EFFECTS OF DISRUPTIVE SELECTION

IV. GENE-FLOW AND DIVERGENCE

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1. INTRODUCTION

In his general discussion of disruptive selection, Mather (1955*a*) argued that it is to be expected to have two different kinds of consequence. In so far as different interdependent classes of phenotype are selected, it is to be expected that disruptive selection, given appropriate genetic variation, will produce a polymorphic population. It has been shown experimentally (Thoday, 1958*a*, 1959, 1960; Thoday and Boam, 1959) that this is so. On the other hand, if different independent phenotypes are selected, disruptive selection might result in the development of physiological isolation between them.

Between these two extremes there are intermediate situations in which a population is to some extent split into two parts selected for different characteristics, but in which the split is not permitted to be complete. Such situations should be very revealing, for they should permit experimental assessment of the relative effectiveness of disruptive selection pressure in promoting and of gene-flow in preventing genetic divergence of parts of a population from one another. The need for some such experimental assessment of the importance of isolation hardly needs stressing, as Mather (1955*b*) pointed out in another paper.

Thoday and Boam (1959) have already shown that isolation is not a prerequisite of divergence under divergent selection pressures. Their experiment, however, involved an extreme amount of gene-flow for, in each generation, 50 per cent. of the genes in each half of their population were derived from the other half. This is twice the gene-flow as would be involved in random mating. The present experiments were started with a view to assessing the amount of divergence possible with 25 per cent. gene-flow, the formal equivalent of random mating. A preliminary account of some of the results has already been published (Millicent and Thoday, 1960).

2. MATERIAL AND METHODS

Selection was for sternopleural chaeta number, and the lines were initiated from the same wild stock (Dronfield) of *Drosophila melanogaster* as that used by Thoday (1958*a*, 1959) and Thoday and Boam (1959) in the earlier experiments on disruptive selection. Methods of maintenance, the number of flies assayed (20 of each sex of

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each culture) and the proportion of flies selected (1 in 20) were the same. There were 4 single pair cultures per line per generation.

Three mating systems were used (table 1). The first system gives 50 per cent. gene-flow between the high and low halves of the population and is identical with that of Thoday and Boam (1959) except that males instead of females were used as the migrators through whom the gene-flow from high to low halves of the population occurred. The second mating system is a modification of the first designed to reduce gene-flow to 25 per cent. The third mating system gives 0 per cent. gene-flow between the high and low halves. The lines maintained with this latter system will for convenience be referred to as lines or populations, though strictly, of course, each is composed of two separate populations, one under directional selection for high and the other under directional selection for low chaeta number.

TABLE 1

The mating and selection schemes giving 50 per cent. and 25 per cent. and 0 per cent. gene exchange

Population	Culture	♀ Parent	♂ parent in generation			
			1	2	3	4 etc.
50 per cent. gene-exchange	A	AH	CH	DH	CH	DH
	B	BH	DH	CH	DH	CH
	C	CL	AL	BL	AL	BL
	D	DL	BL	AL	BL	AL
25 per cent. gene-exchange	A	AH	BH	DH	BH	DH
	B	BH	CH	AH	CH	AH
	C	CL	DL	BL	DL	BL
	D	DL	AL	CL	AL	CL
0 per cent. gene-exchange	A	AH	BH	BH	BH	BH
	B	BH	AH	AH	AH	AH
	C	CL	DL	DL	DL	DL
	D	DL	CL	CL	CL	CL

H indicates the highest, and L the lowest flies chosen from a sample of twenty. The letters A-D indicate the female sub-line from which the designated flies are taken. Only males are chosen to migrate.

The first and third mating systems were used primarily as controls with which the 25 per cent. gene-flow lines could be compared.

Two replicate lines were maintained with each mating system. The lines will be designated 50/A, 50/B, 25/A, 25/B, 0/A, and 0/B, and were initiated as follows. Twelve four-pair cultures of the Dronfield wild stock were set up. These we will refer to as X a-d, Y a-d and Z a-d, as they were used in three groups of four cultures each. The four single pairs of flies used to establish Line 50/A were taken from the four cultures Xa, Xb, Xc, Xd ; so were those used to establish Line 25/B. Lines 25/A and 0/B were established from the Y cultures. Lines 0/A and 50/B were established from the Z cultures. Thereafter Lines 50/A, 25/A and 0/A were cultured coincidentally. Lines 50/B, 25/B and 0/B were likewise cultured coincidentally, but in weeks alternating with those in which the A lines were cultured.

These details are given because they are relevant to the comparison of the lines' behaviour. The basic X, Y and Z groups of culture had different within sex and culture variances, 2·375 for X, 2·085 for Y and 1·735 for Z, the first and last figures being significantly different ($p<0{\cdot}05$).

It will be noted that, in terms of origin, Lines 25/A and 0/B are a comparable pair, whereas in terms of culture times 25/A is to be compared with 0/A.

3. RESULTS

(i) *Divergence*

The results are presented in two forms. Figs. 1-4 illustrate the mean chaeta numbers of the 40 flies assayed in each of the four cultures of

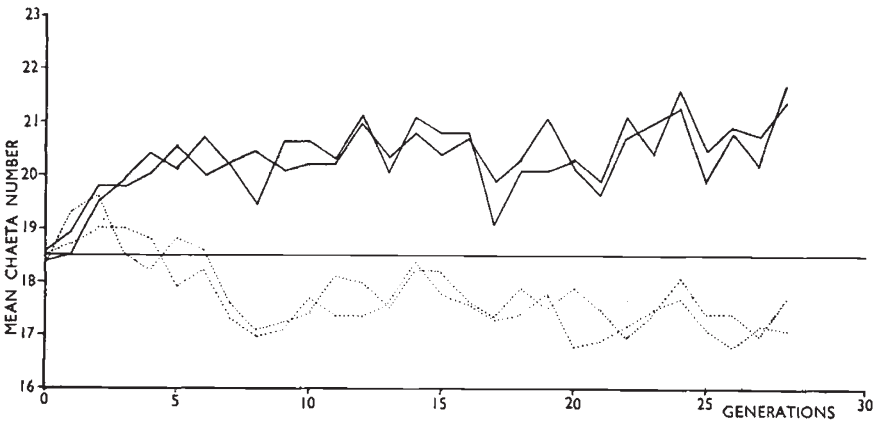

FIG. 1.—Mean chaeta numbers for the 4 female sub-lines of o/A. Solid lines, high cultures and dotted lines low cultures in this and figs. 2-4.

