Morphological and Physical Classification of Galaxies

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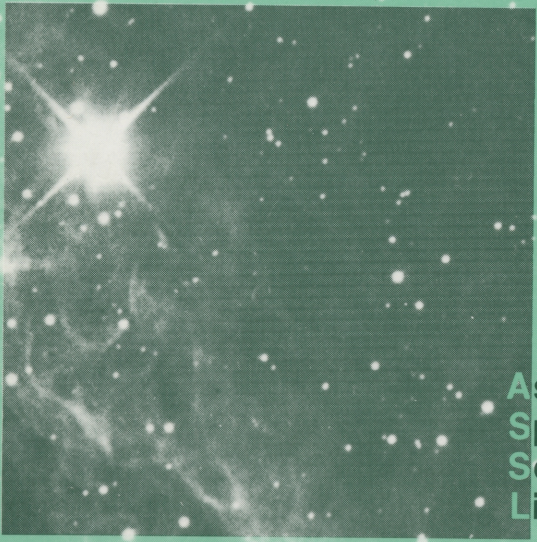

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Participants waiting for the bus to Pompei.

ELLIPTICAL GALAXIES IN X-RAYS

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ABSTRACT. We present a new class of 1D hydrodynamical evolutionary sequences for the gas flows in elliptical galaxies. The model galaxies are described by either King's or de Vaucouleurs' virialized density distributions, and are surrounded by variable amounts of dark matter. Two source terms operate: mass loss from evolving red giants, and a secularly declining heating by type I supernovae. The resulting model galaxies evolve through up to three consecutive evolutionary stages, that we call wind, outflow, and inflow phase. Agreement with the observed trends of the X-ray luminosity with the optical characteristics of the galaxies is achieved for models in which the dark to visible mass ratios is around ten, when the standard SNI rate is assumed.

1 Introduction

As first revealed by *Einstein* observations, normal (non-cD) elliptical galaxies, can be powerful X-ray sources, with 0.5 – 4.5 KeV luminosities L_X ranging from $\sim 10^{39}$ to $\sim 10^{42}$ erg s^{-1} (Forman, Jones and Tucker, 1985; Canizares, Fabbiano and Trinchieri, 1987, hereafter CFT; Fabbiano, 1989).

The X-ray emission strongly correlates with the optical (e.g. blue) luminosity of the observed galaxies, and CFT find $L_X \propto L_B^{1.7\pm0.3}$, but there is substantial scatter at any luminosity, as shown in figure 1 which reproduces CFT data. Since the scatter is substantially larger than expected from measuring errors, the actual variety of astrophysical conditions prevailing in elliptical galaxies could hardly be reduced to the average correlation. Moreover, for $L_B \lesssim 3\times10^{10} L_\odot$ the observed L_X is consistent with an emission due entirely to discrete sources (see also CFT), while only for higher luminosities the evidence for an additional contribution from a hot interstellar medium (ISM) is actually compelling. There is little doubt that evolving stars shed a considerable amount of mass, and therefore one important astrophysical question is how and where elliptical galaxies manage to dispose this gas. Early studies have shown that with standard SN rates (and no Dark matter!) all elliptical galaxies would support a supersonic wind (Mathews and Baker, 1971), and therefore galaxies would contain very little hot gas, and would not be powerful X-ray emitters. One way to prevent the development of galactic winds is to deepen the gravitational potential well, e.g. by assuming the presence of massive dark

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halos, and/or reducing the supernova heating (e.g. Nulsen, Stewart, and Fabian, 1984, Sarazin and White, 1987).

