THE ASTROPHYSICAL JOURNAL, 341:L9–L12, 1989 June 1
© 1989. The American Astronomical Society. All rights reserved. Printed in U.S.A.

X-RAY EVOLUTION OF MODEL ELLIPTICAL GALAXIES

ANNIBALE D'ERCOLE
Osservatorio Astronomico di Bologna
AND
ALVIO RENZINI, LUCA CIOTTI, AND SILVIA PELLEGRINI
Dipartimento di Astronomia, Università di Bologna
Received 1989 February 22; accepted 1989 March 3

ABSTRACT

We present a new set of hydrodynamical models covering the evolution over a Hubble time of the hot gas flows in elliptical galaxies. Standard assumptions are made for the structure of the galaxies and their dark matter halo, while the treatment of the source terms differs from previous similar studies. The gas source from stellar mass loss is treated according to the accurate prescriptions of stellar evolution theory. The energy source from Type I supernovae is assumed to decline with time slightly faster than the rate of mass return from dying stars. As a consequence of the secularly declining SN heating, the flows experience up to three consecutive major evolutionary phases which we call wind, outflow, and inflow phases. We show that the X-ray luminosity of the majority of elliptical galaxies is well accounted for by models still in their outflow phase, X-ray–faint galaxies are still in their supersonic wind phase, while a few among the brightest galaxies might have already experienced the transition to the inflow phase. Agreement with *Einstein* observations (including the previously unexplained large dispersion of the X-ray luminosity for given blue luminosity) is achieved using the "standard" estimate of the SN rate in early-type galaxies.

Subject headings: galaxies: evolution — galaxies: X-rays — galaxies: structure — galaxies: internal motions

As first revealed by *Einstein* observations, normal elliptical galaxies can be powerful X-ray sources (Forman *et al.* 1979), with 0.5–4.5 keV luminosities L_X ranging from $\sim 10^{39}$ to $\sim 10^{42}$ ergs s^{-1} (cf. Forman, Jones, and Tucker 1985; Canizares, Fabbiano, and Trinchieri 1987, hereafter CFT; Fabbiano 1989). The discovery of such high X-ray luminosities excluded early models in which supernovae drive supersonic galactic winds and little hot gas accumulates in the galaxies (Mathews and Baker 1971; MacDonald and Bailey 1981). In order to prevent fast degassing, the galaxies have been supposed to be surrounded by massive dark halos (e.g., Forman, Jones, and Tucker 1985), presumably of the same nature of the dark matter maintaining flat rotation curves in spiral galaxies. Moreover, given the popularity of cooling flow models for the X-ray emission of clusters of galaxies, similar stationary cooling flow models have been proposed for individual (non–cD) ellipticals (e.g., Thomas 1986; Thomas *et al.* 1986; Sarazin and White 1987, 1988).