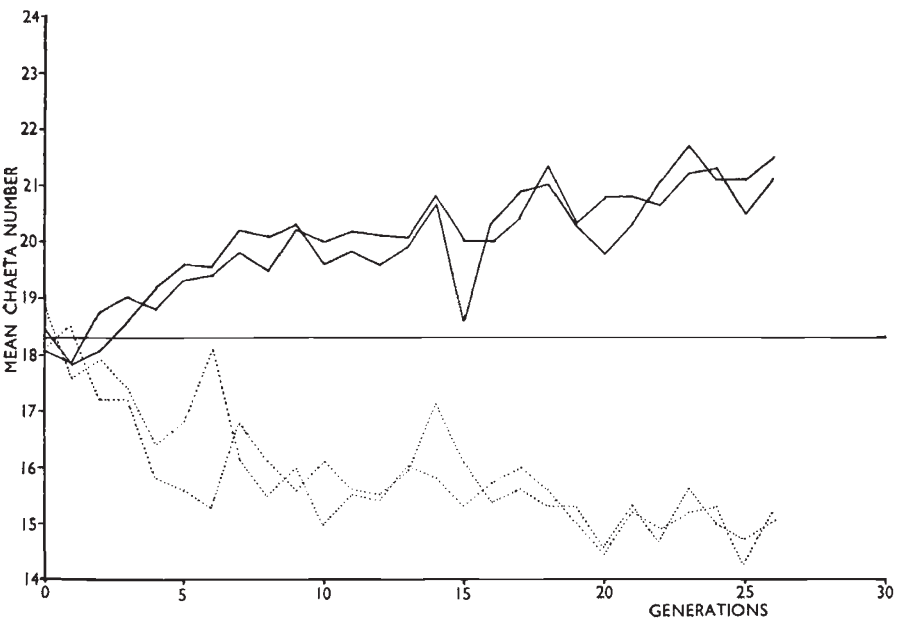

FIG. 2.—Mean chaeta numbers for the 4 female sub-lines of o/B.

each of the o per cent. and 25 per cent. gene-flow populations, and fig. 5 illustrates the rates of divergence in the six " lines " and permits comparisons to be made more readily.

The high and low cultures diverged in mean in each of the six lines. Divergence of the o lines was more rapid than in the other

lines. The effects of gene-flow in the 25 per cent. populations can be seen in the zigzag behaviour of the pairs of cultures, especially after a considerable degree of divergence had occurred.

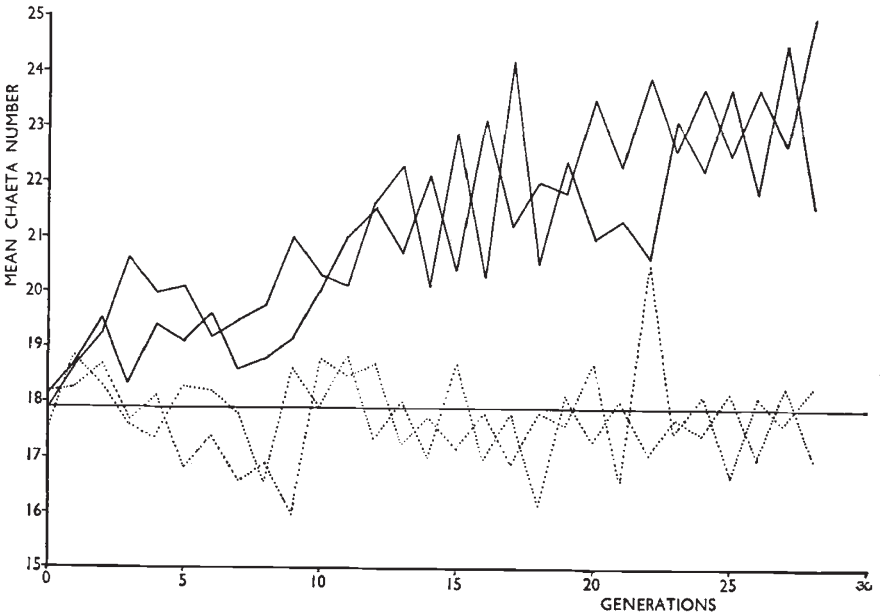

FIG. 3.—Mean chaeta numbers for the 4 female sub-lines of 25/A.

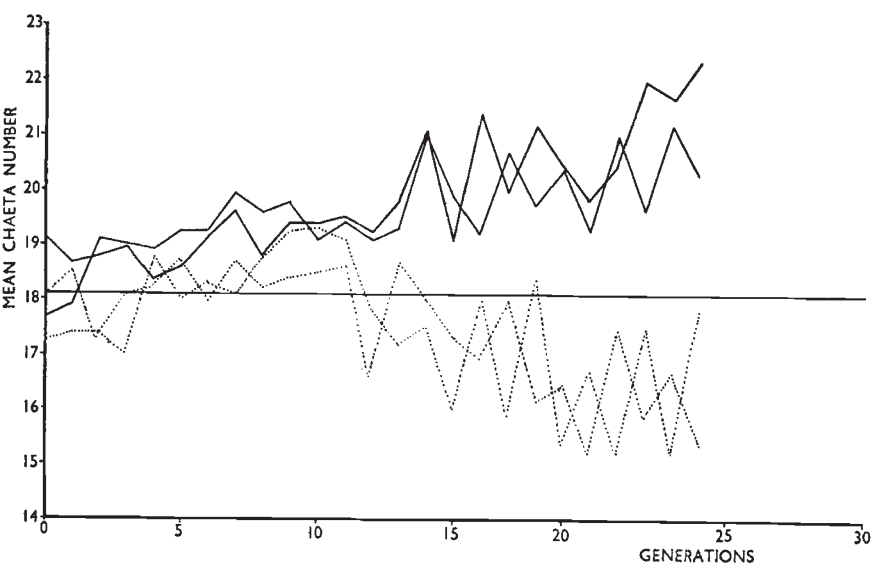

FIG. 4.—Mean chaeta numbers for the 4 female sub-lines of 25/B.

Divergence was greatly impeded by 50 per cent. gene-flow, though some positive difference was maintained. This was not as large as in the population described by Thoday and Boam (1949), neither is it

as consistent. That the 50 per cent. gene-flow populations were less successful than that of Thoday and Boam may be related to the use of males instead of females as migrants in the present population, which would permit any extreme recombinant chromosomes selected on either side to break down more readily by further recombination. It may on the other hand be related to the nature of the genetic variance available in the foundation cultures. The Dronfield wild stock may well have lost some genetic variance in the $2\frac{1}{2}$ years between the initiation of Thoday and Boam's experiment and these, or accidental sampling may be responsible.

