THE ASTROPHYSICAL JOURNAL, 487:L105–L108, 1997 October 1
© 1997. The American Astronomical Society. All rights reserved. Printed in U.S.A.

COOLING FLOWS AND QUASARS: DIFFERENT ASPECTS OF THE SAME PHENOMENON? I. CONCEPTS

LUCA CIOTTI[1] AND JEREMIAH P. OSTRIKER
Princeton University Observatory, Peyton Hall, Princeton, NJ 08544
Received 1997 June 17; accepted 1997 July 22; published 1997 September 2

ABSTRACT

We present a new class of solutions for the gas flows in elliptical galaxies containing massive central black holes (BHs). Modified King model galaxies are assumed. Two source terms operate: mass loss from evolving stars, and a secularly declining heating by supernovae (SNe Ia). Relevant atomic physical processes are modeled in detail. Like the previous models investigated by Ciotti et al., these new models first evolve through three consecutive evolutionary stages: wind, outflow, and inflow. At this point the presence of the BH alters dramatically the subsequent evolution because the energy emitted by the BH can heat the surrounding gas to above virial temperatures, causing the formation of a hot expanding central bubble. Short and strong nuclear bursts of radiation ($L_{\rm BH}$) are followed by longer periods during which the X-ray galaxy emission comes from the coronal gas ($L_{\rm X}$). The range and approximate distribution spanned by $L_{\rm X}$ are found to be in accordance with observations of X-ray early-type galaxies. Moreover, although high accretion rates occur during bursting phases when the central BH has a luminosity characteristic of quasars, the total mass accreted is very small when compared to that predicted by stationary cooling-flow solutions and computed masses are in accord with putative BH nuclear masses. In the bursting phases the X-ray gas luminosity is low and the surface brightness profile is very low compared to preburst or to cooling flow models. We propose that these new models, while solving some long-standing problems of the cooling flow scenario, can provide a unified description of QSO-like objects and X-ray–emitting elliptical galaxies, these being the same objects observed at two different evolutionary phases.

Subject headings: galaxies: active — galaxies: cooling flows — galaxies: evolution — X-rays: galaxies

1. INTRODUCTION

As first revealed by *Einstein* observations, normal elliptical galaxies, both isolated or in groups and clusters, can be powerful X-ray sources with 0.5–4.5 keV luminosities $L_{\rm X}$ ranging from $\sim 10^{39}$ to $\sim 10^{42}$ ergs s^{-1}. This emission is associated with hot gaseous halos within the galaxies, containing $M_{\rm gas} = 10^8$–$10^{11}\ M_\odot$ (see Fabbiano 1989).

In order to explain this observational finding, a certain class of solutions designated cooling flow models have been proposed and extensively investigated (e.g., Fabian, Nulsen, & Canizares 1984; Sarazin & White 1987, 1988; Vedder, Trester, & Canizares 1988). While these models have many attractive features, they are far from giving a totally satisfactory account of the X-ray properties of all elliptical galaxies, since most observed systems are much fainter in the X-rays than the models predict and have different radial profiles than expected. Moreover, the cooling flow models do not solve the question of *where* the cool gas is deposited: over a Hubble time an amount of material comparable to the mass of stars in the galactic core flows into the nucleus, but the expected distortions of the central optical surface brightness and velocity dispersion are not observed.

One possible solution to part of the previous set of problems was proposed by D'Ercole et al. (1989) and Ciotti et al. (1995, hereafter CDPR), who showed that the heating from SNe Ia could be effective in maintaining low-luminosity galaxies in a wind phase over a Hubble time (and so preventing the gas from accumulating in the center). But the most massive galaxies ultimately experience a central cooling catastrophe, leading to a situation similar to a cooling flow. Clearly a component of the explanation is missing and is possibly related to the fact (e.g., Rees 1984) that many (perhaps most) early-type galaxies show a nuclear activity, and, according to the standard interpretation of the AGN phenomenon, a massive BH is at its origin. So it is natural to investigate the accretion of a galactic gas inflow onto galaxies within which lurk massive central BHs ($M_{\rm BH} \sim 10^8\ M_\odot$).

