An Empirical Test of the Meiotic Drive Models of Hybrid Sterility: Sex-Ratio Data From Hybrids Between *Drosophila simulans* and *Drosophila sechellia*

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Manuscript received August 2, 1991
Accepted for publication November 12, 1991

ABSTRACT

Recently, there has been much discussion regarding the hypothesis that divergence of meiotic drive systems in isolated populations can generate the patterns of reproductive isolation observed in animal hybridizations. One prediction from this hypothesis is that the sex ratio of hybrids with heterospecific sex chromosomes should greatly deviate from the Mendelian expectation of 50% female. From sex-ratio data in our Drosophila hybridization studies, we find no such deviation: the sex ratio of offspring of males with introgressed heterospecific *Y* chromosomes with various autosomal backgrounds does not differ from that of the pure species. We also discuss other aspects of the current meiotic drive models.

MEIOTIC drive has intuitive appeal as an explanation for hybrid sterility because drive, if not suppressed, causes half of the gametes to be dysfunctional (CROW 1979). Thus, two independent drive systems could conceivably cause sterility. In addition, *X* chromosome drive against the *Y* is expected to be more common than meiotic drive between the autosomes or between the *X*'s, as discussed in WU and HAMMER (1990) who also provide empirical evidence from Drosophila studies.

HURST and POMIANKOWSKI (1991) and FRANK (1991a,b) used the above argument to suggest meiotic drive between *X* and *Y* as a plausible explanation for HALDANE's (1922) rule. This rule states that if there is sex-limited sterility or inviability in the F_1 hybrids of an interspecific cross, the heterogametic sex will usually be the one affected. In crosses within a species, however, there is no sterility and drive is rarely observed. The paucity of intraspecific drive is usually explained by assuming the presence of modifiers which suppress the drive activity. This is a reasonable assumption since suppressors of known meiotic drive are quite abundant (VOELKER 1972; HARTL and HIRAIZUMI 1977; HIRAIZUMI 1990) and the theoretical conditions required for suppressors to increase in gene frequency are not stringent (ESHEL 1985) [see WU and HAMMER (1990) for further references]. WU (1983) showed that this is especially true of sex-linked drive. If the suppressors which evolve in one species can not suppress the diverged driving loci of another species, hybrids with heterospecific sex chromosomes should either be sterile (two drive systems de-repressed) or produce extremely biased sex ratios (one drive system de-repressed). Below we present data on the sex ratios produced by these hybrids and then discuss the general implications.

Crosses of *Drosophila simulans* and its close relative *Drosophila sechellia* follow HALDANE's (1922) rule; that is, the female F_1 hybrids are fertile while their brothers (F_1 males) are sterile. Linkage analysis has determined that there are at least three *X*-linked factors which cause hybrid male sterility when *D. sechellia* is introgressed into *D. simulans* background (COYNE and CHARLESWORTH 1989). The aims of our studies have been to obtain a physical map of these *X*-linked factors, to examine the phenotypes of these factors, and to determine with what these factors interact to cause sterility. As part of this last aim, we introgressed the *Y* chromosome of *D. sechellia* into *D. simulans* genetic background.

MATERIALS AND METHODS

Y introgression: The introgression of the *Y* chromosome was initiated by crossing *D. simulans* attached-*X* females to *D. sechellia* males (see Figure 1 for cross). The F_1 attached-*X* females were then crossed to *D. simulans* males. The resulting backcross F_2 males (henceforth called F_2) had an *X* chromosome from *D. simulans* and a *Y* from *D. sechellia*. These males had one set of their autosomes entirely from *D. simulans* but the other set was heterogeneous: on average one-half *D. simulans* and the other half *D. sechellia*; subsequently designated as $X_{sim}/\ Y_{sec}$; (A_{sim} or A_{sec})/ A_{sim}. These males were backcrossed to virgin *D. simulans* females for eight more generations to ensure a pure *D. simulans* background. The resulting males are designated as $X_{sim}/\ Y_{sec};\ A_{sim}/\ A_{sim}$ (Figure 1). The identity of the *Y* chromosome of this introgression was confirmed by probing Southern blots with *Stellate* which detects *Y* specific bands (N. JOHNSON, E. CA-

