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The dynamics, shapes and origins of elliptical galaxies

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Recent observational and theoretical work indicates that elliptical galaxies are not the oblate spheroidal objects frequently assumed, but triaxial ellipsoidal bodies. Their forms are in most cases determined less by rotation than by anisotropy in their velocity dispersion structures dating from their earliest formative period. Dissipationless theories of galaxy formation have little difficulty in explaining in a general way the existence of galaxies of this type, although many details remain to be satisfactorily worked out. The domination of the dynamics of ellipticals by residual velocity anisotropy rather than by rotation would seem to be harder to understand in the context of dissipative theories.

1. Introduction

I wish first to discuss the dynamical implications of the rather low rotation velocities in elliptical galaxies that Dr Gunn has mentioned. I hope to show that when one combines these observations with photometric studies and recent theoretical work, one finds onself obliged to revise radically the classical picture of elliptical galaxies in favour of models in which their dynamics are largely determined by accidents of birth. This leads naturally to a discussion of what one might learn from the present configurations of ellipticals of the manner of their formation.

2. Dynamical implications of the observations

(a) *The tensor virial theorem*

Chandrasekhar's tensor virial theorem (Chandrasekhar 1964) provides a valuable insight into the physical significance of the low rotation velocities reported by Dr Gunn. This theorem, which is derived by taking moments of the collisionless Boltzmann equation (the equation governing the evolution of the stellar distributions of galaxies), states that

$$\tfrac{1}{2}\mathrm{d}^2 I_{ij}/\mathrm{d}t^2 = 2T_{ij} + \Pi_{ij} + W_{ij} + S_{ij}, \tag{1}$$

where $I_{ij} = \int_v \rho x_i x_j \,\mathrm{d}^3x$ is a type of moment of inertia tensor, $T_{ij} = \frac{1}{2}\int_v \rho \bar{u}_i \bar{u}_j \,\mathrm{d}^3x$ is the ordered kinetic energy tensor ($\bar{\boldsymbol{u}}(\boldsymbol{r})$ is the streaming velocity at $\boldsymbol{r}$), $\Pi_{ij} = \int_v \rho\overline{(u_i-\bar{u}_i)\,(u_j-\bar{u}_j)}\,\mathrm{d}^3x$ is the pressure energy tensor, $W_{ij} = -\int_v \rho x_i(\partial\Phi/\partial x_j)\,\mathrm{d}^3x$ is the Chandrasekhar potential energy tensor and $S_{ij} = -\oint \rho x_i \overline{u_j u_k}\,\mathrm{d}S_k$. Here I shall confine the discussion to the case when the volume V contains the entire system, when we have $S_{ij} = 0$, although it should be noted that if one retains the surface term S_{ij} one can obtain interesting results by applying the virial theorem to individual components of galaxies (Binney 1979). Suppose that the figure of the system under investigation rotates with steady angular velocity ω about one of its principal axes, which we may call the third axis, x_3. Then one may evaluate $\mathrm{d}^2 I_{ij}/\mathrm{d}t^2$ and find that in the natural coordinate system there are only three non-trivial equations involved in the virial theorem:

$$-\omega^2\delta I = 2T_{11}+\Pi_{11}+W_{11}, \quad (2a)$$

$$\omega^2\delta I = 2T_{22}+\Pi_{22}+W_{22}, \quad (2b)$$

$$0 = 2T_{33}+\Pi_{33}+W_{33}, \quad (2c)$$

where $\delta I \equiv I_{22}-I_{11}$. If we add the first two of these equations, ω drops out of the problem, leaving us with (2c) and