Binney & Tabor (1995, hereafter BT) explored this problem with the aid of spherically symmetric numerical simulations, assuming a homogeneous release of energy in the inner kiloparsec of their galaxy models during the inflow phases. Moreover, BT assumed that all the accretion luminosity was available for the gas heating, as a result of the interaction between a nuclear jet and the surrounding ISM.

In this Letter we explore, by numerical integration of the fully nonstationary equations of hydrodynamics, the modifications on the results of CDPR, assuming the presence of a massive BH in the galaxy center with detailed allowance for the effects on the flow of the radiation emitted by the central BH. As will be shown, the gas over the body of the galaxy is (as noted by BT) really optically thin, but the effect of *energy* exchange between the nuclear *radiation* and the gas flow is nevertheless dramatic. This effect was already known and extensively studied for accreting compact objects (Ostriker et al. 1976; Cowie, Ostriker, & Stark 1978). In a subseqeuent paper (Ciotti & Ostriker 1997, hereafter Paper II), a quantitative analysis of various aspects of the scenario summarized in this Letter, together with an exhaustive description of the input physics and its modelization, will be given.

2. RESULTS

All the results shown here refer to a model of which the parameters are fixed following the line of CDPR. The stellar density profile is a King (1972) distribution, with total blue luminosity $L_B = 5 \times 10^{10}\ L_\odot$, central velocity dispersion $\sigma_{0*} = 280$ km s^{-1}, and core radius $r_{c*} = 350$ pc. The dark matter halo is described by a quasi-isothermal density distri-

[1] On leave from Osservatorio Astronomico di Bologna, via Zamboni 33, 40126 Bologna, Italy.

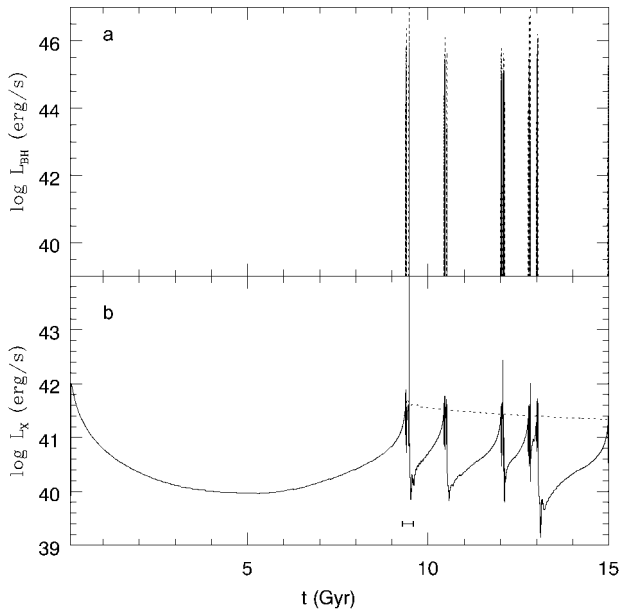

FIG. 1.—(*a*) Time evolution of L_{BH} (bolometric) emitted at the galaxy center. (*b*) Time evolution of L_X for the model with $\epsilon = 0.1$ (*solid line*), and that of the same model with $\epsilon = 0$ (cooling flow: *dashed line*). L_X is calculated inside the galaxy truncation radius and in the range 0.5–4.5 keV. Time interval in horizontal error bar is expanded in Fig. 2.