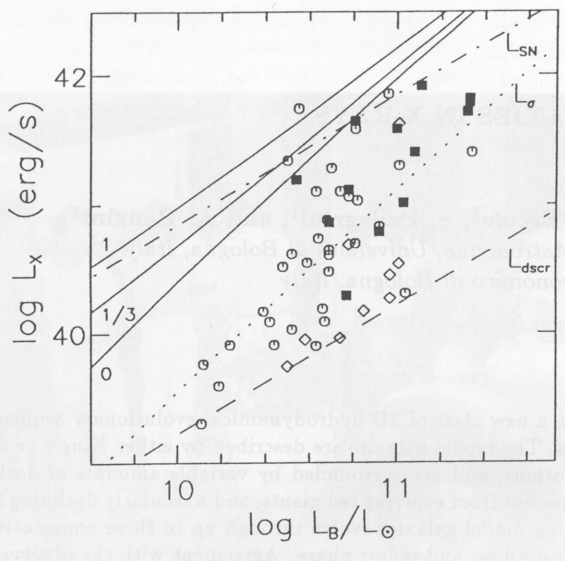

Figure 1. The L_X vs. L_B plot using CFT data. Filled squares and open diamonds refer to galaxies with boxy and disky isophotal shapes, respectively. Open circles refer to galaxies for which this morphological detail is unknown. The dot-dashed line shows L_{SN} at the standard rate ($\vartheta_{SN} = 1$). L_σ is shown by the dotted line, while L_{dscr} represents the expected contribution from discrete stellar X-ray sources (dashed line). Finally the solid lines represent the expected L_X of steady state cooling flow models, for various assumed SN I rates, each labelled by the factor ϑ_{SN}.

The resulting steady state cooling flow models are however far from giving a satisfactory account for the X-ray properties of elliptical galaxies, as the bulk of them are much fainter than the models would predict (see figure 1).

Evolutionary, hydrodynamical calculations which include the time dependence of the source terms have been first constructed by Loewenstein and Mathews (1987b, hereafter LM). LM assumed a nearly constant type I supernova rate, and the mass of the dark matter halo to exceed by a factor of 9 that of visible (stellar) matter; their models develop an inflow from the very beginning, but their ultimate fate is to revert the inflow into an outflow (which would later develop into a supersonic wind), as the stellar mass loss rate secularly declines while the supernova heating remains nearly the same. Apparently, these models are less affected by the X-ray overluminosity syndrome affecting steady-state cooling flow solutions, but this comes from a reduction of both the type I supernova rate and the stellar mass-loss rate by a factor ~ 4 over standard values.

Besides the puzzling large dispersion of L_X for given L_B, other major embarrassments affect inflow models. First, over a Hubble time an amount of material comparable to the mass of stars in the galactic core flows into the centers of these galaxies, while the corresponding distortions of the central optical surface brightness and velocity dispersion are not observed. Second, inflow models exhibit very high central X-ray surface brightness, with the X-ray profile being much more centrally concentrated than the optical profile, in contrast with the rather similar surface brightness distributions exhibited by the three well resolved galaxies (Trinchieri, Fabbiano, and Canizares, 1986; Sarazin and White, 1988).

However, by allowing the SN I rate to decline sufficiently fast with time, massive early inflows can be replaced by winds and outflows, thus preventing the accumulation of large amounts of unseen mass at the center, producing smoother X-ray surface brightness distributions, and allowing large variations in X-ray luminosity at each optical luminosity (Renzini, 1989; D'Ercole et al., 1989, hereafter Paper I; Ciotti et al., 1991, hereafter Paper II). Under this very simple assumption model elliptical galaxies can experience up to three subsequent evolutionary phases, in which an initial supersonic wind is followed by a subsonic outflow until a central cooling catastrophe leads eventually to the onset of an inflow. The duration of the transient outflow phase turns out to be extremely sensitive to virtually every model structural parameter, thus offering a natural explanation for the large scatter in X-ray luminosities.

2 Model galaxies and source terms

Like in previous evolutionary- or stationary-flow studies we assume the distribution of stellar and dark matter to be time-independent, therefore neglecting the effects of stellar mass loss and gas flows on the shape and depth of the gravitational potential well. Similarly neglected are any interactions with surrounding galaxies which might affect the distribution of matter. Star formation is supposed to have occurred all in a single burst at $t = 0$, and then the *passive* evolution of the stellar population is followed. We then consider two distinct classes of models, one in which the distribution of the bright matter density is represented by a King model (King, 1972), and another in which it is represented by the $r^{\frac{1}{4}}$ law (de Vaucouleurs, 1948).

For a first group of models that we call *King Galaxies* (KGs) we assume the stellar distribution to be described by the same density profile used by LM: ρ_{*o} is the central stellar density, r_{c*} the core radius, and the distribution is truncated at the tidal radius $r_t = \delta r_{c*}$; then ρ_{*o}, r_{c*} and the central stellar velocity dispersion σ_* are related by the virial condition $\rho_{*o} r_{c*}^2 = 9\sigma_*^2/4\pi G$. For a second family of models, that we call *de Vaucouleurs' Galaxies* (dVGs), we use the spatial density distribution given in Mellier and Mathez (1987), truncated at $r_t = \delta r_e$, r_e being the effective radius. As for KG models, also for dVG models we use the virial theorem to connect the total stellar mass to the central velocity dispersion.