$$0 = 2(T_{11}+T_{22})+(\Pi_{11}+\Pi_{22})+(W_{11}+W_{22}). \quad (2d)$$

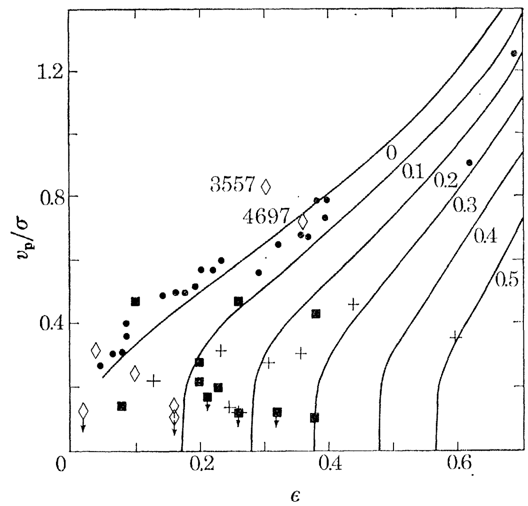

FIGURE 1. A diagram of v_p/σ against ϵ for oblate models. The solid curves show the relation (3) between $v_p/\sigma \equiv \frac{1}{4}\pi(\bar{v}/\bar{\sigma})$ and ϵ for $\delta = 0, 0.1, \ldots$, etc. Details of the evaluation of the W_{ii} and of the projection factor $\frac{1}{4}\pi$ will be found in Binney (1978). The dots show $(v_m/\sigma_m)_p$ for various numerical (Gott 1973, 1975; Larson 1975) and analytical (Wilson 1975) models having $\delta = 0$. Twenty-six observational values of (v_m/σ_m) are shown from the work of Illingworth (1977) (crosses), Davies (1978) (diamonds) and Schechter & Gunn (1979) (squares). The ellipticities used are, where available, those at 5″ to 10″. The two rapidly rotating galaxies observed by Davies are marked with their NGC numbers.

Define four new quantities $\bar{v}$, $\bar{\sigma}$, δ and q by $M\bar{v}^2 = 2(T_{11}+T_{22})$, $M\bar{\sigma}^2 = \Pi_{11}$, $\delta = (\Pi_{11}-\Pi_{33})/\Pi_{11}$ and $q = \Pi_{22}/\Pi_{11}$, where M is the total mass of the system. Physically, $\bar{v}$ may be interpreted as the r.m.s. rotational velocity in the (x_1, x_2) plane, $\bar{\sigma}$ is the r.m.s. random velocity along the x_1 axis, δ is the mean fractional excess of pressure in the x_1 as against the x_3 direction and q is the ratio of the pressures in the x_2 and x_1 directions. Introduce these quantities into (2c) and (2d) to replace $\boldsymbol{T}$ and $\boldsymbol{\Pi}$, set $T_{33} = 0$ (which amounts to discounting the possibility of meridional circulation) and divide (2d) by (2c) to obtain

$$(\bar{v}/\bar{\sigma})^2 = \{(W_{11}+W_{22})/W_{33}\}\,(1-\delta)-(1+q). \quad (3)$$

If one restricts oneself to the simple case of galaxies whose isodensity surfaces are all similar to one another, one may employ a beautiful result from potential theory which states that $(W_{11}+W_{22})/W_{33}$ depends only on the axial ratios (Roberts 1962). That is, the radial density profile factors out of the final answer. Therefore $\bar{v}^2/\bar{\sigma}^2$ is under these circumstances determined by the axial ratios, δ and q alone. If the galaxy is biaxial, one has that $q = 1$ by symmetry, so $\bar{v}/\bar{\sigma}$ depends only on δ and the ellipticity ϵ. Figure 1 shows this relation after the appropriate projection of $\bar{v}$ along the line of sight in the equatorial plane.

These results are exact and rather general but do not lend themselves to direct confrontation with observation. Indeed, if one number characterizes the rotation of a galaxy, it is v_m/σ_m, the ratio of the peak rotation velocity to the central (and therefore maximum) line-of-sight velocity dispersion. Figure 1 shows predictions for the ratio of a *mean* rotation velocity to a *mean* velocity dispersion. The dots plotted in figure 1 do, however, suggest that these two ratios may in fact be nearly equal; each of these points represents the v_m/σ_m of one of the model galaxies of Gott (1973, 1975), Larson (1975) or Wilson (1975). The models in question all have $\delta = 0$, so it is encouraging that their points follow the $\delta = 0$ curve in figure 1. A recent theoretical investigation of the rotation curves of galaxies of constant ellipticity also confirms that isotropic ($\delta = 0$) systems should have $\bar{v}/\bar{\sigma} = v_m/\sigma_m$ to good accuracy (Binney 1979). If we then accept that $\bar{v}/\bar{\sigma} = v_m/\sigma_m$ for galaxies, and suppose that these are oblate spheroidal in form, we may read off from figure 1 the values of δ proper to some real systems. The observational points in figure 1 are from the work of Illingworth (1977), Davies (1978) and Schechter & Gunn (1979). Clearly if ellipticals are oblate spheroidal in form, many of them have appreciable δ values, so, remaining for the moment with the arbitrary assumption of oblate spheroidal form, let me discuss the dynamical interpretation to be placed on this fact.

