INTERACTION BETWEEN INTERGALACTIC MEDIUM AND GALAXIES

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1. INTRODUCTION

There exist two basically different approaches to the explanation of the structure and the evolution of galaxies. The conventional one is to consider galaxies as isolated self-regulating systems. This approach is, of course, largely justified. To illustrate the essential independence of the properties of galaxies from their intergalactic environment, it is enough to compare the mean densities within galaxies (10^{-24} gcm^{-3}) to the mean cosmological density ($\lesssim 10^{-29}$ gcm^{-3}).

However, along with the development of this approach the number of observational and theoretical facts of interaction between galaxies and their environments has grown slowly, but steadily. The first steps towards the breaking-up of the isolation concept were connected with the study of tidal interactions between galaxies (an excellent review of the subject has been given by Toomre (1974)). Since close encounters of galaxies were first considered to be exceedingly rare, this did not seriously change the philosophy of isolation.

But uncomfortable facts continued accumulating. Atlases of interacting galaxies were published first by Vorontsov-Velyaminov (1959) and then by Arp (1966). Somewhat ironically the Atlas and Catalogue of 356 Interacting Galaxies by Vorontsov-Velyaminov was the first of the large atlases of galaxies to be published, whereas the Hubble atlas of stanard galaxies was published two years later (Sandage 1961). As we now know, all galaxies tend to cluster (Soneira and Peebles 1977) and most of them seem to have dwarf companions (Einasto et al. 1975). This greatly enhances the probability of gravitational encounters, and thus the study of tidal effects has become extremely popular recently. These effects are transient, but the whole galactic history may well be described as a comparatively short transition period in the evolution towards the final relaxed state.

Another piece of evidence of non-isolation was due to the discovery of the soft X-ray background and to its interpretation in terms of a hot

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intergalactic medium (Henry et al. 1968). Sunayev (1969) realized that radiation of such a gas may ionize neutral hydrogen in the disks of spiral galaxies. While the details of the process have been the subject of discussion (Felten and Bergeron 1969, Silk 1971, Hill 1974), the conclusion that this radiation may essentially limit the extent of the neutral hydrogen in galaxies has never been contested.

Meanwhile direct indications were obtained that galaxies are not so compact after all as thought earlier. Both the discovery of possible massive coronas of galaxies (Einasto, Kaasik and Saar 1974, Ostriker, Peebles and Yahil 1974) and the Westerbork observations of distant radio galaxies (Willis, Strom and Wilson 1974) enlarged the diameters of galaxies up to 1 Mpc. Despite a tenfold increase in the masses of these galaxies, their mean densities were thus reduced to $(2 \div 3) \cdot 10^{-29}$ gcm^{-3}, a few times the mean cosmological density, and the arguments for the closedness of galaxies lost much of their cogency.

In the following we retain the term "galaxy" for the galaxy proper. Anyway, the extended coronas belong rather to groups of galaxies (Einasto et al. 1975, 1977) than to single galaxies.

There also exist theoretical arguments for galaxies being open systems, based on the reconstruction of the early evolution of galaxies. So, the density law in the outer parts of elliptical galaxies has been explained by the continuing infall from the intergalactic space (Gott 1975) whereas the "pancake" theory of galaxy formation (Zeldovich 1970, Doroshkevich, Sunyaev and Zeldovich 1974, Doroshkevich, Saar and Shandarin 1977) ties the properties of new-born galaxies closely up with the physical conditions in the protocluster within which they have been formed.

Once a galaxy is considered as an open system, the problem is which of its properties are determined by interaction with its environment and to what extent the environment itself is independent of the parameters of the galaxy. For galaxies moving in clusters the conditions of the intracluster gas do not considerably depend on the properties of a particular galaxy (Lea and De Young 1976). The same can be said of the dwarf galaxies in the corona the properties of which are tied up with those of the main galaxy (or galaxies), as shown by Einasto et al. (1976). So these galaxies feel the influence of their environment, which they have no power to regulate.

On the contrary, giant galaxies in groups to some extent determine the properties of their near-by environment. We propose to call these near-by regions the environs of galaxies and to distinguish them from the totally unadjustable environment.

In the following we shall review first the properties of the gaseous component of the intergalactic medium (both the environment and the close environs of galaxies) that galaxies are interacting with (Section 2). In Section 3 we shall discuss the interaction of galaxies with the environmental gas both in clusters and in small groups of galaxies. The interaction of galaxies with their environs will be reviewed in Section 4, and collisions between galaxies and giant gas clouds will be touched upon in Section 5.

2. INTERGALACTIC MEDIUM AROUND GALAXIES

The presence of extremely hot gas in rich clusters of galaxies seems to be a well-established fact (Silk 1973, Field 1975). The mass of this gas is of the same order as (or a few times less than) the total mass of galaxies in a cluster, implying the mean density $10^{-28} \div 10^{-27}$ gcm^{-3}. The temperature of this gas (10^8 K) corresponds to the particle velocities $v \sim 10^3\ \mathrm{kms}^{-1}$ that are of the same order as the velocities of galaxies in the potential well of a cluster.

This fact has naturally led to the construction of adiabatic hydrostatic models for the hot gas (Lea 1975, Gull and Northover 1975).

