 144                      | Kuntschner et al. (2010) |
| NGC3379       | 0.25         | −0.02; +0.03        | 4.69 \times 10^{-2}             | 216                      | Kuntschner et al. (2010) |
| NGC3384       | 0.25         | −0.15; +0.17        | 3.50 \times 10^{-2}             | 161                      | Kuntschner et al. (2010) |
| NGC3585       | 0.36         | −0.05; +0.06        | 1.47 \times 10^{-1}             | 198                      | Fisher (1997) |
| NGC3923       | 0.45         | −0.01; +0.01        | 4.41                            | 250                      | Pellegrini et al. (1997) |
| NGC4125       | 0.41         | −0.01; +0.01        | 3.18                            | 227                      | Bender et al. (1994) |
| NGC4261       | 0.66         | −0.01; +0.01        | 2.38                            | 200                      | Bender et al. (1994) |
| NGC4274       | 0.32         | −0.01; +0.01        | 2.63 \times 10^{-1}             | 252                      | Kuntschner et al. (2010) |
| NGC4365       | 0.44         | −0.02; +0.02        | 5.12 \times 10^{-1}             | 245                      | Bender et al. (1994) |
| NGC4374       | 0.63         | −0.01; +0.01        | 5.95                            | 292                      | Kuntschner et al. (2010) |
| NGC4382       | 0.40         | −0.01; +0.01        | 1.19                            | 187                      | Kuntschner et al. (2010) |
| NGC4472       | 0.80         | −0.00; +0.00        | 18.9                            | 294                      | Bender et al. (1994) |
| NGC4473       | 0.35         | −0.03; +0.05        | 1.85 \times 10^{-1}             | 192                      | Kuntschner et al. (2010) |
| NGC4526       | 0.33         | −0.01; +0.02        | 3.28 \times 10^{-1}             | 232                      | Kuntschner et al. (2010) |
| NGC4552       | 0.52         | −0.01; +0.01        | 2.31                            | 268                      | Kuntschner et al. (2010) |
| NGC4621       | 0.27         | −0.09; +0.13        | 6.08 \times 10^{-2}             | 225                      | Kuntschner et al. (2010) |
| NGC4649       | 0.77         | −0.00; +0.00        | 11.7                            | 315                      | Bender et al. (1994) |
| NGC4697       | 0.33         | −0.01; +0.01        | 1.91 \times 10^{-1}             | 174                      | Binney et al. (1990) |
| NGC5866       | 0.35         | −0.02; +0.03        | 2.42 \times 10^{-1}             | 159                      | Fisher (1997) |

**Notes.** Column 1: galaxy name; Columns 2–4: the hot gas temperature, its uncertainty, and the 0.3–8 keV gas luminosity, from BKF; Column 5: the stellar velocity dispersion as the luminosity-weighted average within an aperture of radius \( R_e / 8 \), with its reference in Column 6.
and that of the \( T_\sigma \propto \sigma^2 \) relation are similar, with the fit being shallower; this could be because not all heating sources depend on \( \sigma^2 \)—see, e.g., the important SNe Ia contribution in \( T_{\text{grav}} \), which produces a much flatter run of \( T_{\text{grav}} \) with \( \sigma \) (Figure 2). The fit was mostly based on gas-rich ETGs, whose \( T' \) show a trend with \( \sigma \), closer to that of \( T_o \) (an aspect further addressed in Sections 5.2 and 6), while gas-poor ETGs depart most from it, since their \( T \)’s change little for largely varying \( \sigma \) (as found by BKF; see Section 5.4).

The right panel of Figure 2 shows the stellar temperature (\( T_2 \)), injection temperature (\( T_{\text{inj}} \)), escape temperature (\( T_{\text{esc}} \)), and the characteristic temperature for the slowly outflowing gas (\( T_{\text{grav}} \)), calculated for a set of representative galaxy mass models (Section 4). At any fixed \( \sigma \) and Sérsic index \( n \), (\( T_{\text{grav}} \)) and (\( T_{\text{esc}} \)) are larger at larger galaxy masses (\( R \)) and mass concentrations (smaller \( \beta \)). The dashed lines represent a reasonable upper limit to the values of each characteristic temperature, since they correspond to the most massive model ETGs with the most concentrated dark matter allowed for by recent studies (Section 4). The (\( T_{\text{grav}} \)) curves lie below the simple approximation of the escape temperature given by \( 4T_\sigma \); (\( T_{\text{grav}} \)) = 4.8(\( T_\sigma \)) for \( R = 3 \), and \( \simeq 5.2(\sigma) \) for the three cases with \( R = 5 \).

