ASTRONOMY
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ASTROPHYSICS

Role of disk galaxies in the chemical enrichment of the intracluster medium

D.S. Wiebe, B.M. Shustov, and A.V. Tutukov

Institute of Astronomy of the Russian Academy of Sciences, Pyatnitskaya str. 48, 109017 Moscow, Russia

Abstract. Elliptical galaxies are often assumed to be the primary source of heavy elements in the intracluster medium (ICM), with the contribution of other morphological types being negligible. In this paper we argue that a role of spiral galaxies in the chemical evolution of the ICM is also important. This statement rests upon our recent calculations of the heavy element loss from a disk galaxy through the hot steady-state galactic wind and dust grains expulsion by stellar radiation pressure. This model reproduces main properties of our Galaxy and, being applied to galaxies of various masses, explains the observed correlation between spiral galaxy mass (luminosity) and metallicity. In our model this correlation develops as a result of the mass dependence of both loss mechanisms, in the sense that less massive galaxies lose metals more efficiently. We show that a typical disk galaxy is nearly as effective in enriching the ICM as an elliptical galaxy of the same mass.

Having estimated the oxygen and iron loss from a single galaxy, we integrate them over the galactic mass spectrum. We show that the 'effective' loss (per unit luminosity) from spiral galaxies is comparable to the loss from ellipticals. The dominant role of early-type galaxies in rich clusters is caused by that they outnumber spirals. We present some arguments to this point, based on recent determinations of the ICM abundances, emphasizing the fact that the ratio of total iron mass to cluster luminosity does not depend on the fraction of cluster spirals in a wide range of the latter, contrary to what one might expect if spirals do not contribute into the ICM Z-abundance.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: intergalactic medium – galaxies: spiral

1. Introduction

Clusters of galaxies are believed to be the only closed chemically evolving systems in the Universe, in the sense that they do not lose matter into the intercluster space. Inside them, however, violent processes of matter and energy exchange between the galaxies and the intracluster medium should occur. This conclusion comes from the fact that heavy elements, which are nearly equally distributed between galaxies and the ICM, can only be produced within galaxies in the course of 'normal' stellar evolution (e.g. Renzini 1997).

Since in recent years the number of the ICM abundance determinations and their accuracy have increased significantly, the interest to the field of the chemical evolution of galaxy clusters has raised, too. Several mechanisms have been suggested to explain the metal transport from the galaxies to the ICM. Among them are enriched gas ejection during the merging of protogalactic fragments (protogalaxies) in the early Universe (Gnedin 1998), ram-pressure stripping of enriched gas both from spiral and elliptical galaxies (Gunn & Gott 1972; Himmes & Biermann 1980; Fukumoto & Ikeuchi 1996), and the hot galactic wind from ellipticals (Matteucci & Vettolani 1988; David et al. 1991; Matteucci & Gibson 1995; Renzini 1997; Gibson & Matteucci 1997; and others).

From these, the last mechanism draws more and more attention as an ultimate explanation of the ICM Z-abundance. Moreover, as Arnaud et al. (1992) pointed out, it was the hypothesis about the galactic wind from ellipticals, which led to prediction of heavy element existence in the ICM (Larson 1974; Larson & Dinerstein 1975). This hypothesis arises from the assumption that ellipticals began their history with the strong starburst followed by multiple supernova events. These explosions after a very short time expelled all the interstellar matter into the ICM, having provided it with heavy elements and thermal energy. At the same time, hot galactic wind is thought to be responsible for establishing the correlation of luminosity (mass) and metallicity, observed in ellipticals.

As several theoretical studies of this process have shown, mass loss from ellipticals is effective enough to explain Z-abundance in the ICM, though this mechanism, according to some of these studies, requires the IMF of high z galaxies to be richer in massive stars than today (Matteucci & Vettolani 1988; David et al. 1991; Matteucci & Gibson 1995; Okazaki et al. 1993). Futhermore, Arnaud et al. (1992) found observational confirmation of the ellipticals being the dominant source of intracluster metals in the apparent increase of the iron mass in galaxy clusters with the growth of the combined E+S0 luminosity. From this they concluded that the role of spiral galaxies in the ICM enrichment is negligible.