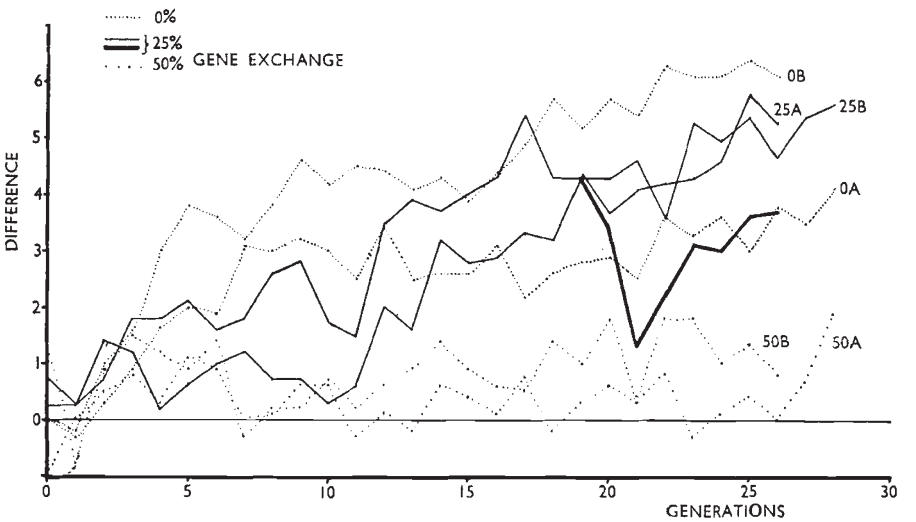

FIG. 5.—Divergence in the different lines. Each graph represents the difference between the mean chaeta numbers of the high and the mean chaeta numbers of the low cultures of the line. The heavy line is the curve for the negative assortative mating sub-line of 25/B (see p. 215).

The 0 populations diverged reasonably readily, but a plateau seems to have been reached rather soon, no doubt partly because of the small population size. Each half of each population is of course maintained by only two pairs of flies per generation and this involves fairly heavy inbreeding.

It is the 25 per cent. gene-flow populations that provide the main interest. They diverged more slowly than the 0, which is hardly surprising. But in time they diverged as much as the 0 populations which is. The comparison that seems most legitimate is that between 0/A and 25/B, which originated from the same cultures. The ultimate divergence of 25/B was greater than that of 0/A. 0/B and 25/A showed similar ultimate divergence, and, though they originated from different cultures they add to the evidence. The two 25 per cent. gene-flow populations taken together diverged a little more than the two 0 per cent. populations. It does not seem that the 25 per cent. gene-flow of the type arranged in these experiments seriously limits the amount of divergence that can occur.

(ii) *Variance and heritability in the selected lines*

Fig. 6 illustrates the within sex and culture mean squares of the different lines. There is no suggestion of change with generation in the 0 per cent. gene-flow lines, little evidence of change in the 50 per cent. gene-flow lines but clear evidence for a steady rise in variance in the

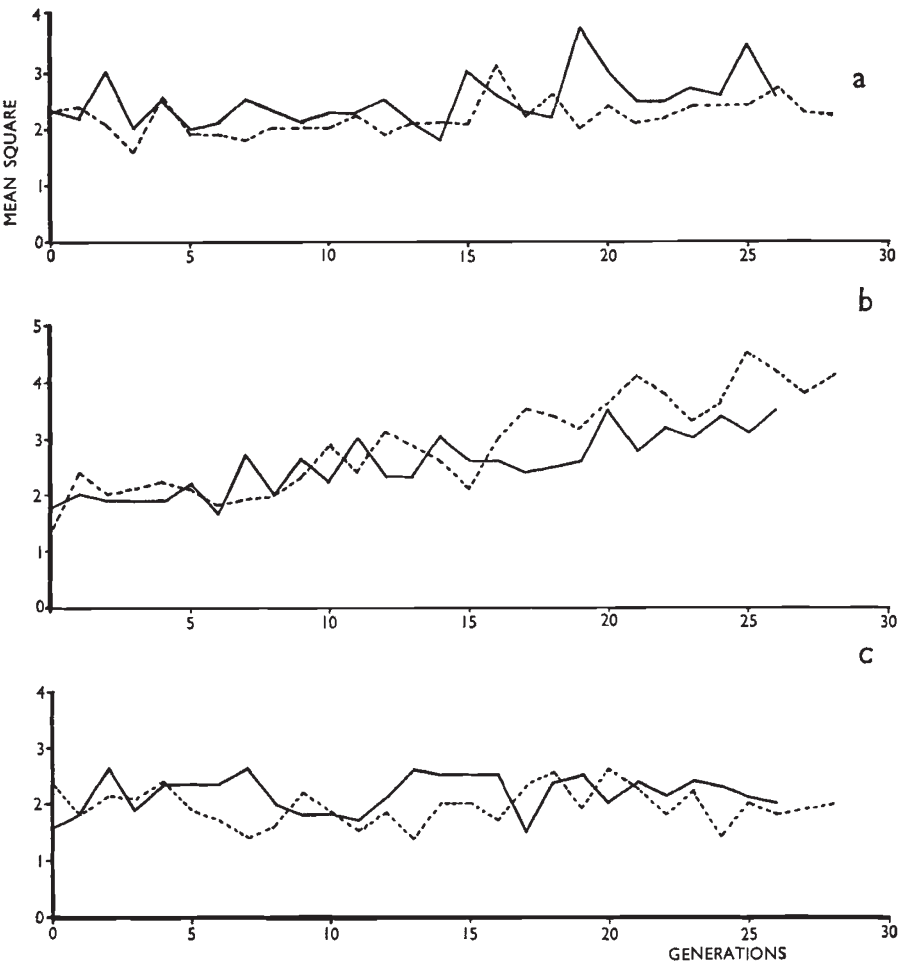

FIG. 6.—The within sex and culture mean squares. a 50 per cent., b 25 per cent., c 0 per cent. gene-flow. Broken curves : A lines. Solid curves : B lines.

25 per cent. gene-flow lines. Disruptive selection in these latter conditions can increase phenotypic variance considerably.

Heritability tests were carried out at different times on the different lines and the coefficients of regression of offspring on parent mean are listed in table 2. Heritability within each half of the 25 per cent. gene-flow lines was high. There is also high heritability in the high halves of the Line 50/A, though heritability in the low halves of the 50 lines was not detectable and the high half of line 50/B has a less

TABLE 2

Heritability tests

Line	Generation tested	High half		Low half	
		b	P	b	P
0/A	13	0·00	large	−0·30	large
0/B	19	0·16	≏0·2	0·23	≏0·02
25/A	21	0·62	<0·001	0·65	<0·001
25/B	17	0·52	<0·001	0·35	<0·01
50/A	21	0·45	<0·001	0·01	large
50/B	17	0·26	≏0·02	0·11	>0·05

significant regression coefficient. Heritability in the 0 per cent. gene-flow lines was negligible, except for the low half of 0/B, where it is significant, the reasons for which will appear later.