As expected, all (\( T_\sigma \)) curves lie below \( T_o \), which overestimates the kinetic energy associated with the stellar random motions (Section 2.2). Note that, according to the virial theorem, (\( T_\sigma \)) is independent of orbital anisotropy, which just redistributes the stellar heating differently within a galaxy; the presence of ordered rotation in stellar motions instead requires a more careful consideration. For any fixed galaxy mass model, this rotation would leave the total stellar heating unchanged or lower it, depending on whether the entire stellar streaming motion or just a fraction of it is converted into heat (Ciotti & Pellegrini 1996). In the worst case that the rotational motion is not thermalized at all, and the galaxy is a flat isotropic rotator, (\( T_o \)) in Figure 2 should be an overestimate of \( \sim 30\% \) of the temperature corresponding to stellar heating (Ciotti & Pellegrini 1996); the possible reduction of (\( T_o \)) should be lower than this, because the massive ETGs in Figure 2 are less flattened and more pressure-supported systems (e.g., Emsellem et al. 2011).

All observed \( T \)'s are located above (\( T_o \)); thus, additional heating with respect to the thermalization of stellar kinetic energy is needed, as noticed previously using (\( T_o \)) (e.g., Davis & White 1996; BKF). The gas can retain the memory of its injection temperature and have additional infall heating, as examined in Sections 5.2 and 5.3.

Finally, the values of (\( T_{\text{inj}} \)) for \( f = 0.85 \) are by far the largest temperatures in Figure 2, larger than (\( T_{\text{grav}} \)) up to \( \sigma \simeq 250 \) km s\(^{-1} \); therefore, SNe Ia should cause the escape of gas from all ETGs up to this \( \sigma \), since the gas at every time is injected with an energy larger than required to leave the galaxy potential. This expectation is fulfilled by all ETGs with \( \sigma \lesssim 200 \) km s\(^{-1} \); their X-ray properties (a low \( L_X \) and \( T \)’s on the order of (\( T_{\text{grav}} \)) agree well with what is expected if outflows are important in them. This result has been suggested previously based on the low observed \( L_X \); now, for the first time, it can be confirmed based on the observed \( T \) values. At \( \sigma > 200 \) km s\(^{-1} \), instead, ETGs may have \( L_X \) far larger than expected for outflows (black symbols), and most ETGs where

\[ E_{\text{SN}} = R_{\text{SN}}E_{\text{SN}}/M_* \] and \( E_{\text{SN}} \) contribute to the required additional thermal energy with respect to that gained from the stellar random motions, i.e., to \( \Delta E_{\text{th}} = 3k(T - T_{\text{grav}})/2\mu m_p \). \( E_{\text{grav}} \) and \( E_{\text{tot}} \) in large part can be radiated in gas-rich ETGs, but they seem to far exceed the required \( \Delta E_{\text{th}} \).

For example, for the highest \( L_X \) of gas-rich ETGs (BKF; see also Section 6). Inflowing ETGs can also benefit from the SNe Ia energy input for the unit mass of injected gas, this is written as \( E_{\text{SN}} \), and \( E_{\text{SN}} \) contribute to the required additional thermal energy with respect to that gained from the stellar random motions, i.e., to \( \Delta E_{\text{th}} = 3k(T - T_{\text{grav}})/2\mu m_p \). \( E_{\text{grav}} \) and \( E_{\text{tot}} \) in large part can be radiated in gas-rich ETGs, but they seem to far exceed the required \( \Delta E_{\text{th}} \). For example, for the highest \( L_X \) of gas-rich ETGs (BKF; see also Section 6). Inflowing ETGs can also benefit from the SNe Ia energy input for the unit mass of injected gas, this is written as \( E_{\text{SN}} \), and \( E_{\text{SN}} \) contribute to the required additional thermal energy with respect to that gained from the stellar random motions, i.e., to \( \Delta E_{\text{th}} = 3k(T - T_{\text{grav}})/2\mu m_p \). We have twice the SNe Ia energy input accounted for the gas, to account for the observed \( T \)’s of gas-rich ETGs, seems to be available in a sufficient amount, even if \( f \) were to be <0.85.