In such models the temperature of gas T is determined only by the value of the potential ϕ (supposing the bulk of gas does not influence the gravitational field of a cluster):

$$T = T_\infty - \frac{\gamma-1}{2\gamma}\ \frac{\mu}{R}\phi , \tag{1}$$

where T_∞ is the constant of integration, γ is the adiabatic exponent, μ is the mean molecular weight of the gas and ϕ the background gravitational potential normalized to $\phi = 0$ at infinity. As the free-free cooling time of the gas of primordial abundances

$$\tau_{ff} = 3\cdot 10^{10}\left(\frac{T}{10^8\ \mathrm{K}}\right)^{1/2}\left(\frac{\rho}{10^{27}\ \mathrm{gcm}^{-3}}\right)^{-1}\mathrm{yr} \tag{2}$$

is both larger than the cosmological time-scale and the dynamical time for the adjustment of the flow (Lea 1976) the assumption of adiabaticity is justified. The enormous amount of energy needed to heat the gas up can be obtained either by the accretion of this gas from outside the boundaries of a cluster (Gull and Northover 1975) or it may be an artefact of the cluster formation processes. In the framework of the "pancake" theory, for example, just the right amount of entropy is produced by the dissipation of the infall velocities in the shock waves at the boundaries of the protocluster (Doroshkevich, Saar and Shandarin 1977).

Recent observations (Mitchell et al. 1976, Serlemitsos et al. 1977) of the Fe XXV line in the X-ray spectra of three clusters of galaxies (Virgo, Coma and Perseus) may demand reconsideration of the problems of

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the origin of the intracluster gas and of its entropy sources (Larson and Dinerstein 1975, Vigroux 1977). But since radiation in lines is negligible for $T \sim 10^{8}$ K (Cox and Daltabuit 1971), the cooling time remains long and the adiabaticity assumption holds.

The only factor capable of changing the adiabatic picture is thermal conductivity. The study of the conductivitv effects has just begun (Lea 1976) and it is not clear how radically conductivity may change the initial adiabatic approximation.

Similar hot gas may exist in groups of galaxies as well (Field 1975, Silk 1974). If these groups (hypergalaxies) are immersed in massive coronas, the situation is much alike to that in the rich clusters of galaxies. It is known that the coronal gas consists only a small percentage of the total mass and its density do not exceed 10^{-3} cm^{-3} (Komberg and Novikov 1975). The temperature of a hydrostatic gaseous corona filling the whole potential well can be found from (1) putting $T_{\infty} = 0$. Using the potential from the model of our Galaxy with a massive corona (Einasto, Jõeveer and Kaasik 1976), we obtain for the region near the Sun $T \sim 2 \cdot 10^{6}$ K. This does not differ much from the first model of the corona constructed by Spitzer (1956).

The cooling time for primordial abundances is large enough, $\tau_{ff} \sim$ $\sim 3 \cdot 10^{9}$ yr, but the possible traces of metals near the galactic plane, in the galactic chromosphere (Sciama 1972) or throughout the whole corona (Cox and Smith 1976, Weisheit and Collins 1977, Larson and Dinerstein 1975) reduce the cooling time considerably. As yet we do not know if the heating of the coronal gas is sufficient to maintain the heat balance. All possibilities have been studied. Weisheit and Collins (1977) supposed that the energy balance is maintained throughout the corona and constructed models of ionization equilibria in the coronas. However, they did not use the adiabatic model of the coronal gas, but the empirical gas density law of Einasto et al. (1974). Field (1975) assumed that the heating rate was independent of the height above the galactic plane and demonstrated that this would lead to the formation of large-scale convective motions (galactic fountain, see also Shapiro and Field (1976)). Slow outflow is also predicted by McKee and Ostriker (1977).

The case of no heating (and cooling being present) has been studied by Hunt and Sciama (1972), Cox and Smith (1976), Tosa and Kato (1972), Hunt (1975). In this case the cooling of the gas in the central regions of the corona provides a sink for it and the problem is that of the infall of the gas. The variety of solutions is large (Cox and Smith 1976), but despite cooling effects, temperatures of the order of $2 \cdot 10^{6}$ K occur in the central regions of the corona.

All the theoretical models listed above can be fitted to the observations of the soft X-ray background, the spectrum of which suggests emission by a hot gas at $T \sim 10^{6}$ K (Gorenstein and Tucker 1972, Yentis et al. 1972). There are indications that the dominant part of the background is generated in nearby regions, closer than the Small Magellanic Cloud (McCammon et al. 1971, 1976) and than M 31 (Margon et al. 1974). To explain the intensity of the background, one has to suppose, however, that the bulk of the gas where X-rays originate has the abundances of the population II at least (Cox and Smith 1976, Field 1975). The values of temperature and density of the gas obtained in this way are also in harmony with the value of the local interstellar pressure $p/k = 2 \cdot 10^3$ $K cm^{-3}$ (Spitzer and Jenkins 1975).

Detailed ionization structure computations by Weisheit and Collins (1976) have enabled them to demonstrate that extensive gaseous coronae around galaxies can produce most of the quasar absorption systems. And it is possible that Hα emission of the gas of our corona has been observed (Golev and Shcheglov 1975).

The recent rediscovery of the radio halo of the Galaxy (Webster 1975) and of an extremely large radio halo reaching up to 15 kpc from the galactic plane near NGC 4631 (Ekers and Sancisi 1977) can be used as an argument for extended coronas. As demonstrated by Kahn and Woltjer (1959), the pressure of the coronal gas is a natural means of the confinement of the halo, and the observed configuration of the halo in NGC 4631 suggests just this kind of confinement.

So we can safely conclude that hot gas exists in clusters as well as in groups of galaxies (or hypergalaxies, to be more exact). But what about cold gas?

The high temperature of ambient gas in rich clusters of galaxies makes survival of clouds of cold gas very difficult. They either evaporate quickly (Cowie and McKee 1976, Cowie and Songaila 1977), or, more probably, fragment into stars during the early evolution of a cluster (Doroshkevich, Saar and Shandarin 1977).

Nevertheless, the existence of clouds on the periphery of clusters where both the temperature and the pressure are small is not excluded (Freeman and de Vaucouleurs 1974).