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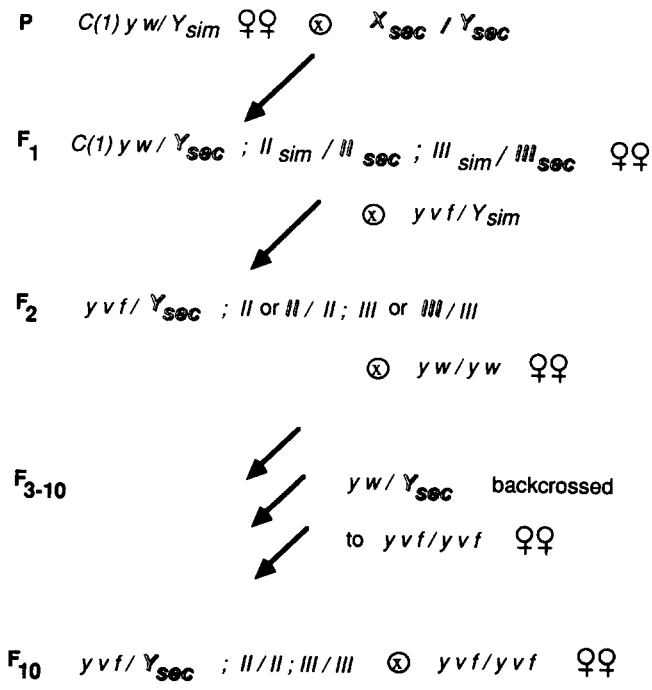

FIGURE 1.—Genetic crosses generating the *Y* introgression. *C(1)y w* is the *D. simulans* attached-*X* chromosome. Between the F_2 and the F_{10} generations we alternately crossed the males to *D. simulans* *y v f* and *y w* females; the presence/absence of the *f* phenotype was examined to ensure the virginity of the females.

BOT, D. PEREZ and C.-I WU, manuscript submitted). We examined the sex-ratios of both the F_2 males and the pure *Y* introgression males. We also were able to construct the reciprocal introgression (*Y* from *D. simulans* in *D. sechellia* background) by crossing the F_2 attached-*X* females (the sisters of the F_2 males) to *D. sechellia* and then backcrossing the resulting fertile males to *D. sechellia* for several generations. The resulting genotype is $X_{sec}/\ Y_{sim};\ A_{sec}/\ A_{sec}$.

Test of *Y* introgressed males: Individual males (less than 1 day old) of the genotype $X_{sim}/\ Y_{sec};\ A_{sim}/\ A_{sim}$ were mated to two virgin *D. simulans* females. The males were removed from the vial after 2 days and after 4 days the females were transferred to another vial in which they were allowed to lay eggs for another 4 days. The offspring emerging from both vials were scored and sexed at 2-day intervals until 19 days had past from the time the vials were established. As a control, we performed the same experiment on pure *D. simulans* males. In this experiment, the flies were kept at 25° with a light/dark cycle of 16L:8D.

Test of the F_2 males: In another experiment, the F_2 males (see Figure 1) were individually mated to two *D. simulans* females. The males and females were kept in a vial for 6 days and then transferred. The offspring emerging from these vials were scored and sexed as in the previous experiment. These flies were maintained at room temperature (22 ± 2°).