The large dispersion of L_X for given optical luminosity is one of the main characteristics of early-type galaxies (see Fig. 1). For $3 \times 10^{10} \lesssim L_B \lesssim 10^{11}\ L_\odot$, this dispersion is about a factor of 50. Below $\sim 3 \times 10^{10}\ L_\odot$, there is very little dispersion, and $L_X \simeq L_{\rm dscr}$, with $L_{\rm dscr}$ being the expected contribution of the discrete sources (cf. CFT). So there is no compelling evidence for a hot gas contribution to L_X (cf. Fabbiano, Gioia, and Trinchieri 1989). On the contrary, above $\sim 10^{11}\ L_\odot$ a hot gas component is present in all the galaxies. A common feature of cooling flow models is that they may explain only the brightest X-ray galaxies. In such models the X-ray luminosity results from four contributions: i.e., $L_X \simeq L_{\rm dscr} + L_{\rm SN} + L_\sigma + L^+_{\rm grav}$, where $L_{\rm SN}$ is the energy input by supernovae, L_σ comes from the thermalization of stellar winds to the stellar velocity dispersion, and $L^+_{\rm grav}$ is the rate at which the gas is heated by inflowing through the galactic potential well. Figure 1 shows that for most galaxies $L_X \ll L_{\rm SN}$, having adopted the standard estimate for the SN I rate in ellipticals, $R_{\rm SN}({\rm now}) = 0.22 \times 10^{-12} L_B$ yr^{-1} (Tammann 1982), and 10^{51} ergs for the kinetic energy injected by each SN. In an attempt to preserve some sort of cooling flow model one is then forced to assume a substantial reduction of $R_{\rm SN}$. For example, Thomas (1986) adopts a 20 times lower rate, and although this leads to "characteristic [gas] temperatures far lower than observed," still L_X cannot be reduced by more than about a factor of 2 (with Tammann's rate $L_{\rm SN} \simeq L^+_{\rm grav}$). In order to achieve a further reduction, thermal instabilities have been supposed to cause matter to drop out of the flow at large distances from the center (thus reducing also $L^+_{\rm grav}$). Still, the reduction in L_X would be at most a factor ~ 3 even in the extreme case of matter condensing out of the flow right on the same spot where it is injected by stars (Sarazin and White 1988). Moreover, since there are even galaxies with $L_X \lesssim L_\sigma$, it has been speculated that red giant stellar winds may never join the hot phase, but rather would quickly collapse into unobservable entities (e.g., Thomas 1986; an assumption criticized by Mathews 1988). Yet, the reduction of the supernova rate, the effectiveness of thermal instabilities, and the reluctance of stellar winds to heat up, not only all remain conjectural, but if the large range in L_X is to be explained, then wild galaxy-to-galaxy variations should also be postulated in the SN rate, as well as in the propensity of matter to go thermally unstable, and of the red giant winds to mix with the X-ray gas. We have then explored alternative possibilities to explain the observed X-ray properties of elliptical galaxies, basically relaxing the *a priori* assumption that all galaxies are inhabited by a cooling flow, and renouncing to the steady state approximation.

In doing so, we move from the fully hydrodynamical study of Mathews and Loewenstein (1986, hereafter ML) and Loewenstein and Mathews (1987, hereafter LM), but apply the same techniques to the exploration of a slightly different domain in the parameter space, in particular concerning the

© American Astronomical Society • Provided by the NASA Astrophysics Data System

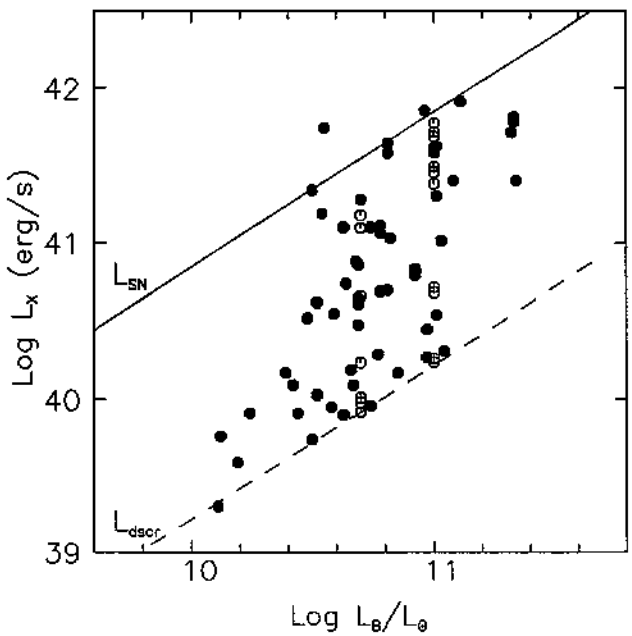

FIG. 1.—The X-ray vs. blue luminosity for detected early-type galaxies from Canizares, Fabbiano, and Trinchieri (1987), and for the present model elliptical galaxies at $t = 15$ Gyr (*filled* and *open symbols*, respectively). The model L_X includes the adopted contribution of discrete sources (L_{dscr}, *dashed line*). The solid line shows the rate of energy input from supernovae L_{SN}, at the current standard rate.