(*b*) *Anisotropy-dominated oblate spheroidal galaxies*

If an oblate galaxy has $\delta \neq 0$, there is for some reason more random motion parallel to the galaxy's equatorial plane than in the perpendicular direction. There are two main ways in which this could occur. Either the velocity ellipsoids at each point are cigar-shaped with their long axes pointing in the azimuthal direction, or they are roughly saucer-shaped with their short axes pointing out of the galaxy's equatorial plane. The distribution function of a galaxy whose velocity ellipsoids are cigar-shaped and orientated azimuthally can be of the classical type, that is, depend on the particle coordinates and velocities only through the particle energy E and azimuthal angular momentum L_z, whereas a non-classical third integral of the type familiar from studies of stellar motion in the solar neighbourhood must be invoked if one wishes to consider galaxies having saucer-shaped velocity ellipsoids.

To my mind there can be little doubt that the non-zero δ, which figure 1 suggests to be characteristic of many elliptical galaxies, are due to the velocity ellipsoids in these systems being saucer-shaped on account of non-classical integrals, rather than cigar-shaped as allowed by the classical picture. The reason for my confidence in this matter is that I can well understand how third-integral dominated galaxies might have been formed, whereas I know of no plausible model of the formation of an anisotropy-dominated galaxy described by the classical picture. Indeed, the formation of third-integral dominated galaxies fits so naturally into some pictures of galaxy formation that it was actually predicted before the low rotation velocities of ellipticals became known (Binney 1975). Thus numerical simulations of the relaxation of stellar systems from irregular initial conditions show that when, after three or four crossing times, a system settles to its state of quasi-equilibrium, any asphericity of the initial conditions will be reflected in a degree of flattening or elongation of the final figure. This was first demonstrated for the relaxation of thin circular sheets of stars like those suggested by the pancake theory of galaxy formation of Zeldovich and collaborators (Sunyaev & Zeldovich 1972) as initial conditions from which the violent relaxation of galaxies might have begun (Binney 1976). Later, Aarseth and I showed that the equilibrium systems formed in numerical experiments of this type owed their shapes to non-classical integrals rather than the peculiar distribution of angular momenta implied by models having distribution functions depending only on classical integrals (Aarseth & Binney 1978).

(c) *Elliptical galaxies as triaxial bodies*

Aarseth & Binney (1978) also showed that the triaxial initial conditions were likely to lead to triaxial equilibrium systems that owed their shapes to two non-classical integrals. Thus if, as I shall argue in a moment, there is a high probability that the initial conditions from which the violent relaxation of ellipticals began were highly irregular, these numerical results indicate that not only is it entirely natural that elliptical galaxies should be found to be dominated by anisotropy but that one is forced to the revolutionary conclusion that they must inevitably be triaxial, because we have no reason to believe that the initial conditions would have been rotationally symmetric and the physics of the relaxation process is such that initial deviations from rotational symmetry will have survived to be reflected in the present relaxed systems. This may seem to be overstating the case somewhat, as Aarseth and I were actually only able to *suggest* that triaxial configurations would be long-lived, because the importance of two-body encounters to our simulations prevented us following the evolution of triaxial systems for more than a tenth of a Hubble time. Our confidence in the existence of long-lived triaxial configurations was, however, buoyed by simple experiments with the motion of single particles in reasonable triaxial potentials, because these experiments strongly suggested that there are enough non-classical integrals to guarantee the persistence of triaxial configurations once they have survived the initial relaxation process, and more recently Schwarzschild (1979) has systematically probed the possible orbits of single particles in given potentials to indicate that probably *any* reasonable triaxial potential may be taken as the starting point for a self-consistent galaxy model that will endure for at least a Hubble time. I therefore now feel there can be little doubt that ellipticals are generically triaxial.