This possibly explains why spiral galaxies lack attention as a potential source of the intracluster metals, though, as Fukumoto & Ikeuchi (1996) argued, a single spiral galaxy could be as effective in the ICM enrichment as an elliptical one, and correlation of iron mass with the combined luminosity of ellipticals and lenticulars is caused by that early-type galaxies outnumber spirals. Furthermore, recently Kauffmann & Charlot (1998) suggested that metals in the ICM had been ejected from the primordial population of spirals that have later merged to form present-day early-type galaxies. In their model, spiral galaxies are not the dominant, but the only source of heavy elements in hot intracluster gas.

Recently we also argued that disk galaxies suffer significant Z-loss (Shustov et al. 1997; hereafter Paper I). We considered two processes leading to heavy element expulsion from disk galaxies: hot galactic wind and dust expelling by the stellar radiation pressure. It was shown that these processes are rather effective and may result in the luminosity-metallicity correlation observed in disk galaxies. In this paper we extend these calculations to the integration of heavy-element production in disk galaxies of various masses over the galactic mass function, thus assessing Z-loss from all disk galaxies in a typical cluster.

In Sect. 2 we briefly describe the chemical evolution model used for computation of heavy element loss from a disk galaxy. In Sect. 3 results of integration of oxygen and iron losses over the galactic mass function are presented and compared with the analogous data for elliptical galaxies. They are discussed in Sect. 4. A conclusion follows that a disk galaxy enriches the ICM as effective as an elliptical one of the same mass.

2. Chemical evolution model

Model of galactic evolution used here is outlined in Paper I and Wiebe et al. (1998). Its primary feature is that in addition to the conventional mass conservation equations for a total gas mass and for a particular element (Tinsley 1980) we solve the energy equation, based on a balance between the turbulent energy input from supernova explosions and its dissipation in cloud-cloud collisions. In Paper I we have successfully used this model to show that disk galaxies suffer significant loss of heavy elements, while in Wiebe at al. (1998) we showed that this model is good in reproducing main characteristics of our Galaxy.

As in Wiebe et al. (1998), here we model the evolution of oxygen and iron. For the oxygen production we interpolate metallicity-dependent yields of Maeder (1992). Iron is assumed to originate both in core-collapse and Ia supernovae. Its production is taken into account according to Thielemann, Nomoto & Hashimoto (1996; SN Ib+II) and Tsujimoto et al. (1995; SN Ia). Each Ia Supernova is assumed to produce $0.6M_\odot$ of iron. Time delay for these SNe is taken to be equal to 3×10^8 years (Tutukov & Yungelson 1994). We use Salpeter-like initial mass function with limits 0.1 and $100M_\odot$.

Within the context of the present paper it is important to remind how we take into account heavy element loss from disk galaxies. We consider two processes ejecting Z into the ICM. They are hot galactic wind and dust expelling by the stellar radi-

ation pressure. Heavy element loss rates due to both processes depend a on galaxy mass, in the sense that low-mass galaxies lose their metals more effectively.

Hot galactic wind forms from merged galactic fountains produced by multiple supernova explosions in OB-associations (Mac Low et al. 1989; Norman & Ikeuchi 1989; Igumentschev, Shustov, & Tutukov 1990). Only a fraction f_{esc} of this wind is lost into the circumgalactic space. Combining observational and theoretical results, we derived in Paper I linear dependence of f_{esc} on the galaxy mass. This dependence is based on two theoretical and several observational points. According to Igumentschev et al. (1990), $f_{esc} \ll 1$ for galaxies with masses greater than $10^{12}M_\odot$. De Young & Gallagher (1990) showed that in a galaxy of $1.4 \times 10^9 M_\odot$ $f_{esc} \leq 0.6$. In Paper I we supplied these theoretical limits with several intermediate observational points, assuming that the surface filling factor of supershells produced by the multiple explosions can be a natural estimate for f_{esc}. Resultant dependence of f_{esc} on the logarithm of the galaxy mass is well fitted by a straight line (see Paper I for details).

