and abnormal cells. This makes the probability that a normal cell will divide in the time interval $(t, t+\Delta t)$ equal to Δt, irrespective of the time since its last division. For the abnormal cells, the corresponding probability is $\kappa\Delta t$.

The development of the process in time depends solely on the state of the configuration at one given time. All links joining neighbouring normal and abnormal cells are equally likely to "break" in unit time. The normal neighbour is replaced by an abnormal daughter cell with probability $\kappa/(\kappa+1)$; with a complementary expression for the probability that the abnormal neighbour is replaced by a normal daughter cell. Such a growth process with $\kappa=\infty$ was considered some years ago by Eden[6], although he did not have the necessary experimental evidence to recognize it as a possible model for tumour growth. On the strength of limited computer simulations, he made the obvious conjecture that the exponent in equation (2) might be 0.5.

We simulated the process by retaining in the computer memory a list of boundary points and updating this list whenever a change in the configuration took place; adding and deleting as necessary. It was then possible to obtain realizations with κ only slightly greater than unity, which would have been prohibitively time-consuming if we had had to scan the entire array periodically. Solutions of such problems are not strongly dependent on the specific distribution of division times postulated[7]. In particular, the exponent in equation (2) is a consequence of the curious diffuseness of the boundary, which is in no way dependent on the specific distribution assumed.

Critical Discussion

Although we have supposed the carcinogenic advantage to reside in a higher rate of cellular division than normal, one might (O. H. Iversen, personal communication) equally well postulate, for example, that the advantage lay in a stronger adherence of the abnormal cells to the basement membrane: the conclusions would not be materially changed. The motility of cancer cells is thought to give cancers their invasive appearance, but our contention is that this is not necessary to account for patterns which seem to us to be more evocative of an evenly balanced contest. The same patterns have been adduced as evidence for a multi-cell origin of tumours. Here again, this is unnecessary, although we certainly do not rule them out. Indeed, to harmonize equation (2) with skin-painting experiments on mice, several hundred initial "hits" must be assumed to reduce the latent periods to a reasonable period. This is certainly not an implausible assumption within the experimental limits.

Our model is non-specific; it does not even distinguish between benign and malignant growths. We have studied the basal layer only and have said nothing about subsequent tumour growth. We envisage that any abnormal growth, even a papilloma, requires a broad and substantial foundation in the basal layer.

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Infall of Matter in Galaxies

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Arguments based on the existence of intergalactic matter are advanced to show that this matter may interact with and be accreted by galaxies to produce observable consequences. The diversity of the phenomena that results from such processes offers a possible understanding of some of the properties of extragalactic systems.

THE most striking result of surveys of the distribution and motions of neutral hydrogen away from the galactic plane[1-3] is the discovery of several high velocity hydrogen clouds or concentrations, nearly all having negative (approaching) radial velocities of up to about 200 km s^{-1}. Oort[4] believes that the clouds represent material of local origin which has left the galactic plane and is being pushed back into it by infalling intergalactic matter. It seems equally plausible, however, to suppose that we are observing the infalling matter itself, which is initially ionized but recombines into neutral clouds when it is decelerated and compressed by interaction with gas near the galactic plane. Both assumptions lead to similar estimates for the rate of infall of material into the galactic plane. I shall adopt the estimate given by Oort[4], which is equivalent to a rate of about 25 $M_\odot$ $pc^{-2}/10^{10}$ yr, if the material is 70% hydrogen. If the infall is assumed to occur uniformly over a disk of radius 15 kpc, the total infall rate for our Galaxy is about 2 $M_\odot$ yr^{-1}.

This accretion rate requires a fairly high density of intergalactic material outside our Galaxy. There is no conclusive evidence for the existence of intergalactic matter, but several observations suggest its presence. X-ray observations[5] are consistent with an intergalactic medium having a temperature of about 2–3 $\times 10^6$ K and a density of the order of 10^{-29} g cm^{-3}. The spectra of distant quasars often show numerous absorption lines which, according to Silk[6], can be produced by relatively cool intergalactic clouds with temperatures between 2×10^4 and 10^5 K. There has also been speculation that the "missing mass" inclusters of galaxies[7] may be intergalactic matter. In the case of the local group it has been argued[4,8] that the fact that our Galaxy and M31 are moving toward each other rules out the possibility that the local group could be expanding, and indicates that there must be a substantial amount of intergalactic matter present; Oort[4] estimates the density of intergalactic matter in the local group to be about 3×10^{-28} g cm^{-3}.