SN heating. Following LM, we define the (mass) specific rate of stellar mass return $\alpha_* = \dot{M}_*/M_*$, while $\alpha_{SN} = 1.4\ M_\odot\ R_{SN}(t)/M_*$ is the contribution from Type I supernovae, and $\alpha = \alpha_* + \alpha_{SN}$. Mathews and Loewenstein assume either $\alpha_{SN} \propto \alpha_*$, or $\alpha_{SN} \simeq$ const, i.e., a virtually time-independent SN rate. This implies an injection temperature $[T_0 = (\alpha_{SN} T_{SN} + \alpha_* T_*)/\alpha]$ which is either constant (ML) or increasing with time (cf. LM's Fig. 2). The latter trend follows from both α_* and α decreasing with time, while α_{SN} remains nearly constant. For the adopted parameters LM models develop a cooling flow from the very beginning, but as T_0 increases with time, their ultimate tendency is to reverse the flow into an outflow, which will soon develop into a supersonic wind. The LM models apparently suffer less from the X-ray overluminosity syndrome than do stationary cooling flow models. This follows from LM having used a present rate of mass return $\alpha_* = 2.2 \times 10^{-20}\ s^{-1}$, which is a factor ~ 3.5 smaller than predicted by stellar evolution theory (Tinsley 1980; Renzini and Buzzoni 1986; Renzini 1989). Moreover, in the reference LM models also the SN rate is reduced by a factor of 4 over Tammann's rate, and so every energy source is effectively reduced by a similar factor over standard values.

Our evolutionary sequences of hydrodynamical models differ from LM sequences in two crucial respects. The first difference concerns the rate of mass return α_*. We adopt $\alpha_* M_* = \dot{M}_* = B(t)\Delta M L_T$, where $B(t)$ is the specific evolutionary flux (stellar death rate) of the galaxy, $\Delta M(t)$ is the total mass which has been lost by each of the stars dying at age t, and L_T is the bolometric luminosity of the galaxy (Renzini and Buzzoni 1986; Renzini 1989). We further adopt $L_T = 2.4 L_B$ for the blue to bolometric conversion for present-day ellipticals, and then $\alpha_* = 2.4 B(t)\Delta M(t)/(M_*/L_B)$, or $\alpha_* = 7.6 \times 10^{-20}\ s^{-1}$ when state of the art values are used for B and ΔM at $t = 15$ Gyr, and $M_*/L_B = 6$ as in LM. We consider this determination to be very robust, at about the 15% level, i.e., much better than the factor of ~ 3 uncertainty often attributed to similar estimates. The second major difference concerns the time dependence of the SN rate. We adopt a secularly decreasing SN rate $R_{SN}(t) = R_{SN}(15)(t/15\ \text{Gyr})^{-s}$, and assume s values such that R_{SN} decreases slightly faster than α_*. In practice, this implies $s \gtrsim 1.4$ when the stellar IMF follows the Salpeter distribution $[\psi(M) \propto M^{-2.35}]$ that we have adopted throughout. It follows that T_0 now *decreases* with time, a difference that has profound consequences on the evolution of the X-ray gas. There are both empirical and theoretical arguments which strongly support the notation of a declining R_{SN}, past the formation of a stellar population which includes the binary progenitors of Type I supernovae (cf. Renzini 1989 and references therein). In particular: (1) in spirals the present rate correlates with the star formation rate of the galaxies, and (2) whatever binary model is adopted, theoretical rates always contain a rapidly decreasing factor. In common with previous studies are the adopted galactic models. We too use the King function for the stellar mass distribution, and an isothermal dark matter halo of mass $M_h = RM_*$, both truncated at a common tidal radius $r_t = \delta r_{c*}$. The model galaxies follow a Faber-Jackson L_B-σ relation and a $\sigma(r)$ relation as given respectively by equations (11) and (23) in Sarazin and White (1987). In practice, each model is determined by five parameters: L_B, δ, R, the stellar mass-to-light ratio M_*/L_B, and the central ratio of halo to star density $\gamma = \rho_{h0}/\rho_{*0}$. Having specified the galaxy model and the source terms $\alpha_*(t)$ and $\alpha_{SN}(t)$, the hydrodynamical equations of mass, momentum, and energy conservation are then numerically integrated using an explicit, Eulerian, fully vectorized code (Bedogni and D'Ercole 1986). As in ML and LM we assume the galaxy to be devoid of gas at $t = 0$, and the evolution up to $t = 15$ Gyr requires $\sim 10^5$ time steps. We did also run one LM model and obtained the same results.