5.3 Outflows and SNe Ia Heating

The gas is not mostly inflowing in all ETGs, while it is hotter than (\( T_o \)) in all of them. When in outflow, the radiative losses are far smaller, but energy is spent in extracting the gas from the galaxy and giving it a bulk velocity. I discuss here the possibility that heating from the SNe Ia energy input accounts for the

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4 All other things being equal, these temperatures are also larger at smaller \( n \) values, due to the galaxy becoming more massive to reproduce the same \( \sigma_\star \), since the stellar mass profile is less steep (e.g., Figure 1).
observed $\Delta E_{\text{th}}$ of ETGs where outflows are likely important (those with low/medium $L_X$—the magenta and cyan symbols in Figure 2).

I assume that the SNe Ia energy is used for the uplift of gas and the kinetic energy with which gas escapes from the galaxy, and, neglecting radiative losses, that the remaining part can account for the observed $\Delta E_{\text{th}}$. Then the energy balance per unit mass of injected gas is $E_{\text{SN}} = E_{\text{grav}} + E_{\text{out}} + \Delta E_{\text{th}}$, where $\Delta E_{\text{th}}$ is the same as in Section 5.2 and $E_{\text{out}} = v_{\text{out}}^2/2$ is the mass-averaged kinetic energy of the escaping material per unit of gas mass. Figure 4 shows $\Delta E_{\text{th}}$ derived from this balance, with $v_{\text{out}} = c_s$, and $c_s$ calculated for $\gamma = 5/3$ and $kT = 0.3$ keV, a temperature on the order of that observed for ETGs that are likely in outflow (Figure 2). Adopting $v_{\text{out}} \sim c_s$ (independent of $\sigma_c$) produces $E_{\text{out}}$ at the upper end of those expected,5 and then the estimate of $\Delta E_{\text{th}}$ may be biased low. With $v_{\text{out}} \sim c_s$, $E_{\text{out}}$ is just $\sim 0.1(f/0.85)E_{\text{SN}}^{\text{tot}}$. The energy needed for gas extraction, $E_{\text{grav}}$, for the same galaxy mass model used in Section 5.2, varies instead from $\sim 1/3(f/0.85)E_{\text{SN}}^{\text{tot}}$ for $\sigma_c = 150$ km s$^{-1}$ to $\sim E_{\text{SN}}^{\text{tot}}$ for $\sigma_c = 250$ km s$^{-1}$; this explains the strong dependence of the predicted $\Delta E_{\text{th}}$ on $\sigma_c$ in Figure 4. It is clear from this figure that, for $f = 0.85$, SNe Ia can account for the required heating in all ETGs with low/medium $L_X$; for $f = 0.35$, however, the temperature increase would fall short of that required for all ETGs. In Figure 4, the energy losses due to radiation are also shown; their small size supports the hypothesis that in most cases they do not significantly affect the energy budget of the gas.

Given the flat distribution of the observed points in Figure 4 and the steep behavior of the curves predicting $\Delta E_{\text{th}}$, the value of $f$ required to account for the observed $\Delta E_{\text{th}}$ increases with $\sigma_c$. In particular, the value $f \sim 0.85$ that is required at high $\sigma_c$ would produce an expected $\Delta E_{\text{th}}$ at low $\sigma_c$ that is larger than observed. A possible solution could reside in the efficiency of the SNe Ia energy-mixing process. In massive, gas-rich ETGs, SNe Ia bubbles should disrupt and share their energy with the local gas within $\sim 3 \times 10^6$ yr (Mathews 1990); for a Milky Way–size bulge in a global wind, however, three-dimensional hydrodynamical simulations of discrete heating from SNe Ia suggest a non-uniform thermalization of SNe Ia energy, with overheated gas from an SNe Ia explosion at the bulge center that is advected outward, carrying a large fraction of SNe Ia energy with it (Tang et al. 2009). For subsonic outflows, the mixing is expected to be more local and more complete (Lu & Wang 2011). The magenta and cyan ETGs in Figure 4 have gas densities and luminosities larger than those considered by Tang et al. (2009); however, if a discrete heating effect were still present at $\sigma_c < 200$ km s$^{-1}$, it could qualitatively explain a