Predicted Accretion Rate

The infall rate to be expected theoretically has been discussed by Oort[4], and may also be estimated from the classical accretion theories of Bondi and Hoyle[9] and Bondi[10]. According to Bondi, the accretion rate for a galaxy of mass M moving subsonically through a medium of density ρ, gas constant $\mathcal{R}$, and temperature T is given by

$$\frac{dM}{dt} \simeq 2\pi \frac{(GM)^2}{(\mathcal{R}\,T)^{3/2}}\,\rho \qquad (1)$$

If we adopt $M = 1.5 \times 10^{11}\ M_\odot$ and assume $\rho = 10^{-29}$ g cm^{-3} and $T = 2.5 \times 10^6$ K, we obtain an accretion rate of only about 0.1 $M_\odot$/yr, indicating that accretion is probably not important for galaxies immersed in the general intergalactic medium; if, however, the ambient density is increased to 3×10^{-28} g cm^{-3}, as estimated for the local group, the accretion rate becomes about 2 $M_\odot$ yr^{-1}, which agrees with the observationally estimated infall rate for our Galaxy.

Theoretical calculations suggest that the collapse of a protogalaxy[11] may leave behind an envelope of uncondensed material which continues to collapse into the central galaxy for a relatively long time. When the boundary of a collapsing protogalaxy is allowed to expand with time, the infall of material from the remnant protocloud can continue at an appreciable rate for well over 10^{10} yr. Infall rates after 10^{10} yr are found to be between 0.4 and 3 $M_\odot$ yr^{-1}; again, these numbers agree with the estimated infall rate for our Galaxy. In fact, a much larger range of accretion rates is possible, and in some cases the formation of a galaxy may extend over such a long period of time that even after 10^{10} yr most of the mass remains in the form of uncondensed intergalactic matter.

Galactic Interstellar Medium and Population I Content

According to Oort[4], the surface density of gas in the galactic plane is 8 $M_\odot$/pc^2; the estimated inflow rate of about 25 $M_\odot$/pc^2/10^{10} yr is then sufficient to double the amount of gas in the galactic plane after about 3×10^9 yr, if no gas is lost. In reality, however, the gas is continually consumed by star formation. Using a method similar to that of Schmidt[12,13], I find values for the rate at which gas is at present being converted into stars in the galactic plane from 15 to 30 $M_\odot$/pc^2/10^{10} yr. Within the uncertainties, this is the same as the rate at which gas is estimated to be flowing into the galactic plane from intergalactic space, suggesting that the galactic gas and Population I content are being sustained by inflow of material from nearby intergalactic space.

If these estimates are correct, most of the present gas content of our Galaxy has not been present since the Galaxy was formed, but represents material which has been acquired more recently by accretion. This alleviates the problem of understanding how the present gas content of the Galaxy has managed to survive for 10^{10} yr without being consumed by star formation and may also explain why the gas content has been exhausted in some galaxies but not in others which are otherwise quite similar (see below). The dynamical pressure of the infalling material can produce observable perturbations in the motion of the gas in the galactic disk, particularly if the infalling material is clumpy in structure; perturbations of the order of 10 km s^{-1} could then be produced. This might account for some of the deviations from circular motion which have been observed in the galactic interstellar material[14,15]. Also, the dynamical pressure of the infalling material is of the same order as that required to trigger the condensation of the interstellar gas into dense, cool clouds[16]; thus the infall of matter may be instrumental in producing the observed cloudy structure of the interstellar medium.

