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Distant encounters between disk galaxies and the origin of S 0 spirals

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Summary. Simulations of the interactions between galaxies have hitherto emphasized the galactic stellar component. I present numerical hydrodynamic calculations of the fate of a disk of gas in a galaxy perturbed gravitationally by an intruder flying by in a hyperbolic orbit. I show that shocks occur even when the pericenter distance of the encounter is so large that the formation of stellar bridges and tails is unimportant. Since distant encounters are frequent, shocks generated in the above way can be expected to influence the structure of the gaseous component of many galaxies. Shocks lead to radial transport of gas in a galactic disk, or to the consumption of gas by star formation, or both. The drastic removal of gas by star formation leads to infrared luminosities quite close to those recently observed (by the Infrared Astronomical Satellite IRAS) in many galaxies in which no dramatic action was suspected previously. Because of the deflection of gas and the induced star formation in the shock, I expect that distant encounters remove gas from the disk, and accordingly I consider the possibility that these encounters are responsible for making S 0 galaxies, as follows. If an intruder flies by with an impact parameter and a speed so large that the victim galaxy receives a velocity perturbation less than the speed of sound in the galactic gas, nothing happens. If the perturbation is larger than the sound speed, but smaller than the mean velocity of the stars (i.e. the average of dispersion and systematic speed), only the gas is redistributed and the victim becomes an S0 type. If the encounter is so close and so slow that even the stars are significantly perturbed, the victim becomes an elliptical galaxy. From an order-of-magnitude estimate of this effect, I find that such a model reproduces the observed correlation between the morphological type of a galaxy and the number density of other galaxies in its immediate neighbourhood.

Key words: galactic evolution – interacting galaxies – clusters of galaxies – hydrodynamics

1. Introduction

It is virtually certain that a large fraction of peculiar galaxies (cf. Arp, 1978) owe their remarkable structure to gravitational interaction with a nearby companion (Toomre, 1974, and references therein). So far, computations of such interactions have mostly considered the behaviour of the collisionless component of galaxies, namely the stars. I will consider the fate of a disk of gas in a galaxy that is exposed to the gravitational pull of an intruding galaxy. Since gas is collision dominated, one expects its dynamics to be rather different from that of the stars, in the following sense. First, tidal bridges and tails in the gaseous component may develop shocks. Second, because the speed of sound is so much less than the average speed of the stars, distant encounters are expected to be quite effective in generating such shocks, even if the stellar component of the galaxy remains relatively undisturbed.

The appearance of shocks leads to a breakdown of the circulation theorem, and thereby to considerable radial motion of the gas. Moreover, shocks compress the gas, and this compression with the accompanying rapid cooling can cause the consumption of gas by star formation. Therefore, I consider the possibility that distant encounters are responsible for making S0 galaxies out of ordinary spirals. The reason for trying yet another generation mechanism for lenticular galaxies is, that other plausible schemes (in particular ram pressure stripping) appear to be in conflict with the data (see e.g. Farouki and Shapiro, 1980, 1981; Gisler, 1980; Larson et al., 1980; Kent, 1981).

2. Encounters between individual galaxies

2.1. Numerical calculations

Consider the flow induced by an intruding galaxy, passing by a flat gaseous disk orbiting in circular equilibrium in a spherical Population II stellar mass distribution. Let the gravitational potential of this mass be given by

$$\Phi = -GM(r^2+r_0^2)^{-1/2}, \quad (1)$$

where M is the total mass of the stars, r is the spherical radial coordinate, and r_0 is a scale length. The mass density distribution corresponding to this potential can be found from Poisson's Equation as

$$\varrho = \frac{3}{4\pi} Mr_0^2(r^2+r_0^2)^{-5/2}. \quad (2)$$

The angular velocity Ω and the orbital speed v of circular orbits in the potential well are

$$\Omega = (GM)^{1/2}(r^2+r_0^2)^{-3/4}, \quad (3)$$

$$v = r(GM)^{1/2}(r^2+r_0^2)^{-3/4}. \quad (4)$$

Clearly, v has a maximum v_m at $r = r_0\sqrt{2}$:

$$v_m = 3^{-3/4}(2GM/r_0)^{1/2}. \quad (5)$$

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Choosing as units the quantities

$$\begin{array}{ll} \text{length} & r_0\sqrt{2} \\ \text{speed} & 3^{-3/4}(2GM/r_0)^{1/2} \\ \text{time} & 3^{3/4}(r_0^3/GM)^{1/2} \\ \text{density} & M/(\frac{4}{3}\pi r_0^3) \end{array} \tag{6}$$

the above equations can be written in the dimensionless form

$$\Phi = -\frac{3^{3/2}}{2}(2r^2+1)^{-1/2}, \tag{7}$$

$$\Omega = (\tfrac{2}{3}r^2+\tfrac{1}{3})^{-3/4}, \quad v = \Omega r, \tag{8}$$

$$\varrho = (2r^2+1)^{-5/2}. \tag{9}$$

In this potential, let there be given a cylindrically symmetric gaseous disk, with density

$$\varrho_g = \varepsilon \varrho, \tag{10}$$

orbiting with circular velocity v_g in the (x, y) plane, let the gas obey a polytropic equation of state

$$P = \varrho^\gamma. \tag{11}$$

Then according to Bernoulli's Equation we have, in dimensionless form,

$$\begin{aligned} v_g^2 &= r^2(\tfrac{2}{3}r^2+\tfrac{1}{3})^{-2/3} + s_0^2\varrho^{\gamma-2} r \frac{d\varrho}{dr}, \\ v_g &= r\{(\tfrac{2}{3}r^2+\tfrac{1}{3})^{-3/2} - 10 s_0^2(2r^2+1)^{(3-5\gamma)/2}\}^{1/2}, \end{aligned} \tag{12}$$

where s_0 is the speed of sound at $r=0$, in units of v_m. Let this gas distribution be perturbed by the gravitational field and the centrifugal acceleration due to an intruding galaxy with mass M', having a potential shape as in Eq. (6), and moving in a hyperbolic orbit with eccentricity e in the (x, y) plane. Then solve the equations of motion of the gas, given the initial conditions (10) and (12).

