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EVOLVING GAS FLOWS IN ELLIPTICAL GALAXIES

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In this paper we briefly report the main results of a new series of hydrodynamical calculations of evolving gas flows in elliptical galaxies (D'Ercole *et al.* 1989). We have started this project having in mind the following main motivations:

- To account for the X-ray properties of nearby ellipticals, with particular reference to the large dispersion in the X-ray luminosity which is observed at given optical luminosity (see e.g. the review by Fabbiano 1989, and this volume).
- To predict their X-ray evolution over cosmological times, and compare with the available data on the soft X-ray background.
- To get information about the dark matter content of these galaxies.
- To provide physically consistent gas density and temperature profiles, which may be useful in the context of AGN models, nuclear jets and X-ray gas interactions, extranuclear activity, and the like.

Our assumptions can be grouped in two cathegories:

A) The Model Galaxies. We assume the galactic distribution of bright and dark matter to be independent of time (i.e. unevolving potential wells). The bright (stellar) matter distribution is represented by either King density models following a Faber-Jackson $L_{\rm B}(\sigma)$ relation (King models, KM), or by a de Vaucouleurs $r^{1/4}$-law models constrained to lie on the $L_{\rm B} - <\mu> - \sigma$ *Fundamental Plane* of Djorgovski & Davis (1987) (de Vaucouleurs models, dVM). Common to both model families is the assumed quasi-isothermal distribution of the dark matter halo. Several parameters are obviously required to identify one model galaxy, the most important being the total luminosity $L_{\rm B}$ and the dark matter to stellar matter ratio $R = M_{\rm halo}/M_*$.

B) The Source Terms. These indeed represent the evolving ingredients in our model galaxies. There is a mass source given by the mass return from evolving stars ($\dot{M}_*$, which is treated according to standard stellar evolution theory (Renzini and Buzzoni, 1986). For $t = 1 - 20$ Gyr, a fair approximation to the rate of mass return is given by:

$$\dot{M}_* \simeq 5.9 \times 10^{-10} L_{\rm B} t^{-1.364} \qquad M_\odot {\rm yr}^{-1},$$

where t is the age of the galaxy in Gyr. Of course, in practice we adopt a single burst stellar population. There is also a heat source from supernovae of type I (the only supernovae so far observed in elliptical galaxies, cf. Tammann 1982). The rate of heat input, that we call the SN luminosity, is given by $L_{\rm SN} = 10^{51}\,({\rm erg})\,R_{\rm SN}(t)$, and we assume the SN rate $R_{\rm SN}$ to be given by:

$$R_{\rm SN}(t) = 2.2 \times 10^{-13} \mathcal{T} L_{\rm B} \left(\frac{t}{15}\right)^{-s} \qquad ({\rm yr}^{-1}).$$

For $t = 15$ Gyr and setting the adjustable parameter $\mathcal{T} = 1$ one recovers the standard SNI rate in ellipticals (Tammann 1982). The adopted time evolution of the type I SN rate is the distinctive characteristic of our models. In other hydrodynamical evolutionary models such as those of Loewenstein & Mathews (1987, hereafter LM) a virtually time-independent SNI rate was adopted. However, arguments exist supporting the notion of a secularly decreasing SNI rate in ellipticals (Renzini 1989a, b; Ciotti *et al.* 1989), and on their basis we have explored s values in excess of ~ 1.4, in such a way to ensure a secularly *decreasing* specific heating $L_{\rm SN}/\dot{M}_*$. On the contrary, in LM models the specific heating was secularly increasing. In summary, the source terms are described by three main parameters: $L_{\rm B}, \mathcal{T}$, and s. Clearly $L_{\rm B}$ gives just the *size* of the stellar population of a model galaxy, while the two latter quantities offer nothing more than a convenient parameterization of the current uncertainties in the present and past SN rate in ellipticals.

Having set all the parameters we then proceed by integrating the one-dimensional hydrodynamical equations of mass, momentum, and energy conservation, using an Eulerian, fully vectorized algorithm (Bedogni and D'Ercole 1986) which in about 100,000 time steps covers the evolution of the flow from $t = 0$ to the present, at $t = 15$ Gyr. It is worth emphasizing that, unlike steady cooling flow models (e.g. Nulsen, Stewart, and Fabian 1984; Sarazin and White 1987, 1988; Vedder, Trester, and Canizares 1988), our evolutionary sequences do not *a priori* impose the nature of the flow, but the system is let free to find its own (time-dependent) configuration, which is the one appropriate to the selected set of parameters. We can actually anticipate that other kinds of flows, such as subsonic outflows, give a better account of the observed X-ray properties of ellipticals.

