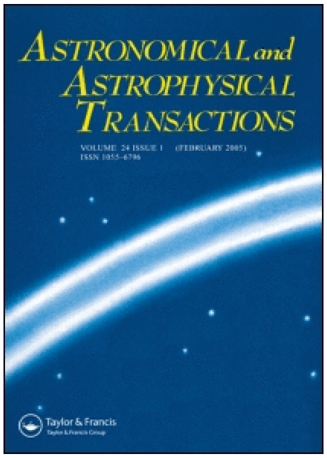

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THE EVOLUTION OF A CLOUDY PROTOGALAXY. CONSTRAINS ON THE INITIAL SIZE

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By the means of a 1-d hydrodynamics code we solve the problem of the interaction of a galactic wind with cloudy surroundings. Compact and diffuse models are used in order to explain the mass and metalicity of the intergalactic gas and giant elliptical galaxies. The results are as follows:

a) The compact models fail to explain the observations, but the diffuse ones are in a good agreement with them,

b) the hot corona has been formed at the stage of the hot protogalaxy and remains in nowadays,

c) the hot corona is richer in heavy elements than the second stellar generation and the intergalactic gas.

KEY WORDS Cloud-evaporation, stellar generation

1 INTRODUCTION

Any theory of galaxy formation and evolution must be able to explain the observational facts. There are three sources of information:

a) our Galaxy,

b) the intergalactic gas in clusters of galaxies,

c) other galaxies (Suchkov, 1988).

Our Galaxy consists of several subsystems with a gap in age, kinematics, spatial distribution and metalicity (Suchkov, 1977, 1988; Marochnik and Suchkov, 1984; Marsakov and Suchkov, 1977). Except for our Galaxy, we can also see discrete subsystems in the galaxy M31 (Sharov, 1982).

This can be explained by the hot model as it is described in (Suchkov, 1988; Berman and Suchkov, 1989). The main point of this model is that the stars have not been formed continuously, but in several active phases with pauses of star formation between them. At the time of a pause the galaxy is hot and looses a large fraction of its mass in a galactic wind.

In elliptical galaxies the subsystems are not separated as clearly as in spiral ones but the hot, rich in heavy elements intergalactic gas in clusters of galaxies (Mitchel and Mushotzky, 1980; Ulmer *et al.,* 1987; Mushotzky *et al.*, 1981) and the dependence of the metalicity on luminosity (Aaronson *et al.,* 1978; Pagel and Edmunds 1981; Faber, 1973; Mould, 1984) cannot be explained by any other model except the hot one.

We have several observations of galactic winds (Yoshiaki Toniguchi *et al.*, 1988; Schaaf *et al.,* 1989) and there are also theoretical models which predict them (Mathews and Baker, 1971; Arimoto and Yoshii, 1987).

In this paper we examine a variant of the hot model in which the galactic wind interacts with cloudy surroundings. In Section 2 we describe the model of a cloudy protogalaxy. In Section 3 the parameters of several variations of the initial conditions are presented. In Section 4 we present and discuss the results of numerical solutions and Section 5 is the conclusion.

2 THE MODEL

In our Galaxy, the angular momentum per unit mass for the stars of the disc is ten times larger than that for the stars of the halo at the same distance from the galactic axis (Marochnik and Suchkov, 1984). That means that the stars of the disc have been formed from the gas of outer regions which had kept its angular momentum at the time of the collapse. On the other hand, the stars of the disc have much higher abundance of heavy elements than the stars of the halo. That means that they have been formed from enriched gas, ejected from the stars of the halo. So there must be mixing of primordial gas from the outer regions with the rich in metals gas ejected from the stars of the halo. Although the gap in metalicity between the two populations is very large, the metalicity gradient is very small if it exists at all (Marochnik and Suchkov, 1984; Pagel and Edmunds, 1981). It is difficult to understand how the surrounding gas could have been mixed so uniformly. The gap in age, metalicity etc. requires a strong explosion and in this case the Rayleigh–Taylor instability is not sufficient to mix the gas from inner and outer regions and make it uniformly distributed.