The numerical technique used to solve this problem has been described in detail elsewhere (Icke, 1979a). The method, called 'Shasta' by its inventors (Boris and Book, 1976, and references therein), uses a second order finite difference scheme. It possesses a 'predictor-corrector' character due to the following. First, the variables are advanced one time step by a finite difference approximation of the flow equations that contains a strong artificial diffusion (I have used the fully explicit variant of this step, because quasi-stationary streaming is nowhere anticipated in a galaxy collision). Second, the effect of the artificial diffusion alone, without transport due to flow, is calculated. Third, the first operation is corrected by subtracting the artificial terms wherever this is possible without creating new extrema in the flow variables. This correction step was executed such that the flow variables remain unchanged when transported on a zero velocity field[1].

About 60 different simulations of the encounter were run on the CDC 7600 at the Lawrence Berkeley Laboratory. I have considered various values of the ratio μ of the mass of the intruder over the mass of the victim galaxy; the pericenter distance p; the eccentricity e; the adiabatic index γ; and the sound speed s_0. Also, I considered prograde as well as retrograde encounters. Except when the eccentricity was extremely large, so that the encounter was very brief, solutions with different values of γ and e resembled each other closely. The value of s_0 was somewhat more important, as can be understood from the following argument. The tidal acceleration A across a galactic diameter $2R$, assuming that both galaxies have equal masses, is

$$A = 4GMRr^{-3}, \tag{13}$$

if r is the distance between the galaxies. The encounter can cause shock waves in the gaseous disk of the victim if A is large enough to give the gas an additional speed of the order of s_0 in about one galactic year $2\pi R/v$, where v is the circular speed at R. The excess speed induced by A during that time is

$$\Delta v \sim 4GMRr^{-3}2\pi R/v = 8\pi v(R/r)^3. \tag{14}$$

Thus, if $\Delta v \gtrsim s_0$, shocks can occur; therefore, if the pericenter distance of the encounter is less than

$$p_0 \sim (8\pi v/s_0)^{1/3}, \tag{15}$$

the flow pattern will be dominated by shocks, and be very different from encounters in which p is larger than this value. It is clear from equation (15) that the solutions depend on s_0, but only weakly because of the one-third power.

The most important parameters are the pericenter distance and the mass ratio of the galaxies. As always in tidal encounters, and as expressed in Eq. (13), the value of μp^{-3} determines, by and large, the severity of the perturbation. In the case of gas flow, however, an additional condition is that the collision be prograde. *Retrograde encounters muss the disk a little, but otherwise have almost no effect*; the flow remains highly supersonic throughout. Therefore, I will only present some prograde encounters from the set of simulation runs, all with pericentre distance $p=4$, adiabatic index $\gamma=1.2$, speed of sound $s_0=0.05$, on a grid of 49 by 49 square cells with dimensionless edge length 0.15. The mass ratios were 0.016, 0.063, and 0.25, so that $\mu p^{-3} = 2.4\ 10^{-4}$, $9.8\ 10^{-4}$, $39.1\ 10^{-4}$. From Eqs. (13)–(15) it is found that the value of the pericentre distance below which shocks can be expected is

$$p_0 = (8\pi\mu v/s_0)^{1/3} \sim (8\pi\mu/s_0)^{1/3}, \tag{16}$$

because, in dimensionless form, v is about unity after it has reached its maximum. For the above parameters, I obtain $p_0 = 2.0$, 3.2, 5.0; since $p=4$ in all numerical solutions presented here, it is reasonable to expect that in the first case, the victim will be disturbed in minor ways only; that in the second case, the perturbation is much more noticeable; and that in the third case, a strong shock is induced. This is indeed the behaviour that is observed (Figs. 1–3).

The potential wells of the galaxies in the above calculations are assumed to remain cylindrically symmetric. If the galaxies came too close, this would obviously be incorrect because of the tidal distortion of the stellar mass distribution. As above, Eq. (16) gives an estimate of the value of the pericenter distance within which such distortions must be expected to occur. The estimate is obtained by putting $s_0=1$, the maximum circular speed in the galaxy. That implies $p_0=0.74$, 1.2, 1.8; since $p=4$, only a weak distortion of the stellar mass distribution is expected.

The most interesting of the above runs is the third, in which a strong shock develops. The shock wave remains centered on the intruder; clearly, the circulation of the inner gas in the victim (i.e. inside the corotation distance of the encounter) is strongly deflected towards the galactic centre, while the gas outside

1 After completion of this project, I have learned that the Shasta scheme in two dimensions can be ill-behaved (B. van Leer, private communication); in quasi-steady flow, this introduces errors on the 15% level. However, the Shasta scheme (especially in the explicit-difference form used here) was primarily designed for the calculation of transient phenomena, and is quite reliable if used as such (M. D. Smith, private communication)