For a clearer understanding of the basic physics of the flows we introduce the quantities $L^-_{\rm grav}$ and $L^+_{\rm grav}$, as well as the ratio $\chi(t) = L^-_{\rm grav}(t)/L_{\rm SN}(t)$. $L^-_{\rm grav}$ is the power required to steadily extract the gas from the galaxy, at the same rate it is released by evolving stars, while $L^+_{\rm grav}$ is the power made available when the same gas inflows through the gravitational potential well, down to the center of the galaxy. For an isolated galaxy, the quantity χ is therefore the ratio between the power required to remove the gas, to the power actually made available by SNI's. If there are no other energy sources, then $\chi >\sim 1$ is a sufficient condition for the galaxy to host an inflow, while $\chi < 1$ is a necessary condition for the galaxy to sustain a wind. We argue that the time evolution of χ plays the key rôle in determining the time evolution of the flows. At this point we can distinguish four possible evolutionary behaviors. To Case 1 belong model galaxies in which at any time $\chi(t) < 1$. The opposite situation we call Case 2, with $\chi(t) > 1$ at any time. Case 3 galaxies are defined as those in which initially $\chi(t) > 1$, but χ *decreases* until at some time $\chi(t) < 1$. Finally, Case 4 is the opposite of Case 3, with χ now *increasing* with time, from initial values below unity, to final values above unity. Clearly, Case 1 galaxies can be able to sustain a supersonic wind from the beginning all the way to the present, i.e. they are always *open*. On the contrary, in Case 2 galaxies a wind is energetically impossible, and most often these *closed* galaxies will host an inflow over the whole time interval. Case 3 galaxies will initially host an inflow, but as χ decreases below unity the tendency will be to turn the inflow into an outlow, and eventually into a supersonic wind. Finally, the opposite tendency will be exhibited by Case 4 galaxies, with initial winds

Fig. 1. The time evolution of the X-ray luminosity $-L_X-$ *(solid line) of a model galaxy with* $L_B = 10^{11} L_\odot$, $M_*/L_B = 17$, $R = 9$, $T = 1$ *(i.e. just Tammann's canonical rate), and* $s = 1.4$. *Other structural parameters include* γ, *the central ratio of dark matter to star density, and* δ, *the ratio of tidal to core radius. For this reference model we have adopted* $(\gamma, \delta) = (0.03, 140)$. *The dotted line gives* L_{SN}, *while the three dot-dashed lines give* L^-_{grav}, L^+_{grav}, *and* L_σ *in order of decreasing luminosity.* L_σ *(not defined in the text) is the thermal power generated by the thermalization of stellar winds to the stellar velocity dispersion. Finally, the dashed line gives the enthalpy flows at the inner grid boundary.*

turning later into inflows, after χ has increased above unity.

Case 1 galaxies contain little gas at any time, and it is well know that their X-ray luminosities fall short of that of many present day ellipticals. Case 2 galaxies correspond to inflow models, and it is also well known that such models tend to predict too large X-ray luminosities. Case 3 galaxies have been investigated by Loewenstein and Mathews, but for the explored set of parameters they do not differ much from Case 2 galaxies. We have therefore concentrated on Case 4 model galaxies, basically the only kind so far left unexplored. We expect these galaxies to begin supporting a strong supersonic wind, but as $\chi(t)$ decreases below unity an inflow will soon or later be established. Indeed, our hydrodymamical models provide a detailed description of how the flows manage to evolve from a supersonic wind to a subsonic inflow. Before passing to the description of the numerical results we remind that χ is basically a function of L_B, M_*, R, T and s, while also the detailed mass distribution in the galaxy (i.e. its *form factor*) can play a rôle.