The second process leading to Z-loss from a disk galaxy is dust expelling by the stellar radiation pressure. Existence of extended dust halo around disk galaxies is demonstrated in a number of observations (Zaritski 1994; Howk & Savage 1997). Using numerical model elaborated by Shustov & Wiebe (1995), we estimated dust loss dependence on a galaxy mass. It turns out that effectiveness of dust expelling decreases with galactic mass, again approaching nearly zero for galaxies with masses $\sim 10^{12}M_\odot$.

A new important feature is included in the present version of our model. In its previous version, described in Wiebe et al. (1998), the galaxy forms at once that leads to high star formation rate in the early galaxy life. To make our model more realistic, in its present version we change the initial conditions by adding the initial accretion phase.

In a collapsing (protogalactic) cloud, the rate of matter accretion onto the cloud core depends only on the cloud initial temperature (e.g. Massevitch & Tutukov 1988). We assume in our standard model that the accretion rate is $100M_\odot$ yr^{-1}. That corresponds to the accretion time 2×10^9 years. During this time mass of the Galaxy grows with constant rate; when it equals to M_G, the accretion stops. This makes the starburst lower and smoother.

3. Results

We perform calculations as follows. Using our Galaxy as a standard, we find proper values of free parameters to reproduce its main properties, including dependence of metallicity on the height above the galactic disk and [O/Fe]–[Fe/H] correlation. After that, adopted values of parameters are kept fixed and used further to model galaxies of different masses.

We investigate the evolution of oxygen and iron ejection from galaxies with masses between 10^{10} and $5 \cdot 10^{12}M_\odot$. Less massive galaxies also eject heavy elements into the ICM, however, as we noted in Wiebe et al. (1998), our model probably
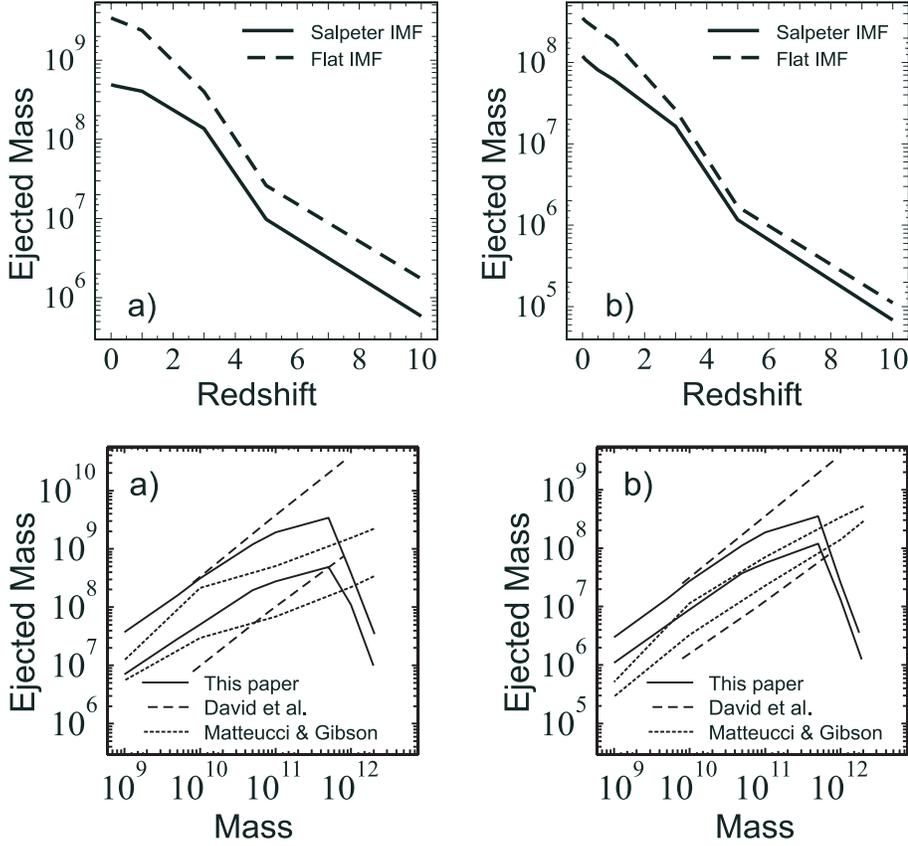
Fig. 1a and b. Redshift (time) dependence of oxygen **a** and iron **b** masses ejected from a galaxy with $M_G = 5 \cdot 10^{11} M_\odot$.