In hypergalaxies the situation is somewhat different. We do observe cold gas clouds (HVC) is our vicinity. The discussion of their local versus intergalactic nature has a long history (see Verschuur 1975), but recent discoveries of the Magellanic Stream (Mathewson, Cleary and Murray 1974), high velocity clouds near M 33 (Wright 1974) and in the Sculptor group (Mathewson, Cleary and Murray 1975) have given us convincing observational proof of the extragalactic nature of at least a part of these clouds. While these observations refer to our close vicinity and some doubts may remain concerning the exact geometry of the location of these clouds, there exists a "model" galaxy where the situation is much clearer. This galaxy is NGC 4631. It has an extended radio halo (Ekers and Sancisi

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1977) and the 21-cm study by Winter (1975) has revealed a number of HI clouds at some tens of kiloparsecs above the galactic plane. This system (including the close companion 4656 and a dwarf elliptical) is a fine example of a hypergalaxy as defined by Einasto et al. (1974).

The theoretical explanation of the nature of the HVC needs some discussion. Recently Giovanelli (1977) put forward a number of arguments against the extragalactic nature of the HVC, but the concept of the ambient hot coronal gas allows us to overcome the difficulties. This gas stabilizes cold clouds against disruption and provides larger pressure and densities than those used by Giovanelli in his calculation of the cooling. The clouds may be both of recent origin, generated by thermal instability of hot gas, or they may be remant of the galaxy formation according to the scenario by Doroshkevich, Saar and Shandarin (1977). The existing limits on the intergalactic neutral hydrogen abundance allow even most of the mass to be HI (Lang 1976).

To conclude this section, we note that the spatial distribution of gas around galaxies need not be spherical. The temperature distribution in the adiabatic case is valid for any geometry of the potential, and gas observes the spatial limits of the potential well. This means that the results obtained so far do not change much even if the mass distribution in clusters of galaxies proves to be flattened instead of spherical as indicated by recent reports (Tifft and Gregory 1976). And there are theoretical reasons to suppose that even the massive coronas around galaxies may not be spherical (Binney 1976).

3. INTERACTION OF GALAXIES WITH THE ENVIRONMENT

Galaxies moving in the ambient gas will be affected by the ram pressure of this gas. The recent sequence of reports on the subject started with the paper by Gunn and Gott (1972). They studied the evolution of galaxies in clusters and explained the observed deficiency of spiral galaxies in rich clusters by the stripping off the interstellar gas due to the ram pressure of the intracluster gas on galaxies. In case of hypersonic flows (the Mach number $M \gg 1$) the condition of stripping is as follows:

$$\rho_c v^2 > -\phi_g \rho_g \ , \tag{3}$$

where ρ_c is the density of the intracluster gas, v - the velocity of a galaxy, ϕ_g - the gravitational potential of a galaxy and ρ_g - the density of the interstellar gas. As both ϕ_g and ρ_g depend on the location within a galaxy, gas in the outer parts of a galaxy gets stripped off first, whereas the central gas may even remain (Zasov 1974).

In these first studies the assumption of hypersonic velocities was used (so also in the papers on the heating up of the intracluster medium

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in the galactic wakes, see Ruderman and Spiegel (1971) and Schipper (1974)). But in rich clusters both the galaxies and the atoms of the intracluster gas are moving in the same potential well, hence the Mach number of their relative motion $M \sim 1$. A detailed numerical study of this case was recently carried out by Lea and De Young (1976). A typical picture of the density distribution is shown in Fig. 1 (Lea and De Young 1976). As expected there develops a bow shock, and simultaneously

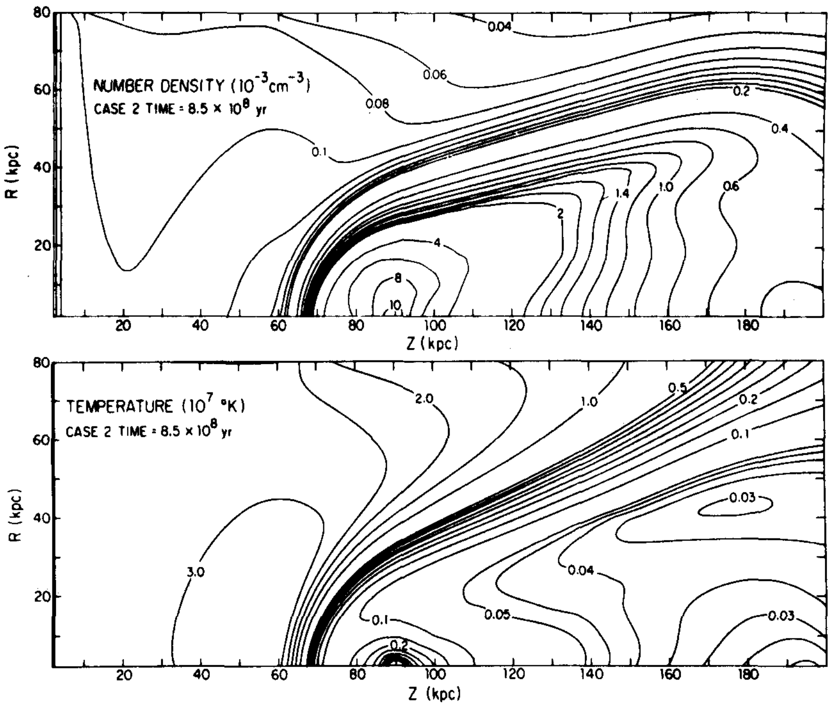

Fig. 1. Density and temperature distribution around a galaxy moving through the intracluster gas (after Lea and De Young 1976). The stellar galaxy with a total mass of 10^{11} $M_\odot$ and with a radius of 15 kpc is centred at $R = 0$, $Z = 90$ kpc. The galaxy is moving from right to left at a velocity of 1000 kms^{-1}, corresponding to the Mach number $M = 1.0$. Note the development of the tail behind the galaxy and the inhomogeneity of temperature within the tail.

