CHAPTER VI

THE CORRESPONDENCE BETWEEN THE DISTRIBUTION OF THE CHROMOSOMES AND OF THE GENETIC FACTORS

Attention has been called to the fact that paired factors are distributed in the same way as are homologous chromosomes, and that factors which are assorted independently are distributed in the same way as non-homologous chromosomes. In proof of the latter point there is Wilson's evidence for a Metapodius with three homologous m-chromosomes. It was found that the extra m goes to the gamete that receives X as often as to the other gamete. Miss Carothers describes a somewhat similar case in certain grasshoppers, in which the distribution of a pair of unequal chromosomes is independent of the distribution of the X chromosome. Not only are the pairs of factors assorted independently, as are the chromosomes, but in Drosophila, where the number of independently assorting groups of factors has been determined, it has been found that the number is identical with the number of chromosome pairs. Moreover, even the relative sizes of the groups—both as determined by the *number of factors* they contain and by the *frequency of crossing over* within them—are the same

as those of the chromosomes. Finally, the distribution of the factors within any one group is what the chromosome hypothesis calls for. For the frequencies of separation (or combination) between the different factors of a group are in a linear relation to each other, and the relation is even specifically of such a type (involving interference) as would be expected to occur if the separations between the factors resulted from the crossing over between two twisted chromosomes which the cytological evidence indicates may occur.

Even in cases where the chromosomes are not distributed in the usual way it is found that the factors have the same unusual method of distribution. For example, in moths there are some cases of extraordinary interest because the chromosomes can be traced to and through the ripening period of the eggs of the hybrid. Certain species of the moth Pygæra that have different numbers of chromosomes were crossed by Federley. The full number (calculated) and the reduced number of chromosomes in the different species are as follows:

	Diploid	Haploid
P. anachoreta	60	30
P. curtula	58	29
P. pigra	46	23

In the hybrids, the full number is the sum of the two haploid sets that went in from the parents. This shows that the chromosomes preserve their individuality through many successive cell divisions in a

foreign cytoplasm. In the maturation a few of the chromosomes seem at times to unite in pairs, but most of them fail to do so, so that while the number of the chromosomes at the first maturation division is slightly less than the full number it is much more than half of that number. Different types of hybrids behave slightly differently in respect to the extent to which union in pairs takes place. The failure to unite indicates that in normal maturation homologous chromosomes mate with each other, for here there are few or no chromosomes that are strictly homologous and yet there is just as much opportunity as in normal maturation for non-homologous chromosomes from the same parent to unite.

When the first spermatocyte division takes place in the hybrid, all the unmated chromosomes divide, but the few chromosomes that are mated presumably separate. Consequently each of the daughter cells has the double number of chromosomes (a set from each parent species), except for the few chromosomes that had been united in pairs. At the second maturation division the chromosomes again divide, so that the spermatozoa too should receive nearly the double number of chromosomes, one set from one species, the other set from the other species.

If, then, the factors are contained in the chromosomes, we should expect that, except for any factors in the few chromosomes that mate and separate, the hybrid would transmit to all its offspring the same

factors, since every spermatozoon receives, with the above exceptions, all the chromosomes (paternal and maternal) that the hybrid contains. On crossing the hybrid to either parent, it is found that the offspring actually are very much alike, *i.e.*, have all received practically the same factors—a striking contrast to the result usually obtained in "backcrosses." In respect to just one character (a larval marking), however, the above relation does not hold, but ordinary Mendelian results are obtained, and this in turn corresponds with the fact that a few chromosomes do undergo segregation. In regard to the other characters, not only are the offspring like each other, but they resemble the hybrid more than either of the pure species, corresponding with the fact that they contain complete sets of chromosomes from both types. But they do not look just like the F_1 hybrid, and correspondingly one set of chromosomes is in the diploid, the other in the haploid number. This is because they receive a set of one species from both parents, but a set of the other species only from the hybrid parent. Federley also shows that when maturation takes place in this triploid individual one set of chromosomes does not undergo mating, but the others—presumably those in the two identical sets—do pair with each other, so that the total number is reduced to one bivalent set, and one single set. If the paired chromosomes separate and the unpaired ones divide, as occurs in the F_1 hybrid, the double number of chromosomes, a set of each species, will again be found in the sperm, as was the case in the first hybrid. In other

words there is expected no return to either parent type, but the hybrid when backcrossed always continues to produce hybrids. Moreover, there is no apparent weakening or other influence exerted by the egg on the foreign chromosomes even in successive generations. The breeding results of Standfuss, who backcrossed other moths for several generations, show exactly this phenomenon—the same type of hybrid constantly produced in every generation.

