

COOLING FLOW MODELS OF THE X-RAY EMISSION AND TEMPERATURE PROFILES  
FOR A SAMPLE OF ELLIPTICAL GALAXIES

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## ABSTRACT

A simple spherically symmetric, steady state, cooling flow description with gas loss (following Sarazin & Ashe 1989), within galaxy models constrained by radially extended stellar dynamical data, is shown to provide generally reasonable fits to the existing data on X-ray emission profiles and temperatures for a set of bright elliptical galaxies in Virgo and Fornax. Three free parameters are needed to specify the model: the external mass flux, the external pressure, and a dimensionless factor, which regulates the mass deposition rate along the flow. Three different assumptions on the supernova rate have been considered. A moderate value for the supernova rate in elliptical galaxies is found to be preferred. Confining pressures of  $p_{\text{ext}} \sim 4\text{--}15 \times 10^3 \text{ K cm}^{-3}$  and significant accretion rates of external material, up to  $4 M_{\odot} \text{ yr}^{-1}$ , are suggested by our models. A possible correlation between  $L_X/L_B$  and the iron abundance in the gas inside ellipticals is pointed out.

*Subject headings:* cooling flows — galaxies: elliptical and lenticular, cD — intergalactic medium — supernovae: general — X-rays: galaxies

## 1. INTRODUCTION

In their simplest form, cooling flow models for the description of the X-ray emission from individual galaxies (see Sarazin & White 1987; Vedder, Trester, & Canizares 1988) have a history of mixed success (see Sarazin 1990 and references therein).

On the one hand, a steady state description of the dynamics of the hot interstellar medium may be too naive in view of the expected time dependence of the basic energy balance during galaxy evolution (see Loewenstein & Mathews 1987; David, Forman, & Jones 1990; Ciotti et al. 1991; Binney & Tabor 1995). In this respect, as with several examples in other physical contexts, one argues that the timescale of the overall evolution of the system under consideration is sufficiently long that a simple steady state analysis can correctly capture the properties of at least some stages of the time-evolving hot gas, and, in particular, that the steady state cooling “inflow” description gives a reasonable representation of the current state of the brightest X-ray ellipticals. Attempts have been made to check in detail the necessary conditions for the applicability of the steady state description by examining the results of hydrodynamical codes (Murray & Balbus 1992).

On the other hand, it was immediately realized that the simplest cooling flow models all suffered from a basic inconsistency with the observations in that, given the piling up of hot gas, the theoretically predicted emission profiles are too bright close to the galaxy center (see Sarazin & White 1988). Various corrections to the cooling flow model have been proposed in order to resolve the problem of the excessive steepness of the surface brightness profile by recognizing that part of the hot gas is bound to decouple from the cooling flow (Thomas 1986; Thomas et al. 1986; Sarazin & Ashe 1989). To some extent, the filamentary structure of the gas noted earlier especially around cD’s (e.g., see Lynds 1970) and dramatically demonstrated on the cluster scale by recent *ROSAT* observations (Sarazin, O’Connell, & McNamara 1992a, b) further encourages attempts in this direction. One might even conclude that some of these observations undermine the very foundation of the

simple spherical, steady state, one-phase cooling flow as a model for the hot gas.

The impact of the constraints posed by stellar dynamical data on the modeling of the X-ray-emitting gas in elliptical galaxies was examined in a previous paper (Bertin, Pignatelli, & Saglia 1993, hereafter BPS). This paper focused on the problem of dark matter and on the galaxy NGC 4472, for which radially extended optical spectroscopic profiles are available (Saglia et al. 1993). This study gave a surprising result and confirmed a well-known fact. The surprise was the finding that the predicted temperatures and surface brightness profiles for the hot gas for models with and without significant amounts of dark matter, if constrained by the same set of stellar dynamical data out to  $\approx R_e$  (the *effective* optical radius), are very similar to each other even out to  $\approx 7R_e$ ; in particular, the temperature profiles are found to be much more sensitive to the assumed value of the intracluster pressure  $p_{\text{ext}}$  than to the amount of dark matter that may be argued to be present. This surprising result urges caution in the use of X-ray data as diagnostics for the presence of dark halos (see Loewenstein 1992; Serlemitsos et al. 1993). The well-known fact confirmed by the analysis of BPS is the central overbrightness problem for the simplest form of cooling flow models for the hot gas: the case of NGC 4472 shows that the use of accurate models for the distribution of the stellar component can only lead to a slight improvement of the predicted X-ray emission profile, which remains too steep and definitely fails at  $R \leq 0.2R_e$ .

In this paper we continue the study started by BPS, by focusing on the modeling of the X-ray-emitting gas for galaxies for which accurate stellar dynamical models are available. In doing so, we may have confidence in the adopted profiles for the functions  $\rho_*(r)$  and  $\sigma_*(r)$ , which characterize the stellar density and velocity dispersion profiles, and for the gravitational potential  $\Phi(r)$ . In view of the study of BPS, here we omit further discussion of the role of dark matter and simply refer to the available best-fit stellar dynamical models (which include, in general, a dark halo). The main goal of this paper is then to test the adequacy of simple steady state, spherical cooling flow

models for the hot gas by studying in detail the role of the decoupling of cold gas from the flow, following the prescriptions of Sarazin & Ashe (1989), and the role of the intracluster medium. The analysis thus basically relies on the variation of three parameters ( $q$ ,  $p_{\text{ext}}$ , and  $\dot{m}_{\text{ext}}$ ; see § 3 below). Qualitatively, the effects of these variations are well known (see papers cited above). Here we would like to make a full, detailed quantitative test in order to ascertain whether a simple uniform choice for  $q$  and physically plausible properties of the intracluster medium can lead to good fits to the X-ray emission profiles and to the temperature profiles (if available) for several objects.

As noted earlier (e.g., see discussion in § 2 of BPS), the presence of a finite pressure at the outer boundary is associated with the existence of an inflow of gas from the cluster. Furthermore, for some objects such as NGC 1399 and NGC 4636 in our sample; see § 4), a significant rate of accretion from the cluster, exceeding  $1 M_{\odot} \text{ yr}^{-1}$ , is found to be necessary in the present framework of steady state cooling flows. Therefore, in this paper we solve the relevant equations treating the outer boundary differently from Vedder et al. (1988) and BPS in that we consider the possibility of an inflow of extragalactic matter as a separate parameter ( $\dot{m}_{\text{ext}}$ ), in addition to the pressure at the external boundary  $p_{\text{ext}}$ , to be adjusted in the fit process (see § 3). For galaxies with a low value of  $L_{\text{X}}/L_{\text{B}}$  for which no significant accretion is required, in order to avoid the formal singular behavior of the solution which would be associated with the so-called stagnation radius (introduced as the radius where the radial velocity of the flow vanishes), we set  $\dot{m}_{\text{ext}} = 0.1 M_{\odot} \text{ yr}^{-1}$ . When the accretion rate is this low, the resulting profiles are hardly affected by the precise value of  $\dot{m}_{\text{ext}}$ .

The physics of the hot gas is intrinsically complex. In this paper we focus on three factors in the problem because of their physical interest. The first factor is the decoupling of cold gas from the hot inflow. The mass decoupling term introduced by Sarazin & Ashe (1989) provides a phenomenological description (with one free parameter, called  $q$ ) of the consequences of small-scale fluid instabilities which are expected to take place in the cooling gas (although different views on the issue exist; see Fabian & Nulsen 1977; Mathews & Bregman 1978; Balbus 1988; Loewenstein 1989, 1990). Therefore, it would be desirable that the fitting value of  $q$  be of order unity, with small variations from one galaxy to another, and that the model profiles turn out to be not too sensitive to  $q$  in the vicinity of the best-fit value. The second factor is the role of the external pressure, which can be constrained to some extent by direct observations of the intracluster plasma. By considering galaxies in the same cluster, i.e., embedded in the same intracluster medium, one can better appreciate whether the adopted values of  $p_{\text{ext}}$  and  $\dot{m}_{\text{ext}}$  are physically plausible. In addition to studying the case of different clusters (as is done below), it would be very interesting to model truly isolated X-ray-bright ellipticals; unfortunately, this case is not easy to find. The third physical factor of the problem addressed in the present analysis is related to the determination of the supernova type Ia rate in ellipticals. The cooling flow models found in this paper appear to give better fits to the data if a value consistent with the recent estimates of Cappellaro et al. (1993) is used.

Although the set of objects modeled in this paper is very small, the results of the fits performed here (§ 4) are of considerable interest. It is found that reasonable fits are obtained with reasonable choices of the parameters involved, *even if the models used are highly idealized*. Furthermore, if we consider that the data on X-ray temperature “profiles” used here are

very crude (with the exception of the *ROSAT* data for NGC 4636, taken from Trinchieri et al. 1994) and that the reduction of X-ray spectroscopic data and their interpretation usually leave several options open (i.e., the choice of the parameters to be used in the fit, such as chemical composition, H I absorption, and number of emitting components involved; see Trinchieri et al. 1994; Pellegrini & Fabbiano 1994), we may regard the theoretical models produced in this paper as “predictions,” to be compared with the better temperature profiles that are currently being gathered with the help of new telescopes and instruments.

## 2. THE SAMPLE

The galaxies that define our sample have been selected on the basis of the following criteria: (1) high X-ray luminosity, (2) availability of good-quality X-ray data, and (3) availability of good-quality stellar dynamical data and of detailed global stellar dynamical models. Criterion 1 is related to our plan to model the X-ray emission and temperature profiles in terms of cooling flows; this is justified only for objects with high  $L_{\text{X}}/L_{\text{B}}$  (see, e.g., Ciotti et al. 1991). In relation to point 2, we have referred to the X-ray contour maps and circularized surface brightness profiles given in the *Einstein* X-ray catalog of Fabbiano, Kim, & Trinchieri (1992), in order to pick out galaxies with high-signal, extended X-ray halos. Requirement 3 allows us to perform a study of the coronal gas within an accurately determined potential well and a detailed quantitative framework for the properties of the stellar component. For this purpose we have made use of the results of the survey of Saglia, Bertin, & Stiavelli (1992, hereafter SBS).

The sample of selected objects thus contains five galaxies: NGC 1399, NGC 1404, NGC 4374, NGC 4472, and NGC 4636. Their optical and X-ray properties are listed in Table 1. All the galaxies selected are fairly round in optical appearance (indeed, this was one of the main selection criteria for the sample of SBS), which makes the use of spherical models at least a reasonable starting point. Columns (5)–(8) of Table 1 describe some X-ray properties of the galaxies, taken from the literature. The radius  $R_{\text{X}}$  denotes the radius of the X-ray-emitting region considered for each source, and  $L_{\text{X}}$  is the total X-ray flux from within  $R_{\text{X}}$ . Column (7) is the best-fit temperature of a single-component Raymond thermal spectrum fitted to the region considered and can thus be taken as an estimate of the average temperature of the gas within  $R_{\text{X}}$ . Finally, it should be noted that the reported total X-ray fluxes in the specified bands are highly dependent on the assumed hydrogen column density along the line of sight. Fabbiano et al. (1992) estimate the count-energy conversion factor by assuming a gas temperature of 1 keV and Galactic absorption.