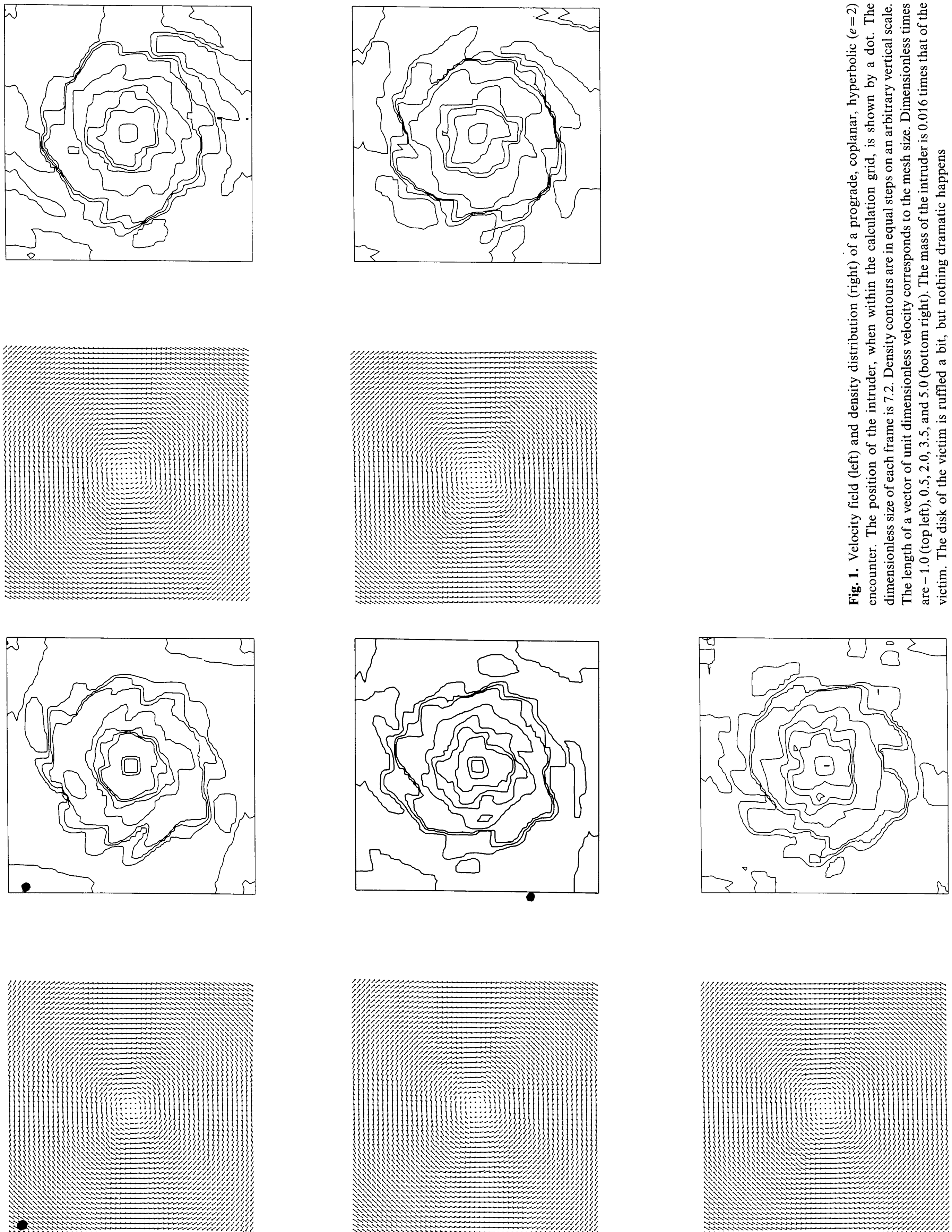

Fig. 1. Velocity field (left) and density distribution (right) of a prograde, coplanar, hyperbolic ($e=2$) encounter. The position of the intruder, when within the calculation grid, is shown by a dot. The dimensionless size of each frame is 7.2. Density contours are in equal steps on an arbitrary vertical scale. The length of a vector of unit dimensionless velocity corresponds to the mesh size. Dimensionless times are −1.0 (top left), 0.5, 2.0, 3.5, and 5.0 (bottom right). The mass of the intruder is 0.016 times that of the victim. The disk of the victim is ruffled a bit, but nothing dramatic happens