Fig. 2a and b. Dependence of theoretical oxygen **a** and iron **b** ejected mass on the mass of a galaxy for spirals (this paper) and ellipticals (previous investigations).

does not work for them, mainly because the assumption of the self-regulated star formation is not valid in small systems. In order to compare our results with existing estimates of heavy element ejection from elliptical galaxies we compute two models: Salpeter IMF ($x = 1.35$) and flat IMF ($x = 0.95$).

Shown in Fig. 1 is a time dependence of ejected oxygen and iron mass from the galaxy with $M_G = 5 \cdot 10^{11} M_\odot$ for the two different cases (throughout the paper the standard cosmological model with $h = 0.5$ is adopted). Introducing in the model the flat IMF with higher proportion of massive star increases both oxygen and iron production nearly by an order of magnitude.

In Fig. 2a our results for oxygen loss (integrated over time to $t = 13 \cdot 10^9$ years) are presented in comparison with predictions of David et al. (1991) and Matteucci & Gibson (1995). Fig. 2b depicts results for iron ejection according to the same papers. In all cases upper curve corresponds to the flat IMF, and lower curve corresponds to the 'ordinary' IMF ($x = 1.35$ for this paper and Matteucci & Gibson; $x = 2.0$ for David et al.).

As it is demonstrated by Fig. 2, disk galaxies with masses less than $5 \cdot 10^{11} M_\odot$ are as effective in enriching the ICM with O and Fe as ellipticals. Specific feature of our model is steep decrease in the heavy element ejection rate for more massive galaxies. This is caused by the adopted form of dependence of the ejection efficiency on the galactic mass, as explained above. The similar decrease of the heavy element ejection rate for massive disk galaxies was argued also by Kauffmann & Charlot (1998). In their model, galaxies with circular velocities

greater than $250 \, \text{km s}^{-1}$ (i.e., slightly more massive than the Galaxy) eject only 20 per cent of the intracluster metals.

To assess the overall production of O and Fe in disk galaxies one has to integrate mass of the element ejected from a single galaxy over the galactic mass function. It is now widely assumed that the present galactic luminosity function (LF) can be described by Schechter (1976) law with reasonable accuracy. We take Schechter function in its original form, assuming that the spiral luminosity function is proportional to it (universality of LF for all morphological types was recently confirmed by Andreon 1998 and Marzke et al. 1998)

$$N = f n_* \int_{l_1}^{l_2} \left(\frac{L}{L_*} \right)^\alpha \exp\left[-\left(\frac{L}{L_*} \right) \right] \, \text{d}\left(\frac{L}{L_*} \right), \qquad (1)$$

with limits l_1 and l_2 being the minimum and maximum luminosities, expressed in units of L_*. Here f is a number fraction of spirals and n_* is cluster richness, as defined by Schechter (1976). One of the quantities computed in our model is final galaxy luminosity. Comparing it with the galaxy mass, we find that in our model the present-day mass-luminosity relation fits the power law