The density distribution of the dark matter halo is assumed to follow a quasi-isothermal law: as in LM, ρ_{ho} is the central dark matter density, r_{ch} is the core radius and the tidal radius r_t is assumed to be the same as for the stellar distribution. The ratio of the total stellar mass and the total dark matter mass is given by $R = M_h/M_*$, $\gamma = \rho_{ho}/\rho_{*o}$ for the KGs and $\beta = r_{ch}/r_e$ for the dVGs.

In order to both reduce the number of model parameters, and explore the fraction of the parameter space actually occupied by real galaxies, we have constrained our models to lie on the Fundamental Plane defined by:

$$L_B = 3.6 \times 10^3 r_e \sigma_*^{1.3}/h \quad (L_\odot), \tag{1}$$

where L_B is the total blue luminosity in solar units, r_e is in pc, σ_* in km s^{-1} and $h = H_o/100$ (Djorgovski and de Carvalho, 1989). For all the KG models we have assumed $r_e = 12r_{c*}$. In conclusion, we identify each KG model by the set of independent parameters $(L_B, \sigma_*, \delta, R, \gamma)$ and each dVG model by $(L_B, \sigma_*, \delta, R, \beta,)$. Note that for KG models $\beta = r_{ch}/r_{c*}$ is uniquely related to R, γ, and δ.

The only secularly evolving ingredients are in our models the source terms: stellar mass loss and supernova heating. Stellar mass loss provides the raw material for our galactic flows, and we study the behavior of these flows under the influence of a time-varying SN heating. For quick calculation, the mass return to the ISM in a single-age stellar population is given by:

$$\dot{M}_*(t) \simeq -1.5 \times 10^{-11} L_B t_{15}^{-1.3} \qquad (M_\odot \mathrm{yr}^{-1}), \tag{2}$$

where t_{15} is the age in unit of 15 Gyr. This expression is valid in the age range from ~ 0.5 to over 15 Gyr (see Paper II).

It is well known that only type I supernovae (actually type Ia) have so far been observed in elliptical and S0 galaxies. A secularly declining SN I rate follows quite plausibly from current views about SN I progenitors (see Paper II for an extensive discussion) and we correspondingly assume:

$$R_{SN}(t) = 2.2 \times 10^{-13} \vartheta_{SN} L_B t_{15}^{-s} \qquad (\mathrm{yr}^{-1}) \tag{3}$$

where ϑ_{SN} is a parameter, such that for $\vartheta_{SN} = 1$ and $t_{15} = 1$ the standard SN I rate in ellipticals is recovered, i.e 0.22 SNU (1 SNU = 1 SN per century per $10^{10} L_\odot$; Tammann, 1982). Moreover we assume s values such that R_{SN} decreases slightly faster than $\alpha_* = \dot{M}_*/M_*$. In practice, this implies $s \gtrsim 1.3$ when the stellar IMF follows the Salpeter distribution. We further assume that each SN injects a total kinetic energy $E_k = 10^{51}$ erg into the ISM of galaxies, and that this energy is completely turned into heat, an excellent approximation for the hot diluted gas we are dealing with (Mathews, 1989). Therefore, the global SN heating (hereafter SN luminosity) is given by:

$$L_{SN}(t) = E_k R_{SN}(t) \simeq 3.24 \times 10^{43} R_{SN}(t) = 7.1 \times 10^{30} \vartheta_{SN} L_B t_{15}^{-s} \qquad (\mathrm{erg\,s}^{-1}). \tag{4}$$

Heat to the ISM is also provided by collisions between stellar winds and/or between winds and the ambient gas, that thermalize relative to the galaxy the kinetic energy carried by stellar mass loss. This process provides heat at a global power:

$$L_\sigma = \frac{3}{2}\alpha(t) \int_0^{r_t} 4\pi r^2 \rho_*(r) \sigma_*^2(r) dr, \tag{5}$$

where $\sigma_*(r)$ is the local, one-dimensional stellar velocity dispersion, $\alpha(t) = \alpha_*(t) + \alpha_{SN}(t)$, and $\alpha_{SN}(t) = 1.4 R_{SN}(t)/M_*$, having assumed that each SN I ejects $1.4 M_\odot$ of material.