The available X-ray emission profiles of NGC 1399, NGC 4472, and NGC 4636 considered in this paper are quite accurate. We refer to IPC data for NGC 1399, combined IPC/HRI data for NGC 4472, and *ROSAT* PSPC data for NGC 4636. Temperature determinations are taken from Serlemitsos et al. (1993; BBXRT data for NGC 1399 and NGC 4472), Forman, Jones, & Tucker (1985; *Einstein* IPC data for NGC 4472), and Trinchieri et al. (1994; *ROSAT* PSPC data for NGC 4636).

NGC 1404 is embedded in the very extended bright halo of NGC 1399. Thus the X-ray total luminosity and the emission profile for NGC 1404 may suffer from subtraction problems; furthermore, the temperature determination is rather uncertain, given the low-energy resolution of the IPC instrument (see Kim, Fabbiano & Trinchieri 1992). Similar problems

TABLE 1  
OPTICAL AND X-RAY PROPERTIES OF THE SELECTED OBJECTS

NGC (1)	Type <sup>a</sup> (2)	$D^b$ (Mpc) (3)	$m_B^a$ (mag) (4)	$R_X$ (5)	$\log L_X$ (ergs s <sup>-1</sup> ) (6)	$\langle T_X \rangle$ (keV) (7)	$\log (L_X/L_B)^c$ (8)
1399.....	E1P	28	9.85	1200 <sup>d</sup> 120 <sup>f</sup>	42.33 <sup>d</sup> 41.63 <sup>f</sup>	$\geq 1.1^e$ 1.02 <sup>f</sup>	31.46
1404.....	E1	28	10.87	300 <sup>d</sup> 220 <sup>g</sup>	41.49 <sup>d</sup> 41.36 <sup>g</sup>	$\geq 0.8^e$ ...	31.10
4374.....	E1	27	9.98	300 <sup>d</sup> 150 <sup>h</sup>	41.16 <sup>d</sup> 40.84 <sup>h</sup>	$\geq 0.8^e$ 0.9–1.3 <sup>h</sup>	30.20
4472.....	E2	27	9.09	810 <sup>d</sup> $\sim 200^f$	42.06 <sup>d</sup> 41.77 <sup>f</sup>	1.2 <sup>e</sup> 0.92 <sup>f</sup>	30.73
4636.....	E0+	27	10.44	600 <sup>d</sup> 1080 <sup>i</sup>	41.99 <sup>d</sup> 42.27 <sup>i</sup>	0.9 <sup>e</sup> 0.87 <sup>i</sup>	30.99

<sup>a</sup> RC3 (de Vaucouleurs et al. 1991).

<sup>b</sup> Faber et al. 1989.

<sup>c</sup>  $L_X$  from col. (6);  $L_B$  in solar units from SBS (see Table 2).

<sup>d</sup> Fabbiano et al. 1992 (0.2–4.0 keV band).

<sup>e</sup> Kim et al. 1992.

<sup>f</sup> Serlemitsos et al. 1993 (0.5–4.5 keV band).

<sup>g</sup> Thomas et al. 1986.

<sup>h</sup> Forman et al. 1985 (0.5–4.5 keV band). For the temperature, a 90% confidence interval is reported.

<sup>i</sup> Trinchieri et al. 1994 (0.1–2.4 keV band). The temperature recorded here was computed as an emission-weighted average.

might affect the X-ray properties reported for NGC 4374 (which is near NGC 4406), although HRI data are also available for this object. Some of these uncertainties might be resolved with the help of *ROSAT* data when analyses of these data have been published.

NGC 1399 and NGC 1404 are at the center of the Fornax cluster, while the remaining three objects are members of Virgo. The choice of the parameter  $p_{\text{ext}}$  for those galaxies sharing the same environment should be made consistent with the presence of a common intracluster medium and with the available observations. For example, *Ginga* (Awaki et al. 1991; Ikebe et al. 1992) and *ROSAT* data (Böhringer et al. 1994) suggest a temperature  $T_{\text{ext}}$  in excess of  $\sim 2$  keV for the intracluster medium in Fornax and Virgo.

The basic properties of the best-fit stellar dynamical models adopted in the following study are summarized in Table 2. As shown by BPS, even if the stellar dynamical data are far from identifying a unique global model for the optical galaxy, it is sufficient to focus our attention on the best-fit model for the mass distribution provided by stellar dynamics since other models compatible with the same set of stellar dynamical data are not expected to produce significant changes in the cooling flow modeling.

In general, the models contain significant amounts of dark matter, as shown by Figure 1, which illustrates the profile of the cumulative mass-to-light ratio for each galaxy. Table 2 lists

the mass-to-light ratio  $M_*/L_B$  for the luminous component and the total mass-to-light ratio  $M/L_B$ . The total luminosities given in the table are taken from SBS. There is a wide range in length scales  $r_L$  (the half-mass radius for the luminous component) and  $r_D$  (the same, but for the dark matter), ranging from  $r_L = r_D = 13$  kpc for NGC 1404 to  $r_L = 28$  kpc and  $r_D = 165$  kpc for NGC 4636 (col. [4] and [7]). Significant differences are also noted in the value of the (one-dimensional) central stellar velocity dispersion  $\sigma_*(0)$  (col. [8]). The galaxy  $M/L_B$  ratio and the scale length of the total mass distribution influence the steepness of the X-ray emission profile, while the central gas temperature depends on the depth of the potential well, i.e., on the value of  $\sigma_*(0)$ . So we would expect objects with a concentrated mass distribution, such as NGC 1404 and NGC 4374, to have a less extended X-ray halo than such “giants” as NGC 1399 and NGC 4636. Furthermore, as a result of its relatively low velocity dispersion, NGC 1404, which is embedded in the X-ray halo of NGC 1399, should appear as a *cold* X-ray source relative to its environment; the opposite should be the case for NGC 4374.

Finally, consider the values of  $L_X/L_B$  (see col. [8] of Table 1). Even for this selected sample of bright E galaxies, there is a very large spread (a factor of 18 between NGC 1399 and NGC 4374). Within the cooling flow description, such a wide spread may simply reflect a different accretion rate from the intracluster medium; in particular, NGC 1399 is expected to accrete

TABLE 2  
STELLAR DYNAMICAL MODELS (FROM SBS)

NGC (1)	$L_B$ ( $10^{10} L_\odot$ ) (2)	$r_L$ (3)	$r_L$ (kpc) (4)	$M_*/L_B$ ( $M_\odot/L_\odot$ ) (5)	$M/L_B$ ( $M_\odot/L_\odot$ ) (6)	$r_D/r_L$ (7)	$\sigma_*(0)$ (km s <sup>-1</sup> ) (8)
1399.....	7.5	136 <sup>''</sup>	18.4	8.0	58.0	6.2	250
1404.....	2.5	90	12.6	4.6	12.0	1.0	200
4374.....	9.2	179	23.5	5.3	14.2	1.0	308
4472.....	21.2	173	22.0	5.0	13.4	2.8	316
4636.....	9.9	215	28.1	8.0	38.6	5.9	227

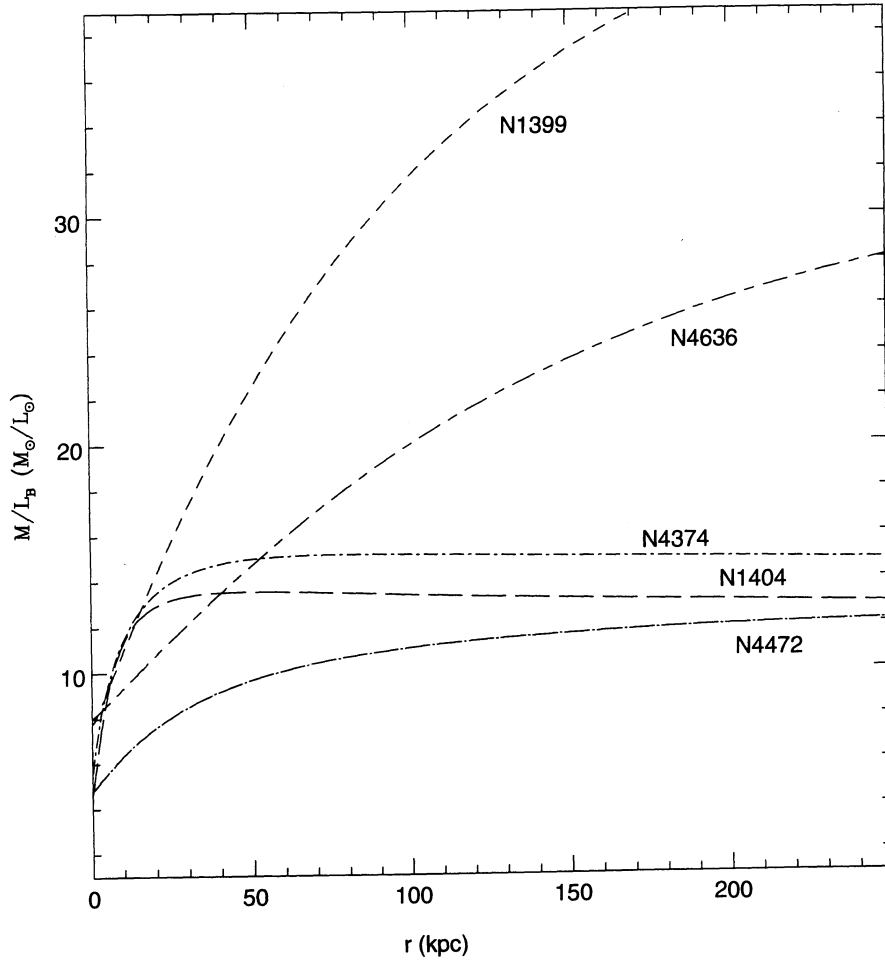


FIG. 1.—Cumulative  $M/L_B$  ratios for the best-fit stellar dynamical models (from SBS) of the five elliptical galaxies of the sample. The models are made of a luminous component of total mass  $M_*$  and of a dark halo (with finite mass) with a different spatial distribution, within a common self-consistent gravitational field. Thus the gradient in the cumulative  $M = M(r)$  reflects the presence of a significant dark halo (see Table 2).

large amounts of hot gas from its surroundings. This point is discussed further in the next section.