RESULTS

***Y* introgression:** Throughout the paper, the sex ratio will be defined as the proportion of females. The progeny from 42 $X_{sim}/\ Y_{sec};\ A_{sim}/\ A_{sim}$ males had an overall sex ratio of 0.503 (1812 females, 1787 males). G-tests with a correction for multiple tests via Sidak's multiplicative inequality procedure were performed on the data from these individual males which produced greater than 40 offspring (SOKAL and ROHLF 1981; ROHLF and SOKAL 1981, table 15). None of the values were significantly different from a 0.5 sex ratio at the 5% level. The data from the males which produced fewer than 40 offspring were pooled; there was no significant deviation from a 0.5 sex ratio in the pooled data. From 43 of the pure *D. simulans* males, 1935 females and 1833 males were produced (sex ratio = 0.514). No individual males produced sex ratios significantly different from 0.5. There is also no significant difference between the overall sex ratios of the two *Y* genotypes nor is there a significant difference between either of the overall sex ratios and 0.5. Table 1 shows a comparison of the distribution of sex ratios from individual males of the pure *D. simulans* (Y_{sim}) males and the introgression males (Y_{sec}). In both cases, only males which produced greater than 40 progeny are tabulated. The distributions are quite similar. We also examined the sex ratios from the reciprocal introgression, ($X_{sec}/\ Y_{sim};\ A_{sec}/\ A_{sec}$). From a small sample taken from mass cultures, the sex ratio was 0.516 (150 females, 141 males). Again, we find no evidence for drive.

TABLE 1

Comparison of sex ratios from progeny of Y_{sec} and Y_{sim} males in *D. simulans* autosomal background

Sex ratio of progeny (proportion female)	No. of Y_{sec} males	No. of Y_{sim} males
0.38–0.40	1	0
0.40–0.44	2	3
0.44–0.48	10	6
0.48–0.52	12	11
0.52–0.56	8	11
0.56–0.60	5	5
0.60–0.62	0	2
Total	38	38
Mean sex ratio	0.5029	0.5142
SD	0.0488	0.0512
Mean sample size	93.63	97.71
SD	19.185	19.639

F_2 males: Fifty percent (60/120) of the F_2 males (see Figure 1) produced progeny. We attribute the 50% sterility to interactions between the X_{sim} and autosomal factors of *D. sechellia*. The number and sex ratios of the progeny from the first 26 fertile males were recorded; the progeny of these males had a sex ratio of 0.503 (511 females, 504 males). Table 2 shows the results for males which produced greater than 10 progeny (we used a less stringent cut-off here because these males in general produced fewer progeny). When the *P* values are corrected for multiple tests (ROHLF and SOKAL 1981, table 15), none of the individuals produced a significantly biased sex-ratio. We note that these males are genetically heterogeneous; their autosomal background ranges from almost

TABLE 2

Sex ratios of progeny from fertile F_2 X_{sim}/Y_{sec} males

Line	No. of females	No. of males	Total	Percent female
3	22	17	39	56.4
4	20	14	34	58.8
5	8	4	12	66.7
6	26	19	45	57.8
8	10	4	14	71.4
12	14	19	33	42.4
17	30	41	71	42.2
24	19	23	42	45.2
27	15	10	25	60.0
30	11	10	21	52.4
31	50	57	107	46.7
32	17	21	38	44.7
37	6	6	12	50.0
38	10	17	27	37.0
39	19	9	28	67.9
40	60	62	122	49.2
41	18	21	39	46.2
43	7	11	18	38.9
44	30	15	45	66.7
46	58	41	99	58.6
51	26	35	61	42.6
52	22	29	51	43.1

Mean sex ratio = 0.5014
Median sex ratio = 0.4964

Only lines producing greater than 10 progeny are displayed. None of the lines are significantly different from a sex ratio of 0.5 when P values are adjusted for multiple tests by Sidak's multiplicative inequality (ROHLF and SOKAL 1981, table 15).

purely homozygous for *D. simulans* to nearly completely heterozygous. The lack of any outliers suggests that there is no autosomal modification of the sex ratio.

DISCUSSION

The generic meiotic drive model for hybrid sterility is distinct from other models, such as the *X*-autosome (DOBZHANSKY 1936; HAUSCHTECK-JUNGEN 1990), *X*-*Y* (COYNE 1985), and the *Y*-autosome (HENNIG 1977; ZOROUS 1986) interaction models, in that it predicts sex-ratio distortion, if one but not the other drive system is de-repressed. The conditions for partial de-repression depend on the genetic assumptions. Our experiments represent an attempt to find sex-ratio distortion under various hybrid genetic backgrounds. The lack of positive evidence would mean that such a model is at best an insufficient explanation for the rather general HALDANE's rule. We do not consider the sterility of various genotypes relevant even though it is (or is not) predicted by a strict meiotic drive model because sterility is also predicted by the nonmeiotic drive models.