In order to assist the interpretation of the numerical results we introduce the quantity $\chi(t) = L_{grav}^-/L_{SN}$, defined as the ratio of the power required to steadily extract from the galaxy the gas shed by stars (L_{grav}^-), to the power actually made available by supernovae. Clearly, $L_{grav}^- = -\alpha \int 4\pi r^2 \phi(r)\rho_*(r)dr$, where $\phi(r)$ is the potential. Both L_{grav}^- and χ are functions of the galaxy parameters (L_B, δ, γ, R), while they are independent of M_*/L_B. The value of χ at $t = 15$ Gyr is plotted versus R in Figure 2, for various choices of the galactic parameters. We note that $\chi \ll 1$ for $L_B = 10^{10}\ L_\odot$ galaxies, for every reasonable combination of the parameters: i.e., with Tammann's SN rate there is ample energy input to sustain a supersonic wind in these fainter galaxies. One then expects low X-ray luminosities, in excellent agreement with the observations (cf. Fig. 1). For $L_B \gtrsim 10^{11}\ L_\odot$ one has $\chi \gtrsim 1$, SN heating is insufficient to prevent inflow, and large X-ray luminosities are then expected, again in agreement with the observations. For intermediate luminosities, a transition between the two regimes has necessarily to take place, and a large sensitivity of L_X to the galactic model is anticipated. Note that no fudge parameters have so far been adjusted.

In Figure 3 the time evolution of L_X is displayed for eight evolutionary sequences relative to $L_B = 5 \times 10^{10}\ L_\odot$ galaxies. The sequences present several common features, and up to three consecutive major phases can be distinguished: respectively, the wind, outflow, and inflow phases. As initially $L_{SN} \gg L_{grav}^-$, supernovae drive a supersonic wind, the mass of hot gas in the galaxy—M_{gas}—drops following the drop of α_*, and so does the X-ray luminosity. However, L_{SN} decreases faster than L_{grav}^-, and when χ drops below 1, supernovae cease to provide enough energy to sustain a wind, and the wind turns into a

© American Astronomical Society • Provided by the NASA Astrophysics Data System

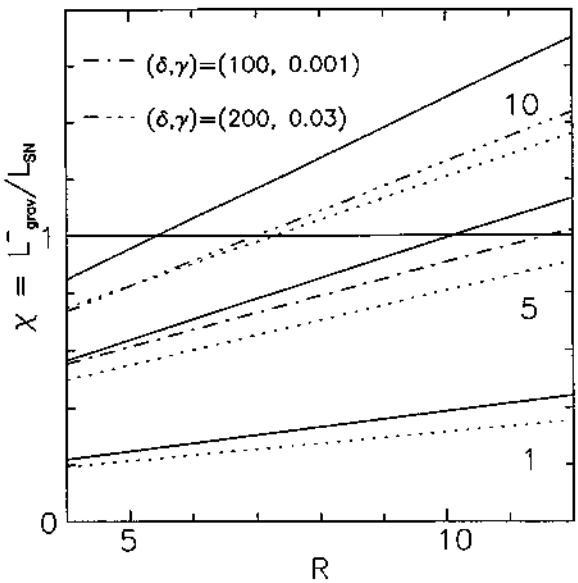

FIG. 2.—The present epoch values of ratio $\chi = L_{grav}^{-}/L_{SN}$ (see text) for the model galaxies as a function of the dark halo to star mass ratio R. The three groups of lines refer to the indicated blue luminosities (L_B) in 10^{10} $L_\odot$ units, with γ (the central ratio of halo to stellar density) = 0.001 (*dotted line*) and 0.03 (*solid line*) and $\delta = 140$ (apart from the two lines with a different indication).