### 3. THE METHOD

We describe the hot coronal gas by means of a standard set of equations under the assumption of a steady state, spherically symmetric inflow in the presence of mass and energy source terms (related to mass and energy injection in the form of hot gas originating from stars and supernovae), of radiative losses (responsible for the observed X-ray emission), and of a mass sink term (describing the decoupling of cold gas from the hot phase; Sarazin & Ashe 1989):

$$\frac{1}{r^2} \frac{d}{dr} (r^2 \rho u) = \alpha \rho_* - q \frac{\rho}{\tau_{\text{dec}}}, \quad (1)$$

$$\rho u \frac{du}{dr} + \frac{dp}{dr} = -\rho \frac{d\Phi}{dr} - \alpha \rho_* u, \quad (2)$$

$$\begin{aligned} & \frac{1}{r^2} \frac{d}{dr} \left[ r^2 \rho u \left( \frac{1}{2} u^2 + \frac{5}{2} \frac{p}{\rho} + \Phi \right) \right] \\ & = -\rho^2 \Lambda(T) + \alpha \rho_* (\epsilon_{\text{inj}} + \Phi) - q \frac{\rho}{\tau_{\text{dec}}} \left( \frac{1}{2} u^2 + \frac{5}{2} \frac{p}{\rho} + \Phi \right). \end{aligned} \quad (3)$$

These equations reduce to the same set used by BPS when  $q = 0$ . Three unknown functions,  $\rho$ ,  $p$ , and  $u$  (mass density, pressure, and radial velocity), describing the hot, X-ray-emitting gas are to be derived by solving the above equations under the appropriate boundary conditions (see below). The gas temperature  $T$  is obtained from the equation of state  $p = \rho k T / (\mu m_p)$ . Note that we are ignoring the contribution of the possible presence of magnetic fields and of various transport processes within the gas. In the following, we will refer to the solutions of this set of equations as “ $q$ -models.”

#### 3.1. Input Parameters for the Hot Gas

The chemical composition of the gas is assumed to be “cosmic” (Allen 1973), with a mean mass per particle  $\mu = 0.63$  in units of the proton mass  $m_p$ . The quantity  $\alpha = 4.75 \times 10^{-19} (M_*/L_B)^{-1} \text{ s}^{-1}$  (with the mass-to-light  $M_*/L_B$  ratio expressed in solar units) is the rate of mass loss of a 15 Gyr old stellar population that is taken to be “quiescent” (i.e., without significant star formation after the initial stage), as given by Renzini (1988). The specific energy of the injected material is derived from  $\epsilon_{\text{inj}} = (3/2) \{ \sigma_*^2 + \vartheta_{\text{SN}} \epsilon_{\text{SN}} [k \hat{T}_{\text{SN}} / (\mu m_p)] \}$ . Here  $\sigma_*$  is the one-dimensional stellar velocity dispersion (averaged over the three directions) taken from the stellar dynamical model,  $\vartheta_{\text{SN}}$  is the SN Ia rate relative to Tammann’s (1982) value (0.22

SN Ia per century per  $10^{10} L_{\odot B}$ ,  $\epsilon_{\text{SN}}$  is the mechanical energy released in a SN Ia explosion normalized to  $10^{51}$  ergs, and  $\hat{T}_{\text{SN}} = 2.8 \times 10^7$  K is an effective temperature associated with the hot supernova ejecta mixing into the gas. Our reference case will be characterized by  $\vartheta_{\text{SN}} = 1/4$  (see Cappellaro et al. 1993) and  $\epsilon_{\text{SN}} = 1$ , but we will also explore the regime of a very low supernova rate,  $\vartheta_{\text{SN}} = 1/16$ , for which the heating is typically dominated by the stellar contribution, and the regime of a high supernova rate,  $\vartheta_{\text{SN}} = 1.1$ , where the heating is generally supernova dominated.

The cooling function  $\Lambda(T)$  is obtained by numerical interpolation of the results of Raymond, Cox, & Smith (1976) and is suitable for an optically thin thermal plasma with cosmic abundances at temperatures  $10^5 < T < 10^8$  K.

### 3.2. Mass Decoupling Term

Following the physical prescription of Sarazin & Ashe (1989), we describe the decoupling of cold material from the hot gas by referring to the timescale

$$\tau_{\text{dec}} = \frac{5}{2} \frac{p}{\rho^2 \Lambda(T)} \left( 2 - \frac{d \ln \Lambda}{d \ln T} \right)^{-1} = \tau_{\text{cool}} \left( 2 - \frac{d \ln \Lambda}{d \ln T} \right)^{-1}, \quad (4)$$

which is the linear growth rate of the thermal instability for comoving, isobaric density perturbations to the smooth (“homogeneous”) flow (Mathews & Bregman 1978). In contrast to the injected mass from the stars, the decoupled cold material is assumed not to exchange momentum or entropy with the hot gas. The dimensionless parameter  $q$  appearing in the continuity equation is considered to be a free (phenomenological) constant parameter of the model, to be determined by the fit process. Note that the decoupling time given above differs from that of most models by Sarazin & Ashe (1989) (hereafter “ $q_s$ -models”) by a factor

$$c(T) = 2 - \frac{d \ln \Lambda}{d \ln T}, \quad (5)$$

which ranges from 2.0 to 3.9 when  $T$  ranges from 0.5 to 1.5 keV. Because of this temperature dependence, the  $q_s$ -models behave like  $q$ -models with a differential  $q = q(r)$ . In practice,  $q_s$ -models with  $q_s = 3q$  and with the values of  $p_{\text{ext}}$  and  $\dot{m}_{\text{ext}}$  suggested by our best-fit models for NGC 1399, NGC 4472, and NGC 4636 are found to differ only slightly from the corresponding  $q$ -models.

### 3.3. Stellar Component and the Gravitational Potential

The three functions  $\rho_*(r)$ ,  $\sigma_*(r)$ , and  $\Phi(r)$  are the stellar mass density, the one-dimensional stellar velocity dispersion (averaged over the three directions), and the gravitational potential of the galaxy (with the contribution of stars and dark matter but, for simplicity, without the contribution of the gas) derived from the best-fit stellar dynamical models described in § 2.

### 3.4. Boundary Conditions and Integration Scheme

Equation (1) is integrated to give for the inward mass flux  $\dot{m}$ :

$$\begin{aligned} \dot{m} &= -4\pi r^2 \rho u \\ &= \alpha [M_*(r_{\text{ext}}) - M_*(r)] - q [D(r_{\text{ext}}) - D(r)] + \dot{m}_{\text{ext}}, \quad (6) \end{aligned}$$

where  $M_*(r)$  is the galactic stellar mass inside a sphere of radius

$r$  and  $D(r) = \int_0^r (\rho/\tau_{\text{dec}}) 4\pi r^2 dr$ . The sign of  $\dot{m}$  is chosen so that it is positive for an inflow. The quantity  $\dot{m}_{\text{ext}}$  is the contribution to the flux due to accretion of external gas. Its value sets one boundary condition at  $r_{\text{ext}}$ . For the models shown in § 4,  $r_{\text{ext}}$  is chosen to be equal to  $R_X$  (see Table 1). Note that in some objects (such as NGC 4374) this radius may fall within the optical galaxy. A second boundary condition is that the pressure at  $r_{\text{ext}}$  be  $p = p_{\text{ext}}$ . The two quantities  $\dot{m}_{\text{ext}}$  and  $p_{\text{ext}}$  are, like  $q$ , free parameters of the model. The third boundary condition is provided at the free boundary  $r = r_s$  (the “sonic radius”), defined as the radius at which  $u = -(5p/3\rho)^{1/2}$ , where the derivatives of the unknown functions  $\rho$ ,  $u$ , and  $p$  are required to be finite. This latter condition implies

$$\rho^2 \Lambda(T) \left[ 1 + q \left( 2 - \frac{d \ln \Lambda}{d \ln T} \right) \right] + \frac{3}{2} \rho u \left( -\frac{d\Phi}{dr} + 2 \frac{u^2}{r} \right) - \alpha \rho_*(r) (\epsilon_{\text{inj}} + 2u^2) = 0 \quad (7)$$

at  $r = r_s$ .

The integration is started at a guess for  $r_s$ , where the mass flux is specified in terms of the parameter  $\epsilon$ , defined as

$$\epsilon = \frac{\dot{m}(r_s)}{\alpha [M_*(r_{\text{ext}}) - M_*(r_s)] + \dot{m}_{\text{ext}}}, \quad (8)$$

which is the gas mass fraction at the sonic radius  $r_s$  that has “survived” the decoupling process. In the case  $q = 0$ , equation (1) is integrated trivially, with the parameter  $\epsilon$  equal to 1. In the opposite limit of large  $q$ ,  $\epsilon$  becomes vanishingly small. The values of  $r_s$  and  $\epsilon$  are varied and the integration iterated until the mass flux  $\dot{m}$  and the pressure  $p$  at  $r = r_{\text{ext}}$  are found to match the specified values of  $\dot{m}_{\text{ext}}$  and  $p_{\text{ext}}$ . Alternatively, when the value of  $r_s$  is seen to shrink below 0.1 pc, so that  $\epsilon$  also becomes very small, a fully subsonic solution is sought. The integration is then carried inward from  $r_{\text{ext}}$  starting with a guess for  $\rho(r_{\text{ext}})$  that is improved, for fixed  $\dot{m}_{\text{ext}}$  and  $p_{\text{ext}}$ , until the central mass flux becomes vanishingly small. The numerical code employed (Toniazzo 1993) uses a double-shooting integration scheme with a variable-step fourth-order Runge-Kutta integrator. In the case  $q = 0$ , a simple shooting method from  $r_s$  outward is found to be viable. When  $q \neq 0$ , such a simple shooting method becomes unstable.

The models illustrated in § 4 have been chosen by the following procedure. For a given galaxy, several models with different parameters have been calculated, with the goal of fitting the emission profile and of matching the value of the integrated luminosity. In the second stage, attention was given to the published constraints on the temperature. The models are quite sensitive to the values of  $q$  and  $\dot{m}_{\text{ext}}$ , and less to  $p_{\text{ext}}$ .

The code has been tested by being checked against the results of BPS, for the  $q = 0$  model of NGC 4472, and against the results presented by Sarazin & Ashe (1989).

### 3.5. Properties of the $q$ -Models

In the construction of the  $q$ -models, we may take advantage of the fact that the values of  $p_{\text{ext}}$  and  $\dot{m}_{\text{ext}}$  have a definite “plausibility” range. It should be stressed that  $p_{\text{ext}}$  and  $\dot{m}_{\text{ext}}$  influence only the outer profiles, while for radii smaller than the optical radius  $R_e$  the major role is played by  $q$ , by the adopted gravitational potential  $\Phi$  (which in particular determines the central temperature in the transsonic part of the flow), and by the adopted supernova rate.