$$L = 1.3 M^{0.9}.$$

Substituting it in (1), we obtain the present-day mass function

$$N = 0.9 f n_* \int_{m_1}^{m_2} \left(\frac{M}{M_*} \right)^{0.9\alpha - 0.1} \exp\left[-\left(\frac{M}{M_*} \right)^{0.9} \right] \, \text{d}\left(\frac{M}{M_*} \right),$$
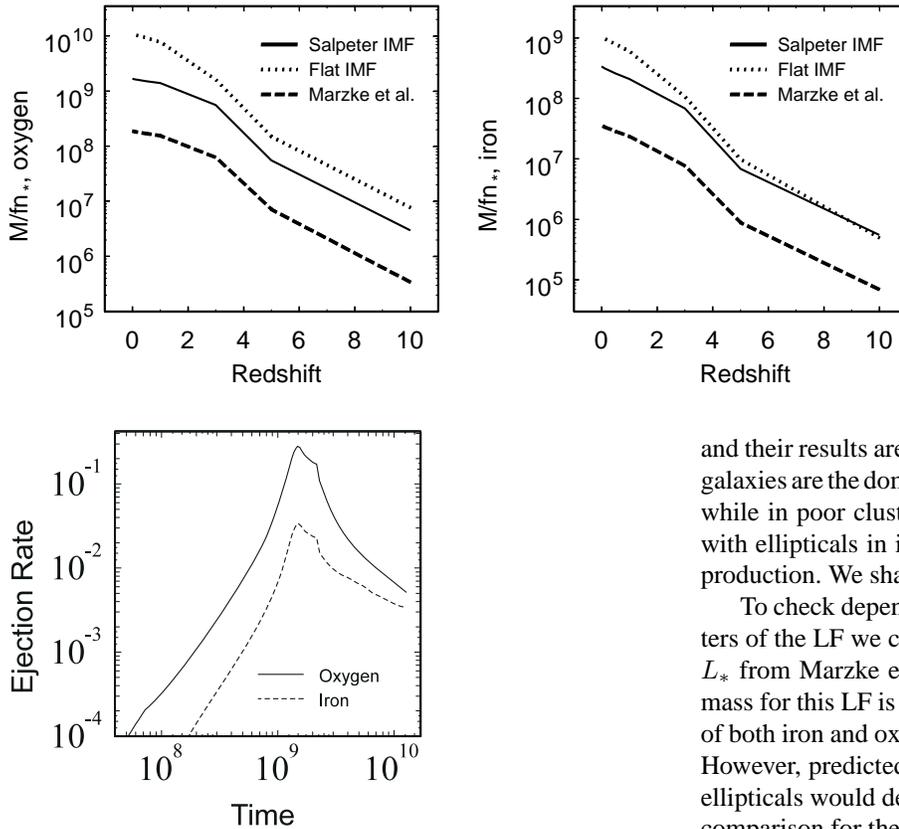
Fig. 3a and b. Integrated oxygen **a** and iron **b** ejected mass vs. redshift for different choices of stellar and galactic mass function.

Fig. 4. Rate of oxygen (a) and iron (b) ejection for our Galaxy as a function of time.

where m_i are mass limits mentioned above and $M_* = (L_*/1.3)^{1/0.9}$. Now we may write the formula for the mass of this element ejected by all galaxies in the cluster

$$M_Z^{\text{tot}} = 0.9 f n_* \int\limits_{m_1}^{m_2} \left(\frac{M}{M_*}\right)^{0.9\alpha - 0.1} \times$$

$$\times \exp\left[-\left(\frac{M}{M_*}\right)^{0.9}\right] M_Z \mathrm{d}\left(\frac{M}{M_*}\right), \tag{2}$$

where M_Z is the mass of heavy elements ejected by the galaxy of the mass M. Using this function we can compute the evolution of the intergalactic oxygen and iron produced in disk galaxies.

Results of integration are presented in Fig. 3 where oxygen and iron yields are shown as functions of redshift. They are computed with $\alpha = -1.3$ and L_* corresponding to absolute magnitude $M_B = -22.5$ (rich cluster case from Matteucci & Gibson 1995). As it was the case for a single galaxy, again the amount of the ejected element is increased by an order of magnitude for the flat IMF. Note that to convert numbers on y-axis into the total mass of the element ejected in the ICM by all disk galaxies in the cluster, one should multiply them by $f n_*$.