The most reliable variant of the hot model which can explain the uniform mixing is the model of the cloudy protogalaxy (Berman and Suchkov, 1991; Berman *et al.,* 1990). In this model a metal-rich galactic wind expands from the core of the system and evaporates the surrounding clouds of primordial gas. These clouds maybe had been formed by small-scale motions and thermal instability at high redshifts (Gurevich and Chernin, 1975) or by thermal-chemical instability (Izotov and Kolesnik, 1984). In both these cases, the role of the hydrogen molecule is crucial and it can explain the required energy-loss for the formation of cold clouds (Shchekinov and Edelman, 1978; Khersonskij and Varsalovich, 1978; Suchkov and Shchekinov, 1977, 1978). It is possible that some of these clouds (especially near the centre where the density was high) became gravitationally unstable and collapsed to form the first stellar generation. Some others (especially far away from the centre) were not gravitationally unstable and evaporated by the galactic wind to form the second stellar generations.

The evaporation of a cloud embedded in a hot medium has been studied by (Cowie and McKee, 1977; McKee and Cowie, 1977; Cowie *et al.*, 1981) but all of them have studied an evaporation by thermal conductivity. In our model, crucial role plays the shockwave and because of that we use a simple evaporation law:

$$\dot{\rho}_{ce} = \beta \rho_{ce} \rho_{gas} \left[\varepsilon + \frac{(u_{ce} - u_{gas})^2}{2} \right], \tag{1}$$

where $\dot{\rho}_{ce}$ is the rate of cloud evaporation, ρ_{ce} is the density of the cloud gas, ρ_{gas} is the gas density, ε is the specific internal energy of the gas, u_{ce} and u_{gas} are the velocities of clouds and gas, respectively, and β is the factor defined as:

$$\beta = V \left[M_{\rm W} \left(\varepsilon_{\rm W} + \frac{U_{\rm W}^2}{2} \right) \tau_{ce} \right]^{-1}, \tag{2}$$

where V is the initial volume of the system, $M_{\rm W}$ is the total mass of the wind, $\varepsilon_{\rm W}$ is its specific internal energy and τ_{ce} is the time scale of cloud evaporation.

As it has been found out (Berman and Suchkov, 1988), if thermal conductivity takes place, the hot corona cannot survive for a long time. On the contrary, the hot corone are ubiquitous in giant early-type galaxies (Forman *et al.*, 1985; Trinchieri and Fabbiano, 1985; Volkov, 1990). So we adopt a model without thermal conductivity.

We assume that the wind does not affect the motion of the clouds, so in the case of a spherical-symmetric model the gas-dynamics equations are the follows:

$$\frac{d\rho}{dt} + \frac{\rho}{r^2} \frac{\partial (r^2 u)}{\partial r} = \dot{\rho}_{ce}, \tag{3}$$

$$\frac{du}{dt} = -\frac{1}{\rho} \frac{\partial P}{\partial r} - \frac{G M(r)}{r^2} - f(r) - \dot{\rho}_{ce} \frac{(u - u_{ce})}{\rho}, \tag{4}$$

$$\frac{d\varepsilon}{dt} = \frac{P}{\rho r^2} \frac{\partial (u r^2)}{\partial r} - \Lambda \rho (2 \mu m_{\rm H})^{-2} + \frac{\dot{\rho}_{ce}}{\rho} \left[\frac{(u - u_{ce})^2}{2} - \varepsilon \right], \tag{5}$$

$$\frac{d\rho_{ce}}{dt} + \frac{\rho_{ce}}{r^2} \frac{\partial (r^2 u_{ce})}{\partial r} = -\dot{\rho}_{ce}, \tag{6}$$

$$\frac{du_{ce}}{dt} = -\frac{G M(r)}{r^2} - f(r), \tag{7}$$

where ρ, u, P and ε are the density, velocity, pressure and specific internal energy of the gas, respectively, $M(r)$ is the total baryonic mass within the sphere of radius r, $\Lambda(T)$ is the cooling function as it is described by Cowie *et al.* (1981) and $f(r)$ is the gravity of the dark halo as it is described by Berman, Suchkov and Mishurov

(1987). We adopt here the dark halo of radius $r_{\mathrm{V}} = 20$ kpc and a core of it of radius $r_{\alpha \mathrm{V}} = 1.2$ kpc. The mass of the dark halo is $M_{\mathrm{V}} = 2 \times 10^{12}\, M_{\odot}$.