We further define L_{grav}^- as the power required to steadily extract from the galaxy the gas shed by stars, and L_{grav}^+ as the power generated by the steady inflow of this gas through the galactic potential well, down to the center of the galaxy. Thus we have:

$$L_{grav}^- = -\alpha(t) \int_0^{r_t} 4\pi r^2 \rho_*(r) \phi(r) dr \tag{6}$$

and $L^+_{\rm grav} = -L^-_{\rm grav} - \dot{M}_*\phi(0)$. In a realistic situation stationary conditions are only seldom verified, or even approached. Nevertheless, these quantities can be very useful to predict several global features of the flows and their evolution (see also CFT; Renzini, 1989). The integrals appearing in these definitions can be expressed as a product of two terms: a dimensional factor, and a dimensionless function of R, β, and δ:

$$L^{\pm}_{\rm grav} = \dot{M}_*(t)\sigma_*^2 F^{\pm}(R,\beta,\delta). \tag{7}$$

In equation (7) the dimensionless *form factors* $F^{\pm}$ are different functions of (R,β,δ) respectively for the KG models (with $\beta = r_{\rm ch}/r_{\rm c*}$ and $\delta = r_t/r_{\rm c*}$), and for the dVG models (with $\beta = r_{\rm ch}/r_{\rm e}$ and $\delta = r_t/r_{\rm e}$). Note that, as expected given our assumptions, the time dependence of $L^{\pm}_{\rm grav}$ is totally controlled by $\alpha(t)$, while the other terms on the r.h.s. of equation (7) describe the properties of the potential well.

We also introduce the function $\chi(t)$, as the ratio of the power required to steadily extract the gas from the galaxy, to the power actually made available by kinetic and supernova heating; so for both KG and dVG models we have:

$$\chi(t) = \frac{L^-_{\rm grav}(t)}{L_\sigma(t) + L_{\rm SN}(t)} \simeq \frac{t_{15}^{s-1.3}}{\vartheta_{\rm SN}} \times \left(\frac{\sigma_*}{300}\right)^2 \times \tilde{F}^-(R,\beta,\delta), \tag{8}$$

where we have neglected $\alpha_{\rm SN}$ in front of α_*, and L_σ in front of $L_{\rm SN}$, and $\tilde{F}^-$ differs from F^- only by a numerical factor.

When the gas lost by stars is allowed to flow freely down to the center of the galaxy (such as in cooling flow models) the global rate at which energy has to be radiated away is given by:

$$L_{\rm inflow} = L_\sigma + L^+_{\rm grav} + L_{\rm SN}, \tag{9}$$

and an X-ray luminosity $L_{\rm X} \simeq L_{\rm inflow} + L_{\rm dscr}$ is expected (see CFT). In figure 1 $L_{\rm inflow}$ is displayed for three values of $\vartheta_{\rm SN}$. To connect σ_* to $L_{\rm B}$ we have used the Faber-Jackson relation. One can clearly appreciate that complete inflow models are far too bright in X-rays than indicated by the observations, a well known embarrassment for cooling flow models. Figure 1 shows that even with no supernovae at all ($\vartheta_{\rm SN} = 0$) $L_{\rm inflow}$ is still too large, basically because $L^+_{\rm grav}$ is too large: if all the gas falls in then too much gravitational energy is liberated, and galaxies become too bright in X-rays.

In the case of outflowing galaxies the global energy balance will indeed imply

$$L_{\rm X} \simeq L_{\sigma*} + L_{\rm SN} - L^-_{\rm grav} + L_{\rm dscr} - L_{\rm out}, \tag{10}$$

where $L_{\rm out}$ is the enthalpy flow at the edge of the galaxy, and where now the gravitational well acts as a sink of energy, contrary to the inflow case described by equation (9). A much wider variety of situations can therefore be expected in the case of outflowing galaxies, and even more if partial winds are allowed (Loewenstein and Mathews, 1987a; Renzini, 1989).