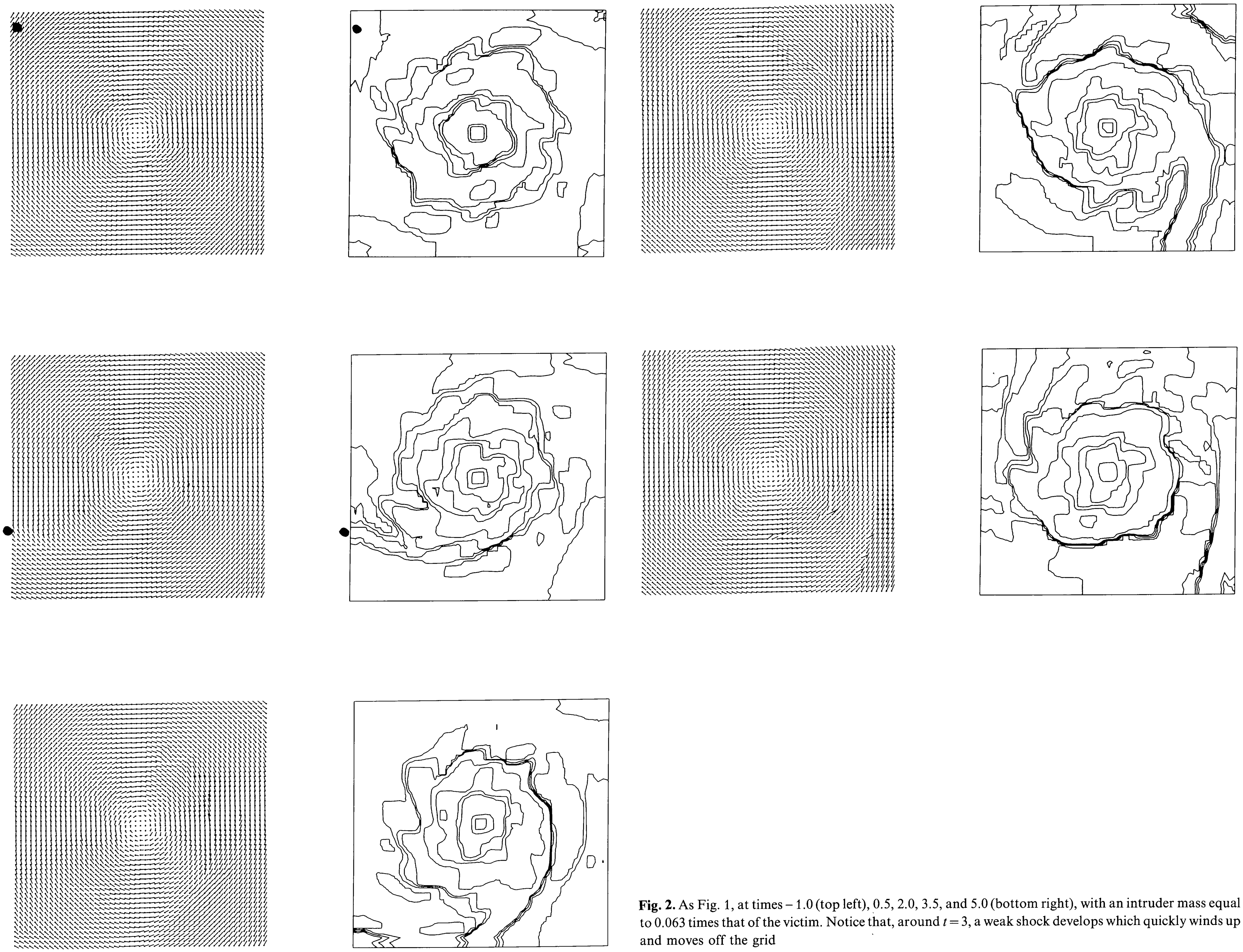

Fig. 2. As Fig. 1, at times −1.0 (top left), 0.5, 2.0, 3.5, and 5.0 (bottom right), with an intruder mass equal to 0.063 times that of the victim. Notice that, around $t = 3$, a weak shock develops which quickly winds up and moves off the grid

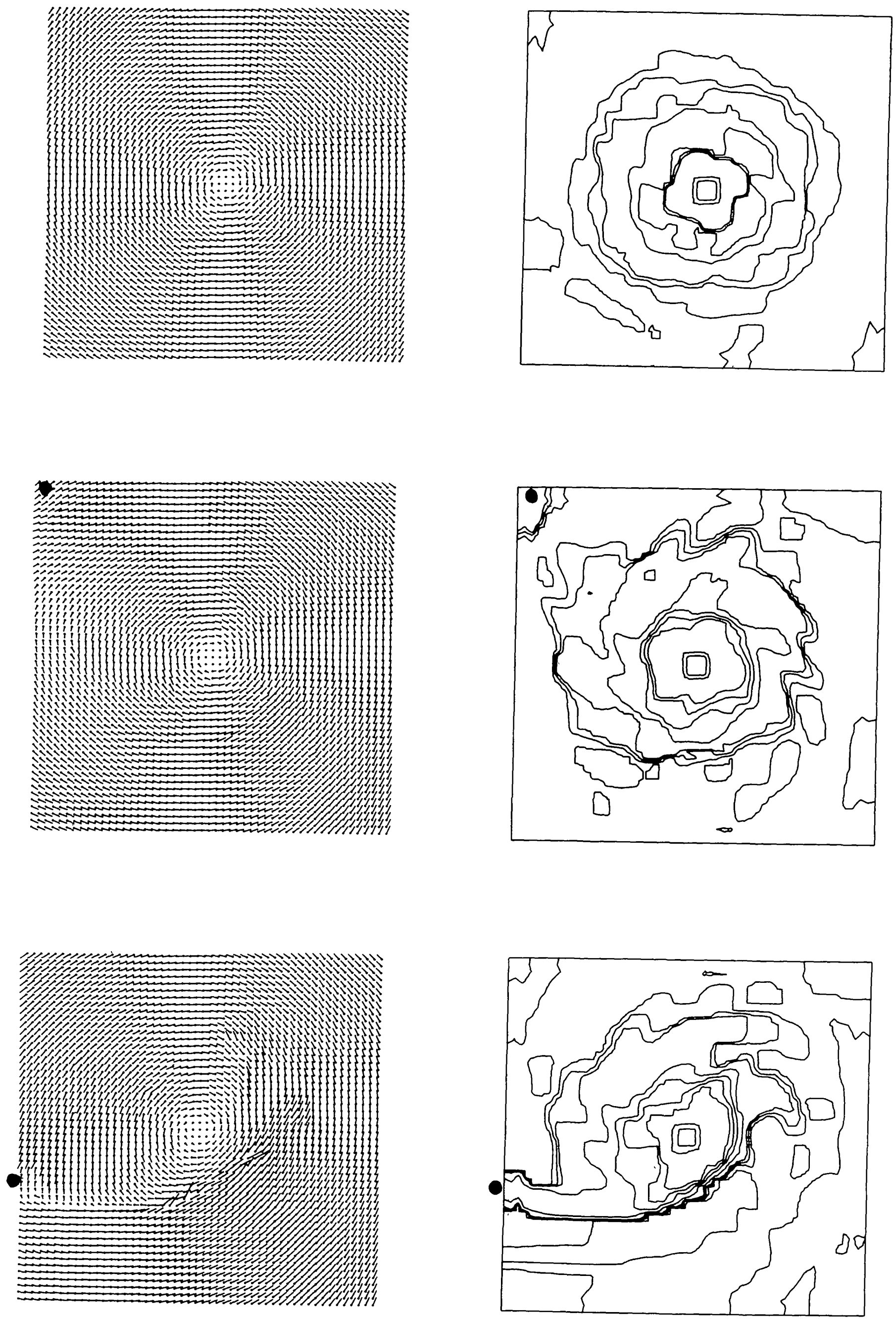

Fig. 3. As Fig. 1, at times −2.5, −1.0, and 0.4. The mass of the intruder equals one quarter of the mass of the victim. Notice that a strong shock develops around $t=0$

corotation is transported away from the victim; some of it is captured by the intruder. A mild velocity discontinuity (insufficiently resolved) is seen on the opposite side of the galaxy.