The absence of sex-ratio distortion in X_{sim}/Y_{sec}; A_{sim}/A_{sim} and X_{sec}/Y_{sim}; A_{sec}/A_{sec} males immediately excludes several possibilities of meiotic drive models. First, the model in which the *X* of one species drives against the *Y* of another species, but not the *Y* of its own species because of the accumulation of drive suppressors on the conspecific *Y* chromosome, is not possible. It is obvious that, under this model, suppressors of meiotic drive are not present in the males of the above genotypes and thus de-repression of drive is expected. This argument applies equally well to *Y* drive against *X*. Second, the observations also rule out the model in which the *Y* drives against the *X* of another species, but not the *X* of its own species due to autosomal suppressors of its own species. In the two genotypes above, the *Y* is the only chromsome introgressed, leaving behind all potential suppressors of its drive.

Another possibility remains untested: that of the *X* driving against the *Y* of another species but not the *Y* of its own species due to autosomal suppressors. Ideally, to test this model, one would like to construct a male of a genotype like X_{sec}/Y_{sim}; A_{sim}/A_{sim} and determine whether *X* can indeed drive against *Y* in the absence of all potential suppressors. Unfortunately, males with such a genotype are invariably sterile [see COYNE and ORR (1989) for "the large *X* effect"]. As we stated previously, sterility is predicted by all models and hence does not support any particular model. We attempted to circumvent this problem by examining X_{sim}/Y_{sec}; (A_{sim} or A_{sec})/A_{sim} fertile males. Since Y_{sec} expresses no drive against X_{sim} as shown above, we might expect some of the males of those genotypes to produce a highly female-biased sex-ratio provided that (1) X_{sim} can drive against Y_{sec} and (2) the drive suppressors on X_{sim} are not completely dominant. In this case, some males having the A_{sec} homolog of the suppressor will have their *X* drive against *Y* de-repressed. The data from Table 2 do not reveal any significant deviation from the Mendelian expectation, again suggesting the lack of meiotic drive. We do note that the data do not rule out the possibility of drive; however, all of the postulated suppressors must be nearly completely dominant. But if the suppressors are dominant, one would not expect sterility in the F_1 (the very observation the meiotic drive models attempt to explain).

Another source of data against the possibility of *X* driving against *Y* comes from the introgression experiments (WU and BECKENBACH 1983; NAVIERA and FONTDEVIA 1986; COYNE and CHARLESWORTH 1986, 1989) which yield males carrying an introgressed segment of the *X* (instead of the entire chromosome) from one species in a genetic background almost entirely from another species. Some of these males are fertile and, if the introgressed segment happens to include a driving (or distorting) locus, a strong female-biased sex-ratio is expected because neither the *Y*-linked nor the autosomal suppressors are co-introgressed. Introgression experiments have been

performed in four regions of the *X* from *Drosophila pseudoobscura* into *Drosophila persimilis* and vice-versa (WU and BECKENBACH 1983) and three regions of the *X* from *Drosophila mauritiana* or *D. sechellia* into *D. simulans* (COYNE and CHARLESWORTH 1986, 1989; C.-I WU, D. PEREZ and N. JOHNSON, manuscript in preparation). In all cases the extent of the introgressions was determined by linkage analysis (WU and BECKENBACH 1983; COYNE and CHARLESWORTH 1986, 1989) or, more directly, by DNA markers (C.-I WU, D. PEREZ and N. JOHNSON, manuscript in preparation). No strong sex-ratio distortion has been detected in any of them; again, there is no positive evidence for *X* drive against *Y*.

Additional comments on the meiotic drive models: The feasibility of mapping *X*-linked sterility factors by either genetic or molecular means to small segments of the *X* chromosome can be evidence against the meiotic drive model of HURST and POMIANKOWSKI (1991). Sterility, under such a model, requires the derepression of two different drive systems. Thus, the region to which the sterility factor is mapped must contain both a driving locus (like *Segregation distorter*) of one system and the target locus (like *Responder*) of another system. Given the increasingly small regions to which we can map these factors (C.-I WU, D. PEREZ and N. JOHNSON, manuscript in preparation), we consider this situation highly unlikely.