A simultaneous attack on the classical picture of ellipticals as oblate spheroids arose from the work of Miller (1978) and Miller & Smith (1979) who numerically followed the violent relaxation of rapidly rotating initially spherical systems of stars. They found that these invariably settle to apparently stable rotating bars of stars which rotate end over end in the same sense as the streaming of the stars, though with somewhat slower angular velocity. In these bars the velocity dispersion appears to be greatest in the direction of the rotation axis. Figure 2 shows that the virial theorem predicts that bars with isotropic velocity dispersion should generally show rather slower rotation than equally aspherical oblate models and it did at one time seem that the Miller–Smith bars might be compatible with the observed properties of ellipticals (Illingworth 1977). Figure 2 shows, however, that few ellipticals lie above the line in the $(\bar{v}/\bar{\sigma}, \epsilon)$ plane above which the virial theorem predicts that one half of all ellipticals would lie if they were prolate spheroidal objects having isotropic velocity dispersion (the scatter in predicted $\bar{v}/\bar{\sigma}$ at fixed ϵ arises due to the random orientation of bars to the line of sight). Moreover, the anisotropic velocity dispersions of the Miller–Smith bars will push more than half of these above the indicated median line. It also seems that few ellipticals have the almost linear rotation curves predicted by Miller & Smith. I therefore doubt that rapidly rotating bar-like configurations are the right model for elliptical galaxies, although it seems likely that systems of this sort play a role in the dynamics of spiral galaxies.

Observation provides one other piece of evidence to support the idea that ellipticals are generically triaxial in addition to those furnished by the dynamical studies reported by

Dr Gunn. This is the twisting of the isophotes of many elliptical galaxies; that is, the tendency of the position angles of the major axes of ellipses fitted to successive isophotal contours to differ slightly from one another. This behaviour, first suggested by Evans (1952) and conclusively demonstrated to occur in a significant fraction of ellipticals by Carter (1978), King (1978), Williams & Schwarzschild (1979) and others, is readily understood in terms of the triaxial model of ellipticals. This is because the ellipticity of the isophotes of many galaxies

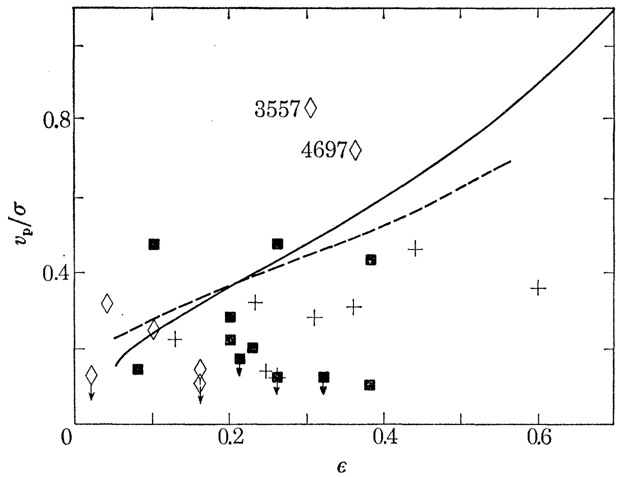

FIGURE 2. A diagram of v_p/σ against ϵ for prolate galaxies. The full curve shows the $(\bar{v}/\bar{\sigma})_p$ value predicted by the virial theorem for prolate spheroidal galaxies seen broadside-on from the equatorial plane. If elliptical galaxies were prolate spheroidal, had $\delta = q = 0$ and were randomly orientated in space, half should have $(\bar{v}/\bar{\sigma})_p$ points above the broken line and half below (Binney 1978). The observational points are as in figure 1.

depends on the isophotal semi-major axis length, so that any model of ellipticals must envisage changes in the three-dimensional shapes of successive isodensity surfaces. If galaxies were biaxial, shape changes of this type would not suffice to account for the isophotal twist phenomenon; one would have additionally to hypothesize that the three-dimensional isodensity surfaces differed from one another in their alignments of the principal axis. This aesthetically unsatisfying situation contrasts strikingly with the position when one admits triaxiality; then the inevitable changes in the shapes of the three-dimensional isodensity surfaces induce as a projection effect isophotal major axis twists for many observers. No additional misalignment of isodensity surfaces is required.

The discussion so far has been incomplete in two respects. I have argued that the observations suggest, independently of whether ellipticals are oblate or prolate structures, that the dynamics of these galaxies are dominated by anisotropy in their velocity dispersion structures and that this velocity anisotropy is a relic of the aspherical initial conditions from which they collapsed. It remains to ask (*a*) whether one may understand why the irregularities of the initial conditions were such as to bequeath the distribution of shapes that we observe today and (*b*) why the velocity dispersion anisotropy of ellipticals is associated with as little rotation as there now appears to be.