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with it long gaseous tails are formed (the analog of wakes occurring in a hypersonic case). The galactic gas is removed mainly by ablation and stripping off the outer parts of the galactic gas in the postshock region. This mechanism is able to remove 80-90 per cent of the galactic gas in 10^9 years. The calculations are made for a spherical galaxy. The removal of gas from disk galaxies must be even more efficient, completely stripping the interstellar gas off the disk.

The gas in the bulge of the galaxy may remain, as indicated also by the computations by Gisler (1976). He started with an initially empty galaxy, the bulk of the interstellar gas being generated by the outflow from the evolving stars.

As shown by Zasov (1974), van den Bergh (1975, 1976) and Komberg (1976), this theoretical picture is supported by observations.

The Virgo cluster spirals are redder than the field galaxies, a fact that can be explained by a deficiency of young stars. Observations of neutral hydrogen (Davies and Lewis 1973) show that spirals in the Virgo cluster contain about twice less hydrogen than the field spirals do.

As star formation pecularities affect galactic morphology first, those differences have led van den Bergh to propose a new classification scheme of galaxies including anemic spirals (van den Bergh 1975, 1976). He stated that "the present morphology of galaxies is, in fact, determined by environmental factors in addition to the genetic heritage that is provided by the proto-galactic angular momentum and density" (van den Bergh 1975).

In conclusion, we should like to point out two more effects. The first is the growth of the central galaxies both in clusters and hypergalaxies by the accretion of the cooling intracluster gas mentioned in a number of papers (Lea and De Young 1976, Komberg 1976, van den Bergh 1975). This accretion can also be used to explain the activity of the central galaxies.

And the second effect is the confinement of the components of radio galaxies by the intergalactic and intracluster matter. While the well-known 5 GHz map of the radio galaxy NGC 1265, proudly displayed in almost any recent review paper, suggests that the radio tail is definitely being swept back by the intracluster medium, the theoretical situation is not too clear. To produce such a picture both the magnetic field geometry has to be adjusted (the galactic magnetosphere model of Jaffe and Perola (1973)) and a sufficient density of relativistic particles has to be provided at large distances from the parent galaxy. A comprehensive review of the recent work on these lines has been given by De Young (1976).

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The interaction of dwarf galaxies with the gaseous corona of (hyper-) galaxies is similar to the picture outlined above. The only significant difference is in the absolute value of temperature, that being a hundred times smaller than within the clusters of galaxies.

The stripping of the gas by the ram pressure from dwarf galaxies was used by Einasto et al. (1974a) and Chernin, Einasto and Saar (1976) to explain the observed morphological segregation of companion galaxies. Massive and/or farway companions contain enough gas to provide for the present-day star formation, whereas less massive and nearby galaxies have been stripped of their gas, in accordance with the simple formula (3), and are ellipticals. The slope of the segregation line on the luminosity-distance diagram (Fig. 2) was used to obtain the approximate $\rho \sim r^{-2}$ law for the spatial distribution of the coronal gas. This density law is evidently non-unique and depends essentially on the geometry of

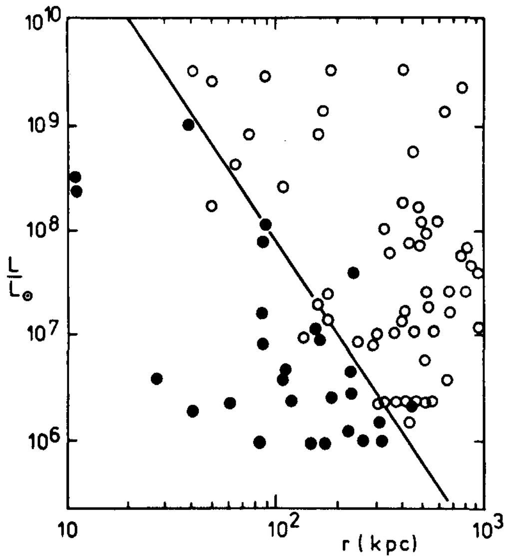

Fig. 2. The plot of luminosity versus distance from the main galaxy for dwarf companions of the Galaxy, M 31, M 81 and M 101 (after Chernin, Einasto and Saar 1976). Elliptical companions (filled circles) lie to the left of the segregation line and spiral and irregular companions (open circles) to the right. The few exceptions are caused by the ellipticity of the orbits and/or projection effects.

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the coronal gas. The absolute values of the coronal density needed for an effective stripping are of the order of 10^{-2} cm^{-3}, that being at least an order larger than the density inferred in the previous section. Chernin, Einasto and Saar (1976) explained this value by removing the process to the early period of a supposedly gaseous corona. We note that the comparatively low temperature ($\sim 10^6$ K) allows for gas clouds to exist in the corona. The collisions of dwarf galaxies with gas clouds enhances the effectivity of stripping by the value of the ratio of cloud and intercloud densities. Moreover, at the transonic velocities slow stripping occurs instead of the instantaneous one. Lea and De Young (1976) have estimated the density of the corona needed to remove gas from globular clusters as 10^{-3} cm^{-3}, a value compatible with the models of the corona (Section 2). A similar result has been obtained by Frank and Gisler (1976).

Let us return once more to the picture of the temperature and density distributions behind a moving galaxy (Fig. 1). The temperature distribution in the tail is far from uniform. In the temperature range encountered in the outer regions of the corona $T \leq 10^6$ K the non-uniform temperature distribution leads to the development of thermal instability (Field 1975) and the possible detachment of portions of the tail. This is in harmony with the recent high-resolution map of the Magellanic Stream (Fig. 3 after Mathewson, Schwarz and Murray (1977)). As demonstrated by these authors, the variation of velocity along the Stream can also be explained by this picture, supposing that cold newlyformed clouds began sinking towards the galactic centre.