subsonic outflow. Still, the SN energy input inflates the gas, but this now leaves the galaxy at a rate which is lower than that at which fresh gas is injected: M_{gas} starts increasing, and so does L_X. During the whole outflow phase M_{gas} and L_X keep increasing while the outflow becomes more and more subsonic. Eventually a thermal instability cannot be avoided, and this actually triggers a central cooling catastrophe, which temporally coincides with the sharp maximum of L_X seen in Figure 3. This marks the transition to the third phase dominated by the inflow. After a quick outward migration to $r \simeq 10$ kpc, the drift of the stagnation radius slows down, while the inflow becomes supersonic at a few 100 pc from the center (a common feature in cooling flow models; see, e.g., LM). Inside the stagnation radius the flow is quasi-stationary, and L_X decreases in pace with α_*, M_{gas}, and L_{SN}. Note that both the wind and the inflow regimes can be quasi-stationary, while the outflow regime is inherently nonstationary. Still, the outflow phase can last for times comparable to the Hubble time, and its duration is extremely sensitive to the galactic model. Hence, relatively small changes in the model parameters (well within expected galaxy-to-galaxy differences) cause L_X to vary by large amounts (cf. Fig. 3). In general, the central cooling catastrophe is delayed when L_B, γ, or R decrease, and when δ or M_*/L_B increase. These behaviors can readily be understood by considering the effect of these parameters on the depth of the galactic potential well and L_{grav}^{-}, or, in the case of M_*/L_B, the effect that the concentration of the stellar distribution has on the radiative losses. Clearly, a more concentrated gas source favors radiation losses, and tends to anticipate the central catastrophe and the transition to the inflow phase.

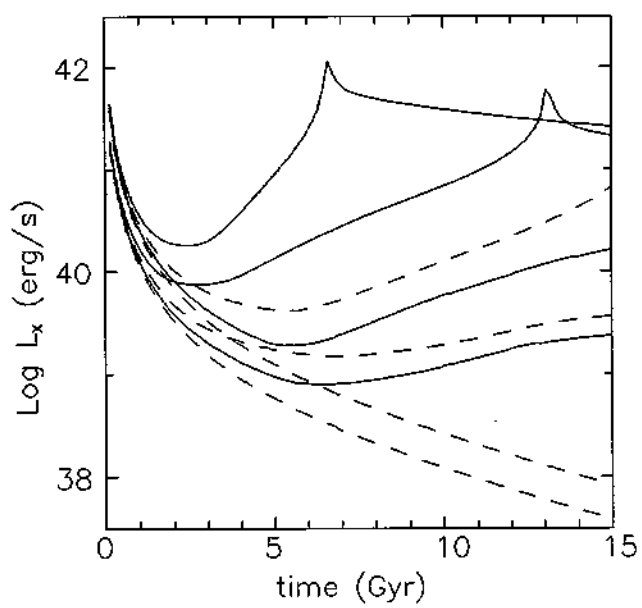

FIG. 3.—The time evolution of the X-ray luminosity L_X for the $L_B = 5 \times 10^{10}$ $L_\odot$ evolutionary sequences with $s = 1.5$ and present SN rate reduced by a factor 1.3 over Tammann's rate. Solid and dashed lines refer to $\delta = 100$ and 140, respectively. For given δ, L_X at $t = 15$ Gyr decreases for the combination (γ/0.003, M_*/L_B) in the sequence (10, 8), (1, 8), (10, 17), and (1, 17). Note that at the present epoch the two brighter sequences are already in the inflow phase, the two fainter ones are still in the wind phase, while the other four sequences are in the outflow phase. For these latter sequences, the transition to the inflow regime will take place at a future time.