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5 For example, in a wind solution, the terminal (i.e., the largest) velocity of the flow is roughly the central sound speed (White & Chevalier 1983); moreover, in this solution, the gas is likely to be already too “fast” with respect to that of most magenta ETGs in Figure 2, due to their $L_X$ (e.g., Trinchieri et al. 2008).
lower \( f \) for these galaxies. It is also possible that \( (T_e) \) has been overestimated (and then the observed \( \Delta E_{\text{inh}} \) underestimated) at low \( \sigma_c \) if these ETGs are less pressure-supported systems (e.g., Emsellem et al. 2011) and stellar rotational streaming is not entirely thermalized (Section 5.1). Another possible explanation could be that ETGs with \( \sigma_c > 200 \text{ km s}^{-1} \) are less outflow-dominated than those at lower \( \sigma_c \) (though this is not supported solely based on \( L_X \), since magenta ETGs are found over the entire \( \sigma_c \) range in Figure 4), so that their \( E_{\text{grav}} \) would be lower than assumed by the curves in Figure 4, and more SNe Ia energy would be available for heating. In this way, \( f \) could have a value <0.85 and possibly be similar for all ETGs.

Finally, a comparison of Figures 3 and 4 shows that the average \( \Delta E_{\text{inh}} \) is slightly larger for the X-ray brightest ETGs (for which it ranges between 0.1 and 0.5 keV) than for the X-ray faintest ones (0–0.3 keV); moreover, while the \( \Delta E_{\text{inh}} \) in Figure 3 can be explained even with \( f < 0.85 \), it is required that \( f \sim 0.85 \) for the X-ray faintest ETGs with the largest \( \sigma_c \) in Figure 4. Both facts are the consequence of the large fraction of SNe Ia energy input that is used in gas extraction where outflows dominate, while all SNe Ia energy remains within the galaxies where inflow dominates.

In conclusion, even for ETGs with low/medium \( L_X \), a fundamental X-ray property such as \( T \) can be accounted for by simple arguments, simply based on realistic galaxy mass models and reasonable SNe Ia heating capabilities. There may, however, be more energy available for the gas in ETGs with \( \sigma_c < 200 \text{ km s}^{-1} \) than can be accounted for by the present simple scenario.

5.4. The Temperature and Gas Flow Status in ETGs of Intermediate Mass

The observed X-ray properties (low \( L_X \) and \( T \sim (T_{\text{esc}}^{-1}) \)) and the energy budget of the gas (e.g., \( (T_{\text{esc}}^{-1}) \) versus \( (T_{\text{inj}}) \)) for ETGs with \( \sigma_c \lesssim 200 \text{ km s}^{-1} \) are all consistent with the expectations for outflows; the large \( L_X \) and \( (T_{\text{grav}}) \) larger than \( (T_{\text{inj}}) \) of ETGs with \( \sigma_c > 250 \text{ km s}^{-1} \) agree with gas that is mostly inflowing. For \( 200 < \sigma_c (\text{km s}^{-1}) < 250 \), however, ETGs show very different \( L_X \) and \( T \), whose values seem unrelated to \( (T_{\text{esc}}) \) and to the relative size of \( (T_{\text{grav}}) \) and \( (T_{\text{inj}}) \) (Figure 2). For example, for \( f = 0.85 \), \( (T_{\text{inj}}) \) exceeds \( (T_{\text{grav}}) \), but most \( f \) values lie well below \( (T_{\text{esc}}) \), and even high \( L_X \) values (incompatible with outflows) are common. One primary explanation could be that \( f < 0.85 \); for example, for \( f = 0.35 \), \( (T_{\text{inj}}) \) becomes lower than \( (T_{\text{grav}}) \) at \( \sigma_c \sim 180 \text{ km s}^{-1} \) (Figure 2).

Four ETGs with \( \sigma_c > 200 \text{ km s}^{-1} \) and very low \( L_X \) (Figure 2, magenta symbols), though, require that \( f > 0.35 \) for them, and then that \( f \) vary from galaxy to galaxy, or that their gas be removed by other processes such as an active galactic nucleus outburst (e.g., Machacek et al. 2006; Ciotti et al. 2010), a merging, or an interaction (Read & Ponman 1998; Sansom et al. 2006; Brassington et al. 2007). An event similar to the latter two is very recent in the past for three of these ETGs (NGC1023, NGC3115, NGC3379), which are very regular in their stellar morphological and kinematic properties, and possible in the other ETG (NGC4621) that hosts a counter-rotating core (Wernli et al. 2002).