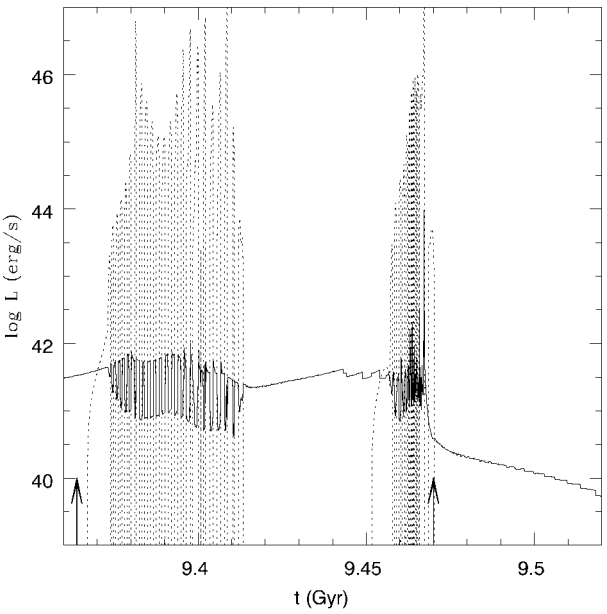

FIG. 2.—Time expansion of the first burst shown in Fig. 1. Solid line is L_X, dotted line is L_{BH}. The temporal substructure of the burst is apparent, and the quasar-like luminosity $10^{45} < L_{BH}/\mathrm{ergs\ s^{-1}} < 10^{47}$ is seen during bursts. Arrows mark epochs of "before" and "during" bursts referred to in text.

bution, with $M_h/M_* = 7.8$ and $r_{ch}/r_{c*} = 4.2$. The SNe Ia rate is the same as that in the King reference model of CDPR. The bolometric luminosity emitted by accretion onto the BH is $L_{BH} \equiv \epsilon c^2 \dot{M}_{BH}$, where c is the light velocity and ϵ is the accretion efficiency, with $10^{-3} \lesssim \epsilon \lesssim 10^{-1}$. The spectral distribution of L_{BH} near the BH is assumed to be $L_{BH}(\nu) \propto L_{BH}\nu^{-0.5}/(\nu_b^{0.7} + \nu^{0.7})$, where $h\nu_b = 1$ MeV. In the present model $\epsilon = 0.1$.

The spherically symmetric hydrodynamical equations are integrated numerically using the Eulerian upwind scheme with time splitting and artifical viscosity as used in CDPR. In the energy equation the contribution of Compton heating (and cooling) of the gas that is due to L_{BH} and to the recycling of the bremsstrahlung radiation produced by the gas heated by the BH activity are included. We allow also for the effect of the photoionization in both cooling and heating of cold gas as well as momentum exchange between photons and electrons. At each radius the radiation field is integrated, considering the gas differential absorption on $L_{BH}(\nu)$ and using for the electrons the Klein-Nishina cross section. In this way the absorbed fraction of L_{BH} is computed self-consistently.

In Figure 1*b* (*solid line*) the temporal evolution of the coronal X-ray luminosity L_X of the gas in the 0.5–4.5 keV band is shown over a Hubble time. The evolution up to the so-called *cooling catastrophe* ($t \simeq 9.4$ Gyr) is analogous to that described in CDPR, but after this time the Compton heating instability completely alters the flow evolution and its properties. At the cooling catastrophe negative infall velocities appear near the galaxy center, with $\dot{M}_{BH} \sim 60\ M_\odot\ \mathrm{yr}^{-1}$, and this accretion produces a strong, energetic feedback resulting in a very high L_{BH} (Fig. 1*a*). The gas in the central regions of the galaxy is strongly heated to temperatures comparable to the Compton temperature associated with $L_{BH}(\nu)$ ($\simeq 10^9$ K) and starts to expand, decreasing its density by more than 2 orders of magnitude, driving a shock wave outward and producing a hot bubble of a few hundred parsecs in diameter. The net effect is, observationally, a large reduction of L_X (Fig. 1*b*), and, hydrodynamically, the interruption of the galactic inflow and the consequent shutoff of L_{BH}. Then the radiative losses increase again, and, after a period of the order of the hot gas cooling time, the cycle repeats. In the model described here this time is of the order of ~1 Gyr. In the case of very high accretion the shock wave can reach the galaxy edge and expel gas from the galaxy. At higher time resolution each burst shows a very complex structure that will be discussed in detail in Paper II: the temporal blowup of the first burst shown in Figure 1 is plotted in Figure 2, showing QSO-like luminosities. An important characteristic of all computed models—of which a single representative is here discussed—is that the fraction of L_{BH} effectively absorbed by the gaseous halo is in the range 10^{-4} to 10^{-2}, but *the gas flows are found to be invariably unstable due to Compton heating for all the explored efficiencies*: in the presence of a massive BH at the center of elliptical galaxies the possibility of a stationary cooling flow seems to be very remote.