TABLE 3  
PROPERTIES OF THE SELECTED MODELS ( $\vartheta_{\text{SN}} = 1/16$ )

NGC (1)	$q$ (2)	$\dot{m}_{\text{ext}}$ ( $M_{\odot} \text{ yr}^{-1}$ ) (3)	$p_{\text{ext}}$ ( $10^3 \text{ K cm}^{-3}$ ) (4)	$r_{\text{ext}}$ (kpc) (5)	$M_{\text{gas}}$ ( $10^{10} M_{\odot}$ ) (6)	$\log L_{\text{X}}$ (ergs $\text{s}^{-1}$ ) (7)	$\langle kT \rangle$ (keV) (8)	$\dot{m}_{\text{ext}}/\alpha M_{*}$ (9)
1399.....	0.8	4.4	8.2	200	19.71	42.31	1.31	3.91
1404.....	0.1	0.9	10.0	50	0.69	41.41	0.52	2.40
4374.....	2.0	0.1	4.9	60	0.24	41.14	0.75	0.07
4472.....	0.8	1.0	10.1	120	4.42	42.02	1.09	0.31
4636.....	0.5	3.0	4.0	160	7.95	42.00	0.84	2.02

For a given distance to the observed object, the measured X-ray surface brightness and temperature at large radii suggest a value for the pressure of the gas  $p_{\text{ext}}$ . In particular, *ROSAT* data may be able to constrain this quantity for many objects (see, e.g., Trinchieri et al. 1994). For models where  $q$  plays a significant role, the amount of gas accreted from the cluster or from the group can be estimated as follows: The mass continuity equation (eq. [1]) evaluated at  $r_s$  can be rewritten as

$$\frac{\dot{m}_{\text{ext}}}{\alpha M_{*}} = \frac{q[D(r_{\text{ext}}) - D(r_s)]}{(1 - \epsilon)\alpha M_{*}} - \delta, \quad (9)$$

with  $\delta \approx 1$ . Since  $r_s$  is very small in our models, it may effectively be replaced by 0, so that the  $D$  terms are related to the total radiated power:

$$L_t = \int_0^{r_{\text{ext}}} \rho^2 \Lambda [1 + qc(T)] 4\pi r^2 dr. \quad (10)$$

Then the continuity equation yields the following estimate for the accretion rate:

$$\frac{\dot{m}_{\text{ext}}}{\alpha M_{*}} \approx \frac{1}{1 - \epsilon} \left( \frac{0.7L_t}{L_{\text{X}}} \right) \left\langle \frac{4qc(T)}{1 + qc(T)} \left( \frac{1 \text{ keV}}{kT} \right) \right\rangle \times \frac{(L_{\text{X}}/10^{41} \text{ ergs s}^{-1})}{(L_{\text{B}}/10^{10} L_{\odot})} - 1, \quad (11)$$

where the angle brackets denote an average over the total (bolometric) emission. Both the numerator and the denominator in equation (11) go to zero when  $q \rightarrow 0$ , so this equation is not useful in this limit. In this limiting case,  $\dot{m}_{\text{ext}}/\alpha M_{*}$  must be estimated directly from the energy equation that can be derived by integrating equation (3). In practice, all the models selected in the following are in the regime of finite  $q$ , with  $q \geq 0.1$  and  $\epsilon < 0.1$ .

The quantity  $L_{\text{X}}$  denotes the power radiated in the relevant X-ray band. Following Sarazin & Ashe (1989), this can be

obtained from the specific emission:

$$b_{\text{X}}(r) = \rho^2 \Lambda_{\text{X}}(T) \left[ 1 + qc(T) \frac{\Lambda(T)}{\Lambda_{\text{X}}(T)} \int_0^T \frac{\Lambda_{\text{X}}(T')}{\Lambda(T')} \frac{dT'}{T} \right], \quad (12)$$

where  $\Lambda_{\text{X}}$  is the emission in the *Einstein* 0.5–4.0 keV energy band. The emission spectrum is assumed to be that computed by Raymond & Smith (1977) for a thermal plasma with cosmic (Allen 1973) abundances. Note the  $q$ -dependence of  $b_{\text{X}}(r)$ , which thus includes the contribution of the cooling gas that gets decoupled from the hot phase. Therefore, the fraction of power radiated in the X-ray band  $L_{\text{X}}/L_t$  for the model of interest depends both on the temperature distribution and on the value of  $q$ . For the selected models of § 4, this fraction ranges from 0.57 to 0.70.

If the heating due to supernovae dominates over other energy sources, the close similarity of the light profile and the X-ray emission profile in the inner parts of X-ray-bright galaxies displayed by existing *Einstein* HRI data is found to occur naturally in models characterized by  $q \gg 1$  (Sarazin 1990). In practice, the value  $q \approx 1.3$  turns out to mark the transition to this asymptotic behavior. As will be shown below, good fits to the relevant profiles are obtained for  $q \approx 0.5$ .

#### 4. THE MODELS

We present three sets of models corresponding to three different assumptions on the SN Ia rate:  $\vartheta_{\text{SN}} = 1/16$ ,  $1/4$ , and  $1.1$ . Tables 3, 4, and 5 summarize the main global parameters of the model in each case.

For each model we compute several profiles. Some profiles are specifically produced for comparison with the observations (see Figs. 2, 3, and 4 corresponding to the three different assumptions on the SN Ia rate). The model X-ray surface brightness  $\Sigma_{\text{X}}(R)$  at projected distance  $R$  is computed by integrating the quantity  $b_{\text{X}}$  of equation (12) over the line-of-sight line element  $dl$ . For those cases where comparison is made with *Einstein* IPC and *ROSAT* PSPC data, the surface brightness profiles are convolved with Gaussians of  $110''$  and  $60''$  FWHM,

TABLE 4  
PROPERTIES OF THE SELECTED MODELS ( $\vartheta_{\text{SN}} = 1/4$ )

NGC (1)	$q$ (2)	$\dot{m}_{\text{ext}}$ ( $M_{\odot} \text{ yr}^{-1}$ ) (3)	$p_{\text{ext}}$ ( $10^3 \text{ K cm}^{-3}$ ) (4)	$r_{\text{ext}}$ (kpc) (5)	$M_{\text{gas}}$ ( $10^{10} M_{\odot}$ ) (6)	$\log L_{\text{X}}$ (ergs $\text{s}^{-1}$ ) (7)	$\langle kT \rangle$ (keV) (8)	$\dot{m}_{\text{ext}}/\alpha M_{*}$ (9)
1399.....	0.6	4.1	7.6	200	19.55	42.29	1.24	3.65
1404.....	0.1	0.6	7.6	50	0.66	41.35	0.60	1.60
4374.....	0.8	0.1	6.3	60	0.51	41.35	0.85	0.07
4472.....	0.8	0.6	12.6	120	4.55	42.01	1.22	0.19
4636.....	0.4	3.0	3.8	160	8.20	42.02	0.80	2.02

TABLE 5  
PROPERTIES OF THE SELECTED MODELS ( $\vartheta_{\text{SN}} = 1.1$ )

NGC (1)	$q$ (2)	$\dot{m}_{\text{ext}}$ ( $M_{\odot} \text{ yr}^{-1}$ ) (3)	$p_{\text{ext}}$ ( $10^3 \text{ K cm}^{-3}$ ) (4)	$r_{\text{ext}}$ (kpc) (5)	$M_{\text{gas}}$ ( $10^{10} M_{\odot}$ ) (6)	$\log L_x$ ( $\text{ergs s}^{-1}$ ) (7)	$\langle kT \rangle$ (keV) (8)	$\dot{m}_{\text{ext}}/\alpha M_*$ (9)
1399.....	0.4	3.3	9.9	200	22.65	42.33	1.40	2.94
1404.....	0.1	0.3	8.9	50	0.65	41.33	0.67	0.80
4374.....	0.3	0.1	15.1	60	1.32	41.60	1.07	0.07
4472.....	0.3	0.3	12.6	120	6.00	42.14	1.17	0.09
4636.....	0.2	1.8	4.1	160	9.14	42.06	0.80	1.21

respectively. The process of fitting to the observed surface brightness data is especially aimed at reproducing the *shape* of the observed profiles. The data points shown in the figures are treated by allowing for a modest adjustment of the conversion factor from count rates (given by the original data sources) to the physical units. In the following, when we talk about “overbright” models we will mean those for which the model X-ray luminosity significantly exceeds the  $L_x$  value given in Table 1.

The projected emission temperature is computed from

$$T_X(R) = \int dl \left\{ \rho^2 \Lambda_X(T) T \right. \\ \left. \times \left[ 1 + qc(T) \frac{\Lambda(T)}{\Lambda_X(T)} \int_0^T \frac{\Lambda_X(T')}{\Lambda(T')} \frac{T' dT'}{T^2} \right] \right\} / \Sigma_X(R), \quad (13)$$

which is an emission-weighted temperature of the gas. [Note that the weight entering the integral over the line of sight