Two series of evolutionary sequences have been calculated, both with $R = 9$ (for uniformity with ML and LM), i.e., all our model galaxies are assumed to have the same proportion of stellar to halo matter. In the first series $s = 1.4$, and Tammann's rate is adopted at $t = 15$ Gyr. In the second series $s = 1.5$ and the present rate has been reduced by a factor of 1.3. For each series we have adopted $L_B = 5 \times 10^{10}$ and 10^{11} $L_\odot$, $M_*/L_B = 8$ and 17, $\gamma = 3 \times 10^{-3}$ and 3×10^{-2}, and $\delta = 100$, 140 (for $L_B = 5 \times 10^{10}$ $L_\odot$), and 140, 200 (for $L_B = 10^{11}$ $L_\odot$). No models with $L_B = 10^{10}$ $L_\odot$ have been computed, because a very low X-ray luminosity is affirmatively anticipated ($L_X \simeq L_{dscr}$), with all the models still in the wind phase (cf. Fig. 2). Similarly, for the same galactic parameters, all the models with L_B somewhat in excess of 10^{11} $L_\odot$ are expected to be in the inflow phase, with $L_X \simeq L_{SN}$. The X-ray luminosity of all the computed models (at $t = 15$ Gyr and inclusive of the pedestal contribution L_{dscr}) is plotted in Figure 1. From the comparison with the observations we conclude that subsonic outflows prevail in the majority of the observed galaxies, although some of the brightest of them might already be in the inflow phase. Fainter galaxies are still in their supersonic wind phase. It is therefore the prevalence of outflowing galaxies which generates the L_X dispersion seen in Figure 1. Moreover, galaxies in the inflow phase are exempt from the embarrassing concentration of unseen matter in the core which was of concern in LM sequences. Our numerical experiments indicate that the ratio R and the present SN rate jointly control the transition galaxy luminosity L_B at which outflows dominate, while the time slope s controls primarily the rapidity of the transition, i.e., the width of the L_B range in which a large dispersion in L_X is produced. Note that a reduction of R would require a reduction also of $L_{SN}(15)$—and vice versa, so as to keep $\chi(15) \simeq 1$ for $L_B \simeq 5 \times 10^{10}$ $L_\odot$. For dark matter accounting for 90% of the mass of galaxies ($R = 9$), we find excellent agreement with the observations when Tammann's rate (or a slightly lower value) is adopted, and the SN rate declines with time slightly faster than the rate of mass return from dying stars. This latter indication tend to favor a Type I SN model in which the rate is controled by the same clock controling stellar evolution, such as in the case of the white dwarf + red giant precursors (cf. Greggio and Renzini 1983; Renzini 1989).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

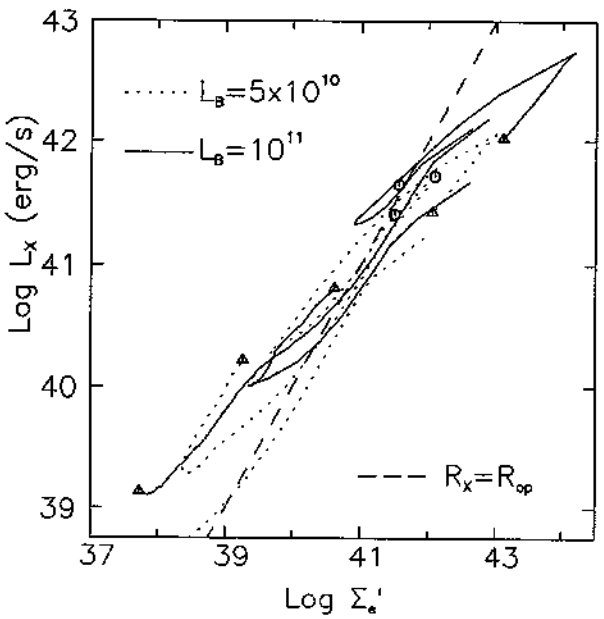

FIG. 4.—A representative selection of evolutionary sequences in the log L_X – log Σ_e' plane. For each L_B, the three displayed sequences terminate in a different regime (wind, outflow, or inflow), and the termination point (at $t = 15$ Gyr) is marked with a triangle. The dashed line is the locus where the X-ray and optical distributions have the same effective radius. Also displayed as open circles are the three galaxies N4472, N4636, and N4649 for which detailed X-ray surface brightness profiles are available (Trinchieri, Fabbiano, and Canizares 1986.