When evaluated at the present epoch, equation (8) provides useful indications about the present character of the flow for every set of model parameters. We note that for $\vartheta_{\rm SN} = 1$ and low values of R one has $\chi \ll 1$ for every reasonable combination of the parameters, i.e. with the standard SN rate and without dark matter all galaxies would sustain a supersonic wind and the classical Mathews and Baker (1971) result is recovered. We also note that for low values of σ_* the present χ is less than unity with the standard SN rate, i.e. there is ample energy input to sustain a supersonic wind in these fainter galaxies, even with e.g. 10 times more dark than visible matter, and low X-ray luminosities are predicted. On the contrary, at the opposite extreme ($\sigma_* \gtrsim 300\,\mathrm{km\,s^{-1}}$), i.e. for optically bright galaxies, one has $\chi \gtrsim 1$ even for modest amounts of dark matter, SN heating may be insufficient to prevent inflows, and large X-ray luminosities are then expected. 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 parameters is therefore anticipated.

3 The evolutionary sequences

To describe the evolution of the hot gas in the model elliptical galaxies we solve the time-dependent, Eulerian equations of gasdynamics with galactic source terms (see Paper II). We assume the model galaxies to be initially devoid of gas.

So many parameters are required to fully determine a model galaxy that testing the influence of each possible combination of them would have been a rather cumbersome matter. We therefore focused on few such combinations, trying to get some general insight from their effects on our models. Our hydrodynamical models reproduce the pattern in figure 1 provided that the parameter combinations imply present χ values about unity for medium-luminosity galaxies ($L_{\mathrm{B}} \simeq 5 \times 10^{10} L_{\odot}$); we further restrict to only one value of the other supernova parameter s, adopting $s = 1.5$ for all our simulations (see Paper II). Indeed, for χ values much different from unity most galaxies would now be in either a wind or an inflow phase, and so they would be either too faint or too bright X-ray emitters. This requirement restricts the possible combinations of ϑ_{SN} and R: so, for example for $\vartheta_{\mathrm{SN}} = 1$, a dark to visible mass ratio R$\approx$ 10 is required, a value which drops to ≈ 3.3 if one assumes $\vartheta_{\mathrm{SN}} = 0.5$. These figures are somewhat sensitive also to the relative distributions of the dark and visible mass, i.e. to the parameter β.

The X-ray evolution of all the $L_{\mathrm{B}} = 5 \times 10^{10} L_{\odot}$ KG models is shown in figure 2. Models differing only for their central velocity dispersion show that the larger σ_*, the sooner the model galaxies experience their cooling catastrophe and the associated X-ray brightening. So, while at $t = 15$ Gyr some models have already experienced their transition to the inflow phase, others are still in their outflow or wind phase. For this particular set of parameters we therefore expect a very high sensitivity of L_{X} to variations of σ_* in the range $\sim 240 - 265$ km s^{-1}, with L_{X} increasing from $\sim 10^{38}$ to over 10^{41} erg s^{-1}. We emphasize that this extreme sensitivity of L_{X} on σ_* is the key characteristic of our model galaxies, and can therefore account for the very steep correlation of L_{X} with L_{B}, see figure 1. As already mentioned, the larger σ_* the deeper the potential well (i.e. the larger the binding energy per unit mass), the harder for the gas to leave the galaxy, and the sooner in the evolution the transition to the X-ray bright evolutionary phases. In turn, the Faber-Jackson relation ensures that – on average – the brighter the optical luminosity of the galaxy, the larger σ_*, and therefore the larger also the X-ray luminosity. Note, however, that models in the critical range of σ_*'s will also be very sensitive to changes in every other parameter; see Paper II for a thorough discussion of the action of each parameter. There is a close similarity to the case of early galactic wind models for the chemical evolution of elliptical galaxies (e.g. Larson, 1974; Arimoto and Yoshii, 1987), according to which in the more massive (and now brighter) galaxies the deeper potential well ensures star formation and metal enrichment to proceed further before being discontinued by the development of a wind, thus establishing the observed metallicity-luminosity correlation.