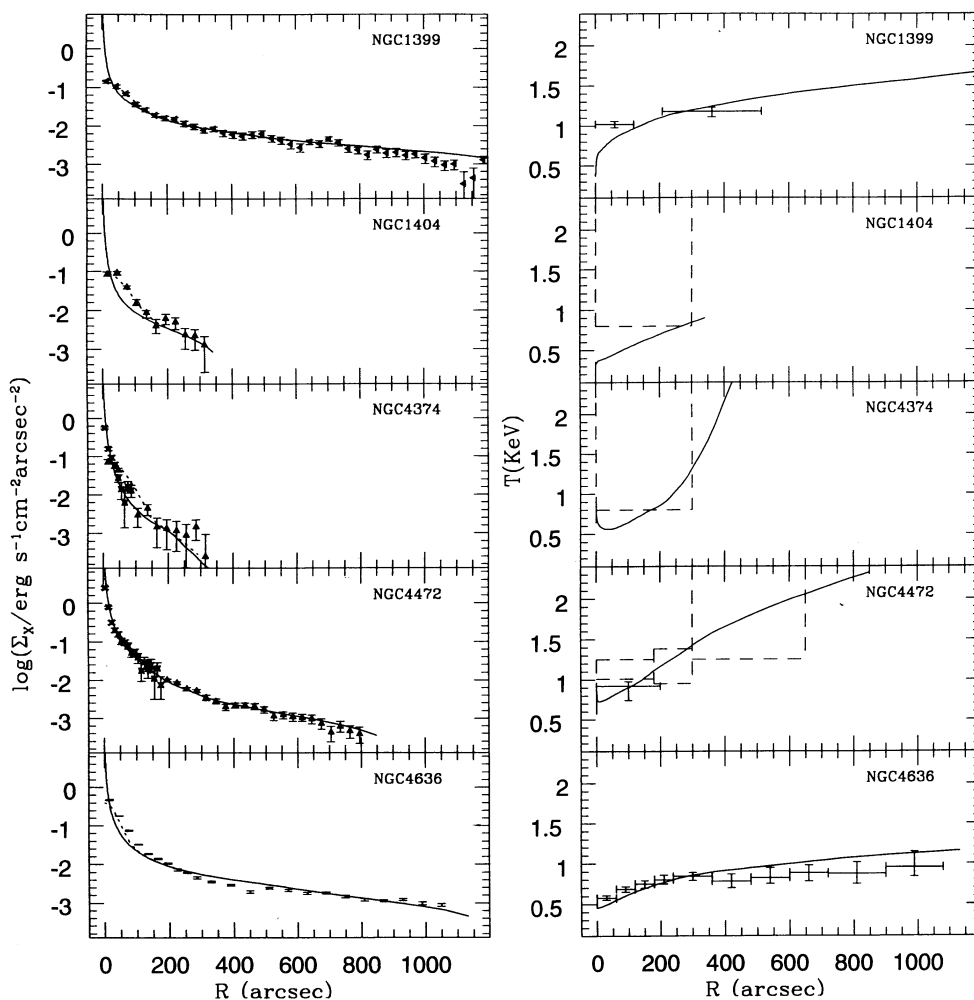


FIG. 2.—X-ray emission and temperature profiles for the selected models with  $\vartheta_{\text{SN}} = 1/16$ . *Left*: Solid lines show model X-ray surface brightness profiles; dotted lines (shown for all the objects with the exception of NGC 4472) are the result of convolution with a Gaussian PSF, suitable for comparison with the IPC or PSPC data (see text). *Triangles*, *Einstein* IPC data (Fabbiano et al. 1992); *crosses*, *Einstein* HRI data (for NGC 4472; Fabbiano et al. 1992); *bare error bars*, *ROSAT* PSPC data (for NGC 4636; Trinchieri et al. 1994). *Right*: X-ray temperature profiles. Solid lines show projected emission temperature (see eq. [13]); regions outlined by dashed lines are 90% confidence intervals derived from *Einstein* IPC data (Kim et al. 1992); error bars are temperature estimates derived by the BBXRT (for NGC 1399 and NGC 4472; Serlemitsos et al. 1993) and the *ROSAT* PSPC (for NGC 4636; Trinchieri et al. 1994) instruments.

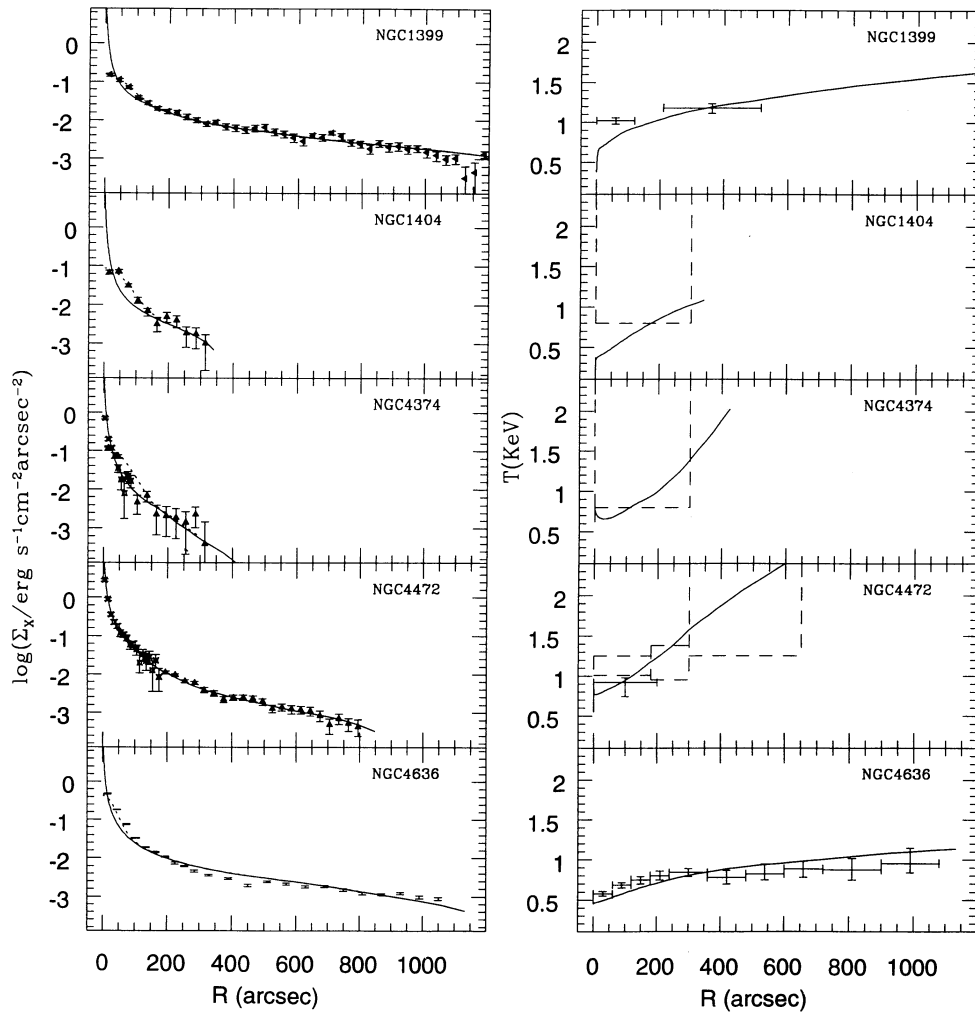


FIG. 3.—Same as Fig. 2, but for  $\vartheta_{\text{SN}} = 1/4$  models

differs slightly from  $b_x(r)$  in the term that describes the contribution of the decoupled gas.] In Tables 3–5 we report for each model the value of an emission-averaged [i.e., based on  $\Sigma_x(R)$ , over the whole galaxy] temperature  $\langle kT \rangle$ . In general, this latter quantity is different from the temperature that could be derived from a best fit to the emitted radiation by a Raymond spectrum. The result of this fit depends on the sensitivity of the instrument as a function of photon energy; in particular, it will be biased toward the peak of the detector quantum efficiency. Figure 5 shows more in detail the emission profiles of the three brightest objects, comparing the results of models obtained for different assumed SN Ia rates. The profiles of some physical quantities [temperature  $T(r)$ , particle density  $n(r) = \rho(r)/(\mu m_p)$  and mass flux  $\dot{m}(r)$ ] describing the intrinsic properties of the models are shown in Figure 6.

#### 4.1. Global Properties of the Selected Models

If we exclude the case of NGC 1404, which turns out to be a peculiar object in this modeling context (see comments below), the selected models are characterized by a fairly uniform value of  $q$  which decreases smoothly when the assumed value of  $\vartheta_{\text{SN}}$  is increased.

The model accretion rates  $\dot{m}_{\text{ext}}$ , which are smaller for higher assumed values of  $\vartheta_{\text{SN}}$ , show wide variation from galaxy to galaxy. The models for NGC 4374 all have a nominal value of  $0.1 M_{\odot} \text{ yr}^{-1}$ . For NGC 4472,  $\dot{m}_{\text{ext}}$  ranges from  $1 M_{\odot} \text{ yr}^{-1}$  to  $0.3 M_{\odot} \text{ yr}^{-1}$ . The latter value refers to the overbright model with  $\vartheta_{\text{SN}} = 1.1$ ; in this case, a lower accretion rate would not be compatible with the existing surface brightness and temperature data at large radii. The accretion rates in NGC 1404 are not large, but  $\dot{m}_{\text{ext}}$  is significant when the adopted supernova rate is small. In contrast, for any of the assumed choices of  $\vartheta_{\text{SN}}$ , most of the gas present in NGC 4636 is found to originate from the outside (about 67% for the lowest value of the supernova rate). The energetics of NGC 1399 appears to be dominated by a substantial accretion of external gas.

The values of the external pressure  $p_{\text{ext}}$  identified by our modeling procedure are on the high side, ranging from  $4 \times 10^3$  to  $1.5 \times 10^4 \text{ K cm}^{-3}$ . The latter value refers to NGC 4374 for a high assumed supernova rate; lower values of  $p_{\text{ext}}$  would also give reasonable models for this galaxy. In general, these relatively high values of  $p_{\text{ext}}$  are produced in order to fit a fairly flat surface brightness profile in the outer parts and are consistent with the overall increase in the temperature profiles in the



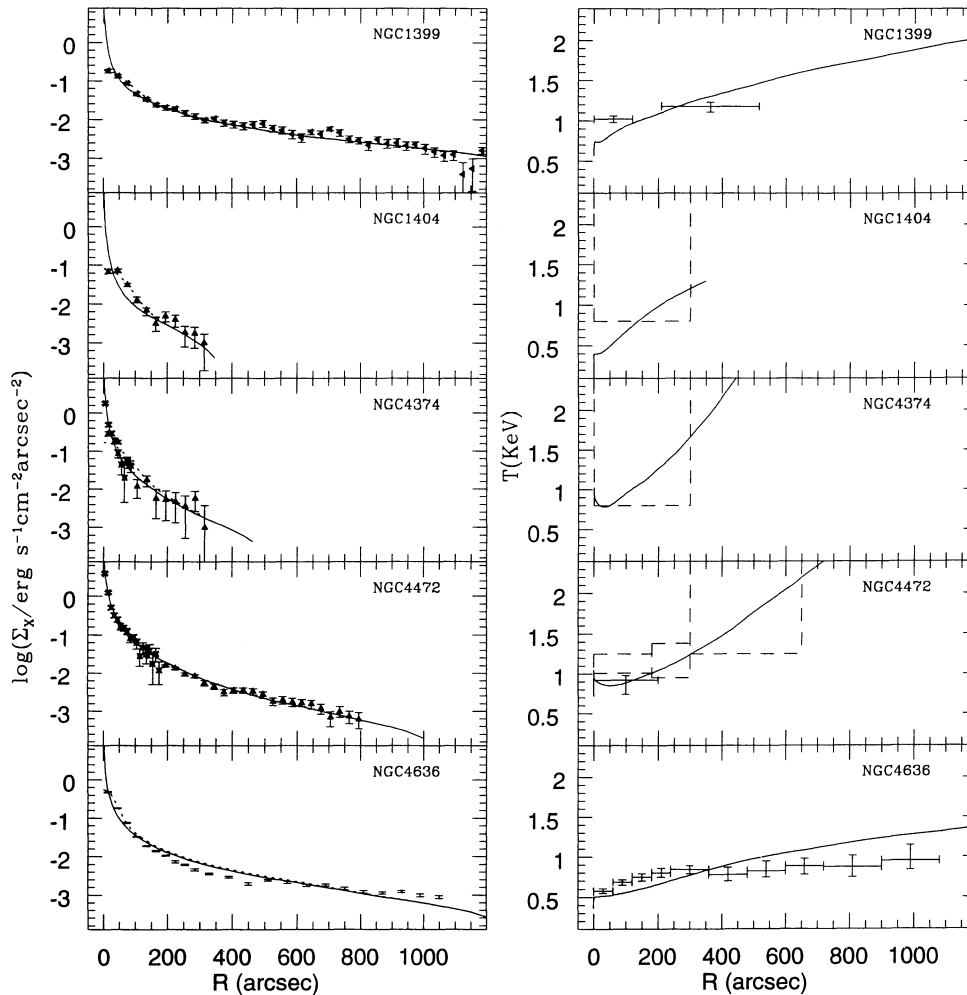


FIG. 4.—Same as Fig. 2, but for  $\vartheta_{\text{SN}} = 1.1$  models

outer regions suggested by the existing data (see also Böhringer et al. 1994).