To compare our results with the predictions about O and Fe ejection from elliptical galaxies presented by Matteucci & Gibson (1995) we computed two models corresponding to their cases of a rich and poor cluster. Parameters of these models

and their results are listed in Table 1. It is obvious that elliptical galaxies are the dominant source of heavy metals in rich clusters, while in poor clusters, rich in spirals, the latter ones catch up with ellipticals in iron production and exceed them in oxygen production. We shall return to this point in the next section.

To check dependence of our results on the adopted parameters of the LF we computed oxygen and iron yields with α and L_* from Marzke et al. (1998). Evolution of O and Fe ejected mass for this LF is also shown in Fig. 3. In this case production of both iron and oxygen is decreased by an order of magnitude. However, predicted mass of O and Fe ejected into the ICM by ellipticals would decrease, too, so this cannot change results of comparison for the two morphological types.

4. Discussion

Hypothesis on a hot galactic wind associated with the burst of star formation in elliptical galaxies, being satisfactory in explaining temperature and abundance of the ICM, contradicts to an apparent lack of bright ellipticals in the young Universe, found in various deep field surveys (Kauffmann, Charlot, & White 1996; Zepf 1997). A number of effects has been proposed to explain this fact, intragalactic and intergalactic extinction being among them. Another explanation was suggested by Kauffmann & Charlot (1998). They argued that ellipticals did not form in a single burst of star formation but formed later during merging of disk galaxies. That is why we do not see their bright early stages.

In this paper we do not intend to go into details of the elliptical galaxies formation. Our goal is to investigate the ICM-enriching role of a single non-interacting disk galaxy. However, our model has to deal with the problem of the initial starburst, too. Shown in Fig. 4 is the evolution of the rate of heavy element expulsion for our Galaxy (considered as a standard). It is obvious that, though the rate is high enough even at the present epoch, the bulk of Z-loss occurs at early stages of galaxy's life as a result of intense star formation and related high supernova rate. Thus, this initial starburst is an important factor determining the effectiveness of heavy element loss from disk galaxies. As we pointed out in Wiebe et al. (1998), it is impossible to avoid the initial starburst within the framework of our model without breaking consistency between the current theoretical parameters of disk galaxies and observational data. Similar phase of

Table 1. Predicted mass of elements ejected into the ICM from all cluster E+S0 galaxies and spirals.

Cluster	α	M_{B}^*	n_*	f	E+S0		Spirals	
					O	Fe	O	Fe
Rich	-1.3	-22.5	115	0.2	1.10(11)	4.04(10)	3.9(10)	7.9(9)
Poor	-1.3	-22.0	20	0.7	3.77(9)	1.19(10)	1.9(10)	3.8(9)
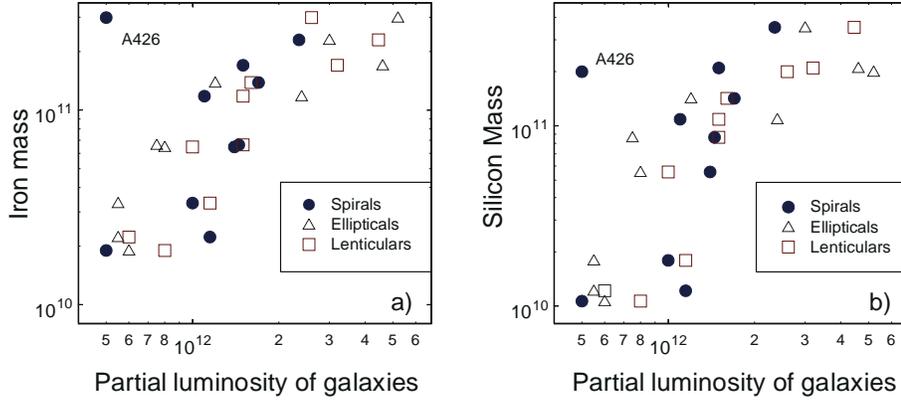
Fig. 5a and b. Iron **a** and silicon **b** masses in the galaxy clusters vs. partial luminosity of galaxies of various morphological types.

the high star formation rate (though not so intense as in our model) is obtained, e.g., in hydrodynamical modelling of our Galaxy by Raiteri et al. (1996) and Samland et al. (1997).