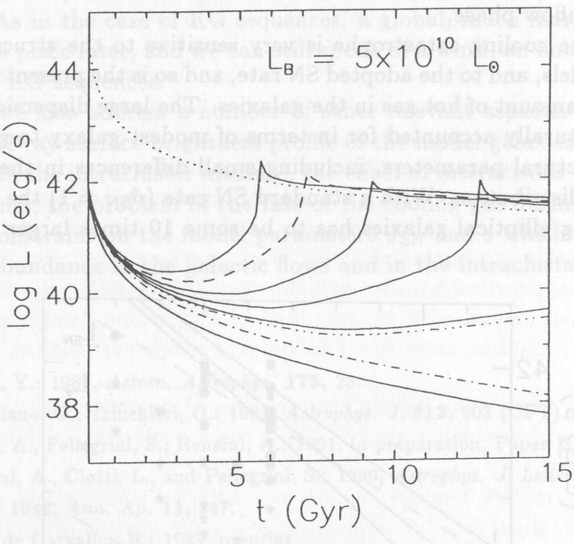

Figure 2. The X-ray evolution of various models with $L_B = 5 \times 10^{10} L_\odot$. Solid lines represent sequences which differ only for their value of the central velocity dispersion, from 220 to 280 km s^{-1}: the larger σ_*, the earlier the transition to the inflow phase marked by the sharp peak of L_X. Models with lower X-ray luminosity are at present still in their wind or outflow phase at present.

In essence, we propose that *both the $L_X - L_B$ correlation, and the metallicity-luminosity correlation, are two manifestations of the same underlying cause, i.e. of the fact that optically brighter galaxies are also gravitationally more tightly bound, as dictated by the Faber-Jackson relation.* The presence of metallicity gradients in ellipticals add further support to this scenario (see Franx and Illingworth, 1990).

In figure 3, just analogous to figure 1, we plot the X-ray luminosity at $t = 15$ Gyr for all the models constructed for this display, and characterized by $0.8 \leq \chi \leq 1.4$ and various optical luminosities. A comparison between these two figures makes clear the degree of success of the present class of evolutionary sequences in accounting for the observed X-ray luminosities of elliptical galaxies. Such a comparison indicates a remarkable prevalence of outflows, with the X-ray faint galaxies (those with $L_X \simeq L_{dscr}$ in figure 1) being still in their wind phase, and perhaps only a handful among the brightest galaxies having already experienced the transition to the inflow phase. We conclude that this class of models is able to successfully reproduce the richness of X-ray properties exhibited by real galaxies, just where cooling flow models had failed.

4 Conclusions

The main results of our study can be summarized as follows.

• The gas flows in model galaxies experience up to three consecutive evolutionary phases: the wind, outflow, and inflow phases. The first phase is characterized by supersonic winds, which tend to decelerate until a subsonic outflow is established. This outflow phase can be maintained for many Gyr until a central cooling catastrophe triggers the transition to the inflow phase.

• The epoch of the cooling catastrophe is very sensitive to the structural parameters describing the models, and to the adopted SN rate, and so is the present X-ray luminosity which reflects the amount of hot gas in the galaxies. The large dispersion in L_X at given values of L_B is naturally accounted for in terms of modest galaxy-to-galaxy differences in any of the structural parameters, including small differences in the amount of dark matter and in its distribution. With a standard SN rate ($\vartheta_{SN} = 1$) the mass of the dark matter surrounding elliptical galaxies has to be some 10 times larger than that of the visible matter.

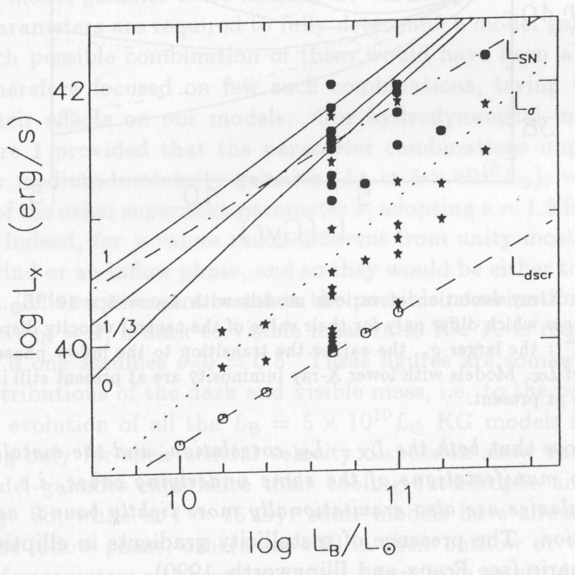

Figure 3. The L_X vs. L_B plot for our whole set of model galaxies at t=15 Gyr, in the same format as figure 1. L_X includes the expected contribution from discrete sources (L_{dscr}). Filled circles represent model galaxies which are in their inflow phase, stars and open circles represent galaxies respectively in their outflow and wind phase.