2.2. Gas transport and star formation

The speed at which gas is transported by deflection through the shock can be determined from the above simulations, and similar ones not explicitly presented here. The mean dimensionless velocity deflection, averaged along the shock, is $\Delta v = 0.05$, 0.21, and 1.06 for an intruder/victim mass ratio $M_i/M = 0.016$, 0.063, and 0.25, repectively. One expects that, to first order, $\Delta v/(M_i/M)$ is about constant, and indeed I find the value of this ratio to be 3.1, 3.3, and 4.2, respectively. As expected, the simulations show that $\Delta v \sim 1$ is a reasonable value for distant encounters of galaxies with near-equal masses.

If one follows the streamlines of the gas throughout the encounters, it turns out that the net radial displacement of gas due to the interaction is less than 50% for mass ratios $M_i/M < 0.1$. In the case $M_i/M = 0.25$, the largest value used, one finds a much stronger effect: the radius to which the gas is deflected inward is about one third of the radius from which it came, at the point where the shock is strongest. Thus, gas is grossly redistributed in the victim galaxy only if the intruder has a mass in excess of about one fifth of that of the victim.

The calculations of the encounters between a galactic disk and an intruding galaxy do not specify in detail the ultimate fate of the gas in the disk. The deflection of the streamlines through the shock merely redistributes gas, the behaviour of which outside the collision corotation distance is simple: because of its low density, it is likely to just remain there, so that I expect that *many lenticular galaxies have large gaseous rings around them*. Indications for this kind of behaviour exist (e.g. Sandage, 1966, p. 42), although the optical data do not always discriminate between gaseous and stellar rings. Recent results obtained at the Westerbork Synthesis Radio Telescope show evidence of large gaseous rings around lenticular galaxies (H. van Woerden, private communication). Inside corotation, matters are more complex. If star formation is induced, the new stars must either have a high mass, so that they burn out quickly, or they must have low mass, so that they are red, because no big blue excesses are observed in S0 galaxies (S. Kent, private communication). It is not implausible that new stars formed by the tidal shock deep in the galaxy have low mass, because the shearing motions across a strong shock would discrupt big condensations (Icke, 1979b). This is in keeping with the behaviour of barred spirals, in which the shocks do not appear to lead to massive star formation either (in ordinary spirals, the shocks are more oblique, and hence much less disruptive). It is not known what might cause the stars to be predominantly massive (heavier than five solar masses, say). Knapp et al. (1980) conclude that the initial mass function of the new stars in M82 must be heavily biased towards massive stars, unless the process that converts gas into stars is more than 50% efficient.

If the formation of new stars removes a considerable fraction of the gas, then the "starburst" triggered by the encounter must be spectacular by any standards. If the victim galaxy contains, say, 15% of its total mass in gas, and if most of this (e.g. two thirds) collapses into stars, then I expect a star formation rate of some $10^{10}/M$ stars of M solar masses per galactic year, or 40 $(M_\odot/M)$ per year. The product of stellar luminosity and lifetime is about $\varepsilon M_c c^2$, where ε is the mass-to-energy conversion efficiency (about 0.5%), and M_c is the participating core mass (about 1.5 $M_\odot$). Consequently, the total power P in the above "maximal" starburst is about

$$P = 40\varepsilon M_c c^2 (M_\odot/M) \quad \mathrm{J\,yr^{-1}}. \tag{17}$$

or, equivalently,

$$P = 4\;10^{12}\;(M_\odot/M) \quad L_\odot \tag{18}$$

If M is the mass of an O5 star, this implies $P = 10^{11} L_\odot$, that is about 200,000 simultaneous Orion nebulae. The infrared emission of the galaxy M82, which has probably suffered a recent encounter with M81, shows a power of this magnitude, and a "10^5 Orions" model appears to fit most of the data on M82 (Jones and Rodríguez-Espinosa, 1984).

From this, it follows that it is possible to remove most of the galactic gas in one shock-induced starburst without coming in conflict with the observations. The power thereby generated seems outrageous at first sight, but recent IRAS observations have turned up dozens of previously unsuspected galaxies with M82-type behaviour (Aaronson and Olszewski 1984; Wright et al., 1984; Cutri et al., 1984; Joseph et al., 1984). Moreover, even milder encounters, such as that between M101 and NGC 5474 (Van der Hulst and Huchtmeier, 1979) can conceivably lead to noticeable starburts, witness the occurrence of five supergiant H^+ regions in M101, with an integrated power of about 6 10^8 $L_\odot$ (Israel et al., 1975; Fabbiano et al., 1982). The maximal starburst needed to process virtually all galactic gas, as discussed above, would generate a predicted power of at most about 100–200 times that in the large H^+ regions of M101.

3. Consequences for a population of galaxies

3.1. Morphology and local environment

It has been shown by Dressler (1980) and confirmed by Wirth and Gallagher (1980) and by Bhavsar (1981) that there is a relationship between the morphological type of a galaxy and the surface number density of galaxies in its immediate neighbourhood. The correlation is such that there is an increase in the frequency of elliptical and S0 galaxies, and a corresponding decrease in spirals, as the local density increases. Two things stand out in these observations. First, the great clarity of the correlation; this is quite astonishing when compared with earlier efforts to find trends in galaxy populations. Second, the dependence of galaxy type on local density is extremely weak: if the fraction of ellipticals is F_E, and if the local space number density of galaxies is n, then Dressler's data indicate $F_E \propto n^k$, with $1/7 < k < 1/5$. Similar low-slope correlations are seen in the S and S0 populations. In this section, I try to relate the distant encounters discussed above to the evolution of galaxy morphology.