A similar behavior of the chromosomes has been recently described by Doncaster in a cross between other species of moths, and is illustrated in the following figures. The full number of chromosomes in the moth Biston hirtaria is shown in Fig. 48, *a*. There are 28 in all, of which four are small. Another species, Biston zonaria, has something over a hundred very small chromosomes (Fig. 48, *b*). The reduced number of chromosomes of the former species is 13 (one large one being coupled with a small one), of the latter 56. The chromosome group of the hybrid (zonaria ♀ by hirtaria ♂) is shown in Fig. 48, *c*. The exact number of chromosomes is difficult to count, but there are 14 large ones and about 56 small ones. In this hybrid a stage is passed through that resembles the synapsis stage. When the chromosomes emerge from this stage (Fig. 48, *c'*), almost the full number are found present, although Doncaster thinks that a few of them have united in pairs; for as shown in the figure there are now 12 or 13 large and 50 or 51 small chromosomes. These are a few less than the full number present before synapsis. In this case, how-

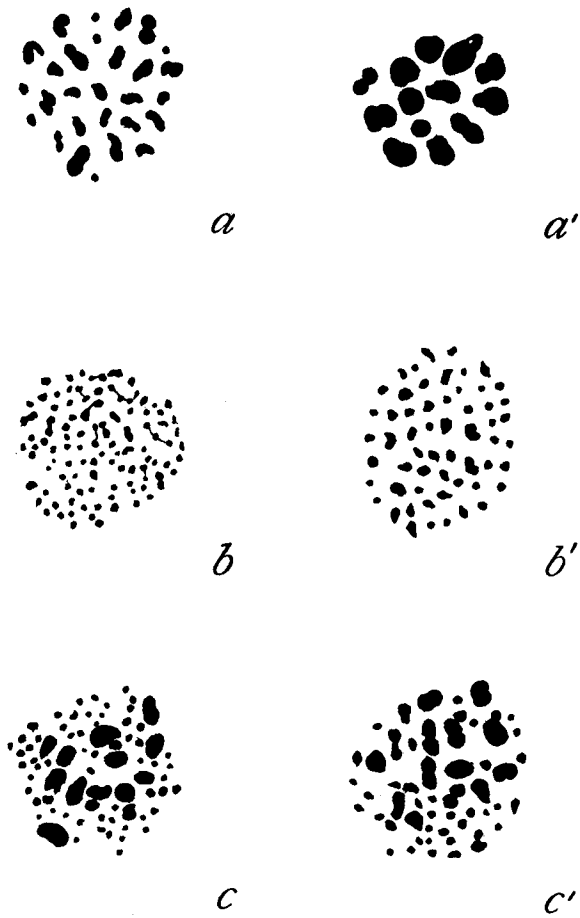


FIG. 48.—Biston hirtaria; *a*, spermatogonial chromosomes; *a'*, primary spermatocyte chromosomes (reduced number). Biston zonaria; *b*, spermatogonial chromosomes; *b'*, primary spermatocytes (reduced number). Hybrid, out of zonaria female by hirtaria male; *c*, spermatogonial chromosomes; *c'*, primary spermatocytes. (After Harrison and Doncaster.)

ever, no data concerning the genetic behavior of the hybrids have been reported.

Another instance of parallelism between unusual chromosome phenomena and genetic results is that found in Œnothera lata and semilata by Lutz, Gates and Thomas. The normal chromosome number in Œnothera lamarckiana is 14, but the race called lata always has 15 chromosomes, *i.e.*, one kind of chromosome exists in the triploid number. This is true even of lata plants which originated independently of the ordinary stock, in widely different races of Œnothera. The same results apply to semilata, which appears to be a variety of lata. Lata and semilata occasionally arise "spontaneously" from lamarckiana, in a small per cent. of the offspring of any one individual, and the explanation for this may be found in the fact that occasionally, in the gametogenesis of lamarckiana, two mated chromosomes, instead of separating, pass to the same pole (non-disjunction) so that the offspring would have three chromosomes of this type and contain 15 chromosomes in all. The behavior of the extra chromosome in the lata individuals is also of interest, for it is found that in gametogenesis, when the mated chromosomes separate, the extra chromosome does not divide regularly as do unpaired chromosomes in moths, but tends to pass to one pole. This would result in half the gametes containing it and transmitting the lata condition and the other half being normal. Very often, however, the chromosome lags on the spindle and so fails to be included in the nucleus of either daughter

cell, or it may even be torn apart, as if by spindle fibers from opposite poles. Consequently less than half of the gametes (at least the sperm, for gametogenesis was not studied in the female organs) receive the extra chromosome. The proportion varies greatly in different individuals. This conforms with the genetic result that lata individuals, crossed to lamarckiana, give varying proportions of lata offspring but never produce offspring more than half of which are lata.