We should stress that the high value of  $\vartheta_{\text{SN}} = 1.1$  suggested by van den Bergh & Tammann (1991) would imply that the energy input is dominated by supernovae. This explains why the corresponding selected models tend to be characterized by larger pressures  $p_{\text{ext}}$  (especially for the objects with small  $r_{\text{ext}}$ ) and by smaller accretion rates  $\dot{m}_{\text{ext}}$ . Note that, in the case of a high supernova rate, the selected models for NGC 4374 and NGC 4472 are overbright by factors of 2.4 and 1.4, respectively.

The mass of the gas  $M_{\text{gas}}$  recorded in the tables gives the integral of  $\rho$  out to  $r_{\text{ext}}$ . The numbers here are found to be quite large compared to previous estimates (see Forman et al. 1985; Thomas et al. 1986). This is particularly true for NGC 1399 and NGC 4636, for which the mass of the hot gas is of the same order as that of the stellar component. One obvious worry is that, under these conditions, the self-gravity of the gas should be incorporated in the model. Fortunately, the models do have sizable amounts of dark matter, so that even in the worst case (model  $\vartheta_{\text{SN}} = 1/16$  for NGC 1399) the gas actually makes up no more than 6% of the total mass inside  $r_{\text{ext}}$  (this percentage drops to 3% for NGC 4636, to 2% for NGC 4472 and NGC 1404, and to less than 1% for NGC 4374).

NGC 1404, as might have been anticipated, turns out to be somewhat peculiar. Its peaked emission profile and its larger  $L_X/L_B$  require a small value for the parameter  $q$  (0.1), independent of the assumed supernova rate (however, the  $q = 0$  models are ruled out). The cooling flow models for this object also stand out because of their relatively flat  $\dot{m}$  profiles (see further discussion in item 3 below). It appears that the characteristics of this galaxy mostly result from the interaction with its environment, dominated by NGC 1399. From the point of view of the observational input, one has to face a nontrivial subtraction problem since the galaxy is embedded in the bright halo of NGC 1399. The models adopted are clearly oversimplified with respect to the actual physical situation. Nevertheless, we find no particular difficulty in fitting the emission profile of NGC 1404. In view of its shallow potential well and of the constraints posed on  $p_{\text{ext}}$  by the apparent proximity to NGC 1399, a relatively low average X-ray emission temperature ( $\approx 0.6$  keV) is predicted for the hot gas.

From the properties of the environment identified by our models, it turns out that the intergalactic medium in Virgo and Fornax should be characterized by relatively high densities, so that ram-pressure stripping may be expected to be efficient. Indeed, this is suggested by White & Sarazin (1991), who find a correlation between the dispersion in  $L_X$  for a given  $L_B$  and the

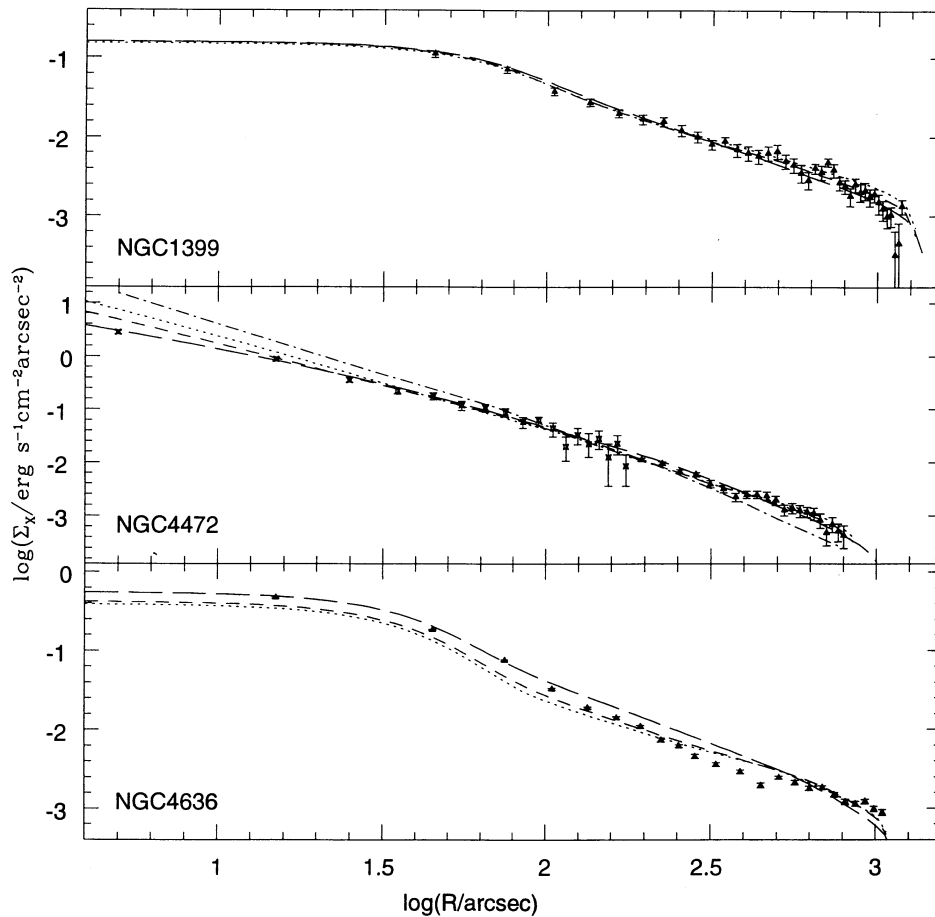


FIG. 5.—X-ray emission profiles for the brightest objects, showing in detail behavior in the innermost regions: *dotted lines*, models with  $\vartheta_{\text{SN}} = 1/16$ ; *short-dashed lines*, models with  $\vartheta_{\text{SN}} = 1/4$ ; *long-dashed lines*, models with  $\vartheta_{\text{SN}} = 1.1$ . Data points are *Einstein* IPC and HRI and *ROSAT* PSPC data (as in Fig. 2). For NGC 4472, the dash-dotted line showing the largest excess of emission in the central region corresponds to the FF models of BPS (with  $q = 0$ ).

local number density of galaxies. On the other hand, the effectiveness of ram-pressure stripping largely depends on the velocity of the galaxy relative to the medium (Gaetz, Salpeter, & Shaviv 1987). In particular, for typical values of  $\rho(r_{\text{ext}})$  in our models ( $10^{-3}$  amu), the condition for efficient stripping (see White & Sarazin 1991, eq. [10]) does not seem to be satisfied for velocities below  $500 \text{ km s}^{-1}$ . Indeed, the X-ray isophotes of NGC 1399 and NGC 4636 are fairly round.

After submission of this paper, some interesting results from the *Advanced Satellite for Cosmology and Astrophysics (ASCA)* mission have come to our attention (Loewenstein et al. 1994; Mushotzky et al. 1994), which may provide an additional way to discriminate between our models based on their average temperatures  $\langle kT \rangle$  (see col. [8] of Tables 3–5). For NGC 4636, the *ASCA* temperature measurements are consistent with those of Trinchieri et al. (1994; based on *ROSAT* data), which are accounted for in our models. For NGC 4374 and NGC 1404, the respective values of 0.74 and 0.75 keV seem to point in the direction of the choice  $\vartheta_{\text{SN}} = 1/4$ . For these two galaxies, a quick investigation has shown that it is possible to produce models characterized by average temperatures consistent with the *ASCA* values; in particular, in the case of NGC 1404, a model with  $q = 0.2$ ,  $\dot{m}_{\text{ext}} = 0.9 M_{\odot} \text{ yr}^{-1}$ ,  $p_{\text{ext}} = 2.2 \times 10^4 \text{ K cm}^{-3}$ , and  $\vartheta_{\text{SN}} = 1/4$  gives  $\langle kT \rangle = 0.79 \text{ keV}$  with a reasonable emission profile.

#### 4.2. Surface Brightness and Temperature Profiles

For four objects in our sample, both the emission and the temperature profiles compare well with the available *Einstein* IPC data. The case of NGC 4636 stands out because the photometric fit is unsatisfactory for both IPC and *ROSAT* PSPC data. While the latter data are closer to the model profiles, they also show a clear lack of circular symmetry; nevertheless, the temperature profile is sufficiently well reproduced. The impact of the assumed supernova rate  $\vartheta_{\text{SN}}$  is best noted in the innermost parts of the profiles, as shown in Figure 5 (logarithmic scale) in comparison with HRI data. In the low- $\vartheta_{\text{SN}}$  case, we find an excess of emission with respect to the innermost *Einstein* HRI data points for the galaxy NGC 4472; when a higher supernova rate is considered, the fit to the high-resolution HRI data in the central regions definitely improves. No important changes in the emission and temperature profiles on the large scale are noted. For a high supernova rate ( $\vartheta_{\text{SN}} = 1.1$ ), the model temperature profile of NGC 4636 is not fully satisfactory when confronted with *ROSAT* PSPC data; this might be improved by allowing for a larger  $\dot{m}_{\text{ext}}$ , but in such a case the model would be overbright.

Figure 5 also shows the behavior of the best-fit model for the case  $q = 0$  considered by BPS. This gives convincing evidence that the  $q$ -models are indeed able to remove almost completely