Spiral Structure and Hubble Sequence

If the galactic gas and Population I content are continually replenished by the inflow of intergalactic material, the classical "winding up" problem of spiral structure becomes less serious, since the age of the spiral arm material may be considerably less than that of the galaxy itself. When a galaxy acquires new material by accretion, the accreted material will almost inevitably form a spiral pattern, since any clumps or density fluctuations which may be present in it will always be drawn out into spiral arcs by differential rotation. Thus it is possible that the spiral patterns seen in many galaxies may be produced by the accretion of intergalactic material. (It should be noted that even the currently popular density wave theories of spiral structure do not account for the origin of the spiral pattern, which must be generated by some extraneous mechanism.) An almost limitless variety of patterns can be produced by the accretion of clouds of material which differ in size, shape, and angular momentum.

The principal features of the Hubble sequence[17] can also be understood on the hypothesis that spiral arms represent recently accreted material. The only physical property which varies in a strongly systematic way along the Hubble sequence from SO to Sc is the relatively superficial one that the SO galaxies contain no gas or young stars, whereas the spiral galaxies contain gas and young stars in a proportion which increases systematically along the sequence Sa→Sc (ref. 18). This can be understood if the SO galaxies represent cases where the collapse of the initial protogalactic cloud took a relatively short time, and the infall of material was completed long ago. The spiral galaxies, on the other hand, may represent cases where, because of less favourable initial conditions, the surrounding intergalactic matter has taken a much longer time to condense, and infall of material is still going on. If the accretion of new material tends to occur sporadically or at a variable rate, a galaxy which has recently experienced active accretion of new material will show a high gas density and a relatively open spiral pattern (Sc), whereas if some time has elapsed since a significant amount of new material was last acquired, the gas content will be partially depleted by star formation, and the arms will be relatively tightly wound (Sa).

Evidence for this interpretation is provided by the correlation of galaxy type with occurrence in clusters. Theoretical collapse calculations[11] predict that in a dense cluster of galaxies, where each protogalactic cloud is confined to a relatively limited volume of space, the collapse of a protogalaxy should take much less than 10^{10} yr, and there should be little intergalactic material left at the present time. Most or all of the galaxies in such a dense cluster should then be elliptical or SO galaxies. On the other hand, in a very loose cluster or in the space between clusters, a protogalactic cloud can become much more extended, and its collapse may well take longer than 10^{10} yr; one should then expect to see many galaxies which are still accreting material, that is, many spiral galaxies. These predictions agree with the fact that the galaxies in massive, dense clusters such as the Coma cluster are nearly all elliptical or SO galaxies, whereas spirals predominate among field galaxies and in small, loose groups such as the Hercules cluster and the local group[7,19].

It is possible that some of the barred spirals may represent disk galaxies which have accreted material that happens to be rotating in a plane which is tilted with respect to the disk. Accumulation of material along the line of intersection of the two planes could then produce a "bar" along which the material, having lost much of its angular momentum, falls in toward the nucleus. The radial velocity measures in the barred spiral NGC 1365[20] do in fact appear to indicate inflow of material into the nucleus.

Structural and Kinematic Peculiarities

Some galaxies have structural peculiarities which make them difficult, if not impossible, to classify in the Hubble system[17,21]. It is often difficult to see how the irregularities could be interpreted in terms of a self-sustaining wave pattern, and it is hard to avoid the impression that they are short lived and of relatively recent origin. Also, in many galaxies the gas exhibits substantial deviations from circular motion, often associated with a chaotic or irregular appearance of the galaxy. Examination of photographs of galaxies and of the available kinematic data suggests that in many cases some peculiarities may be caused by infall of intergalactic matter.

For example, NGC 5128—the peculiar galaxy associated with the radio source Cen A—has the appearance of a giant spherical galaxy surrounded by a broad irregular dark band of absorbing material, which may represent material which has recently fallen into the galaxy and is in the process of collapsing to a disk, but has not yet settled into equilibrium. From observations of the radial velocity of the gas in this galaxy, Burbidge and Burbidge[22] concluded that the gas and dust in NGC 5128 are moving systematically inward with respect to the stars with a velocity of the order of 100 km s^{-1}. Other studies[23,24] do not confirm a systematic inward motion, but show nevertheless that large inward velocities are present near the centre of the galaxy; inward velocities of the order of 100 km s^{-1} are observed in 21 cm absorption[23], and up to ~ 300 km s^{-1} in Hα emission[24]. All studies agree that large turbulent velocities are present in the gas.