We first describe one particular evolutionary sequence, and we chose the case of a KM galaxy belonging to Case 4 behavior, as described above. Fig. 1 shows the time evolution of several luminosities, as detailed in the caption. We distinguish three major, consecutive evolutionary phases: respectively the wind, outflow, and inflow phase. 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 $\dot{M}_*$, and so does the X-ray luminosity. However, L_{SN} decreases faster than L^-_{grav}, and at $t \simeq 1$ Gyr χ increases above 1, supernovae cease to provide enough energy to sustain a wind, and the wind turns into a 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. Radiative losses then increase, and eventually a global thermal instability cannot be avoided. This actually

triggers a central cooling catastrophe, which temporally coincides with the sharp maximum of L_X seen in Fig. 1. 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 L^+_{grav} and L_{SN}, actually asymptotically approaching the sum of the two. Note that both the wind and the inflow regimes can be quasi-stationary, while the outflow regime is inherently non-stationary. Still, the outflow phase can last for times comparable to the Hubble time, and its duration is extremely sensitive to the galactic model. While the wind and the inflow phases can reasonably be modelled in the stationary approximation, this is not possible for the outflow phase.

Moving from our reference model, we have started the exploration of the multidimensional parameter space, and up to now some 50 sequences have been computed. Each takes some 3 minutes on the Cray. The main results for the KM galaxies can be summarized as follows:

- The age at which the galaxies experience their outflow-inflow transition is extremely sensitive to virtually every model parameter, including the form factor. This is a quite attractive property of our sequences, which then easily reproduce the observed dispersion of L_X at given L_B, while at the same time also implying a poor correlation of L_X with other galaxy parameters.
- The bulk of X-ray galaxies are well reproduced only by models still in their outflow phase.
- The faintest X-ray galaxies are well accounted by models still in their supersonic wind phase.
- A few among the brightest galaxies may have already experienced the transition to the inflow regime. Only a minority of galaxies exhibit the X-ray luminosities predicted by cooling-flow models.
- Large galaxy to galaxy differences in gas density are then to be expected. This may be relevant in the context of *Extranuclear Activity*.
- A fairly large evolution of gas density and M_{gas} is predicted, althought not as large as it would be in pure inflow models. In such models very large amounts of gas would be present at early epochs, therefore producing very large X-ray luminosities. These can be estimated from $L_X \simeq L^+_{grav} + L_{SN}$, and Fig. 1 shows how dramatic is at early epochs the difference between the actual L_X of our models and that of cooling flow models. For example, during the early outflow phase the actual L_X is $\sim 1\%$ of the luminosity of the corresponding cooling flow solution. This stryking difference suggests that the soft X-ray background might be used to further constrain the parameter space.

Exploratory sequences have also been constructed for dVM galaxies, characterized by the $r^{1/4}$-law for the surface brightness profile. The typical central density singularity is removed by truncation at either 100 or 200 pc from the galaxy center (consistent with the observed core radii of some ellipticals, cf. Kormendy 1987). There is an important qualitative difference between KM and dVM sequences. In KMs the velocity is positive everywhere during the wind and the outflow phase. On the contrary, in dVMs there is a sort of dynamical decoupling between the core and the outer region of the galaxy; a *mini-inflow* can be present in the center since the beginning, even when the rest of the galaxy is supporting a supersonic wind.

This is obviously due to the very high central star density typical of these models: the central *gas* density is in fact high enough for the whole local SN heating to be efficiently radiated away, a consequence of the radiative losses scaling with the square of the gas density. This kind of gasdynamical core-envelope decoupling tends to persist even for the models which eventually develop a substantial inflow in the core: they may still present an outer wind originating from a fair fraction of the whole galaxy. We conclude that in dVMs the phase characterization which works so well for KM sequences is less applicable, and a *partial wind* appears to be the most frequent pattern exhibited by these evolving gas flows.

Finally, we have started exploring also the effect of an ambient pressure, such as that real galaxies experience in a cluster. With $P_{\rm ext} = 2 \times 10^{-3}$ cm^{-3} K the effect is already rather dramatic. For example, a model still in the wind phase at $t = 15$ Gyr shifts to inflow at $t = 6$ Gyr when this external pressure is applied (from the beginning, of course). Yet, an outflow phase at $t = 15$ is recovered if the amount of dark matter is reduced, from $R = 9$ to $R = 4.5$. Note, however, that the effect of the environment can hardly be reduced to that of a spherically symmetric pressure applied at the outer boundary. On the other hand, when the effect of such a pressure is important we can safely anticipate strong ram pressure effects in a more realistic situation.

In conclusion, our numerical experiments single out three main model ingredients controlling the nature of the flows: 1) The SN rate and its cosmological evolution, 2) The amount of dark matter and its distribution about individual galaxies, and 3) The environment and notably the ram pressure. This is hardly a new conclusion (see for example LM), but this new series of evolutionary sequences emphasizes the necessity of exploring a wider range of possibilities, compared to the restricted domain of mere cooling flow models.

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