A second explanation could be that \( (T_{\text{inj}}) \) exceeds \( (T_{\text{grav}}) \) only in the present epoch: while \( (T_e) \) and \( (T_{\text{grav}}) \) are independent of time, \( T_{\text{inj}} \) may have been lower in the past (Equation (1)), to the point that \( (T_{\text{inj}}) \) may have been lower than \( (T_{\text{grav}}) \) for more ETGs than in Figure 2 (which represents a snapshot of the present epoch). The gas then could have accumulated and radiative losses become important, even for the gas injected in later epochs. In fact, the population synthesis models of Section 2 predict that \( M_\text{SNe} \) was larger at early times (e.g., by \( \sim 6 \) times at an age of 3 Gyr); to keep \( T_{\text{inj}} \) high in the past, then, from Equation (1), \( M_\text{SNe} \) must decrease with time \( t \) at a rate similar to or steeper than that of the stellar mass losses (\( M_* \propto t^{-1.3} \), Ciotti et al. 1991). Recent observational estimates indicate instead an SNe Ia rate that decays close to \( t^{-1} \) (Maoz et al. 2011; Sharon et al. 2010); thus, \( T_{\text{SN}} \) and \( (T_{\text{inj}}) \) should be increasing with time, reaching the values of Figure 2 in the present epoch. Then a “cooling effect of the past” would explain a moderate or high \( L_X \) even where \( (T_{\text{inj}}) \) exceeds \( (T_{\text{grav}}) \) in Figure 2.

Both explanations, \( f < 0.85 \) and/or a lower \( (T_{\text{inj}}) \) in the past, can account for the lack of a widespread presence of outflows for \( 200 < \sigma_c (\text{km s}^{-1}) < 250 \). Both, though, require a mechanism different from the SNe Ia energy input to cause degassing in some low \( L_X \) ETGs in the same \( \sigma_c \) range.

Another possibility is that partial winds become common for \( \sigma_c > 200 \text{ km s}^{-1} \): these ETGs host an inner inflow and an outer outflow (e.g., MacDonald & Bailey 1981), with variations in galactic structure causing different sizes of the inflowing regions and different \( L_X \) (Pellegrini & Ciotti 1998). This possibility holds even for \( f = 0.85 \) and for both kinds of time evolution of \( (T_{\text{inj}}) \); in fact, if the flow is decoupled, ETGs may host a central inflow even if \( (T_{\text{inj}}) \) is larger than \( (T_{\text{grav}}) \). Similarly, the observed \( T \)'s can be lower than \( (T_{\text{esc}}) \) in ETGs where the outflow is only external; in this case, the observed \( T \)'s may be lowered also by radiative losses in the central inflowing region.

6. THE TEMPERATURE OF INFLOWS AND OUTFLOWS

In Figure 2, the hottest gas is in ETGs with the highest \( L_X \), and the coolest gas is in ETGs with the lowest \( L_X \) (as also found by BKF). This feature is also present in the \( L_X - \sigma_c \) relation, where ETGs with \( kT > 0.4 \text{ keV} \) have the brightest X-rays (with one exception) and those with \( kT < 0.3 \text{ keV} \) have the faintest X-rays (BKF). All this may seem contrary to the simple expectations that hotter gas is needed for escape and that the hotter the gas, the stronger the outflow and the lower the gas content. We re-examine this point below, first across the entire \( \sigma_c \) range and then at fixed \( \sigma_c \) values.