(iii) *Asymmetry and fertility*

The regression coefficients of bilateral asymmetry of sternopleural chaeta number on generations are listed in table 3. The measure of asymmetry used was the sum of the difference between sides, sign ignored, divided by total chaeta number (A/T), a transformation that to some extent compensates for the correlation in the Dronfield stock

TABLE 3

Regressions of A/T on generations

	b	P
0/A	0·20	>0·05
0/B	0·04	large
25/A	0·56	<0·001
25/B	−0·04	large
50/A	0·42	<0·001
50/B	0·15	<0·001

of asymmetry with mean. It has been suggested by Reeve (1960) that A/T-6 would be a better transformation. However, as A/T has some slight empirical justification (Thoday, 1958*b*), but A/T-6 is based solely on intuitive "knowledge" of the true physiological relations in flies, we prefer A/T. The regressions are calculated using A/T × 1000 for convenience.

All the regressions are positive except that for 25/B which is negligible, the joint regression is significant, and there is significant variation of the coefficients. It is notable that the significant responses are all in the disruptive selection lines. These figures suggest that disruptive selection can pick out developmentally unstable genotypes though it does not always do so.

Fertilities, as measured by the number of flies produced per culture, were also assessed in the lines. They declined significantly with generations of selection, but as there were no significant differences between the regression coefficients of the different lines they are relatively uninformative.

(iv) *Chromosome assays*

At generation 25 or 27 the selection experiment was ended, and genomes were extracted from the lines for chromosome assay.

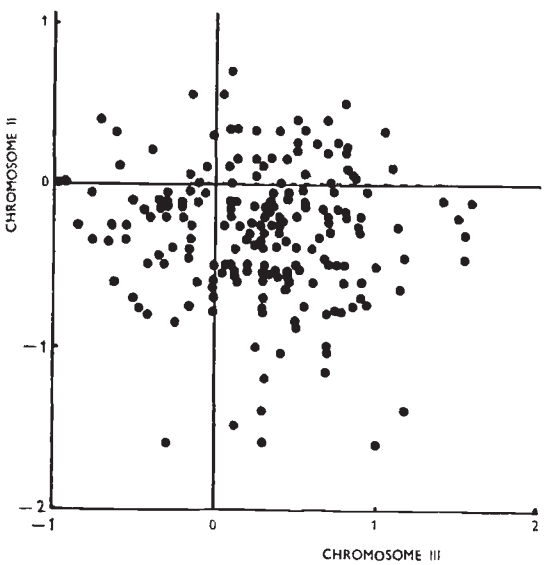

FIG. 7.—The results of assaying the Dronfield wild stock against *y bw st*. Differences o chaeta number between +/*bw* and *bw*/*bw* flies are plotted as second chromosome effects : differences between +/*st* and *st*/*st* are plotted as third chromosome effects. This fig. is plotted on the same scale as figs. 8-13.

The genomes were extracted using a newly made *ŷy bw*/*bw st*/*st* stock and the *y bw*/*bw st*/*st* inbred stock that was used for similar assays by Thoday and Boam (1959).

It was decided to extract genomes from all the flies that would have been used to maintain the selection lines had they been continued. The flies were selected as if for continuance of the lines and by mating males to the attached X stock, and females to the *y bw st* stock, and selecting ten F_1 males from each fly's progeny, ten genomes were preserved from each of them. Chromosome IV as was ignored.

Each of the 480 F_1 males was mated to a *ŷy bw*/*bw st*/*st* female and the resulting 480 genomes were preserved by repeated crossing to females of the attached-X stock. In due course the genomes were assayed by counting five flies of each sex and each eye colour. It was

not, of course, possible to grow all the assay cultures together. The assays were done in six batches of 80. No overall difference between the batches emerged so that we may treat them together.

Differences of sex difference between assays of different genomes detect variation of X chromosomes. The markers *bw* and *st* enable effects of Chromosomes II and III to be assessed. The results showed little effect that could be associated with Chromosome I (X). The effects of Chromosomes II and III are illustrated in figs. 8-13, in which the differences between $+/bw$ and bw/bw flies are plotted as effects of Chromosome II, and the differences between $+/st$ and st/st flies are plotted as effects of Chromosome III, as was done by Thoday and Boam (1959, fig. 3). Fig. 7 shows the results of a comparable assay of genomes taken from Dronfield stock females for comparison. We are indebted to Mr Gibson for permission to use his data.

It should be stressed that Mr Gibson's assay was made with the $y/y\ bw/bw\ st/st$ inbred stock that was used by Thoday and Boam (1959), whereas the present assays were made against the $\hat{yy}\ bw/bw\ st/st$ stock which had been newly bred for the purpose, since it seemed necessary to make preservation of X chromosomes as well as the two large autosomes possible. The two assays are not therefore strictly comparable. In particular the attached X stock, being newly synthesised, was more variable than the inbred stock, so that results may be blurred by significant variation of the marker chromosomes with whose effects the effects on chaeta number of the extracted chromosomes are compared.

i. *The o lines.* The assays of Line o/A (fig. 8) show clearly that both Chromosome II and Chromosome III contribute to the difference between the high and low halves of this line. Comparison of this assay with that for the Dronfield stock suggests that there are more extreme low third chromosomes and high second chromosomes in the o/A line, and that there is more association between high seconds and thirds and between low seconds and thirds. That the high half has the most effective new chromosomes is consistent with the behaviour of the means illustrated in fig. 1.

The assay of o/B is strikingly different. The low half of o/B responded more than the low half of o/A (figs. 1 and 2), and this was clearly the cause of the greater divergence of o/B. The assay shows that this was due to the establishment, in the low half of o/B, of new second chromosomes of extreme low chaeta number effect. It further shows that this low line, despite its small population size, was heterozygous for these low second chromosomes. Such low second chromosomes have not been found in the Dronfield wild stock, and seem likely to be recombinant products of Dronfield chromosomes. Their heterozygosity in the low half of o/B explains the heritability results given on p. 205, and seems to imply that they must be chromosomes that give flies of low fitness when homozygous. These low chromosomes are reminiscent of the recombinational lethals shown by Gibson and Thoday

(1960) to be responsible for the low chaeta number flies in the polymorphic population produced by Thoday and Boam (1959). They are, however, not the same. Mr Gibson has tested them, and they are not homozygous lethal in his test conditions, and they are not lethal