For the initial density we assume that

$$\left.\begin{array}{rcl} \rho^{o}_{gas}(r) & = & \rho^{o}_{gas}(r_{\mathrm{W}})\,(r_{\mathrm{W}}/r)^{k} \\ \rho^{o}_{ce}(r) & = & \rho^{o}_{ce}(r_{\mathrm{W}})\,(r_{\mathrm{W}}/r)^{k} \end{array}\right\}, \tag{8}$$

where r_{W} is the radius of the core of the galaxy from which the wind expands and k is a parameter in the range between 0 (the density is constant) and 2 (quasi-state collapse). Since there is a compact core it is not plausible that $k = 0$. It is not also plausible that $k = 2$ since the trajectories of the population II stars in our Galaxy require that there a rapid collapse must have been happened. Because of that we suggest that $k = 1$ and the initial temperature of the surrounding gas is equal to 10^4 K. We also assume that the initial velocities of clouds and surrounding gas are equal to zero.

3 PARAMETERS OF THE MODELS

All of the models have the same specific energy of the wind and its initial velocity is also the same for all of them. This assumption is reliable since the cause of the galactic wind is the same: supernova explosions. We adopt $T_{\mathrm{W}} = 5 \times 10^7$ K and $U_{\mathrm{W}} = 1500$ km/s. If the mean molecular weight is $\mu = 0.6$, we have the total specific energy about 4×10^{49} erg/$M_{\odot}$.

We study compact and diffuse models. The compact ones must have a short time of cloud evaporation because the free-fall time is very small and the clouds must be evaporated earlier than the time when they reach the centre of the galaxy. For the same reason, the time on which the wind blows must also be small. The parameters of the models are shown in Table 1.

Table 1.

Model *(1)*	R *(2)*	r_{W} *(3)*	M_{W} *(4)*	t_{W} *(5)*	τ_{ce} *(6)*	M_{gas} *(7)*	M_{ce} *(8)*
1	20	2	10	1	22	10	100
2	20	2	50	1	4.4	10	100
3	100	5	10	10	20	10	100
4	100	5	10	10	22	10	100

In column (1) is the number of the model, in column (2) is the initial radius of the system, in column (3) is the radius of its core, in column (4) is the total mass of the wind, in column (5) is the time on which the wind blows, in column (6) is the cloud-evaporation time, in columns (7) and (8) are the total masses of the surrounding gas and clouds, respectively.
In both tables mass is measured in $10^9\, M_{\odot}$, times 10^7 years and radius in 1 kpc.

4 RESULTS AND DISCUSSION

At the final stage of the evolution of every model we have three components: a cold, dense nucleus which will form a new stellar generation, a diffuse hot envelope which we observe as a hot corona, and the gas expelled from the galaxy, and we assume that this is the observed intergalactic gas. The nucleus is sharply separated from the corona, but the outer boundary of the corona is smeared and we assume that it is at the initial radius of the system. So the nucleus is formed by the inner layers, the corona by the intermediate and the intracluster gas by the outer ones. The final stages of all of the models and also model of Berman and Suchkov (1991, hereafter, BS), are presented in Table 2.

Table 2.

Model (1)	M_N (2)	M'_N (3)	Z_N (4)	Z'_N (5)	M_{cor} (6)	Z_{cor} (7)	M_{ej} (8)	Z_{ej} (9)	a (10)
1	47	108	0.21	0.093	1.4	0	11	0	0.39
2	53	98	0.44	0.24	2.5	0.60	59	0.42	0.53
3	47	48	0.079	0.078	7.7	0.21	65	0.073	0.99
4	47	48	0.065	0.064	3.4	0.21	68	0.092	0.99
BS	56	–	0.14	–	2.0	0.10	42	0.05	–

In column (2) is the mass of the mixture which reaches the centre, in column (3) is the total mass of the nucleus (the value in column (2) plus the unevaporated mass of the clouds). In columns (6) and (8) are the masses of the corona and the intergalactic gas, respectively. In columns (4), (5), (7) and (9) are their metalicities in units of the metalicity of the wind, and in column (10) is the evaporated fraction of the mass of the clouds.