3. The formation of anisotropy-dominated spheroidal galaxies

(a) *Tidal interactions*

Until recently it was widely believed that the shapes of galaxies depended on the angular momenta that they acquired by tidal interaction with their neighbours at the protogalactic stage (e.g. Peebles 1969). More recently, Efstathiou & Jones (1979) have used 1000-particle simulations of dissipationless formation and virialization of stellar systems in the expanding Universe to show that little angular momentum is acquired by tidal interactions between neighbouring protogalaxies. Thus it is not to be wondered at that most elliptical galaxies are found observationally to be slowly rotating. This does not, however, imply that tidal interactions between protogalaxies were unimportant for the development of the shapes of elliptical galaxies. Indeed, two simple calculations suggest that the shapes of both ellipticals and rich clusters of galaxies may have been determined by early tidal interactions via the tendency that these have to enhance the anisotropy energies of expanding condensations.

At a sufficiently early epoch, the development of the shape of a condensation may be followed in the linear approximation due to Peebles (1969). A convenient measure of the anisotropy of a condensation is furnished by its Chandrasekhar tensor W_{ij}: define q by

$$q \equiv (3W_{zz} - \mathrm{tr}\, W)/\mathrm{tr}\, W,$$

where W is defined below (1), to find that if the perturbation is oblate spheroidal with small ellipticity $\epsilon(\equiv 1-b/a)$, one has $q \approx \frac{4}{15}\epsilon$. Now apply Peebles's solution for the density and potential perturbations $\delta\rho(t)$ and $\delta\phi(t)$ of growing density enhancements in an Einstein–de Sitter universe to these equations to find that the associated anisotropy energy q of a perturbation grows as $t^{\frac{2}{3}}$ (Binney & Silk 1979). That is, the anisotropy energy of a density inhomogeneity grows as a first order quantity when one follows the evolution of a perturbed Einstein–de Sitter universe. This should be contrasted with Peebles' result that the angular momentum grows at this stage only as a second order quantity.

Now ask what would happen if, not withstanding the conclusion of the foregoing paragraph that the anisotropy energy and therefore the ellipticity ϵ grows in step with the density contrast, a density perturbation had emerged from the period of linear growth as a nearly spherical structure. Would it remain spherical during its period of nonlinear growth, or be seriously distorted by the tidal fields of neighbouring condensations? A simple calculation of the distortions induced by neighbours shows that even in these circumstances the condensation would have adopted substantially elliptical form by the time it had attained maximum expansion (Binney & Silk 1979). Thus the conclusion seems inescapable that by the time that condensations of all types reached maximum expansion, they will in the mean have had highly eccentric shapes.

What do these considerations allow us to say about (*a*) the angular momenta and (*b*) the true figures of galaxies? Thuan & Gott (1977) have shown that if the arrangement of matter around a protogalaxy is uncorrelated with the orientation of the protogalaxy, the latter will on average acquire a dynamically important measure of angular momentum by tidal torquing against the background. Thus the angular momentum poverty of elliptical galaxies can only be understood if the assumption of Thuan & Gott, that there is no correlation between the orientation of a protogalactic figure and the quadrupole moment of the 'hole' in which it sits, is false. The analysis just described, by indicating that the quadrupole moments of galaxy and hole are linked as cause and effect, offers a direct explanation of why such angular-momentum suppressing correlations do exist, but for the benefit of those who like to think in terms of correlation functions it may be worthwhile to make the same point in another way. Consider what will happen if in a region A whose matter is destined to fall into a certain galaxy, the density is higher than at a second point B situated a similar distance from the protogalactic centre in some other direction. Then the density at a point A′ which lies beyond A though in the same direction as A, is likely to be higher than the density at a point B′ which lies as far beyond B as A′ lies beyond A, because proximity to a high density region in a correlated density field biases towards high density. The quadrupoles of the galaxy and the surrounding matter will therefore tend to be aligned and angular momentum exchange expressed. The larger the region outside a protogalaxy which is highly correlated with it, but fails to fall into the final system, the lower will be the system's angular momentum. In a low density Universe, such unbound yet highly correlated regions should be very extensive and the angular momentum typically acquired correspondingly low.