In Primula, a striking case of correspondence between abnormal genetic and chromosome phenomena has been found, that appears strongly in favor of the chromosome hypothesis, although the discoverer, Gregory, has hesitated to draw this conclusion. Two giant races of the primula (P. sinensis) were found to have twice the number of chromosomes characteristic of other domesticated races. The breeding experiments with these plants show that they also have a double set of factors as compared with the same factors in ordinary primulas. While in ordinary plants each chromosome is double and, therefore, each factor is represented twice, for instance by A and A, in the giants there are four like chromosomes, hence four factors AAAA. If the giant race contains some factors already mutated, such as A^1, the giant might contain one, two, three, or four of the mutant factors A^1. Such plants would be $AAAA^1$ or AAA^1A^1 or $AA^1A^1A^1$ or $A^1A^1A^1A^1$. As stated above, the breeding work shows that there is a quadruple set of factors, but the evidence is as yet insufficient to de-

cide whether a mutant factor A^1 has as its mate (always pairs at maturation with) a special one of the remaining A's or may become the mate of any one of the three. On the chromosome hypothesis we should expect, on the whole, the latter to be true. Whichever of these views becomes established the parallel between the double set of chromosomes and the double set of factors is the important fact. Gregory admits this, but adds the caution: "Yet on the other hand the tetraploid number of chromosomes may be nothing more than an index of the quadruple nature of the cell as a whole."

In the preceding cases it has been shown that the factors and the chromosomes have the *same method* of distribution. In the case of sex and sex linked factors it can even be shown that they have the *same* distribution as the sex chromosomes. This identity of distribution holds not only for F_2 results and F_3 tests, but for all kinds of backcrosses as well. The relation holds, moreover, for all known sex linked factors, of which in Drosophila there are more than forty cases, and for all combinations of sex linked factors. Not to interpret this evidence to mean that the factors are contained in and carried by the chromosomes is to reject a mechanistic basis known to exist in the cell. Nothing is gained if, in order to avoid the obvious connection between the inheritance of the character and the transmission of the chromosome, we assume that something else in the cell, a portion of the cytoplasm, perhaps, also follows the distribution of the sex chromosomes. Such a postu-

late only adds an unknown and improbable assumption and leaves the situation less clear than before.

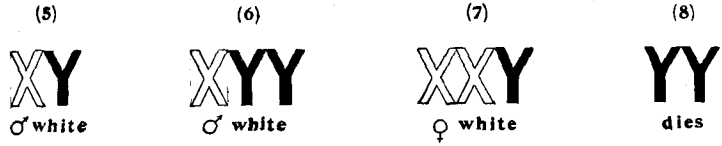
The advantage of the chromosomal interpretation as applied to the sex chromosomes is nowhere better illustrated than in the history of a process called non-disjunction, which was discovered by Bridges. Furthermore this case, supported on the one hand by extensive and definite experimental breeding and on the other hand by cytological investigation, offers the most direct evidence yet obtained concerning the relations of particular characters and particular chromosomes, for in this case an abnormal distribution of the sex chromosomes goes hand in hand with an identical abnormal distribution of all sex linked factors. It was found that females from a certain strain of white-eyed flies gave, on out-crossing, about 5 per cent. of unexpected classes. For instance, one of the white females crossed to a red-eyed male (wild type) produced not only red-eyed daughters and white-eyed sons, as expected, but also a few white-eyed daughters and a corresponding number of red-eyed sons. The approximate percentage in which these classes appeared is as follows:

Red ♀	White ♂	White ♀	Red ♂
47.5%	47.5%	2.5%	2.5%

In general, therefore, there were 95 per cent. of expected forms and 5 per cent. of offspring that were apparently inconsistent with expectation on the chromosome theory. Closer inspection of these