There is a growing body of evidence that the star formation bursts did occur in most galaxies but are hidden from optical surveys by the dust absorption (see e.g. Blain et al. 1998). In Wiebe et al. (1998) we argued that at the time of the starburst a typical galaxy is able to accumulate enough dust to screen out stellar radiation. In the most favorable conditions absorption can amount to several magnitudes.

Another factor, strongly affecting our results, is the used method of accounting for the dependence of Z-loss efficiency on the galactic mass. The 2D hydrodynamical models of a blow-out of the galactic disk (Igumentschev et al. 1990), being a useful instrument for estimate, cannot be considered as a full treatment of gas dynamics of heavy element loss from the Galaxy. Note, however, that in dense gaseous disks, where all processes governing the self-regulated star formation (shock waves, ionizing radiation, etc.) have relatively short distance scales, the star formation efficiency is determined by the local gas parameters and does not depend on global characteristics of a galaxy. This means that the final gas metallicity within the framework of our model does not depend on the mass of a galaxy. This fact is well illustrated by Table 2 where final metallicities are given with and without taking into account mass-dependent Z-loss. Thus, we have no way of reproducing the observed mass-metallicity correlation other than mass-dependent galactic wind and dust grain expelling. Keeping in mind that we are able to obtain the above correlation in our model (probably, underestimating Z-loss from low-mass galaxies), we may say that this model is reasonably accurate.

Apparently, we have a contradiction with the results of Arnaud et al. (1992), who argued for the hot wind from ellipticals as the only significant mechanism of ICM enrichment with

Table 2. Present-day oxygen abundance in open and closed models.

Mass,	Oxygen abundance [O/H]			
$\log(M_{\mathrm{G}}/M_\odot)$	Open model		Closed model	
	Stars	Gas	Stars	Gas
10	-0.4	-0.3	0.2	0.1
11	-0.1	-0.1	0.2	0.1
12	0.1	0.1	0.2	0.1
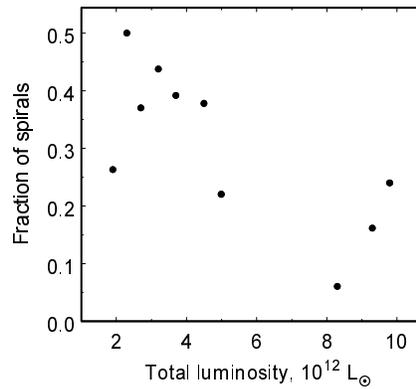
Fig. 6. Fraction of spirals as a function of total cluster luminosity.

heavy elements. According to our data, both elliptical and disk galaxies give comparable contributions into the chemical evolution of the ICM. One of the basic premises of Arnaud et al. (1992) paper was the correlation on the intracluster gas mass – luminosity diagram for ellipticals and the scatter on the same diagram for spirals. One may conclude from this fact that ellipticals, in general, play the dominant role in the intracluster medium evolution, while the spirals do not. However, as the theoretical modelling of elliptical galaxies evolution show, all
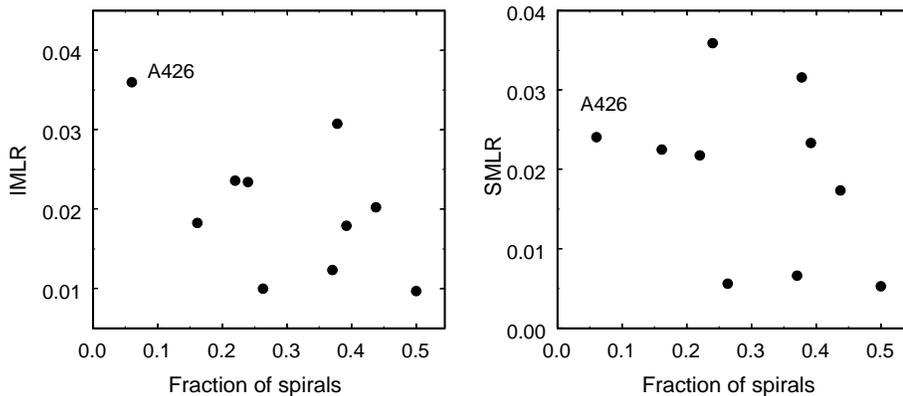
Fig. 7a and b. Iron mass-to-light ratio **a** and silicon mass-to-light ratio **b** for a sample of galaxy clusters.