A proper consideration of whether outflowing ETGs possess hotter or colder gas than inflowing ones requires that all \( T \)'s be rescaled by a temperature equivalent to the depth of the potential where the gas resides (e.g., by \( T_e \)). Is there a trend in the distance of the observed \( T \)'s from \( (T_{\text{esc}}) \)? This is examined in Figure 5, where temperatures are rescaled by \( T_e \) and the \( \sigma_c^2 \) dependence of all curves in Figure 2 is removed. Figure 5 shows that for \( \sigma_c < 200 \text{ km s}^{-1} \) the observed points reach \( (T_{\text{esc}}) / T_e \), a result similar to that in Figure 2, and that they fall below it with increasing \( \sigma_c \) (with a transition region of large dispersion in \( T/T_e \)). Therefore, ETGs with \( \sigma_c < 200 \text{ km s}^{-1} \) are indeed the hottest relative to the virial temperature; since in these ETGs outflows are important (Section 5.1), the flow is relatively hotter in outflows, and \( T \) increases from outflows to inflows only in an absolute sense. The \( T \)'s of the X-ray brightest ETGs should show a dependence on \( \sigma_c^2 \) if the gravitational heating of the gas dominates SNe Ia heating, and then they should lie within a horizontal zone in Figure 5. The observed distribution does not disagree with this kind of dependence, but more cases are needed to firmly establish its presence; such a dependence is not expected, though, since the SNe Ia heating should easily dominate the gravitational heating (Section 5.2).
Finally, I compare the $T$’s at similar $\sigma_c$ in the most populated region of Figure 5 for $200 < \sigma_c (\text{km s}^{-1}) < 250$. Here, the variation of $T/T_\sigma$ is the largest and is covered by ETGs of all X-ray emission levels; the X-ray brightest ETGs have $T/T_\sigma > 1.1$, while the lowest $T/T_\sigma$ values belong to the X-ray fainter ETGs. For example, two of the three lowest $T/T_\sigma$ values in the figure (those of NGC3379 and NGC4621) belong to the X-ray faintest group. While heating sources seem abundant in gas-rich ETGs, accounting for their $T$’s (see, e.g., Figure 3 and the additional possibility of MBH heating; Section 2.4), even after taking into account their radiative losses, this result remains more difficult to explain for ETGs of low/medium $L_X$ and may require ad hoc solutions. It may be another representation of what is mentioned in Section 5.3: that $\Delta E_{\text{inj}}$ can be larger for the X-ray brightest ETGs than for the X-ray faintest ETGs, due to the different employment of SNe Ia input energy; or it could be that $f < 0.85$ in these ETGs, so that SNe Ia cannot make their gases hotter than this (Figure 4). Moreover their galaxy structures may be very different from an average one, so that dividing all $T$’s for the same $T_\sigma$ produces a biased view; or the evolutionary history of the gas may have been peculiar. Certainly, this trend needs further investigation and, if confirmed, will provide the basis for further theoretical work.

7. CONCLUSIONS

This work focused on the origin of the hot gas temperatures recently derived for a sample of ETGs observed with Chandra, down to galaxy masses and X-ray luminosities smaller than ever before. A few characteristic mass-weighted average temperatures were defined for a gas distribution $\rho_{\text{gas}}(r) \propto \rho(r)$, such as for the gas shed by stars: the virial temperature ($T_\text{vir}$); the injection temperature ($T_{\text{inj}}$), that is the sum of ($T_\sigma$) and of a temperature equivalent to the SNe Ia kinetic energy input (with a factor $f$ allowing for its uncertain thermalization); the escape temperature ($T_{\text{esc}}$), defined as the temperature equivalent to the energy required for escape from the gravitational potential; a fiducial value for the temperature of escaping gas, evaluated on a streamline of very subsonic velocity ($T_{\text{esc}}^{\text{fiducial}} = 0.6(T_{\text{esc}}^{\text{vir}})$); and, finally, the temperature equivalent to the energy liberated by the inflow of gas to the galactic center, ($T_{\text{esc}}^{\text{grav}}$). These temperatures were then calculated for a set of representative galaxy mass models, made by the superposition of a central MBH and of a stellar and a dark mass density distribution, with parameters constrained by the fundamental scaling laws of ETGs and recent observational findings. The main properties of the characteristic temperatures are the following.

1. All temperatures scale as $\sigma_c^2$ (except for $\langle T_{\text{inj}} \rangle$) and increase for larger and/or more concentrated mass content. For the adopted set of representative galaxy mass models, ($T_{\sigma}$) is lower than $T_\sigma$ (by $\sim 0.1$–0.2 keV), ($T_{\text{esc}}^{\text{grav}}$) $\approx 5\langle T_\sigma \rangle$, and ($T_{\text{esc}}^{\text{grav}}$) $\approx 2\langle T_{\text{esc}}^{\text{grav}} \rangle$; the temperature that can be produced by infall heating, though, will be much lower than ($T_{\text{esc}}^{\text{grav}}$), due to energy losses in radiation, the kinetic energy of mass condensations, and mass drop-outs from the flow.