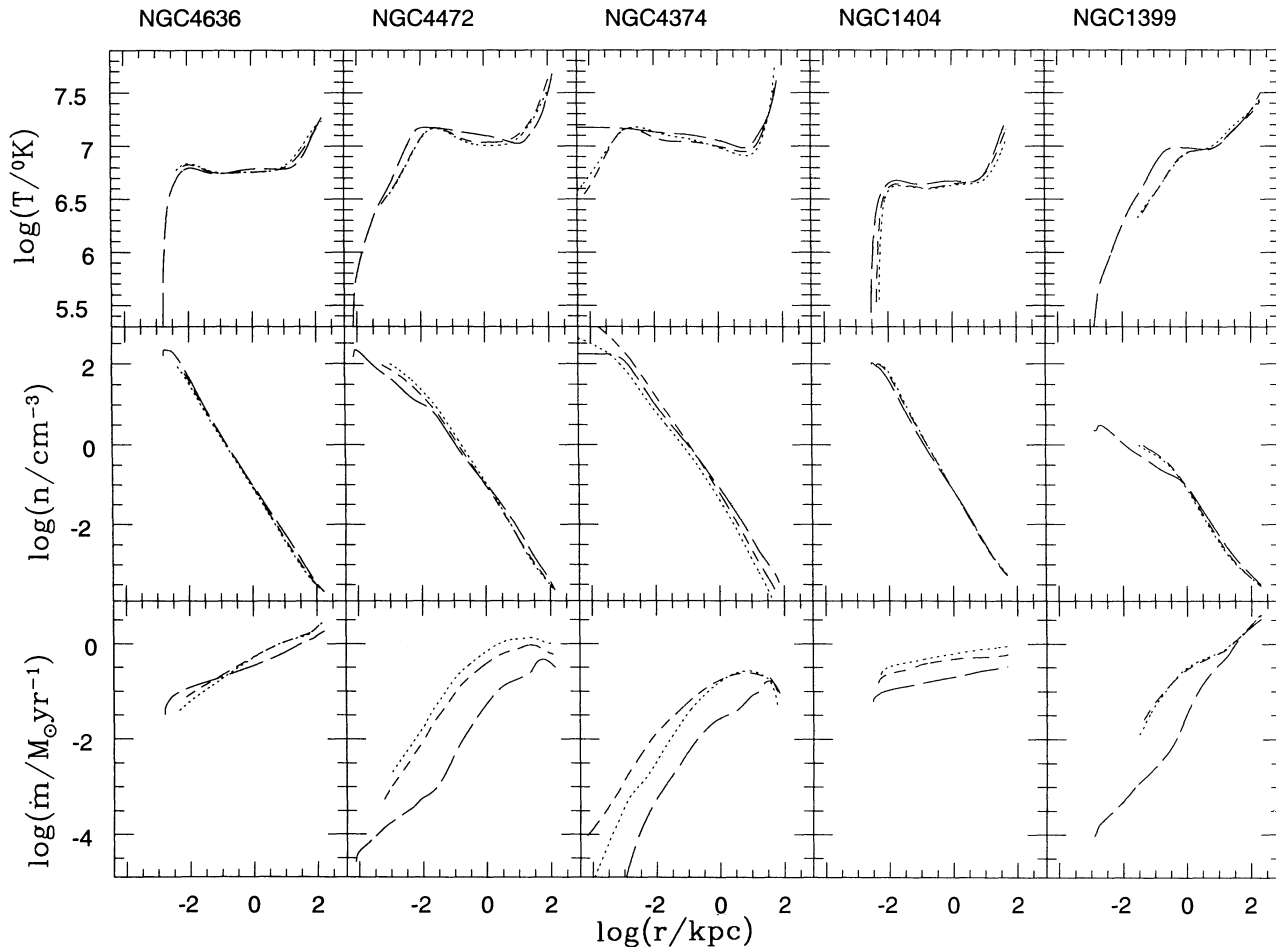


FIG. 6.—Intrinsic properties (temperature, particle density, and mass flux) of the selected models: *dotted lines*, models with  $\vartheta_{\text{SN}} = 1/16$ ; *short-dashed lines*, models with  $\vartheta_{\text{SN}} = 1/4$ ; *long-dashed lines*, models with  $\vartheta_{\text{SN}} = 1.1$  (as in Fig. 5).

the objection raised against simple cooling flow models in relation to the predicted emission profiles.

#### 4.3. Intrinsic Profiles

In Figure 6 we summarize the properties of the intrinsic profiles that characterize the selected models.

For the three galaxies (NGC 1399, NGC 1404, and NGC 4636) with the highest values of  $\dot{m}_{\text{ext}}/\alpha M_{\star}$ , the accretion rate ( $\dot{m}$ ) profiles are monotonically increasing; for NGC 1404 and NGC 4636, characterized by the lowest model values of  $q$ , such profiles are relatively flat. For NGC 4374 and NGC 4472, the accretion rate is nonmonotonic in the vicinity of  $r_{\text{ext}}$ .

From Figure 6 one can see that our models are computed down to very small radii ( $r < 10$  pc). The models are probably unphysical at such small galactocentric distances, but the profiles are shown in order to display the internal properties of the models and of the boundary conditions that have been adopted.

#### 4.4. Consistency of the Steady State Cooling Flow Description

In Figure 7 we present the characteristic timescales for the models selected under the assumption  $\vartheta_{\text{SN}} = 1/4$ . In each frame the three curves represent, as a function of galactocentric

radius, the cooling timescale  $\tau_{\text{cool}}$  (see eq. [4]), the flow timescale [i.e., the time necessary for a fluid element to reach the center by moving at the fluid velocity  $u(r)$ ], and the sound crossing time [i.e., the time necessary for a signal moving at the speed  $u_s = -(5p/3\rho)^{1/2}$  to reach the center]. Models characterized by smaller values of  $q$  (as is the case for NGC 1404) tend to have smaller values of the flow timescale at  $r_{\text{ext}}$ .

From Figure 7 one can see that the flow timescales actually exceed the Hubble time in the outer parts of the flow (*dashed lines*). On the other hand, while the cooling times are even longer (*solid lines*), pressure equilibrium is guaranteed by the short ( $\sim 10^8$  yr) sound crossing times (*dotted lines*). We must conclude that the steady state scenario is, strictly speaking, unjustified at very large radii; the calculated profiles are also shown there to describe the properties of the models at the outer boundary.

#### 4.5. Some General Trends from the Selected Sample of Galaxies

From the above discussion we find that, for a very low value of the supernova rate, the profiles are best fitted by models characterized by high values of  $q$ ; nevertheless, the central parts of the surface brightness profiles of the models are too steep. In contrast, based on  $\vartheta_{\text{SN}} = 1.1$ , the model temperature

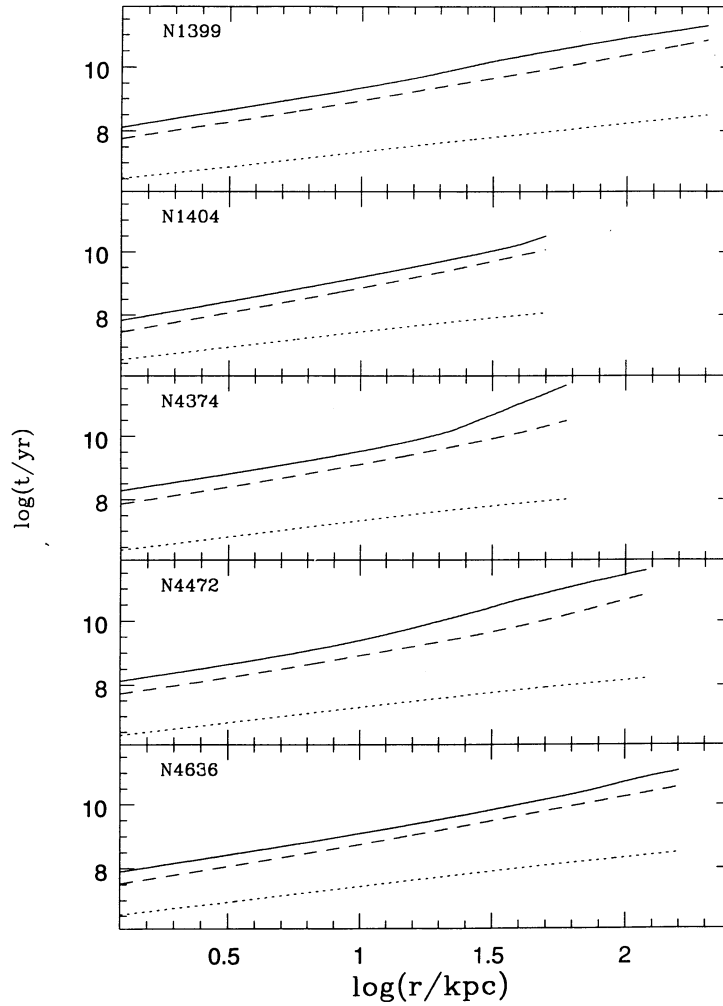


FIG. 7.—Characteristic timescales in the cooling flows for the selected models with  $\vartheta_{\text{SN}} = 1/4$ : *solid lines*, cooling times; *dashed lines*, flow times; *dotted lines*, sound crossing times (see text).

in the outer regions of NGC 4636 seems to be higher than that observed, while the model X-ray luminosities for NGC 4472 and NGC 4374 are in excess of the observed values by factors of 1.4 and 2.4, respectively. The intermediate case ( $\vartheta_{\text{SN}} = 1/4$ ) is probably the one to be preferred if one assumes a strictly constant rate from galaxy to galaxy, although the innermost data point for the HRI profile of NGC 4472 is not well accounted for.

In our limited sample of galaxies, two potentially interesting correlations have been noted and are shown in Figure 8. The right frame gives the correlation between  $\dot{m}_{\text{ext}}/\alpha M_*$  and  $(L_X/10^{41} \text{ ergs s}^{-1})/(L_B/10^{10} L_\odot)$ :

$$\frac{\dot{m}_{\text{ext}}}{\alpha M_*} \approx a \frac{(L_X/10^{41} \text{ ergs s}^{-1})}{(L_B/10^{10} L_\odot)} - b. \quad (14)$$

A linear regression gives  $a = 1.51, 1.53,$  and  $1.20$  and  $b = -0.11, 0.11,$  and  $0.40$  (for  $\vartheta_{\text{SN}} = 1/16, 1/4,$  and  $1.1,$  respectively). This may be compared to the estimate given in equation (11). Thus a natural interpretation for the different  $L_X/L_B$  values that are observed in our sample of elliptical galaxies suggests that, because of dilution, the iron abundance in the hot gas of X-ray-bright ellipticals should anticorrelate with  $L_X/L_B$ . The opposite trend would result if the higher  $L_X/L_B$

ratios were ascribed to higher SN Ia rates, but this would be hard to justify.

In this scenario of a “diluted cooling flow” one would expect a metallicity gradient to be established preferentially for objects having high  $L_X/L_B$ . The decoupling of the gas from the cooling flow would enhance the effect. Clearly, a quantitative assessment of the actual dilution factor would require a full modeling of the history of the galaxy-cluster interaction, which is well beyond the limits of the steady state analysis adopted in this paper. Such a detailed modeling would provide a determination of the size of the above-mentioned metallicity gradient. At this stage we feel encouraged by the qualitative trends reported by Loewenstein et al. (1994) and Mushotzky et al. (1994).