I suspect that the clarity of the correlation found by Dressler (1980) is mostly due to his decision to correlate galaxy morphology with a purely *local* environmental property (the surface number density of galaxies in the immediate vicinity), rather than with some global property that is more difficult to define and to reproduce by independent observers (e.g. cluster membership, cluster richness, and the like). Because it appears that galaxy clustering continues in almost scale-free fashion on all observed length scales (cf. Longair and Einasto, 1978), a global environmental property would indeed seem to be a poor choice for a variable with which to correlate galaxy morphology.

Therefore, I will follow Dressler's approach, and consider the fate of a galaxy due to interaction with its immediate environment. To this end, I divide the forces acting on a galaxy into two regimes: one, the gravitation due to the smeared-out effect of all galaxies outside the immediate vicinity, and two, interactions within the specific volume of the galaxy. If n is the local number density of galaxies, anything happening inside a box with volume $V = 1/n$, centered on the galaxy, belongs to the "immediate environment", while anything else is supposed to contribute only to the smeared-out "distant" forces. Interactions within V are treated as a two-body encounter.

Any passage of a galaxy through the specific volume V is assumed to be one of three possible types. The first type is an interaction in which the combination of the pericenter distance and the flyby speed is such that the tidally induced velocity perturbation is less than the speed of sound. The second type is such that the encounter is in an intermediate range, where the induced velocity perturbation is larger than the speed of sound but smaller than the average velocity (i.e. without splitting into systematic and dispersive motion) of the stars in the galaxy. The third type is every encounter in which the velocity perturbation is larger than in the second.

The first type of encounter does nothing to the victim; this seems a pretty safe assumption. The target of the second type of encounter becomes an S0; this is the most audacious of the three cases, because it is supposed that the stellar component is not disturbed much at all, while the gas in the galactic plane, once transported radially over large distances, does not return to its original spiral configuration. In the third case, the victim becomes an elliptical galaxy. This is not as bold as the previous assumption, because many more numerical calculations exist on this subject (cf. Aarseth and Fall, 1980, and references therein).

3.2. Dependence of encounters on local number density

An order-of-magnitude estimate of the probabilities of these encounters, and of their dependence on the local galaxy number density, is readily given. In an area with local number density n, consider the specific volume $V=1/n$. Let an intruding galaxy move through this volume at constant speed σ, moving along a straight line with impact parameter b (Keplerian orbits could be used, but for the distant encounters considered in this estimate the effort is not warranted). The tidal acceleration A, across the galaxy diameter $2R$, due to the passage, is

$$A=4RGMr^{-3}, \tag{19}$$

assuming that the galaxies have equal mass M; here r is the distance between the galaxies, given by

$$r^2=b^2+\sigma^2t^2. \tag{20}$$

The collision can cause shocks so long as A is large enough to give the gas an additional speed of the order of the sound speed s in half a galactic year (from one tidal bulge to the next; presumably two shocks develop, as in the case of a barred spiral). Half a galactic year is approximately equal to R/v, where v is the galactic rotation speed. Accordingly, the excess speed induced by tides during that time is

$$\Delta v=4gGMRr^{-3}\pi R/v\sim 4\pi gv(R/r)^3. \tag{21}$$

The geometrical factor g makes allowance for the configuration of the collision. The numberical calculations mentioned in Sect. II show that $g\sim 1$ for prograde, and $g\sim 0$ for retrograde encounters. Encounters out of the galactic plane are probably not very effective either in generating shocks, so that g must be expected to be at most $\frac{1}{2}$, and probably less than that.

Every half galactic year, the excess Δv is amortized by passage through a shock. Because of the results obtained in the numerical calculations, it must be expected that even distant encounters between galaxies can lead to transport of gas in their disks, since even collisions with large impact parameter [cf. Eq. (15)] can generate shocks in the galactic gas. On these shocks, the circulation theorem breaks down, so that gas between the galactic center and the center of mass of the pair will move inward, while gas elsewhere moves outward. The largest admissible impact parameter for this mechanism is much larger than that for stellar tidal interaction. The gas transport rate through a circumference due to this mechanism is $2\pi HR\varrho\,\Delta v$, where H is the thickness of the gas layer and ϱ is its density. Because the total gaseous mass is $\pi HR^2\varrho$, the fraction ΔF_{S0} of gas transported per unit time is

$$\Delta F_{S0}=\frac{2\pi HR}{\pi HR^2}\,\Delta v=8\pi gvR^2r^{-3}. \tag{22}$$

Now I apply the assumption that only occurrences within the specific volume V have a local effect: the above is integrated over the time it takes to cross V, to obtain

$$\delta F_{S0}=8\pi gvR^2\int r^{-3}dt=8\pi g\,\frac{v}{\sigma}\,R^2\int(b^2+y^2)^{-3/2}dy, \tag{23}$$

with integration limits

$$\sigma t\equiv y=\pm\tfrac{1}{2}n^{-1/3}, \tag{24}$$

which yields

$$\delta F_{S0}=8\pi g\,\frac{v}{\sigma}\,\frac{R^2}{b^2}\,n^{-1/3}(b^2+\tfrac{1}{4}n^{-2/3})^{-1/2}. \tag{25}$$