2. $\langle T_{\text{inj}} \rangle$ is by far the largest of the characteristic temperatures due to the important SNe Ia contribution (independent of $\sigma_c$); for $f = 0.85$, it is larger than the minimum injection temperature for global escape up to $\sigma_c \sim 250$ km s$^{-1}$.

The comparison of the characteristic temperatures with those observed, in the $T - \sigma_c$ plane, shows the following.

1. The best-fit $T - \sigma_c$ relation previously found for X-ray bright ETGs reproduces the average trend of the observed $T$ down to low temperatures and low $L_X$. ETGs with low/medium $L_X$ show the largest departures from this fit, which can be explained by the variety of gas-flow phases possible in them (winds, subsonic outflows, partial winds), where the main input energies (from SNe Ia and gas infall) are used in different ways.

2. All observed $T$’s are larger than $\langle T_{\sigma} \rangle$; the additional heating of gas $\Delta E_{\text{inj}}$, with respect to that provided by the thermalization of stellar motions, is $\Delta E_{\text{inj}} \approx 0.1$–0.5 keV for the X-ray faintest ETGs and $\Delta E_{\text{inj}} \approx 0.5$–3 keV for the X-ray brightest ETGs (for a representative galaxy mass model).

3. In a stationary situation, $\Delta E_{\text{inj}}$ of the X-ray brightest ETGs can be accounted for by the energy input of SNe Ia and gas infall, even if they are much reduced with respect to standard assumptions (i.e., $f$ can be $< 0.85$). The gravitational heating produces a $T \propto \sigma_c^{-2}$ trend that may be present in the X-ray brightest ETGs; the SNe Ia heating, though, is expected to be dominant.

4. $\Delta E_{\text{th}}$ can be provided by SNe Ia in X-ray fainter ETGs, where outflows are important; most of the SNe Ia energy is needed for gas extraction, and less for the kinetic energy of the escape. The value of $f$ to account for the observed $\Delta E_{\text{th}}$ increases with $\sigma_c$, until the entire SNe Ia energy ($f \approx 0.85$) is required at the highest $\sigma_c$. With this $f$, though, at low $\sigma_c$ the observed $\Delta E_{\text{th}}$ is lower than expected. Possible solutions require a different efficiency of the SNe Ia energy-mixing process, or an overestimate of ($T_{\sigma}$) at low $\sigma_c$, if these ETGs are less pressure-supported systems, or a more complex flow status than in the simple scheme adopted.

5. At low $\sigma_c \lesssim 200$ km s$^{-1}$, $\langle T_{\text{inj}} \rangle$ is larger than $\langle T_{\text{esc}}^{\text{grav}} \rangle$, the $L_X$ values are low, and the $T$’s are on the order of ($T_{\text{esc}}^{\text{sub}}$): all this agrees well with what is expected for outflows. At high $\sigma_c > 250$ km s$^{-1}$, $\langle T_{\text{inj}} \rangle$ is lower than $\langle T_{\text{esc}}^{\text{grav}} \rangle$, and the high $L_X$ and $T$ values can be explained by the mostly inflowing gas. For $200 < \sigma_c (\text{km s}^{-1}) < 250$, instead, there is a large
variation in $L_X$ and $T$. Possible explanations could be that the SNe Ia energy input varies from galaxy to galaxy; and/or that $(T_{\text{inj}})$ was lower in the past due to the different time evolutions of the mass loss and the SNe Ia rate; or that partial winds become common, with the flow status less related to the values of $(T_{\text{inj}})$, $(T_{\text{grav}})$, and $(T_{\text{esc}})$. 6. When measured relative to the depth of the potential well, the observed temperatures $T/T_{\sigma}$ are larger for $\sigma_c < 200$ km s$^{-1}$ (outflows) and lower for $\sigma_c > 250$ km s$^{-1}$ (inflows). The observed $T$s then increase from outflows to inflows only in an absolute sense, and the gas is relatively hotter in outflows. In the intermediate region of $200 < \sigma_c$ (km s$^{-1}$) $< 250$, lower $L_X$ values tend to correspond to lower $T$ and $T/T_{\sigma}$ values, which requires ad hoc explanations and deserves further observational and theoretical investigation.

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