In Figure 3 we show the distribution of L_X from 9 to 15 Gyr. The dashed histogram shows the model distribution of L_X given in Figure 1, and the solid line shows data for (nonboxy) early-type galaxies taken from Figure 1 of CDPR. Finally, the dotted histogram is the distribution of L_X for the same model, with the cooling flow assumption of $\epsilon = 0$. We see that the model with $\epsilon = 0.1$ has a distribution, over time, of L_X, surprisingly similar to that of observed galaxies, but the cooling flow model (as is well known) produces far too much radiation. In Figure 4 the X-ray surface brightness profile (Σ_X) of the presented model is shown at two different epochs, before and during bursts (vertical arrows in Fig. 2). Also shown is the cooling flow profile for the same galaxy at $t = 15$ Gyr. Note how Σ_X is characterized by a well-defined core before a burst, alleviating the problem of the too cuspy Σ_X that afflicts cooling flow models (Canizares, Fabbiano, & Trinchieri 1987). Certainly interesting is the fate of the transient cold shell surrounding

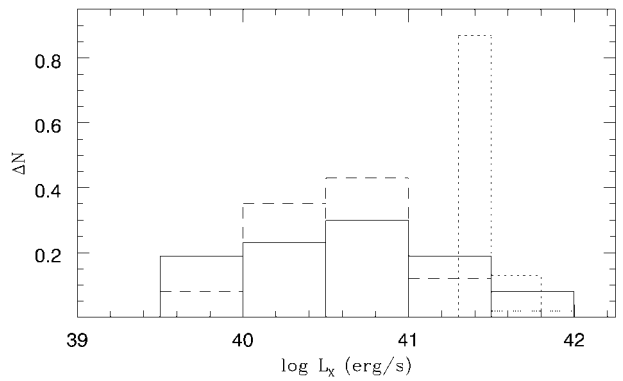

FIG. 3.—Statistical distribution of L_X for observed galaxies (*solid histogram*) in the range $10.4 < \log(L_B/L_\odot) < 10.8$ derived from Fig. 1 of CDPR. The dashed histogram represents the time distribution of L_X for the presented model from 9 to 15 Gyr, while the dotted histogram shows the cooling flow ($\epsilon = 0$) model; clearly the bursting model provides a better fit to the observed distribution of L_X.