If the shapes of galaxies are due to tidal interactions between protogalaxies in the nonlinear régime, there is a clear implication that galaxies will tend to have nearly prolate shapes, because the tidal field experienced by any particular galaxy will generally be dominated by that of its nearest neighbour. However, consideration of another implication of this theory indicates that it is unlikely to be correct, at least in its simplest form, the difficulty being that any theory that ascribes the shapes of elliptical galaxies to tidal interactions with *other* galaxies predicts that the more massive galaxies should be the most spherical. For example, Binney & Silk (1979) find that tidal distortions predict for large galactic masses M, $\epsilon \sim M^{-\frac{1}{3}}$. Efstathiou & Ellis (1978) and van den Bergh (1977) find, on the contrary, that the observations indicate that ϵ tends to increase somewhat with mass. I believe that this failure of tidal theories has to be taken seriously, for it seems unlikely that an attempt to wriggle out of the problem by appealing to a different formation mechanism (for example cannibalism) for the most massive galaxies will cure the problem rather than shift it to some other range of galactic masses. The tidal theory of the origin of the shapes of ellipticals does, however, provide insight into the self-tidal distortion which may well have been responsible for the shapes of ellipticals, to which I now turn.

(*b*) *Lin, Mestel & Shu effect, pancakes and self-tidal distortion*

It has long been known that an initially spherical, pressure-free cloud flattens strongly when it is allowed to collapse under its own gravity (Lin *et al.* 1965). What is less widely recognized is that one of the flattening processes responsible for this effect works equally well when a nearly spherical cloud expands like a small piece of the Universe against the pull of self-gravity, so that an initially nearly spherical region of uniform density can become progressively more flattened until eventually it starts to collapse along one of its principal axes while the other two are still expanding (Icke 1973). Both kinematic and dynamic effects are involved in the classical Lin–Mestel–Shu process. The kinematic effect is that if during a collapse both short and long axes are shrinking at the same pace, the short axis will go to zero before the long one, thus causing the flattening to increase without limit. Applied to an expanding system this kinematic effect tends to reduce the flattening. The heart of the Lin–Mestel–Shu instability is, however, a dynamical effect that may be described as self-tidal distortion, whereby the shortest axis is subject to the greatest (negative) acceleration. Therefore, if a slightly flattened system starts out with equal rates of expansion along all its principal axes, its flattening will grow steadily as it expands. This process may be investigated quantitatively by following the expansion of an initially slightly spheroidal uniform density body from conditions of density and expansion similar to those proper to a protogalaxy in an $\Omega = 0.1$ universe at redshift $z = 1000$. Small deviations of the figure of the body from spherical symmetry and of the expansion rate from isotropy grow during the expansion and subsequent collapse, so that when the density of the body first becomes infinite, the body forms either a sheet or a needle. The radius of the sheet or the half-length of the needle, expressed as a fraction of the post-virialization equilibrium radius of the system, furnishes an estimate of the overall anisotropy of the cloud and therefore of the ellipticity to be expected of the final relaxed system. Thus if a system forms a disk whose radius is similar to that of the final equilibrium state, it will relax to a highly flattened structure, whereas the formation of a very small disk indicates that the system is still fairly isotropic and will relax to a nearly spherical configuration. Hutchings, working in Berkeley, has performed such calculations and finds that 1% fluctuations in either the ellipticity or the isotropy of the Hubble flow at $z = 1000$ (when the amplitude of the density fluctuations was of order 2%) cause figures to form about 10^9 years after the big bang, whose major axes are roughly equal in length to the gravitational radius of the final configuration. Thus although Hutching's calculations overestimate the true effect by their failure to take into account the reduction in the strength of the destabilizing L.M.S. terms due to the protogalaxies being at large red shifts no more than perturbations on the smooth background, they do suggest that the only galaxies which will not be highly aspherical will be those few whose velocity and shape perturbations exactly cancelled one another. A fuller investigation along these lines, one which took into account the correction due to the presence of the background at early times and violent relaxation effects, would be of considerable value. A first step in this direction has recently been taken by White & Silk (1979), who have derived an analytical approximation to the expansion of an aspherical inhomogeneity in a Friedmann background.