This expression must be integrated over all values of the impact parameter b allowed within the specific volume V. The probability that a target with number density n and cross section $2\pi b\,db$ is hit by a point moving with speed σ during a time Δt is $2\pi n\sigma\,\Delta t\,b\,db$. Therefore, the expectation value of the gas fraction transported is

$$F_{S0}=2\pi n\sigma\,\Delta t\int\delta F_{S0}b\,db, \tag{26}$$

which, with Eq. (25), gives

$$F_{S0}=16\pi gvR^2\Delta tn^{2/3}\int\frac{1}{b}\,(b^2+\tfrac{1}{4}n^{-2/3})^{-1/2}db. \tag{27}$$

The upper integration limit follows from the consideration that b should be less than the passage distance required to generate a velocity perturbation about equal to the sound speed; accordingly,

$$b_{max}=(4\pi g\,v/s)^{1/3}R. \tag{28}$$

Even allowing g to be as small as 0.1, this gives values of b_{max} that are large compared with R. The lower limit of b is taken to correspond to a velocity perturbation equal to the circular speed v in the galaxy, since a more severe perturbation than this would surely tidally distort the main body of the galaxy; therefore,

$$b_{min}=(4\pi g)^{1/3}R. \tag{29}$$

The case in which b is smaller than this limit will be considered separately below. Performing the integration in Eq. (27) gives

$$F_{S0}=32\pi^2gnvR^2\Delta t\,\log\left\{\frac{[4(4\pi gnR^3v/s)^{2/3}+1]^{1/2}-1}{[4(4\pi gnR^3)^{2/3}+1]^{1/2}-1}\,(s/v)^{1/3}\right\}. \tag{30}$$

Because this is the expectation value of the fraction of the gas removed, I interpret F_{S0} as the probability that the galaxy is an S0 type, in a region with number density n. Note that the gas transportation process envisaged above is not an all-or-nothing one, like for example ram pressure stripping. This allows for a certain fraction of "anaemic" spirals among the population of incipient S0 galaxies. It would appear, however, that a lack of gas is not the only cause of anaemia, because there exist many normal galaxies with a gas content as low as that of anaemics (Bothun and Sullivan, 1980).

I assume that collisions with $b<R$ lead to the formation of ellipticals, either by merging or by violent relaxation of the individual galaxies involved in the collision. The probability for the occurrence of either is expected to be proportional to v/σ, i.e. the speed with which the stars move in a galaxy divided by the encounter speed. The reason for this is that, when $v\sim\sigma$, a star of the intruding galaxy is at a loss to know where it belongs, as it were, so that considerable changes in the stellar orbits, or even merging, may be expected (cf. Van Albada and Van Gorkom, 1977; White, 1979; Aarseth and Fall, 1980). Allowing a proportionality factor h of order unity, I get

$$dF_E=2\pi hnv\,\Delta t\,b\,db, \tag{31}$$

or, after integration over impact parameters,

$$F_E=F_E^0+\pi hv\,\Delta t(4\pi g)^{2/3}nR^2, \tag{32}$$

in which F_E^0 is the fraction of elliptical galaxies that would be there if $n=0$. The time needed to cross the specific volume is

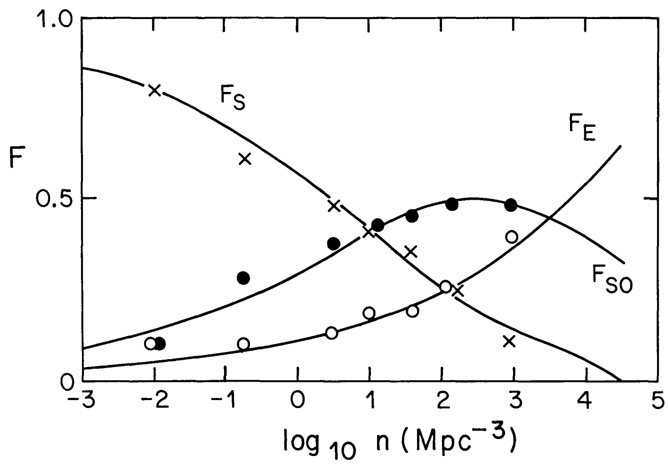

Fig. 4. The fraction of spiral galaxies F_S, ellipticals F_E, and lenticulars F_{SO}, plotted against the local galaxy number density n. Data from Dressler (1980); full lines are the best fit of Eqs. (38)–(41) to these data, yielding parameters (48)–(50)

$$\Delta t = 1/(\sigma n^{1/3}), \tag{33}$$

so that Eqs. (30) and (32) become

$$F_{SO} = 32\pi^2 g n^{2/3} \frac{v}{\sigma} R^2 \log \{ \}, \tag{34}$$

$$F_E = \pi h \frac{v}{\sigma} (4\pi g n R^3)^{2/3} + F_E^0. \tag{35}$$

Furthermore, again following the assumption that only encounters within the specific volume are important, σ is identified with the velocity dispersion in a region with density n. This is in keeping with the idea that the target galaxy interacts with those outside its specific volume only by way of the average smeared-out forces of all 'distant' galaxies. Accordingly,

$$n \sim \sigma^2/4\pi G M R_c^2, \tag{36}$$

where R_c is a characteristic radius of the local clump with density n (Rood et al., 1972; but cf. Bahcall, 1981, whose data appear to indicate $n \propto \sigma^{6/5}$). Using $v^2 = GM/R$, the above becomes

$$(\sigma/v)^2 = 4\pi n R R_c^2. \tag{37}$$

Substitution of this expression into Eqs. (34, 35) finally gives

$$F_{SO} = 2^{19/6}\pi^{4/3} g^{5/6} \frac{R}{R_c} Z^{1/6} \log \left\{ \frac{[(Zv/s)^{2/3}+1]^{1/2}-1}{(Z^{2/3}+1)^{1/2}-1} (s/v)^{1/3} \right\}, \tag{38}$$