During the three main evolutionary phases the distribution of the hot gas inside the galaxies is subject to considerable variations, which manifest themselves as an evolution of the X-ray surface brightness distribution. For a concise description of this aspect of the models, an effective X-ray surface brightness $\Sigma_e = L_X/(8\pi^2 R_X^2)$ can be introduced, where R_X is the effective radius inside which a luminosity $\frac{1}{2}L_X$ is sampled. As we are primarily interested in a comparison with the optical distribution, an even more concise description is provided by $\Sigma_e' = L_X/(R_X/R_{op})^2$, where $R_{op} \simeq r_{c*}(\delta)^{1/2}$ is the optical effective radius. In Figure 4 we plot some of our evolutionary sequences in the log L_X – log Σ_e' plane (somehow analogous to the classical H-R diagram of stellar evolution). In this plane, $R_X = R_{op}$ for models lying on the dashed line. Above and below the line, the X-ray profile is respectively broader and narrower than the optical profile. Our evolutionary tracks tend to cluster about the line, with the minimum and maximum Σ_e' (or Σ_e) coinciding respectively with the wind-outflow and outflow-inflow transitions. Plots of this kind may become a useful tool when future X-ray satellites will start gathering fresh new data. In a subsequent paper, a thorough description and discussion of the models will be presented, together with further explorations of the parameter space and of other astrophysical ramifications (also including environmental effects).

We are grateful to Dr. Pepi Fabbiano for valuable discussions and suggestions, and we wish to acknowledge the Piano Spaziale Nazionale for the partial support of this work through the grants PSN 85076, 85079, 87035, and 87037.

REFERENCES

Bedogni, R., and D'Ercole, A. 1986, *Astr. Ap.*, **157**, 101.
Canizares, C. R., Fabbiano, G., and Trinchieri, G. 1987, *Ap. J.*, **312**, 503 (CFT).
Fabbiano, G. 1989, *Ann. Rev. Astr. Ap.*, **27**, in press.
Fabbiano, G., Gioia, I. M., and Trinchieri, G. 1989, preprint.
Forman, W., Jones, C., and Tucker, W. 1985, *Ap. J.*, **293**, 102.
Forman, W., Schwarz, J., Jones, C., Liller, W., and Fabian, A. 1979, *Ap. J. (Letters)*, **234**, L27.
Greggio, L., and Renzini, A. 1983, *Astr. Ap.*, **118**, 217.
Loewenstein, M., and Mathews, W. G. 1987, *Ap. J.*, **319**, 614 (LM).
MacDonald, J., and Bailey, M. E. 1981, *M.N.R.A.S.*, **197**, 995.
Mathews, W. G. 1988, in *Cooling Flows in Clusters and Galaxies*, ed. A. C. Fabian (Dordrecht: Kluwer), p. 279.
Mathews, W. G., and Backer, J. 1971, *Ap. J.*, **170**, 241.
Mathews, W. G., and Loewenstein, M. 1986, *Ap. J. (Letters)*, **306**, L7 (ML).
Renzini, A. 1989, in *Evolutionary Phenomena in Galaxies*, ed. J. Beckman (Cambridge: Cambridge University Press), in press.
Renzini, A., and Buzzoni, A. 1986, in *Spectral Evolution of Galaxies*, ed. C. Chiosi and A. Renzini (Dordrecht: Reidel), p. 135.
Sarazin, C. L., and White, R. E. 1987, *Ap. J.*, **320**, 32.
———. 1988, *Ap. J.*, **331**, 102.
Tammann, G. 1982, in *Supernovae: A Survey of Current Research*, ed. M. Rees and R. Stoneham (Dordrecht: Reidel), p. 371.
Thomas, P. A. 1986, *M.N.R.A.S.*, **220**, 949.
Thomas, P. A., Fabian, A. C., Arnaud, K. A., Forman, W., and Jones, C. 1986, *M.N.R.A.S.*, **22**, 655.
Tinsley, B. M. 1980, *Fund. Cosmic Phys.*, **5**, 287.
Trinchieri, G., Fabbiano, G., and Canizares, C. R. 1986, *Ap. J.*, **310**, 637.

LUCA CIOTTI, ANNIBALE D'ERCOLE, SILVIA PELLEGRINI, and ALVIO RENZINI: Dipartimento di Astronomia and Osservatorio Astronomico, CP 596, I-40100 Bologna, Italy

© American Astronomical Society • Provided by the NASA Astrophysics Data System