• The correlation of X-ray and optical luminosities, and the $L_X - \sigma_*$ correlation are seen as an ongoing manifestation of the fact that brighter galaxies are characterized by a larger binding energy per unit mass, i.e. as an implication of the Faber-Jackson $L_B - \sigma_*$ relation, not unlike the L_B-metallicity correlation which is established at the formation epoch of elliptical galaxies. In this scenario, type II SNe are responsible for the early establishment of galactic winds, and type I SNe for their maintainance long after any star formation has ceased, with most galaxies supporting outflows up to the present epoch and beyond.

- The main difference between the behavior of the flows in KGs and dVGs is the presence of a small *mini-inflow* only ~ 300 pc in size, near the center of the dVG models. This is due to the very centrally peaked concentration of matter near the center, which favors an early, localized cooling catastrophe. Therefore, for most of the time dVG models present small mini-inflows coupled to outer winds or outflows, much similar to those typical of KG sequences. As in the case of KG sequences, a global, much more extended cooling catastrophe takes place later, and we can still speak of a wind, an outflow, and an inflow phase just as for KG sequences.

In Paper II we also address a number of other relevant aspects. These include the evolution of the X-ray surface brightness profile of the model galaxies, the interaction of galactic flows with the intracluster medium, the effect of interactions with other galaxies and merging events, the problem of the fate of the cooling gas during the inflow phase, and finally the constraint on the model parameters ϑ_{SN} and s which in principle can be set by the iron abundance in the galactic flows and in the intracluster medium.

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Discussion

R. Bender - It is interesting that very luminous S0 objects, like Sombrero, have comparably low X-ray luminosity when compared to E's of the same luminosity. The same is true for disky ellipticals which have lower X-ray luminosity than boxy ellipticals in the range where the luminosity function of these two types overlap. So, there may be a dependence of X-ray luminosity on other parameters like M_*/L_B (see Bender et al., 1990) or shape. All these further parameters are difficult to test from observations, but may possibly be tested with your models or modifications of them.

A. Renzini - Indeed. In figure 1 boxy and disky galaxies are represented with different symbols, and there is some indication in the sense that you mention, although the statistics is certainly poor. Supposing that the X-ray–boxyness correlation exists, we have envisaged two possible, albeit still speculative explanations. One possibility is that merging events (supposed to cause the boxy isophotal distortion) could trigger an earlier transition to the inflow phase, with the associated X-ray brightening. The other possibility, is that the early-type galaxies which are in part rotationally supported (i.e. the diskies) may be characterized by a lower binding energy per unit luminosity (actually a lower L^-_{grav}/L_B ratio) compared to boxies. If so, their χ would be systematically smaller, and therefore they would be more likely to support winds rather than inflows.

P. Pişmiş - Have any of the galaxy you considered active nuclei, at least in a mild manner in the form of jets, lobes etc.? If yes is there a correlation between activity and their X-ray behavior?

A. Renzini - Our models neglect any nuclear activity which could contribute to the heating of the ISM. However, our models show a great variety of inflow rates, from no inflow at all during wind/outflow phases, to quite small rates in the case of nuclear mini-inflows, to quite large rates during the global inflow phase. This may help explaining the great variety of nuclear activity behaviors exhibited by ellipticals and bulges. Observationally, the optical, X-ray, and radio luminosity all correlate to each other to some degree.

M. Franx - How well is the contribution from discrete sources known? It appears that the analysis is quite dependent on this.

A. Renzini - The discrete source contribution adopted in figure 1 is just the lower envelope of the data points. This is somewhat fainter than the contribution adopted by CFT. None of our conclusion is particularly dependent on this assumption.

M. Franx - Are the points near the line of the discrete source contribution upper limits?

A. Renzini - Yes, some of them are upper limits. This further indicates that in these galaxies the contribution from a hot ISM is very small, much smaller than predicted by inflow models.

J. Melnick - The catastrophic cooling phase should be associated with optical emission. Therefore, if as you propose, the most X-ray luminous galaxies are in the inflow phase one would expect a substantial fraction of them to harbor active nuclei, or have optical filaments in the central regions. Is that the case?