A model has the right of surviving only if it is in agreement with the observations. The constraints are many but the most important of them are: 1) $M'_{\rm N}/M_{ej} \simeq 1$ and 2) $Z'_{\rm N}/Z_{ej} \geq 1$, where $M'_{\rm N}$ and M_{ej} are the masses of the second stellar generation and the intergalactic gas, respectively, and $Z'_{\rm N}$ and Z_{ej} are their metallicities.

The compact models fail to explain the observations. Because of the small radius of the system, the clouds reach the centre quickly with only a little fraction of their mass evaporated. The unevaporated fraction and a part of the mixture of primordial gas, wind and the evaporated fraction of the clouds go to the nucleus and form the second stellar generation.

In model 1 we have $M'_{\rm N}/M_{ej} = 10$ and $Z_{ej} = 0$. In model 2 the energy of the wind is 5 times greater, the parameter τ_{ce} is 5 times smaller and the situation is better ($M'_{\rm N}/M_{ej} = 1.6$ and $Z'_{\rm N}/Z_{ej} = 0.57$) but it is not good enough to save this model. A smaller value of τ_{ce} could give results in permitted boundaries but there remain two significant problems: 1) For $t = (7 \div 8) \times 10^7$ yr the X-ray luminosity of model 2 is as high as 10^{45} erg/sec, much higher than any observed one for an isolated galaxy. 2) The rate of energy ejection in model 2 is 7×10^{45} erg/s. If we adopt the assumption of Heckman *et al.*, (1987) that the infrared luminosity is connected with energy flux of the wind by the correlation $\dot{E}_{wind} \sim 0.1L_{\rm IR}$, we will estimate $L_{\rm IR} = 7 \times 10^{46}$ erg/s. The very luminous infrared galaxy 0413+122 has $L_{\rm IR} = 2 \times 10^{46}$ erg/s (Suchkov, 1988), but it is an exception. Usual infrared galaxies have much smaller infrared luminosities than 2×10^{46} and 7×10^{46} erg/s, so the observations are not in agreement with the assumption of so high energy ejection that is required by the compact models. We cannot increase significantly the time on which the wind blows because the free-fall time is about 4×10^7 yr. We cannot also decrease significantly the energy of the wind because in model 2 half of the mixture goes to the centre and the other half is blown away. On the other hand, in model 1 with 5 times less energy of the wind, the 80% goes to the centre and only 20% to the intergalactic space. So we can conclude that the compact models have too many problems and the initial protogalaxy cannot be compact.

The diffuse models can explain the observational facts. In model 3, we have $M_{\rm N}/M_{ej} = 0.74$ and $Z_{\rm N}/Z_{ej} = 1.07$ (in diffuse models the clouds evaporate almost completely and we may use $M_{\rm N}$ and $Z_{\rm N}$ instead of $M'_{\rm N}$ and $Z'_{\rm N}$). In model 4, we have 0.71 and 0.70, respectively. These models differ from each other only in the value of τ_{ce} and because of this difference they have very different ratios $Z_{\rm N}/Z_{ej}$. We can explain this as follows: at early times the clouds have small velocities but at the final stages of their free-fall to the centre they reach so high velocities that the parameter $\varepsilon + (u_{ce} - u_{gas})^2/2$ is much higher than its initial value. On the other hand, ρ_{ce} will be smaller because a large fraction of the mass of the clouds has already been evaporated. If the parameter τ_{ce} is small, then the greater fraction of the mass of the clouds will be evaporated at earlier times. So there will be a larger fraction of metal-rich gas in the inner layers which will form a new stellar generation. We can also conclude that the evaporation rate is high at the first and final stages and because of that the outer and the inner layers of the mixture will be poorer in heavy elements than the intermediate ones. So the corona will be richer in heavy elements than both the second stellar generation and the intergalactic gas. As we see, the final result is strongly dependent on τ_{ce}. This is not strange because models 3 and 4 have no other differences, so this parameter may vary only in a narrow range. It is plausible that the results of both of them are in permitted boundaries.