Galaxies with Active Nuclei

In some cases the accreted material may have little or no net angular momentum about the centre of the galaxy; it will then fall directly into the nucleus and become highly condensed in the potential well at the centre of the galaxy. This will lead to a high rate of star formation and a high luminosity in the nucleus of the galaxy, and a strong emission spectrum will be produced by the dense, turbulent gas in the nucleus—as observed in galaxies with active nuclei. Since there is now considerable evidence[25] for continuity in the properties of the various types of objects having active nuclei, including the Seyfert galaxies, radio galaxies, and quasi-stellar objects (QSOs), it may be that all are manifestations of nuclear activity caused by rapid accretion of intergalactic material. This possibility has already been suggested by Shklovsky[26] as an explanation for radio galaxies.

If a galaxy accretes matter at a "typical" rate of, say, 1 $M_\odot$ yr^{-1}, and if the material is transformed into stars as fast as it is accreted, then after about 10^8 yr a nearly constant luminosity of $\sim 10^{10} L_\odot$ is attained. An inflow rate of this order, if concentrated in the nucleus of a galaxy, will produce a bright nucleus with a strong emission spectrum. If the galaxy is surrounded by a relatively dense, cool cloud of intergalactic material—for example, with a density of 2×10^{-28} g cm^{-3} and a temperature of 10^5 K—the accretion rate predicted by equation (1) for a galaxy of mass 10^{11} $M_\odot$ is about 70 $M_\odot$ yr^{-1}, sufficient to produce a luminosity of $\sim 5 \times 10^{11}$ $L_\odot$ from normal processes of star formation. Under the same circumstances the accretion rate for a giant elliptical galaxy with a mass of 10^{12} $M_\odot$ is about 7×10^3 $M_\odot$ yr^{-1}, leading to a luminosity of about 5×10^{13} $L_\odot$, which is comparable with that of QSOs.

Although normal star formation processes may explain, at least in part, the luminosities and the emission spectra of the QSOs, additional mechanisms are required to account for the apparently non-thermal continuous emission, most of which occurs at infrared wavelengths; the variability in luminosity; and the radio emission (also variable) which is sometimes observed. Burbidge and Stein[27] have proposed that the continuous spectra of the QSOs and similar objects can be explained by many small non-thermal sources distributed throughout the nucleus of a galaxy; the basic energizing mechanisms for the individual sources might be pulsars or similar objects. Also, Rees[28] has recently shown how the radio emission might be explained by a model in which the energy source is provided by a large number of pulsars or similar objects embedded in a dense disk of gas at the centre of a galaxy. It seems at least energetically feasible that the optical outbursts of the QSOs can be produced by the same basic "flare" mechanism which Rees has proposed to explain the radio outbursts, since the energies involved are of the same order, and are comparable with the gravitational energy available from the formation of a pulsar or other highly collapsed object.

Thus the chief properties of QSOs and similar objects may be accounted for by the formation of large numbers of pulsars in the nucleus of a galaxy where there is a high rate of star formation due to the infall of intergalactic matter. I note that if the primary energy source is gravitational rather than nuclear, the requirements for the accretion theory are somewhat eased, since the gravitational energy available from the formation of collapsed objects may substantially exceed the total nuclear energy available from a given mass of material.

If the QSOs and radio galaxies are indeed explainable by rapid accretion of intergalactic matter, it is tempting to interpret the "jets" observed in the QSO 3C273 and the radio galaxy M87 as "accretion tails" where the infalling material is focused into a narrow wake behind the accreting galaxy, as predicted in classical accretion theories. Such an explanation would account naturally for the highly condensed and collimated nature of these jets, and would allow the optical and radio emissions from the jets to be explained by the same mechanisms which account for the nuclear activity.

I note, finally, that the accretion hypothesis would account readily for the fact, as established from counts of distant quasars, that these objects were more numerous in the past than they are at present[29]; this would be expected on the basis of the accretion picture, since both the amount and the density of uncondensed intergalactic material would have been higher during the earlier stages of expansion of the universe.

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