Thus by envoking interaction between galaxies and the environment a large number of observed facts can be explained. This in its turn may be considered as strong support for the existence of the yet hypothetical galactic coronas and the more certain hot intracluster gas.

4. INTERACTION BETWEEN GALAXIES AND THEIR ENVIRONS

The interaction of the galactic coronas with the main galaxies is more complicated than the stripping-off effects of the preceding section. As the specific angular momentum of the corona is probably less than that of the galaxy, shearing motions must occur near the galactic plane (de Vaucouleurs 1964, 1972, Cox and Smith 1976). The galactic magnetic fields will further complicate the situation. At the present time only the properties of the local (within a few kpc) galactic magnetic field have been inferred from observations (Verschuur 1974, Heiles 1976). The geometry of the field on the galactic scales ($\sim$10 kpc) and its extension in the z-direction has not even been speculated upon. The only guess made for the interpretation of the radio halos (see Kaplan and Pikelner 1963) is that the magnetic field is randomly tangled.

If the galactic magnetic field were effectively confined to the galactic plane, the torques applied by a non-rotating corona to the ro-

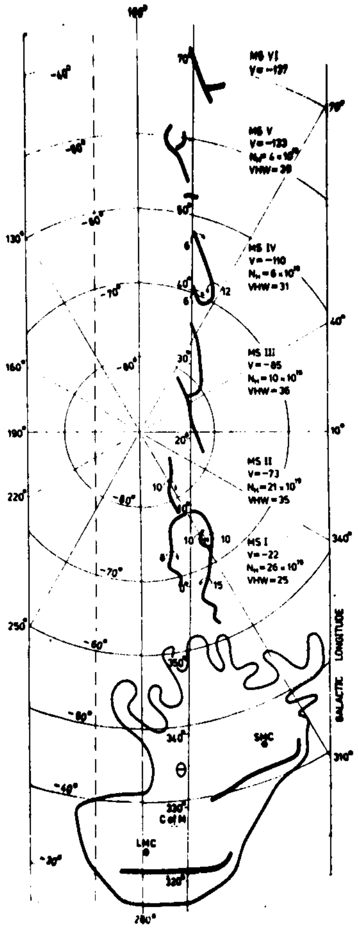

Fig. 3. The neutral hydrogen density map for the Magellanic Stream (after Mathewson, Schwarz and Murray 1977). The surface density contour corresponds to $5 \cdot 10^{19}$ cm^{-2}, and lines inside it represent steep density gradients. For smaller clouds only HI ridges are shown (thick lines). Looped arrows indicate the direction of the rolling motions of the gas. The galactocentric radial velocities V and the velocity half-widths VHW are given in kms^{-1}, the mean surface density N of HI in cm^{-2}. Compare the density distribution of the separate clouds with that of the tail in Fig. 1.

tating galactic disc might be substantial and even lead to stopping of rotation (Cowsik and Lerche 1975). As galaxies are yet rotating, coronas cannot exist, or, more probably, the configuration of the galactic magnetic field is different. The possibility of the rotation of the inner parts of coronas cannot be a priori rejected either. Anyway, these problems have completely neglected up to the present time and any progress along these lines demands more information on the large-scale magnetic field.

Gaseous galactic coronas consist of two components - hot gas and cold clouds. The degree of ionization in the clouds may be small enough for them not to be governed by the magnetic field. In the vicinity of NGC 4631, e.g., the distribution of neutral hydrogen is not correlated with the radio profiles of the halo (Ekers and Sancisi 1977). Independently of the character of the corona (static, infalling or outflowing), cold clouds form and fall into the galaxy.

Larson (1972) was the first to realize that such infall may lead to star formation in galaxies, to structural peculiarities, and affect the chemical evolution of galaxies. All these effects have been confirmed by later work.

As a review of the chemical evolution models will be given at this symposium by much more qualified specialists than the authors are, we touch on it only briefly here. Among a variety of the evolution models (Audouze and Tinsley 1976) the infall models are rather popular. By postulating continuous infall of gas of primordial composition the metallicity distribution of dwarf stars is naturally explained. In the present situation where a number of different models exist we can at least say that the infall models do not contradict observations.

Let us turn now to the star formation induced by infall. As argued by Jaaniste and Saar (1976, 1977), the collision of infalling clouds with the galactic gas may finally result in the cooling of the gas (by radiation of energy from isothermal shocks and subsequent adiabatic expansion, as modelled by Zimmermann (1968)). If the assumption by Quirk (1972) that the gas density in galaxies is kept just below the gravitational instability limit, is justified, the collisions trigger off star formation. The characteristic time of gravitational instability $\tau_o = (4\pi G\rho)^{-1/2}$ is $2\cdot 10^8$ years for the typical interstellar gas density. This picture of slow star formation as opposed to the rapid formation in spiral shock waves (Shu et al. 1972) has been supported recently by Madore (1977). He found that both the $\tau \sim \rho^{-1/2}$ dependence and the numerical value of $\tau \sim 10^8$ yr fit the observed picture best.

Indirect evidence supporting the same picture follows from the numerical experiments of propagating star formation by Mueller and Arnett (1976), who obtained the best fit with observed galaxies for the "regeneration time" $1.7\cdot 10^8$ years.