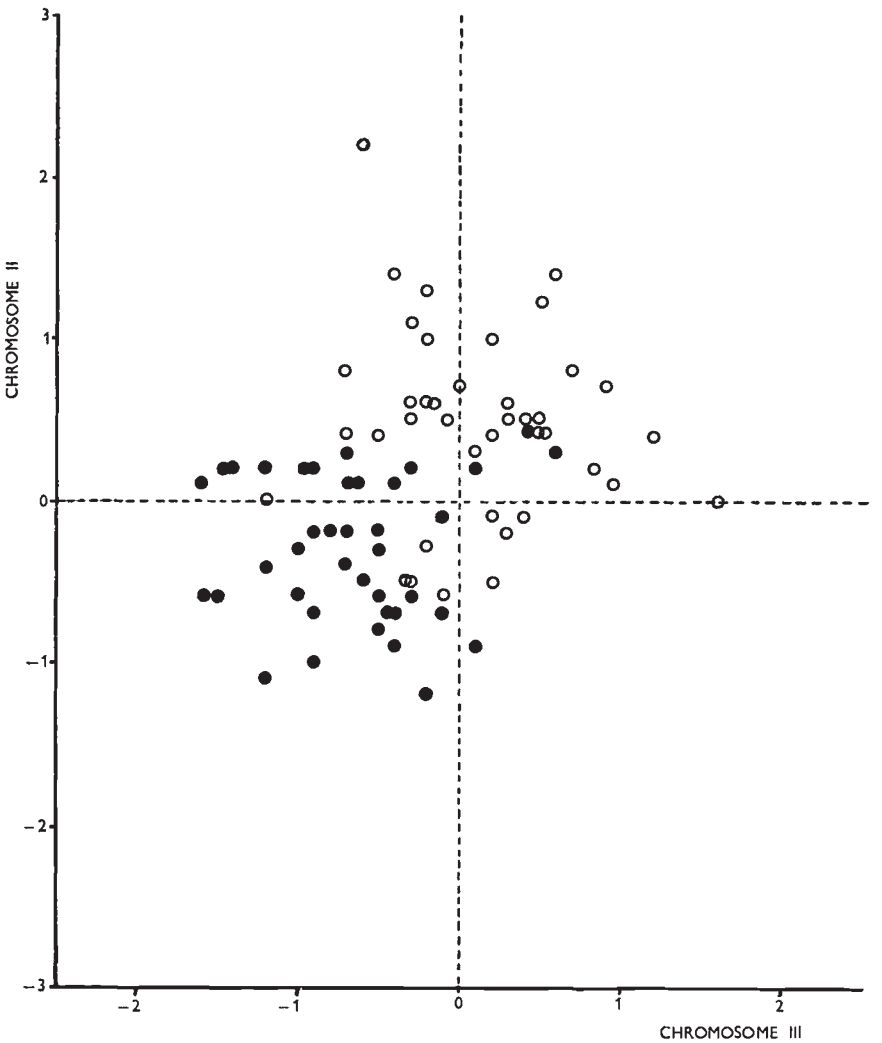

FIG. 8.—The assay results for o/A. Open circles: genomes from the high half of the line: solid circles: genomes from the low half.

when combined with his recombinational lethals. Further tests of these chromosomes are in hand. They may prove to give sterility which would explain the heterozygosity of the line.

The assay also shows that high second chromosomes were produced in the high half of o/B.

ii. *The 25 lines.* 25/A like o/A responded mostly on the high chaeta

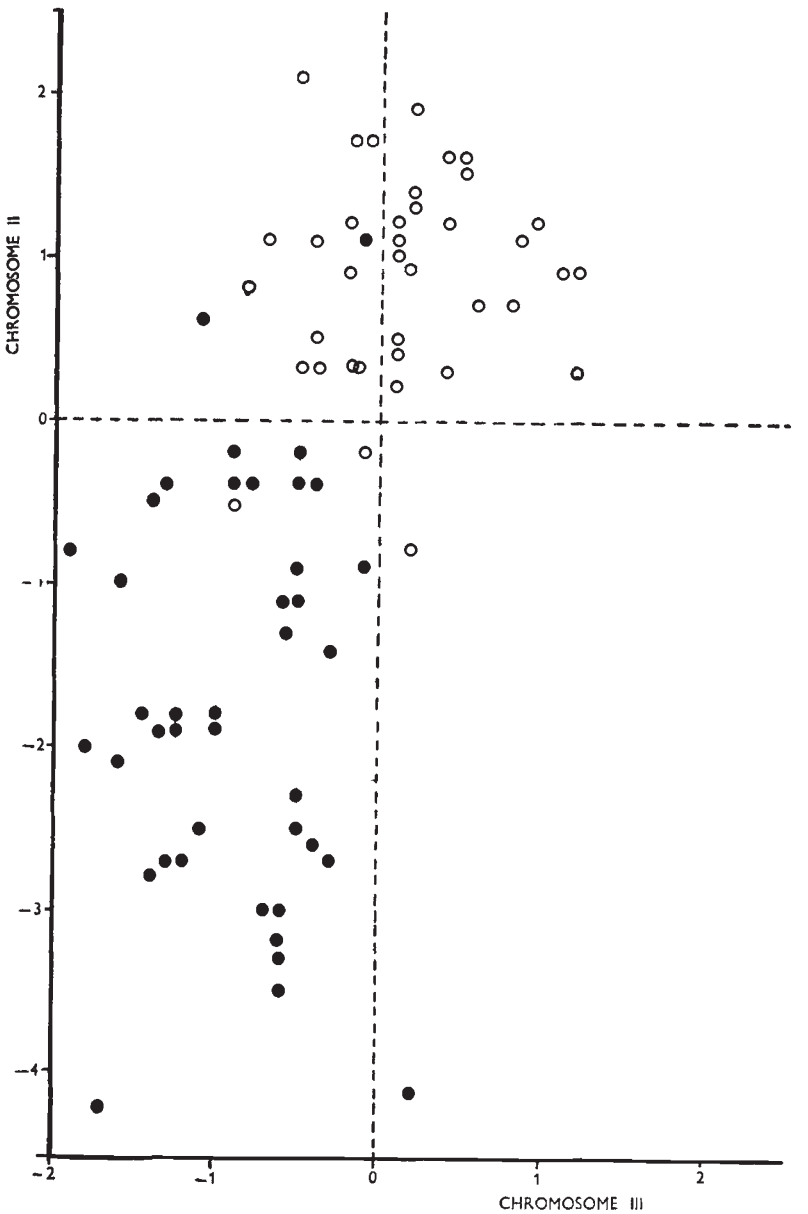

FIG. 9.—The assay results for o/B. Open circles: genomes from the high half of the line: solid circles: genomes from the low half.

number side (fig. 3). The assay results (fig. 10) are similar in kind to those for 0/A, but the responses have clearly involved both the second and the third chromosomes. There is greater variation in the assay