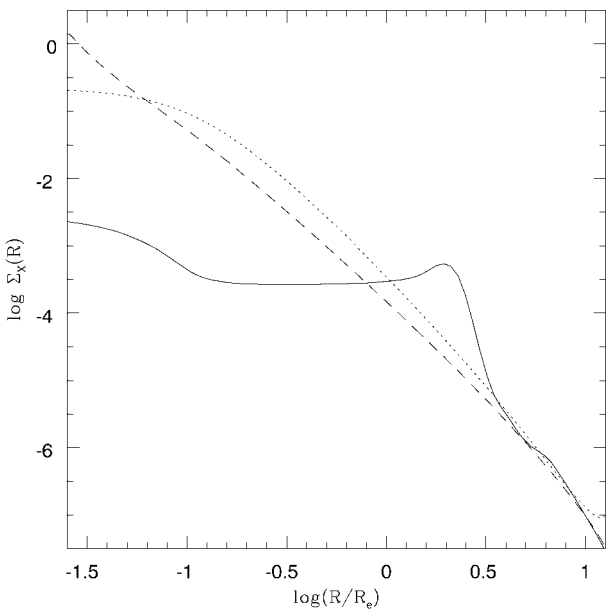

FIG. 4.—The surface brightness Σ_X profile (in arbitrary units) at $t \simeq 9.36$ (*dotted line*, immediately before a burst), and $t = 9.47$ (*solid line*, during bursts), corresponding to the vertical arrows in Fig. 2. The dashed line is the cooling flow model at $t = 15$ Gyr. Note the very centrally bright, cuspy profile of the cooling flow, the more normal core-halo structure of the preburst profile, and the low Σ_X of the postburst profile.

the hot bubble (especially in low-ϵ solutions) during the flaring activity, when the central gas surface brightness is very low. Because of Rayleigh-Taylor instability the shell will break up, and perhaps cold fingers of gas should be observable inside the hot low-density bubble, accreting on the central BH. So, the presence of the central heating source produces in a natural way a multiphase ISM on galactic scales, while the same phenomenon may be harder to obtain (Balbus 1991) in the cooling flow scenario.

Figure 5 shows the bremsstrahlung spectra in the preburst (*dotted line*) and during burst (*solid line*) phases, compared to the cooling flow (*dashed line*) spectrum. The emitted spectrum is never as soft in this set of models as it is in cooling flow models, and, during bursts, occasionally it will have a very hard tail.

3. DISCUSSION AND CONCLUSIONS

In this Letter we show how the presence of a massive central BH in early-type galaxies is able to produce naturally both the observed X-ray underluminosity with respect to the pure cooling flow expectations and the large observed scatter in L_X at fixed L_B. As can be seen from Figure 1, L_X—except in the very short period of bursts—is always lower than that of the corresponding inflow model with $\epsilon = 0$. Moreover, the statistical distribution of observed data compared with the amount of time spent at each L_X by the model here discussed is eloquent (Fig. 3). Finally, because of the strong feedback on the gas flows of the radiation emitted by the accretion, the total mass accumulated by the BH over 15 Gyr is very low ($\sim 3 \times 10^8$ $M_\odot$), to be compared with the $\sim 10^{10}$ $M_\odot$ of the correspondent $\epsilon = 0$ model. The same model in pure cooling flow (without the initial SNe Ia-driven wind-outflow phases) would have accumulated in its center $\sim 10^{11}$ $M_\odot$ of gas.

From an observational point of view, it is interesting to note that during the accretion phases the galaxy luminosity is dominated by L_{BH} (with highest values at 10^{46}–10^{47} ergs s^{-1}), while during the quiescent BH phases the galaxy emission is due only to the diffuse hot gas L_X. The total energy emitted by the accretion when $L_{BH} > 10^{42}$ is $\sim 7.5 \times 10^{61}$ ergs, while during the same phases the total energy emitted by the coronal gas is $\sim 5.6 \times 10^{57}$ ergs. The ratio between the total time spent by the galaxy when $L_{BH} > L_X$, and the total time spanned by the simulation is $\sim 10^{-2}$: very few galaxies should be caught in an AGN-like phase even though most contain central BHs.

Thus, the Compton heating instability could be an alternative possibility to that advocated by Fabian & Rees (1995) in order to explain why the nuclei of elliptical galaxies are not luminous sources of radiation as expected if they host a massive central