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Angular dimensions of high-velocity clouds are usually a few degrees (Hulsbosch 1974). Assuming that their mean distance coincides with that of the Magellanic Clouds, we obtain one kpc as a typical cloud diameter. The regions of so large dimensions will be streched out by differential rotation before stars ignite, thus forming spiral arcs (Larson 1972). A step further has been made by Jaaniste and Saar (1976, 1977), who noted that the infalling clouds may form a layer. The existence of such a layer, containing the Magellanic Stream, some northern streams and dwarf satellite galaxies has been suggested by Lynden-Bell (1976), Einasto et al. (1976b), Kunkel and Demers (1976). The origin of such a layer may be explained either as a relict of the period of galaxy formation (Saar and Jaaniste 1976, Doroshkevich, Saar and Shandarin 1977) or by the "tail cutting" mechanism of Mathewson, Schwarz and Murray (1977). Both these explanations can be supported by the fact that the plane of the cloud layer is close to the supergalactic plane (de Vaucouleurs and Corwin 1975). By the way, this plane is almost perpendicular to the galactic plane.

If gas clouds are really accreted from such a layer the formation of a spiral structure is inevitable. As shown by Jaaniste and Saar (1976) the spirals constructed by using real rotation curves are close to the observed spirals (Fig. 4). The properties of the spiral arms resemble those obtained from the density wave theory - in both cases spiral arms are explained as a star formation wave (Roberts 1972), no matter what the triggering mechanism is.

The largest difference is that the accretion mechanism explains bars as spiral arms in the central regions of solid-body rotation, while for the density-wave theory they are an external element. Of course, the mechanism described above cannot be considered as a theory yet, but it has attractive properties and may allow of a variety of structures which appear by introducing relative motions and/or displacements between the accretion layer and a galaxy.

The assumption of the plane geometry of infalling gas clouds has to be checked by observations. Gerard (1973) did not find any neutral hydrogen outside the planes of six edge-on spiral galaxies to the limit of $1.4 \cdot 10^{19}$ cm^{-2}, which is yet a little larger than the predicted surface density $5 \cdot 10^{18}$ cm^{-2} (Jaaniste and Saar 1976). But there are galaxies where there is positive evidence for the existence of clouds. These are NGC 4631 (Winter 1975) and M 81 with about one-third of neutral hydrogen out of the plane (Gottesman and Weliachev 1975). The displacement of the major axes of the optical and low-intensity radio images of NGC 6822 and M 33 (Davies 1972) can also be interpreted as evidence for accretion layers seen almost edge-on and there is evidence of the existence of more or less uniform hydrogen layers around spiral galaxies (Davies 1974).

The arguments leading to the spiral structure include the assumption of homogeneous clouds and a homogeneous galactic gas layer. In

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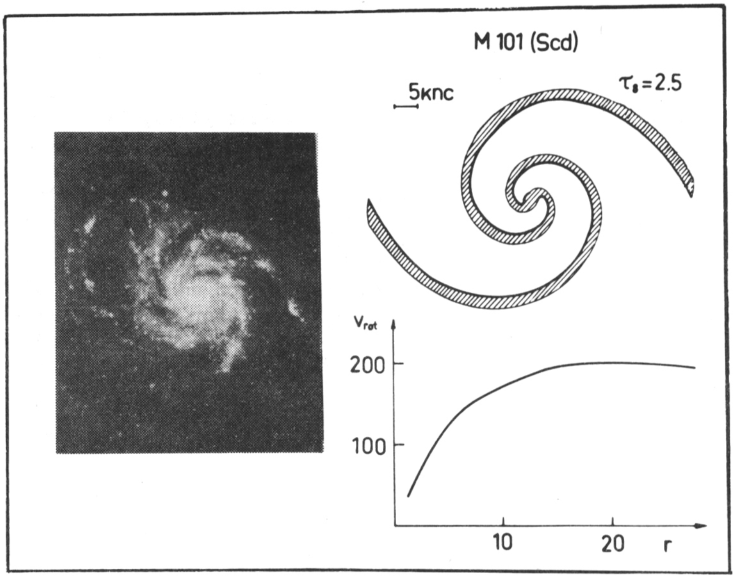

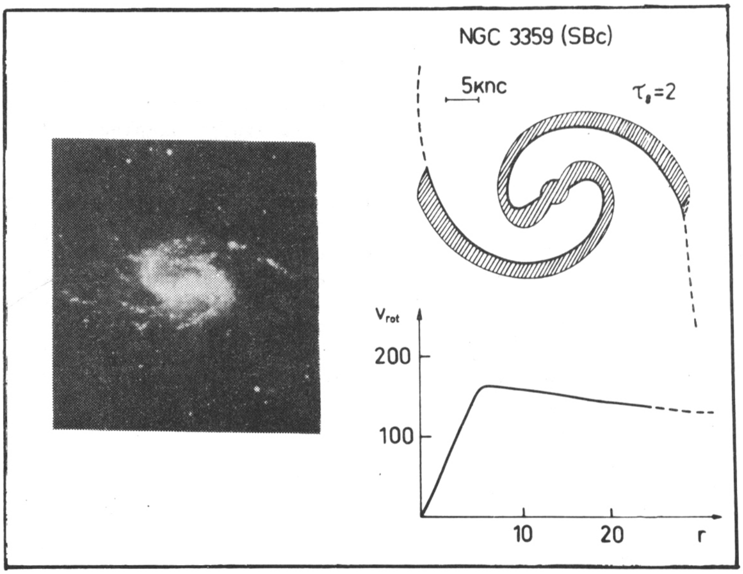

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reality the high-velocity clouds have a two-component structure (Davies, Buhl and Jagolla 1976, Cram and Giovanelli 1976, Greisen and Cram 1976, Giovanelli, Verschuur and Cram 1973, Giovanelli and Haynes 1976), small dense clouds being embedded in a tenuous background. The interstellar gas is similarly known to consist of clouds embedded in warm gas, its most recent model introducing three components of the gas (McKee and Ostriker 1977). During accretion the dense small clouds of both media have good chances to miss each other. So the galactic clouds collide mainly with the warm widely distributed material of the accreting clouds, and the further evolution proceeds along the lines described above towards the formation of a spiral structure. The momenta of these clouds change only little, which leads to small-amplitude oscillations about the galactic plane. As demonstrated by Haud (1977), these oscillations are in harmony with the observed z-oscillations of young stars (Dixon 1967 a, b, 1968).