A. Renzini - Yes, to some extent. As I mentioned a moment ago an X-ray–optical–radio correlation appears to exist. Our models are not designed to follow the fate of the cooling material, in particular whether it is used to form stars or jupiters, or it is accreted by a central black hole. However, we argue that, if there is a time in the evolution of these galaxies when an intense burst of star formation may take place in the nucleus, quite naturally this is the moment of the central cooling catastrophe, when up to $\sim 10^9 M_\odot$ of material rapidly cool off. We speculate that this may coincide with a major optical display, quite in the mood of the AGN model that you and Terlevich have proposed.

J. Melnick - The X-ray surface brightness distribution of ellipticals follows quite closely that of the optical light. Can you reproduce this feature in your models?

A. Renzini - Yes, for the three galaxies for which there exist sufficient *Einstein* data. As shown in the figure below, the X-ray surface brightness distribution is subject to major changes in the course of the evolution, through the three stages. In particular, during the outflow phase it follows quite closely the optical distribution (represented by the solid line), while during the inflow phase it is much more centrally peaked, as well known also for the case of cooling flow models. We conclude that the three galaxies are most likely still in their outflow phase.

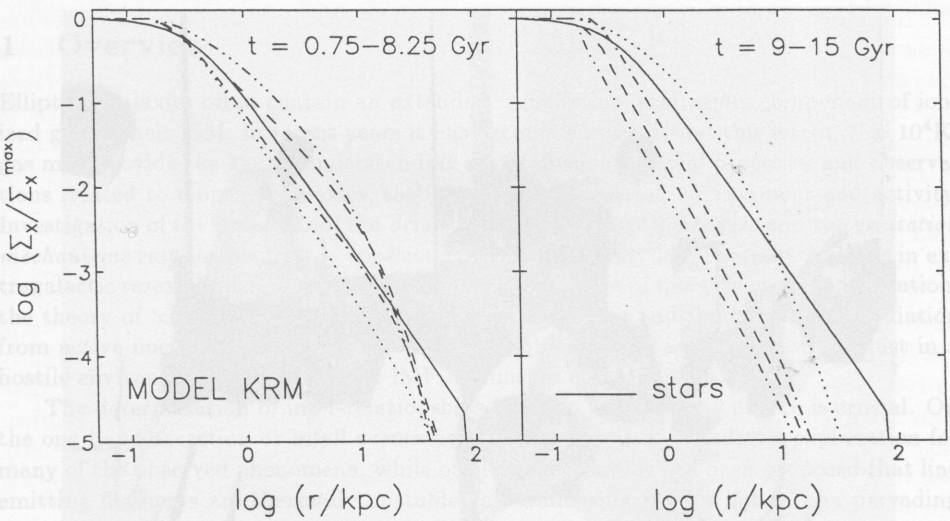

Figure 4. The evolution of the X-rays surface brightness profile for a selection of representative times during the various evolutionary phases of the "KRM" model defined by $(L_B, \sigma_*, \delta, R, \gamma, \vartheta_{SN}, s)$=($5 \times 10^{10}$ ergs^{-1}, 270 km s^{-1}, 180, 9, 0.0125, 2/3, 1.5). In the left panel models in the wind phase (dotted line) and outflow phase (other lines) are displayed. In the right panel a model towards of the outflow phase is shown (dotted line) together with a few models in their inflow phase (other lines). The optical surface brightness profile is also shown for reference (solid line).

I. King - I would like to clarify your distinction between King models and de Vaucouleurs models. At a central concentration of 2.2-2.3 they are nearly identical. Thus your distinction should really be central concentration.

A. Renzini - Indeed, the difference is in the center only. Basically, our $r^{\frac{1}{4}}$-law models have much higher central stellar densities compared to *King* models.

I. King - Ah, I see. You have fitted each kind of model to the same density curve. In that case it is just the difference in central cusp that matters.

A. Renzini - Yes, for your second comment. But we have used two different density curves for the two kinds of models (i.e. we have not approximated a *de Vaucouleurs'* density law by adjusting the parameters of a *King's* density law).

Alvio Renzini answering Bender's question.

PROCEEDINGS

Morphological and Physical Classification of Galaxies

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