Especially model 3 can explain very well the observations and we study it in details. In Figure 1 we can see the evolution of the X-ray luminosity and the growth of the mass of the nucleus with time. We can see that 2/3 of the final nucleus mass is formed before 2×10^9 yr and 1/3 is formed little by little in a period of 8×10^9 yr as a cooling flow. From the curve we can estimate the present rate of star formation by cooling flow to be close to 0.8 $M_\odot$/yr. This value is an agreement with previous results, specifically, with the result of Monica Tosi (1988) that the mass accretion rate in our Galaxy is $0.3 - 1.8$ $M_\odot$/yr now; and with the result of Mathews and Bregman (1978) that the mass accretion rate in giant galaxies M87 and NGC 1275 is lower than 30 $M_\odot$/yr. The X-ray luminosity is very high at $t \sim 10^9$ yr, but at $t \sim 10^{10}$ yr it is about 10^{41} erg/sec. The final mass of the corona is 7.7×10^9 yr. Both the final mass and the final luminosity are in agreement with the results of Forman *et al.* (1985) and Volkov (1990). So we can assume as Berman and Suchkov

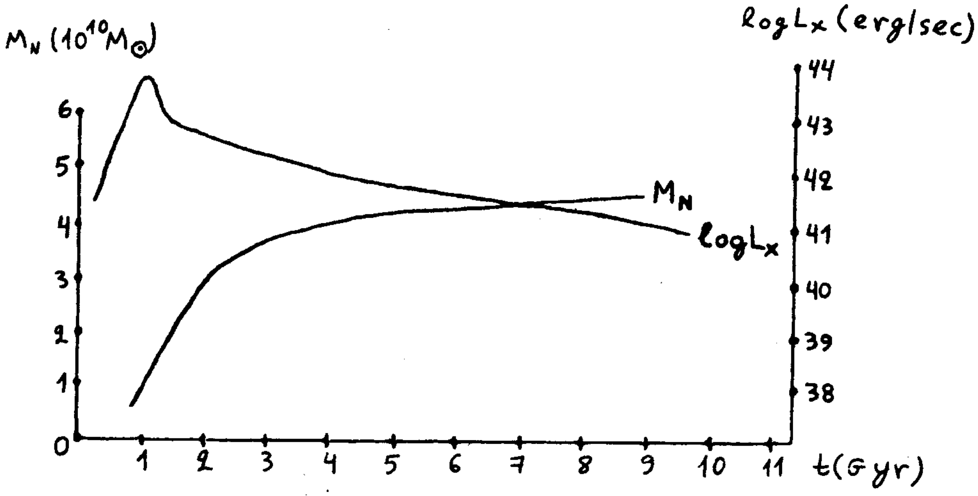

Figure 1 The dependence of the X-ray luminosity and mass of the nucleus on time. The X-ray luminosity is measured in erg/sec and its logarithm is defined as log L_x. The mass of the nucleus is defined as $M_{\rm N}$ and is measured in 10^{10} $M_\odot$; time, t, is measured in Gyr.

(1988, 1989, 1991) and Suchkov *et al.* (1987) that the hot corona of galaxies have been formed at the phase of protogalaxy and they remain in nowadays.

There are many differences between the final results of model 3 and the same model but with the evaporation law

$$\dot{\rho}_{ce} = \beta\rho_{gas}\left[\varepsilon + \frac{(u_{ce} - u_{gas})^2}{2}\right].$$

The solution of it is given by Berman and Suchkov (1991). Of course, the dependence on the cloud evaporation law is not unexpected. The law of cloud evaporation is unknown but it is encouraging that both of the laws give reliable results.

5 CONCLUSIONS

The cloudy model has the great advantage that it can explain the uniform mixture of the primordial and metal-rich gas within the frames of the hot model. This model can also explain the existence of the hot corona, intergalactic gas in the clusters of galaxies with abundance in heavy elements close to the solar one, and the cold nucleus which is clearly separated from the corona and will form a new stellar generation. Of course, constrains from observations are many and there should be done much more in order to find out if the cloudy model can be in agreement with all of the observations.

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