$$F_E = \pi h (g/2)^{1/2} \frac{R}{R_c} Z^{1/6} + F_E^0, \tag{39}$$

$$Z \equiv 32\pi g n R^3. \tag{40}$$

Assuming now that at $n=0$ all galaxies are either spirals or ellipticals, the fraction F_S of spiral galaxies is

$$F_S = 1 - F_E - F_{SO}. \tag{41}$$

3.3. *Fit to the observations*

The equations (38–41) describe the relative frequencies of S0, elliptical, and spiral galaxies in an environment with local galaxy number density n. *The most obvious characteristic of these is their weak dependence on Z, or equivalently on n: only the one-sixth power.* It is instructive to trace the ancestry of this behaviour. Consider equation (31). The product $nv\Delta t$ occurs because we are calculating a collision probability. Because of the restriction to the specific volume V, Eq. (33) substitutes $1/\sigma n^{1/3}$ for Δt. The identification of σ with the velocity dispersion in an environment with number density n leads immediately to $\sigma \propto n^{1/2}$ and to $(\sigma/n) \propto n^{1/2}$ [Eqs. (36) and (37)]. Consequently, $F_E \propto n^{1/6} \propto Z^{1/6}$; the same argument, although a little more involved, holds for F_{SO}. This proportionality would appear to be quite robust, depending mostly on the use of the approximation that encounters can be calculated as a general background interaction giving the velocity dispersion of the galaxies, plus individual perturbations within the specific volume of each galaxy.

By means of the abbreviations

$$2^{19/6}\pi^{4/3} g^{5/6} \frac{R}{R_c} \equiv A, \tag{42}$$

$$v/s \equiv H, \tag{43}$$

$$\pi h (g/2)^{1/2} \frac{R}{R_c} \equiv B, \tag{44}$$

the Eqs. (38)–(41) take the form

$$F_{SO} = A Z^{1/6} \log \left\{ \frac{[(ZH)^{2/3}+1]^{1/2}-1}{(Z^{2/3}+1)^{1/2}-1} H^{-1/3} \right\}, \tag{45}$$

$$F_E = F_E^0 + B Z^{1/6}, \tag{46}$$

$$F_S = 1 - F_E - F_{SO}. \tag{47}$$

I have tried to fit these equations to the data obtained by Dressler (1980), using A, B, and F_E^0 as free parameters. I have assumed that the dimensionless quantity $H \sim (200\ \mathrm{km\ s^{-1}})/(1\ \mathrm{km\ s^{-1}}) = 200$, but it turns out that a fit with $H=20$ gives parameter values that differ by no more than 15% from the former (this is important because the average sound speed s might be large in a hot interstellar medium). The best fit is shown in Fig. 4. The parameters of this solution are

$$A = 0.65, \tag{48}$$

$$B = 0.43, \tag{49}$$

$$F_E^0 < 0.06. \tag{50}$$

Also, since $Z=1$ in this fit corresponds to $n = 3200\ \mathrm{Mpc^{-3}}$, it follows from Eq. (40) that

$$g R^3 = 3.15\ 10^{-6}\ \mathrm{Mpc^3}. \tag{51}$$

Using the definitions (38) and (39), I also obtain

$$g = 0.39, \tag{52}$$

$$h = 6.6, \tag{53}$$

$$R_c = 580\ \mathrm{kpc}, \tag{54}$$

on the assumption that $R = 20$ kpc.

In a method like this, error estimates of the parameters are difficult to give unambiguously. From tinkering with the fitting procedure at fixed R, it appears certain that the fraction of elliptical galaxies at $n=0$ cannot be larger than the 0.06 given in Eq. (50) without spoiling the fit considerably. This implies that no more than 6% of all galaxies start their lives as ellipticals. The uncertainties in g, h, and R_c are about 30, 20, and 30%, respectively.

4. Concluding remarks

It is gratifying that the simple estimate presented in Sect. 3 fits the data so well, but almost equally well-fitting alternatives exist (Kent, 1981). Moreover, a few other problems remain.

First, the hydrodynamics are strictly two-dimensional, due to computer time limitations. I expect that non-coplanar encounters do not quite yield such strong shocks as I found above, because the calculations of stellar orbits during galaxy encounters show (Toomre, 1974) that an extra degree of freedom suppresses orbit-crossing.

Second, some observers find (e.g. Dressler, 1980) that the underlying stellar component (notably the central bulge) of S0 galaxies is systematically different from that of ordinary spirals. Although some rearrangement of the stars by frequent encounters appears possible, and although star formation in the gas transported inward may contribute to an anomalous bulge, this evidence does present a difficulty. So far, however, I remain somewhat unconvinced that the light of the extreme Population I can be that well, and that unambiguously, separated from the light of the other stellar populations (in the absence of the clear indicators provided by the blue stars marking this component in spiral galaxies). Moreover, it would appear that the scatter in bulge/disk ratio of spirals is much larger than the alleged systematic difference between S and S0 types, so there is quite a bit of manoeuvering space for interpretation.

Third, Dressler's (1980) observations pertain to the surface number density of galaxies in the sky. He gives a re-scaling of this to spatial number density, which I have adopted. But this involves an interpretation step that I do not know how to circumvent. Perhaps the situation is not so bad, though, because a galaxy that has a neighbour in projection is very likely to be actually close to it, due to the nature of the galaxy distribution (cf. Longair and Einasto, 1978).

Fourth, the estimates of what constitutes a "distant" encounter imply an assumption about the radius of a galaxy. In the above (see Sect. 3) this radius was assumed to be about 20 kpc. However, if galaxies have really large and massive haloes, the above estimates do not apply in such a simple form at all.

Fifth, if the proposed mechanism is at least approximately correct, one should expect to see faint fossil spiral arms outside the main disk of the galaxy for a billion years or so after the interaction (B. Balick, private communication). At long wavelengths, such fossils might be observable.

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