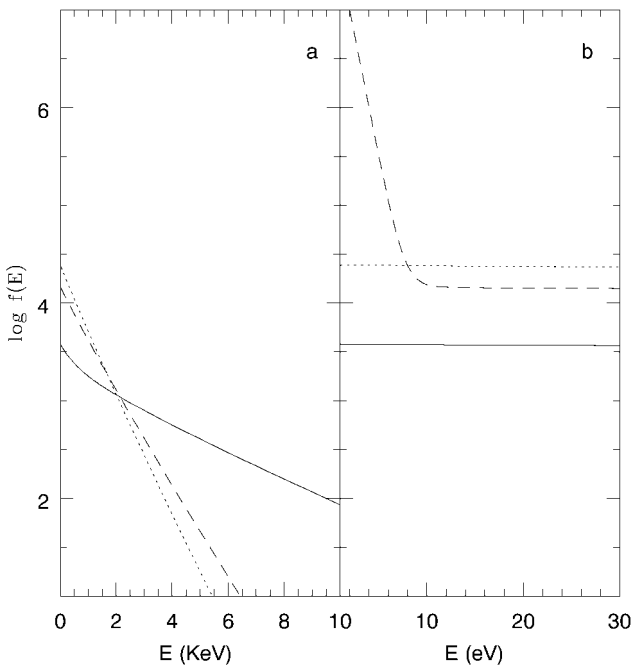

FIG. 5.—(*a*) Spectral energy distribution (in arbitrary units) of the coronal L_X, for the same models shown in Fig. 4. (*b*) Blowup of (*a*) at low energy. Note the soft (UV) component in the cooling flow spectrum and the hard, high-energy tail in the postburst spectrum.

BH. A clear prediction of this model is that some significant fraction of QSOs should be embedded in high-temperature, low surface brightness X-ray bremsstrahlung halos.

In other works to be reported in Paper II we varied the efficiency in the range $10^{-3} \leq \epsilon \leq 10^{-1}$ and the galaxy luminosity in the range $10^{10} \leq L_B/L_\odot \leq 10^{11}$, with results very similar to those shown in Figures 2–5. We are well aware that in the real accretion phenomenon a disk geometry for the infalling gas seems to be inescapable. Then the accretion luminosity will be emitted preferentially along polar directions. It is clear that (at least) fully two-dimensional hydrodynamical simulations are required for a better understanding of this problem, and to follow the development and the final fate of the gas instabilities. We are working in this direction, but we expect that many of the quantitative features of the present work will be carried over to the more complicated calculations.

We would like to thank Giuseppe Bertin, James Binney, Annibale D'Ercole, Bruce Draine, Silvia Pellegrini, and Alvio Renzini for useful discussions and advice. This work was supported by NSF grant AST9424416. In addition L. C. was supported by NSF grant AST9108103 and by the Italian Space Agency (ASI) with contracts ASI-94-RS-96 and ASI-95-RS-152.

REFERENCES

Balbus, S. 1991, ApJ, 372, 25
Binney, J., & Tabor, G. 1995, MNRAS, 276, 663 (BT)
Canizares, C. R., Fabbiano, G., & Trinchieri, G. 1987, ApJ, 312, 503
Ciotti, L., D'Ercole, A., Pellegrini, S., & Renzini, A. 1995, ApJ, 376, 380 (CDPR)
Ciotti, L., & Ostriker, J. P. 1997, in preparation (Paper II)
Cowie, L. L., Ostriker, J. P., & Stark, A. A. 1978, ApJ, 226, 1041
D'Ercole, A., Renzini, A., Ciotti, L., & Pellegrini, S. 1989, ApJ, 341, L9
Fabbiano, G. 1989, ARA&A, 27, 87
Fabian, A. C., Nulsen, P. E. J., & Canizares, C. R. 1984, Nature, 311, 733
Fabian, A. C., & Rees, M. J. 1995, MNRAS, 277, L55
King, I. 1972, ApJ, 174, L123
Ostriker, J. P., McCray, R., Weaver, R., & Yahil, A. 1976, ApJ, 208, L61
Rees, M. J. 1984, ARA&A, 22, 471
Sarazin, C. L., & White, R. E., III. 1987, ApJ, 320, 32
———. 1988, ApJ, 331, 102
Vedder, P. W., Trester, J. J., & Canizares, C. R. 1988, ApJ, 332, 725