Another possibly interesting trend that is noted is a fairly tight correlation between  $\dot{m}_{\text{ext}}$  and the ratio  $r_h/r_L$ , where  $r_h$  denotes the half-mass radius of the total (dark + luminous) mass distribution of the galaxy. Here the offset of NGC 1404 might be due to the peculiarities of this object pointed out above. While the X-ray emission and temperature profiles appear to be of modest significance in diagnosing the presence of dark halos in galaxies (see BPS), the total X-ray luminosity might be a significant indicator (see also Bertin et al. 1994). We recall that no other significant correlations of  $L_X/L_B$  with

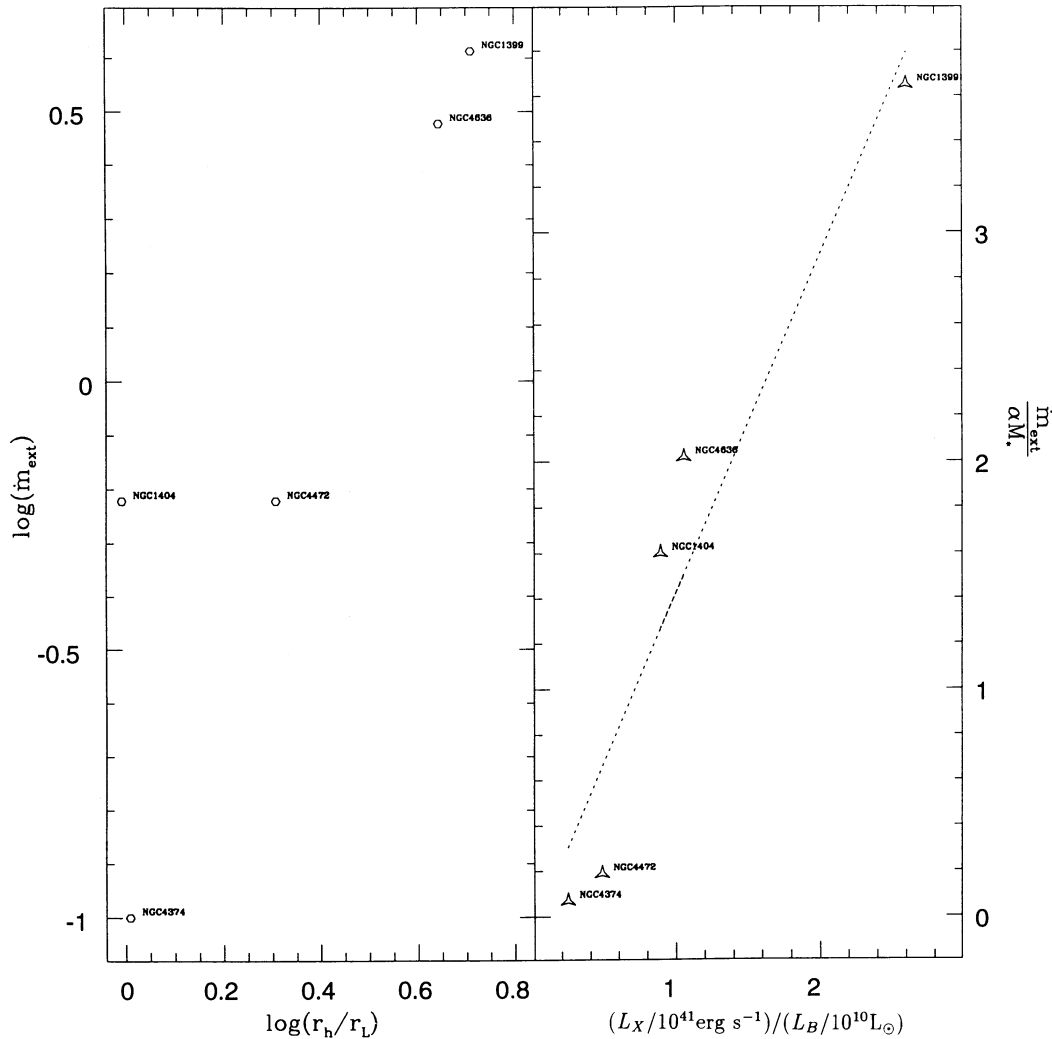


FIG. 8.—*Left*: The mass accretion rate  $\dot{m}_{\text{ext}}$  is found to be higher for diffuse halos ( $r_h$  is the half-mass radius of the total [dark + luminous] mass, while  $r_L$  is the half-mass radius of the luminous component). *Right*: Scaling of the dilution parameter  $\dot{m}_{\text{ext}}/\alpha \dot{M}_*$  with the relative X-ray luminosity  $(L_X/10^{41} \text{ erg s}^{-1})/(L_B/10^{10} L_\odot)$ . Here the values of the dilution parameter and of the luminosity  $L_X$  are taken from the selected models of Table 4 ( $q_{\text{SN}} = 1/4$ ).

intrinsic galaxy properties have been noted (see White & Sarazin 1991).

## 5. CONCLUSIONS

We have shown that, within galaxy models constrained by radially extended stellar dynamical data, a simple spherically symmetric, steady state, cooling flow description with gas loss generally compares well with the existing data on X-ray emission profiles and temperatures for a set of bright elliptical galaxies.

Three free parameters are needed to specify the model (1) the external mass flux  $\dot{m}_{\text{ext}}$ , which represents accretion of intergalactic gas and increases the X-ray luminosity of the galaxy, (2) the external pressure  $p_{\text{ext}}$ , which depends on the X-ray temperature of the cluster or group embedding it and helps confine the gas in the galactic potential well, and (3) the dimensionless coefficient  $q$ , which parameterizes the decoupling of thermally unstable clouds of cooling gas from the homogeneous phase (Sarazin & Ashe 1989) and regulates the mass deposition rate along the flow.

The use of the  $q$ -parameter especially leads to significantly better fits to the X-ray emission profiles with respect to the  $q = 0$  models, while the derived temperature profiles are consistent with, but only loosely constrained by, the existing data. Nevertheless, it is evident that in some cases the assumption of spherical symmetry is an oversimplification; in addition, we must be aware that the steady state condition is not fulfilled in the outer regions.

We have found that a value for the supernova rate in elliptical galaxies consistent with the estimate of Cappellaro et al. (1993) is favored by our models. Confining pressures of  $p_{\text{ext}} \sim 4\text{--}15 \times 10^3 \text{ K cm}^{-3}$  and significant accretion rates of external material, up to  $4 M_\odot \text{ yr}^{-1}$ , are suggested by our models. Finally, we have argued that the value of  $L_X/L_B$  should anticorrelate with the iron abundance in the gas inside ellipticals.

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## REFERENCES

- Allen, C. W. 1973, *Astrophysical Quantities* (London: Athlone)
- Awaki, H., Koyama, K., Kunieda, H., Takano, S., Tawara, Y., & Ohashi, T. 1991, *ApJ*, 366, 88
- Balbus, S. A. 1988, *ApJ*, 328, 395
- Bertin, G., et al. 1994, *A&A*, 292, 381
- Bertin, G., Pignatelli, E., & Saglia, R. P. 1993, *A&A*, 271, 381 (BPS)
- Binney, J., & Tabor, G. 1995, preprint
- Böhringer, H., Briel, U. G., Schwarz, R. A., Voges, W., Hartner, G., & Trümper, J. 1994, *Nature*, 368, 828
- Cappellaro, E., Turatto, M., Benetti, S., Tsvetkov, D. Yu., Bartunov, O. S., & Makarova, I. N. 1993, *A&A*, 268, 472
- Ciotti, L., d'Ercole, A., Pellegrini, S., & Renzini, A. 1991, *ApJ*, 376, 380
- David, L. P., Forman, W., & Jones, C. 1990, *ApJ*, 359, 29
- de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fouqué, P. 1991, *Third Reference Catalogue of Bright Galaxies* (New York: Springer) (RC3)
- Fabbiano, G., Kim, D.-W., & Trinchieri, G. 1992, *ApJS*, 80, 531
- Faber, S. M., Wegner, G., Burstein, D., Davies, R. L., Dressler, A., Lynden-Bell, D., & Terlevich, R. J. 1989, *ApJS*, 69, 763
- Fabian, A. C., & Nulsen, P. E. J. 1977, *MNRAS*, 180, 479
- Forman, W., Jones, C., & Tucker, W. 1985, *ApJ*, 293, 102
- Gaetz, T. J., Salpeter, E. E., & Shaviv, G. 1987, *ApJ*, 316, 530
- Ikebe, Y., et al. 1992, *ApJ*, 384, L5
- Kim, D.-W., Fabbiano, G., & Trinchieri, G. 1992, *ApJS*, 80, 645
- Loewenstein, M. 1989, *MNRAS*, 238, 15
- . 1990, *ApJ*, 349, 471
- . 1992, *ApJ*, 384, 474
- Loewenstein, M., & Mathews, W. G. 1987, *ApJ*, 319, 614
- Loewenstein, M., Mushotzky, R. F., Tamura, T., Ikebe, Y., Makishima, K., Matsushita, K., Awaki, H., & Serlemitsos, P. J. 1994, *ApJ*, 436, L75
- Lynds, R. 1970, *ApJ*, 159, L151
- Mathews, W. G., & Bregman, J. N. 1978, *ApJ*, 224, 308
- Murray, S. D., & Balbus, S. A. 1992, *ApJ*, 395, 99
- Mushotzky, R. F., Loewenstein, M., Awaki, H., Makishima, K., Matsushita, K., & Matsumoto, H. 1994, *ApJ*, 436, L79
- Pellegrini, S., & Fabbiano, G. 1994, *ApJ*, 429, 105
- Raymond, J. C., Cox, D. P., & Smith, B. W. 1976, *ApJ*, 204, 290
- Raymond, J. C., & Smith, B. W. 1977, *ApJS*, 35, 419
- Renzini, A. 1988, in *Windows on Galaxies*, ed. G. Fabbiano, J. S. Gallagher, & A. Renzini (Dordrecht: Kluwer), 255
- Saglia, R. P., et al. 1993, *ApJ*, 403, 567
- Saglia, R. P., Bertin, G., & Stiavelli, M. 1992, *ApJ*, 384, 433 (SBS)
- Sarazin, C. L. 1990, in *The Interstellar Medium in Galaxies*, ed. H. A. Thronson, Jr., & J. M. Shull (Dordrecht: Kluwer), 201
- Sarazin, C. L., & Ashe, G. A. 1989, *ApJ*, 345, 22
- Sarazin, C. L., O'Connell, R. W., & McNamara, B. R. 1992a, *ApJ*, 389, L59
- . 1992b, *ApJ*, 397, L31
- Sarazin, C. L., & White, R. E., III. 1987, *ApJ*, 320, 32
- . 1988, *ApJ*, 331, 102
- Serlemitsos, P. J., Loewenstein, M., Mushotzky, R. F., Marshall, F. E., & Petre, R. 1993, *ApJ*, 413, 518
- Tammann, G. 1982, in *Supernovae: A Survey of Current Research*, ed. M. Rees & R. Stoneham (Dordrecht: Reidel), 371
- Thomas, P. A. 1986, *MNRAS*, 220, 949
- Thomas, P. A., Fabian, A. C., Arnaud, K. A., Forman, W., & Jones, C. 1986, *MNRAS*, 222, 655
- Toniazzo, T. 1993, *Tesi di Laurea*, Università di Pisa
- Trinchieri, G., Kim, D.-W., Fabbiano, G., & Canizares, C. R. 1994, *ApJ*, 428, 555
- van den Bergh, S., & Tammann, G. 1991, *ARA&A*, 29, 363
- Vedder, P. W., Trester, J. J., & Canizares, C. R. 1988, *ApJ*, 332, 725
- White, R. E., & Sarazin, C. L. 1991, *ApJ*, 367, 476