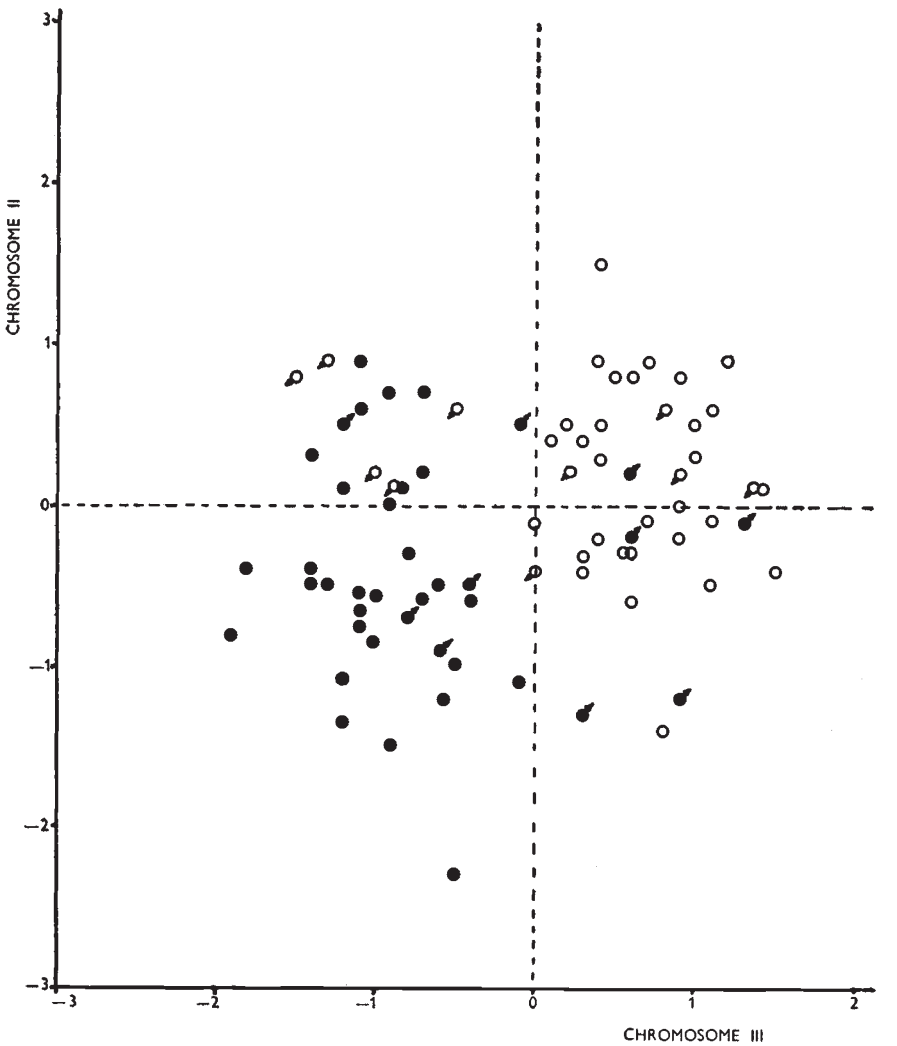

FIG. 10.—The assay results for 25/A. Open circles: genomes from the high half of the line: solid circles: genomes from the low half. The genomes from flies responsible for the gene-flow in the line are marked with arrows showing the direction of migration.

data for 25/A than in that for 0/A, and there is less overlap between the non-migrant genomes than there is between the genomes of the two halves of 0/A. We conclude that though 0/A and 25/A both diverged (fig. 5), the disruptive selection involved in 25/A produced a greater range of chromosome types than did the directional selection in 0/A.

The range is also greater than in the Dronfield stock. It is as if the gene-flow in 25/A permitted a transfer of genes to the appropriate half of the population which could not occur with complete isolation.

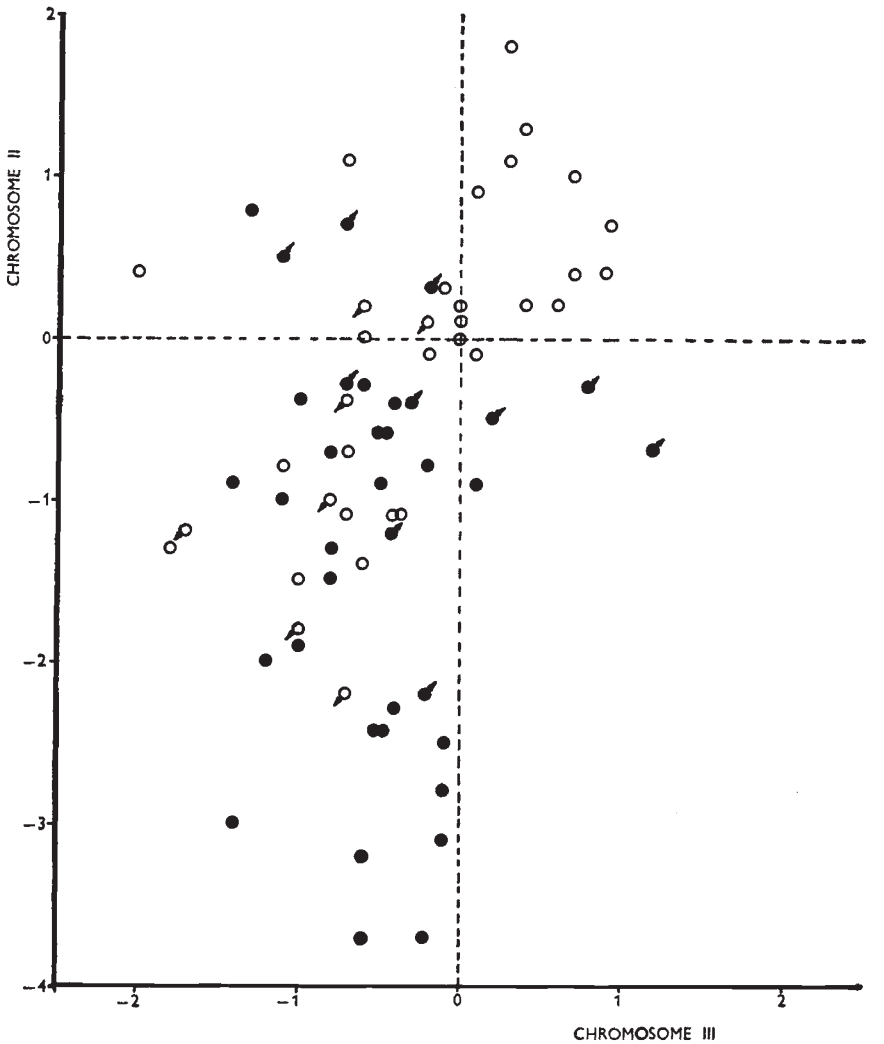

FIG. 11.—The assay results for 25/B. Open circles: genomes from the high half of the line: solid circles: genomes from the low half. The genomes from flies responsible for gene-flow in the line are marked with arrows showing the direction of migration.