Sunyaev & Zeldovich (1972) and Doroshkevich and co-workers (Doroshkevich *et al.* 1978, and references therein) were among the first to draw attention to the effect just discussed. In a series of papers, they have argued that coupled density and velocity perturbations set up by adiabatic primordial fluctuations will have led in this way to the collapse of flattened masses of gas. These workers then argue that if the primordial fluctuations were adiabatic, there would have been so little power on small scales that protogalatic clouds would have failed to fragment during collapse to disk configurations, so that strong shock fronts and the formation of giant pancakes of gas would have resulted. It is important to realize that two quite independent thoughts are involved here. On the one hand it is being pointed out that because large gas clouds will have enjoyed very little pressure support, they will have collapsed highly anisotropically. On the other hand it is being asserted that these clouds will have failed to fragment during their collapse phase. Personally, I accept the first point but not the second, because (*a*) I believe that gas contracting with a Mach number near 100 and a prodigious Reynolds number will have experienced no difficulty in developing small-scale density fluctuations *ab initio* by the nonlinear process associated with the name of Riemann (see, for example, Lamb 1932) and (*b*) because if pancake formation had been general, there would only be E5–E7 galaxies, as even strongly warped and puckered pancakes relax to highly flattened systems (Aarseth & Binney 1978). But I am inclined to think that the basic idea behind the Soviet work is correct; the shapes of ellipticals are due to the development of anisotropy during the expansion of bound regions. The anistotropy develops partly on account of initial velocity perturbations and partly due to initial deviations from spherical symmetry.

(*c*) *Mergers*

Aarseth and White (this symposium) discuss the possibility that the galaxies we see today were formed by the merger of earlier generations of smaller systems. Is velocity anisotropy in ellipticals a relic of mergers? White tells us that if such mergers did indeed take place, the observed rotation rates of giant ellipticals imply that they tended to result from head-on collisions, which suggests that the fragments merged on their first close passage. The merger simulations of Aarseth & Fall (on which Aarseth reports) confirm that this picture, rather than one in which galaxies in virialized groups do most of the merging, is correct. This being so, there is little difference between the merger picture and the anisotropic collapse and accretion model described above in that a realistic version of the latter is bound to countenance the formation of short-lived subfragments.

4. Conclusions

I have tried to demonstrate that recent observations of elliptical galaxies suggest that we should abandon the old picture of oblate spheroidal ellipticals with isotropic residuals, in favour of triaxial velocity-anisotropy dominated systems. These systems generally rotate rather slowly because the dispositions of protogalaxies and their surroundings tended to be correlated, which suppressed the acquisition of angular momentum by tidal interaction with the environment. Tidal distortion can in a general way account for the aspherical shapes of ellipticals, although the simplest type of theory, in which distortion by neighbours is responsible for the development of anisotropy, predicts an unobserved decline in the typical ellipticity of galaxies of large mass; one has only to broaden the concept of tidal distortion to embrace self-tidal distortion in the form of the instability of Lin *et al.* (1965), which seems to provide an adequate anisotropy-inducing mechanism. Another way of understanding the shapes of ellipticals is in terms of galaxy formation by rather head-on mergers of fragments, but this picture does not differ markedly from that of a realistic anisotropic collapse and accretion model.

Dissipation would, however, seem less easily reconciled with the prevalence in ellipticals of high degrees of velocity anisotropy. The dissipational pancake theory of the Moscow group, which led to the prediction that galaxies should be anisotropy-dominated, makes one uneasy about the degree of homogeneity that it attributes to violently collapsing clouds and anyway gives rise to too many highly flattened galaxies. By contrast, the more chaotic dissipational models discussed by Larson (1975) and more recently by White & Rees (1978) will probably prove unable to produce galaxies with the requisite residual velocity anisotropy, although the truth of this guess has yet to be proved. Dissipative theories of galaxy formation also run the risk that by concentrating the available angular momentum they will produce galaxies that spin too rapidly.

Of great interest is whether ellipticals and similar systems (for example rich clusters of galaxies) are typically oblate or prolate in structure, or whether all types of triaxial body are equally common. Combined X-ray and optical studies of rich clusters may enable us to determine the individual shapes of at least these systems reliably (Strimpel & Binney 1979) and with enough accurate photometry and velocity dispersion measurements it may be possible to address the problem of the shapes of elliptical galaxies statistically by exploiting the fact that if galaxies are oblate in form, they will exhibit the highest velocity dispersions and surface brightnesses when they appear most elongated, whereas prolate galaxies will tend to be least compact and possess the smallest line-of-sight velocity dispersions under these circumstances.

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