The dense components of the accreting clouds will also retain their momenta and will fall through the galactic plane. As the pressure outside the plane is smaller, they may have no chances to undergo gravitational collapse and they may return by evaporation to their previous two-component form. These hydrogen clouds will perform complex oscillations around the galactic plane. A numerical study of this process by Haud (1977) demonstrated that a quasistationary picture may emerge in some cases (a kind of standing wave of the wavelength comparable to the galactic dimensions).

This result can be interpreted as explaining the nature of warping of the neutral hydrogen disks of galaxies. With the sensitivity of 21-cm observations improving it seems that warping is almost as frequent a disease as spiral structure is. The bending of the plane of our galaxy has been studied in detail (Oort, Kerr and Westerhout 1957, Gum, Kerr and Westerhout 1960, Habing 1966). Observations have revealed the existence of warping also in nearby M 31 (Roberts and Whitehurst 1975), in M 33 (Rogstad, Wright and Lockhart 1976) and large-amplitude warps in M 83 (Rogstad, Lockhart and Wright 1974). A systematic search for warping in edge-on spiral galaxies has been commenced by Sancisi (1976). In

Fig. 4. Theoretical spiral patterns, rotation curves and photographs of two spiral galaxies after Jaaniste (1977). Rotation velocities V_{rot} are given in kms^{-1}, radii r in kpc, time lapses from the collision of clouds to the ignition moment τ_8 in units of 10^8 years. The widths of the spiral arms have been determined from the lifetime of bright OB stars ($3 \cdot 10^7$ years). Thick lines denote the location of new-born stars, dashed lines - hydrogen (radio) arms. Note that the theoretical spiral patterns are pictured face-on (inclination angle 90°), whereas the inclination angles of the observed images are 73° for M 101 and 40° for NGC 3359.

extreme cases the height of the hydrogen layer above the galactic plane is comparable to the dimensions of the galactic disk.

An attempt to reproduce the observed pattern on the basis of the accretion theory has been made by Haud (1977). Using realistic values for the densities and velocities of the infalling clouds, the surface density of gas in the Galaxy and a detailed dynamical model of the Galaxy, he constructed a relief map of the Galactic plane.

Theoretical and observational maps (Gum, Kerr and Westerhout 1960) are compared in Fig. 5. Despite a number of simplifying assumptions made during the calculation the two maps agree rather well. In this model warping is caused by the oscillation of clouds about the galactic plane, and a steep increase in the height of the gaseous layer in the outer regions is due to a similar decrease in the surface density of the galactic hydrogen (Burton et al. 1975). Of considerable interest is also the formation of ring structures above the galactic plane similar to the Arp ring in M 81 (Gottesman and Weliachew 1975).

It has to be noted, however, that in order to produce systematic warping, the infalling clouds were considered to be orbiting in one and the same direction. Prevalence of one of the directions of rotation is needed anyway. Such an ordering may be explained as a remnant of the initial random distribution of the angular momenta of the (primordial) clouds or by the gradients of the cloud velocities within the layer, caused probably by the motion of the galaxy in its orbit inside the hypergalaxy.

An alternative explanation for warping has been proposed by Kahn and Woltjer (1959). If a galaxy is moving (with its corona) with respect to the intergalactic gas, the flow of this gas around the corona will create regions of enhanced and diminished pressure located intermittently on the "surface" of the corona. The pressure distribution propagates inside the corona and can affect the gas of the galactic disk to produce symmetric warping. This mechanism needs a tightly bound corona, otherwise instead of warping displacement of the galactic gas may occur (Zasov 1974a).

Up to the present the most popular theoretical explanation of the bending phenomena has been the tidal influence of companion galaxies (Hunter and Toomre 1969, Byrd 1976). But, as noted by Sancisi (1976), large-scale bending is observed in galaxies with no close companions, and there clearly some other mechanisms similar to those described above must be invoked.

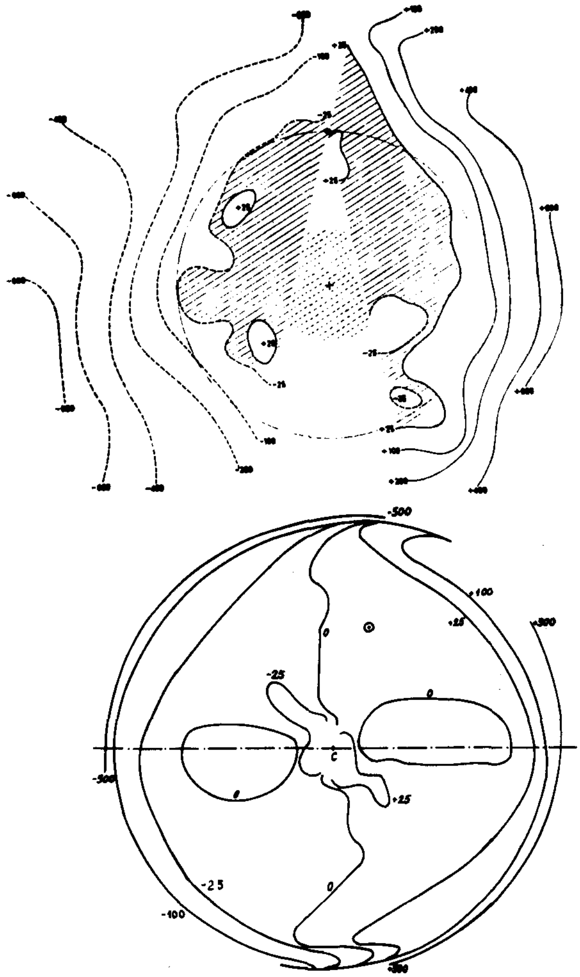

Fig. 5. Relief maps of the height of the maximum hydrogen density above the galactic plane. The location of the Sun is indicated by o, that of the galactic centre, by a cross. The upper map is based on observations (Gum, Kerr and Westerhout 1960), the bottom map is borrowed from Haud (1977). Dash-dotted line in the theoretical map indicates the intersection of the planes of the Magellanic Stream and of the Galaxy. Numbers at contours indicate the corresponding height values (in pc). While theoretical profiles possess too steep gradients at the outer regions, qualitative agreement between the two pictures is good.