With complete isolation, bristle decreasing genes homozygous in the high half, and bristle increasing alleles homozygous in the low half could limit divergence. With some gene-flow these genes could be transferred and exploited. We thus see the possibility that isolation may sometimes be a factor *limiting* divergence, as suggested by Thoday (1953, 1958*c*).

The assay of 25/B genomes (fig. 11) is quite different, and rather like the assay of 0/B (fig. 9). There was some response in Chromosome III but 25/B responded largely in Chromosome II, and its low half is clearly heterozygous for a powerful second chromosome effect.

These low second chromosomes have been tested by Mr Gibson,

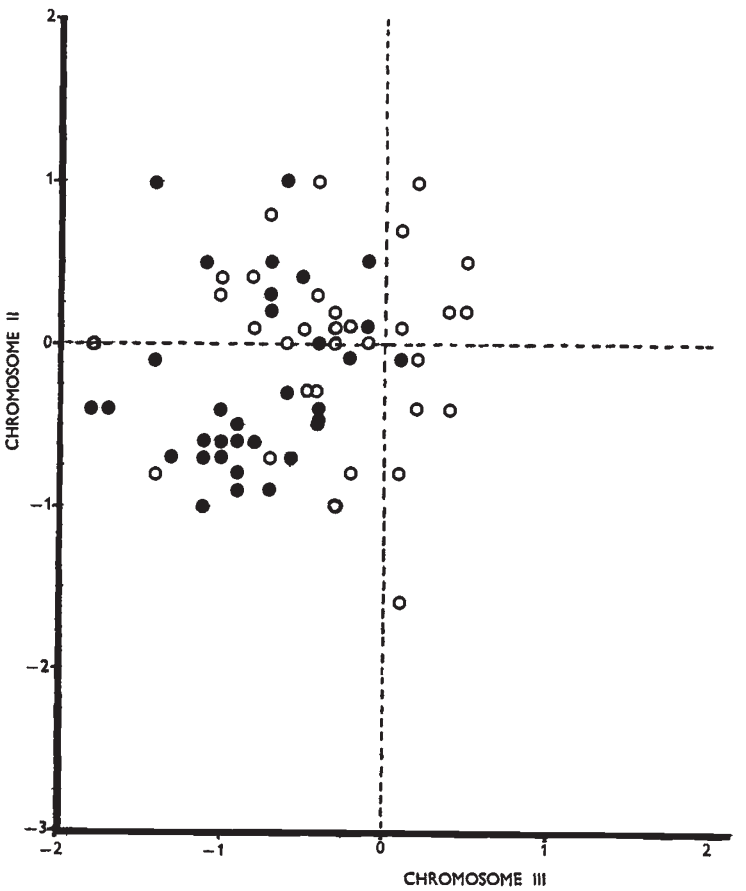

FIG. 12.—The assay results for 50/A. Open circles: genomes from the high half of the line: solid circles: genomes from the low half.

and prove homozygous viable and different from the low second chromosomes of the original polymorphic population of Thoday and Boam (1959), though it is not yet known whether they are the same as the low second chromosomes in 0/B. It is clear and striking that 25/A and 25/B achieved the same order of divergence by different genetical means, and that neither of these divergences had the same cause as that in the original population of Thoday and Boam.

iii. *The 50 lines.* The assays of the 50 lines are less informative, which is not surprising in view of the slight and variable divergence

achieved in these lines. However, comparison of these assays (figs. 12 and 13) with that for the Dronfield wild stock, show clearly that disruptive selection has increased the variety of second chromosomes. There are higher chaeta number second chromosomes in both assays, and lower second chromosomes in 50/B than in the wild stock. The

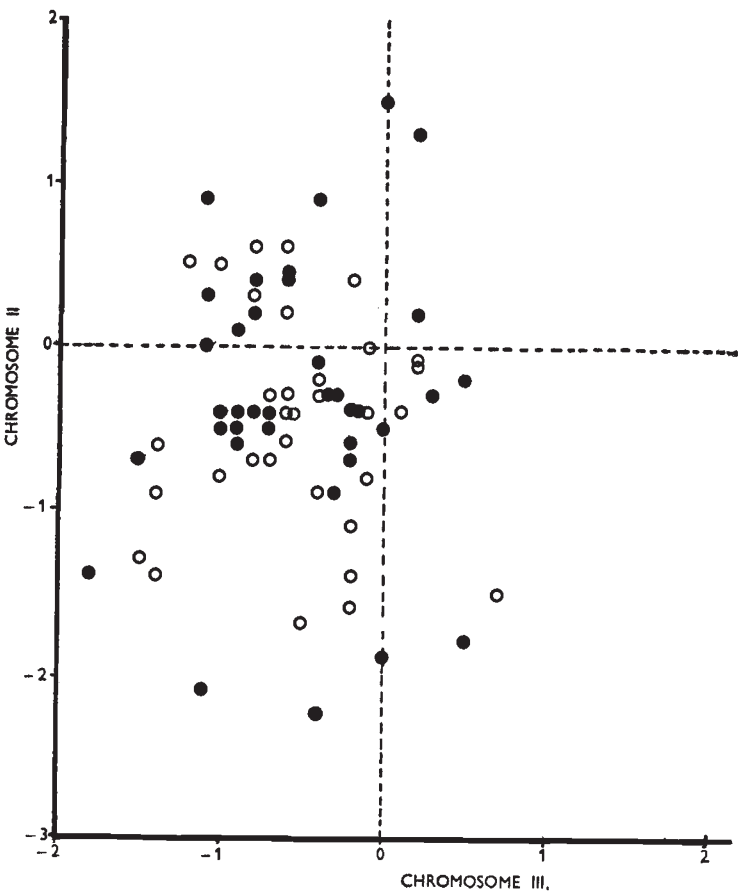

FIG. 13.—The assay results for 50/B. Open circles: genomes from the high half of the line: solid circles: genomes from the low half.

range of third chromosome effects is 2·3 chaetæ in each assay which is also the range in the Dronfield assay, so that there is no evidence that new third chromosomes were produced in this line.

It is to be noted that 50/B shows clear signs of producing low second chromosomes, but that 50/A does not. 50/B originated from the same foundation cultures (Z) as 0/A which showed no sign of such extreme low second chromosomes. We thus have three populations 0/B (from Y), 25/B (from X) and 50/B (from Z), all from different foundation cultures all producing extreme low second chromosomes such as

have never been found in the Dronfield stock. These facts strengthen the view that the origin of such extreme chromosomes is recombinational rather than mutational (see also Gibson and Thoday, 1960). We know that the 0/B and 25/B low second chromosomes differ from the low second chromosomes in Thoday and Boam's (1959) D^+ population. It is almost certain that the 50/B low second chromosomes are different for they give less extreme chaeta numbers. It seems as if the Dronfield wild stock can produce recombinant second chromosomes in several ways.