the gas ejected from the cluster ellipticals (in a typical cluster) cannot account for its amount in the ICM. So, the bulk of the intracluster gas should have primordial origin (see Okazaki et al. 1993 for discussion), and the lack of correlation between the intracluster gas mass and spiral luminosity, being of great interest on its own, has only a little bearing on the problem investigated.

In 1992 Arnaud et al. had only six clusters with known metallicities *and* morphological populations. Recently, new data about the ICM chemical composition have become available (Fukazawa et al. 1998). Here we combine them with morphological data compiled by Arnaud et al. (1992) to understand if our results disagree with the current observations.

In Fig. 5 we show iron and silicon mass in the clusters versus partial luminosity of spirals, ellipticals, and lenticulars (all data needed to compute these quantities were taken from Fukazawa et al. and Arnaud et al.). These two plots reveal the surprising fact: both iron and silicon masses follow nearly the same path for all morphological types, with the only exception of A426 (Perseus cluster). It is noteworthy that according to Andreon (1994) the number of spirals in this cluster is underestimated by a factor of 2 or 3.

However, one might argue that the fact that iron (or silicon) mass in the cluster correlates with a partial luminosity of any morphological type is not so meaningful. Renzini et al. (1993) suggested that it is the ratio of iron mass to cluster luminosity (IMLR) that does make sense in studying the ICM chemical evolution. If we plot fraction of spirals versus total luminosity for galaxies from Arnaud et al. (1992) sample (Fig. 6), we see that in the range of luminosities from 10^{12} to $10^{13} L_{\odot}$ fraction of spirals drops from 0.5 to approximately 0.1. One might expect that the IMLR should decrease in spiral-rich clusters because of decreasing number of metal sources.

To check if this is the case, we plot in Fig. 7 the ICM iron mass to light ratio (IMLR) and silicon mass to light ratio (SMLR) versus fraction of spirals in galaxy clusters. In both cases there is an apparent correlation between these two values. However, it rests mainly upon the cluster A426 which we have already mentioned. So, if we drop this cluster from consideration, Figs. 5 and 7 reveal that, first, iron and silicon masses in the galaxy clusters increase with the luminosity of *any* morphological type. Second, there is no clear correlation between the IMLR (or SMLR) and a fraction of spirals in the cluster.

5. Conclusion

In this paper we investigate the role played by disk galaxies in the chemical evolution of the ICM. We show that if a mass of the galaxy does not exceed $\sim 5 \cdot 10^{11} M_{\odot}$ it contributes nearly the same amount of metals into the ICM as an elliptical galaxy of comparable mass. However, we have found that massive spirals are able to retain their heavy elements and thus do not participate in the ICM enrichment. Integration of the heavy element yields of galaxies over the galactic mass spectrum shows that while ellipticals do play the determining role in the chemical evolution of rich clusters, spirals can be significant source of Z in poor clusters.

We should mention briefly some moments which are important for future improvement of our model: there are evidences that the galactic mass function changed in time (e.g. because of coalescense of early galaxies); new important data on abundance of other chemical elements are expected from space experiments; dynamical interaction of gas and galaxies in the clusters seems to be important and it should be investigated in more details.

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