results showed that the exceptions could be explained, if, occasionally, the two X chromosomes failed to disjoin in the reduction division, both passing out of some of the eggs of the white-eyed mother into the polar body, or, conversely, both remaining in the egg. If the two white-bearing X's should remain in the egg then such an egg fertilized by a Y sperm would give rise to a white-eyed daughter. Likewise the no-X egg fertilized by the X sperm of a red-eyed male would give a red-eyed son. The white daughters would, as just shown, contain two X's and one Y chromosome, unlike ordinary daughters, which contain two X's only. Since in these females there are three sex chromosomes instead of a pair, at the reduction division two must pass into one cell and one into the other. This division might take place in four ways: $\frac{XY}{X}$, $\frac{X}{XY}$, $\frac{Y}{XX}$ and $\frac{XX}{Y}$ (representing the egg below and the polar body above in each case). The first two types of reduction, depending on a more symmetrical pairing of the chromosomes, might be more frequent than the other two types. There would then be four types of eggs—a large number of X and XY eggs, and a few XX and Y eggs. Let us suppose that an XXY white female is mated to a red male. The progeny produced by the X bearing sperm would be:

The same series of eggs fertilized by the male-producing sperm, which carries a Y chromosome, would give:



If we consider these eight kinds of progeny we see that the exceptional white females (7) would be expected to repeat the process and be non-disjunctional. This is what actually occurs, for all white females that are the product of such a cross do, in fact, give non-disjunction in the next generation.

The red males (4) are an exceptional class but should not give exceptional results when bred to any normal female, nor should they transmit non-disjunction. This has been shown to be true.

The red females are not alike in composition, half of them (1) should behave like normal females heterozygous for white and the other half (2) should give exceptions. There are in fact found to be these two kinds of red females in equal numbers.

The white males (5) and (6) are not alike; one kind (5) is normal and the other (6) has two Y chromosomes. The latter should be expected to produce some XY sperm. These sperm would give daughters which would not be exceptions, but such females, with a formula XXY, should produce exceptions. In fact from half of the white males (5 and 6), daughters are produced that give non-disjunction.

The results bear out to a remarkable degree the hypothesis that they are due to a non-disjunction of the sex chromosomes caused by the presence of a Y chromosome in the females.

The hypothesis is capable of verification and Bridges has made a study of the chromosomes of the non-disjunctional females. He finds that such

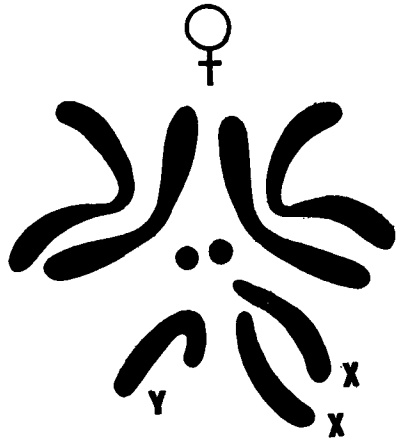


FIG. 49.—Group of chromosomes of an XXY female of a non-disjunctional "line."

females contain an extra chromosome whose size and position show that it is a supernumerary sex chromosome. The normal group of chromosomes of the female of Drosophila ampelophila is shown in Fig. 2, and a group from a non-disjunction female in Fig. 49. They differ by one chromosome, namely, the extra Y.

One additional fact must be mentioned. If an XXY female should be fertilized by an XYY male

some females would be produced that are XXYY, owing to the union of an XY egg with an XY sperm or an XX egg with a YY sperm. One such female was found—she had two X and two Y chromosomes.

Here then is a case that seemed at first to be in direct contradiction to the scheme of sex linked inheritance based on the chromosome hypothesis, which proved, however, on further examination to give a brilliant confirmation of that theory; for not only can the hereditary results be accounted for, but the theory on which they were based was directly confirmed by a microscopical study of the chromosomes themselves.

Cases indicating non-disjunction have also been obtained in Abraxas, by Doncaster. As stated in the chapter on Sex Inheritance, he has found a strain in which the males have 56 chromosomes—the normal number, but the females have only 55 instead of 56 chromosomes. It seems reasonable, then, to suppose that such females arose by the passing of the two sex chromosomes, ZZ, to one pole (spermatocyte) leaving none at the other pole of the cell. The sperm resulting from the no-Z cell fertilizing a Z egg would give a ZO individual which would be a female with 55 chromosomes. All the daughters of the ZO female would be ZO and her sons ZZ individuals: and the race would continue in this fashion. On the other hand, if the ZZ sperm produced by non-disjunction fertilized a W egg, a male WZZ, corresponding to the XXY female of Drosophila, would be formed. Such a male would give rise to some sperm

carrying both Z and W, and if such a ZW sperm fertilized a zero egg of the 55 chromosome female, a 56 chromosome female would be produced. Doncaster actually found such a female among offspring from a cross of a female from the 55 chromosome race with wild type male, and he found also the genetic exceptions required on the assumption that this male was a WZZ form.