4. DISCUSSION

The results reported here leave no doubt that disruptive selection is capable of bringing about divergence of high and low components in a population despite 25 per cent. gene-flow between the two. The result is a polymorphism (see fig. 14). We expected this in view of the

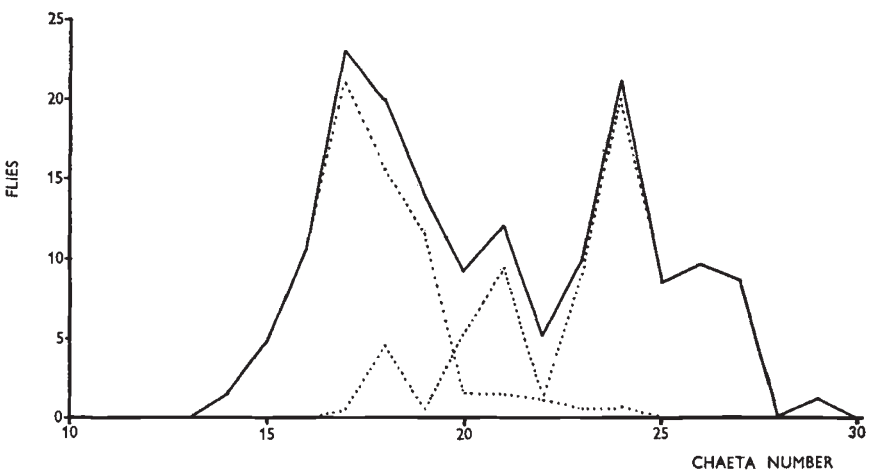

FIG. 14.—The distribution of chaeta number in generation 25 of line 25/A. The dotted lines continue the distributions of the halves of the populations.

results of Thoday and Boam (1959) who obtained divergence with 50 per cent. gene-flow. As we also expected, the divergence achieved with 25 per cent. gene-flow is greater than that in Thoday and Boam's population. Their divergence was 3 chaetæ per fly, after 37 generations, whereas the two 25 per cent. gene-flow populations had differences of 5 chaetæ per fly.

The present divergences were the result of heterogeneity of both second and third chromosomes, but it does not seem that either of the present lines produced more extreme chromosomes than were produced in Thoday and Boam's D^+ line. The D^+ low chromosome II gave the same order of chaeta number as that in 25/B, but the D^+ high Chromosome III was more effective than any high chromosome in

the present lines. The greater divergence obtained in the present lines, does not, then, arise from the production of more diverse chromosomes. In fact the diversity of chromosomes obtained from Line 25/A is considerably less than that in the D^+ line though the difference between high and low halves of 25/A is nearly twice as great as in D^+. The greater divergence was perhaps possible because the 25 per cent. gene-flow system permits the selection of extreme chromosomes in homozygous form. It is interesting to note in this connection, that the extreme low second chromosomes in the D^+ line were homozygous lethal (Gibson and Thoday, 1959) whereas those in 25/B are not (Gibson, unpublished).

It is of considerable importance that the present assays, together with the results of Gibson's tests which demonstrate the extreme low Chromosome II in 25/B to be different from that in the D^+ line, show that none of the three lines, D^+, 25/A or 25/B has responded to disruptive selection in the same way. This makes it unlikely that the Dronfield stock is peculiar in possessing a few heterozygous loci from which a polymorphism can readily be built up by selection. On the contrary, it is now clear that there are many ways in which this population can respond to disruptive selection despite its initiation from one wild female and her mate(s), and subsequent inbreeding in the laboratory. This is a nice demonstration of the remarkable genetic versatility of a wild stock of an outbreeding species.

The most striking fact about the responses in the two 25 per cent. gene-flow lines is their magnitude relative to the responses in the 0 per cent. gene-flow lines. The divergence of the two completely isolated halves of the two 0 per cent. gene-flow lines, was no doubt limited by the very small population size involved, and with larger population sizes we would expect isolation to permit greater divergence than 25 per cent. gene-flow. Nevertheless, the results suggest that in a heterogeneous habitat there will be plenty of scope for the divergence of an appropriate range of ecotypes despite random mating between them, as suggested by Thoday and Boam (1959), and Thoday (1960).

It is possible to object to this conclusion on the grounds that the present 25 per cent. gene-flow lines are maintained by a positive assortative mating system. To test the cogency of this objection we have taken a sub-line from Line 25/B and maintained it under disruptive selection with negative assortative mating. The mating system was exactly as in table 1, with the exception that the males taken from cultures A and B for mating with females of cultures C and D were selected for high chaeta number and the males taken from cultures C and D for mating with females of A and B were selected for low chaeta number. The results are illustrated in fig. 5. The change in regime at first reduced the difference between the high and low halves of the population, but recovery was rapid, and the demonstration that disruptive selection can maintain a difference

even with 25 per cent. gene-flow and negative assortative mating is clear. It seems reasonable to conclude that disruptive selection could produce and maintain considerable deviation under random mating.

5. SUMMARY

1. Two populations of *Drosophila melanogaster* have been exposed to disruptive selection with positive assortative mating and 25 per cent. gene-flow between the half selected for high and the half selected for low sternopleural chaeta number.

2. Two lines were run with 0 per cent. gene-flow between their halves, and two with 50 per cent. gene-flow. All the six lines were established from the same wild stock " Dronfield ".

3. Divergence was greatly limited by 50 per cent. gene-flow, but with 25 per cent. gene-flow it was, though slower, ultimately of as great magnitude as with complete isolation (0 per cent. gene-flow).

4. Chromosome assays showed the disruptive selection lines to contain a greater variety of chromosomes than the Dronfield wild stock. The two 25 per cent. gene-flow lines had responded in different ways for one contained extreme chaeta number second chromosomes, the other did not.

5. One of the 0 per cent. gene-flow lines was heterozygous for extreme low second chromosomes in its low half. This and the similar second chromosome in the 25 per cent. line may prove to be genetically the same, but they are certainly genetically different from the extreme low second chromosomes in the polymorphic population D^+ established by Thoday and Boam from the Dronfield stock. In addition one of the 50 per cent. gene-flow lines contained less extreme low second chromosomes. No such chromosomes have been found in the Dronfield stock.

6. The D^+ low second chromosome is known to be a recombinant product of other second chromosomes in the stock, and evidence points to these new ones also being recombinational in origin. There seem to be several ways in which this stock may respond to selection to produce polymorphisms.

7. The magnitude of the divergences in the 25 per cent. gene-flow lines is strong evidence that random mating cannot prevent divergence under disruptive selection. This conclusion is given force by the maintenance of most of the difference between the low and high halves of one 25 per cent. gene-flow population when put under a similar regime with negative assortative mating.

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