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5. COLLISIONS BETWEEN GALAXIES AND INTERGALACTIC GAS CLOUDS

While the collisions of gas clouds with galaxies reviewed in the previous section are essentially local phenomena, galaxies may collide with clouds of nearly galactic size having radii of 15 kpc and masses around 10^9 M_o. Evidence for the existence of such clouds has been summarized by Freeman and de Vaucouleurs (1974), who have also proposed a collision model to explain ring galaxies. Collision of spiral galaxies with such massive clouds will lead to the "peeling off" of the galactic gas by the cloud. Since the spatial distribution of gas in spiral (disk) galaxies is ring-shaped (Roberts 1975), a face-on collision will result in the formation of a compressed gaseous ring with subsequent star formation there. As stressed by Freeman and de Vaucouleurs, the variety of initial conditions inherent in the collision model may allow to explain a large class of peculiar galaxies. They estimate the collision probability for a spiral galaxy during its lifetime at 3 per cent, a large value if we take into account the spectacular appearance of the resulting objects. A fine example of a peculiar structure constructed by using a collision is presented in Fig. 6 (after Freeman and de Vaucouleurs 1974).

Since the gaseous rings are no more stabilized by the gravitation of the stellar galaxy they are prone to instabilities. As demonstrated by Theys and Spiegel (1977), the rings fragment into complexes of dwarf galaxies which strongly resemble the "nests of galaxies" discovered by Vorontsov-Velyaminov (1975).

As the clouds referred to here have masses comparable to those of galaxies, the collision model borders on the domain of galaxy-galaxy collision problems. It is natural to suppose that clouds so large will eventually develop some kind of inner structure, which brings the problem even closer to that of collisions between galaxies. Interesting as it is, this subject lies outside the scope of the present review.

6. CONCLUSION

If taken at face value, the number of effects of the ambient medium on the galactic structure listed in this review seems to imply that interaction with the intergalactic medium solely determines the evolution of galaxies. This, naturally, is not so, and there exist "inside" theories for all the phenomena we tried to explain. Differences in the gas content of galaxies can be explained to some extent by the mechanism of galactic winds (Mathews and Baker 1971); spiral structure is the subject of the elegant and well-developed theory of density waves (see, e.g., Lin 1976) and collective effects have been proposed to explain the bending phenomenon (Lynden-Bell 1965). High-velocity hydrogen clouds may be just a local population (Giovanelli 1977) or may be formed by the cooling of the galactic fountain at one kpc above the galactic plane (Shapiro and Field 1976). No "inside" theory for ring galaxies has been proposed yet, but some modification of the explosion theory of spiral pat-

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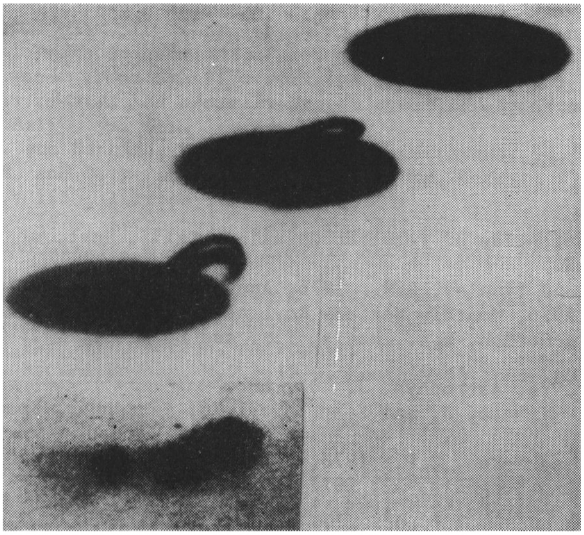

Fig. 6. An example of the collision between a disk galaxy and an intergalactic cloud after Freeman and de Vaucouleurs (1974). Three successive phases of the penetration of the cloud through the galaxy and the peeling-off of the gas ring are shown. Compare the last phase with the photograph of NGC 7828-29 = Arp 144 at the bottom.

tern (van der Kruit, Oort and Mathewson 1972) seems to be usable.

All this is natural. Pure self-consistent theories have always had much more appeal for theoreticians than "dirty" mechanisms invoking outside factors. Nevertheless, we are dealing with real phenomena which frequently do not approve of our aesthetic principles. And maybe the goal of the closure of an open system has its own charm.

As usual, there also exists a middle path. Most of self-consistent mechanisms need an external perturbing agent which provides for the flow of energy needed to maintain oscillation modes (see Toomre 1969). Even if this is the only role of the ambient medium in the galactic evolution, it is unquestionably an important one.

Since galaxies have passed only the first steps of their evolutionary route, they may not have had time enough to detach themselves com-

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pletely from the medium they were born in. So the interaction between galaxies and the ambient medium can be considered simply as final touches in the process of galaxy formation. And if there will be a period of independence in the evolution of galaxies, their ultimate fate is determined once more by external factors. If the mean density of the universe is less that the critical one galaxies will die cold, lone and miserable but otherwise they will merge together into a hot bath of radiation.

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