In FRANK's (1991a,b) model, meiotic drive is the ultimate though not necessarily the proximate cause of sterility. COYNE, CHARLESWORTH and ORR (1991) provided a list of criticisms against FRANK's model, which FRANK (1991b) defended. COYNE, CHARLESWORTH and ORR (point 4) correctly indicated the difficulty FRANK's (1991a) model has in explaining sterility. Unlike HURST and POMIANKOWSKI's (1991) model which have both *X*-drive and *Y*-drive leading to the mutual destruction of the sex chromosomes (and hence, sterility), FRANK postulated only *X*-drive against *Y*. His model seems to assume that sex-linked meiotic drive is the result of defective meiosis and that sterility will result if there is further tampering of that process. In his rebuttal (FRANK 1991b), he stressed the meiotic defect of meiotic drive systems. HURST and POMIANKOWSKI (1991) also assumed meiotic defects although their model does not depend on that assumption.

Since both the *X*-linked (*Sex-ratio*) and autosomal (*Segregation Distorter*) meiotic drive systems known in Drosophila are now believed to be the result of spermiogenic (postmeiotic) failure (NOVITSKI, PEACOCK and ENGEL 1965; TOKUYASU, PEACOCK and HARDY 1972; HAUSCHTECK-JUNGEN and MAURER 1976), FRANK's (1991b) challenge of the widely accepted view should be discussed. He cited NOVITSKI, PEACOCK, and ENGEL (1965) and COBBS, JEWELL and GORDON (1991) as evidence of meiotic defects in a sex-linked drive system. However, if the *Y* indeed degenerates during meiosis, the resultant nullo-*XY* sperm will produce *XO* sterile sons. DENELL and MIKLOS (1971) have shown, by using the attached-*XY* technique, that nullo-*XY* sperm are nearly normal in their production and fertilization. Such nullo-*XY* sperm escape distortion (COBBS 1986). In other words, for *Sex-ratio* males to produce an all-female progeny, the actual segregation of the sex chromosomes must be normal; otherwise, they would produce 50% sterile sons. HAUSCHTECK-JUNGEN and MAURER (1976) did find some aberration in the cytology of *Sex-ratio* males' meiocytes but concluded that the segregation of sex chromosomes is normal.

The *male-sex-ratio* trait (*msr*, COBBS, JEWELL and GORDON 1991) is an interesting possibility of an interference with drive resulting in sterility. However, it has not been shown that the polygenic *msr* factors indeed are *Sex-Ratio* specific; their effect on non-*Sex-Ratio X* chromosomes, other than that of the L116 strain, has not been tested (G. COBBS, personal communication). In addition, *msr* factors are not suppressors of drive as required in FRANK's (1991a,b) model since these factors cause massive non-disjunction on all chromosomes.

Both HURST and POMIANKOWSKI (1991) and FRANK (1991a,b) also attempted to extend their models to explain the inviability aspect of HALDANE's rule as well. FRANK (1991a) postulated that meiotic defects may have pleiotropic effects on mitosis and HURST and POMIANKOWSKI (1991) referred to the idea of transposable elements being responsible for Segregation Distortion (contrary to the results of POWERS and GANETSKY 1991). These suggestions are not necessary. It would have been quite a laudable accomplishment to provide a reasonable explanation for just the sterility aspect of HALDANE's rule because MULLER's (1940) hypothesis seems adequate as an explanation for the inviability aspect. The remaining mystery is the extremely rapid evolution toward (heterogametic) male sterility (C.-I. WU, manuscript submitted for publication).

Meiotic drive has many unusual properties which defy the great tenets of population genetics, as enumerated by CHARLESWORTH and HARTL (1978). It has served as the last resort for many of the inexplicables, such as the persistence of deleterious variants, the fixation of pericentric inversions (HEDRICK 1981; but see COYNE 1989) and the decline of population fitness. Sex-linked drive can even theoretically cause population extinction (GERSHENSON 1928; HAMILTON 1967). On the other hand, the evolution of hybrid sterility/inviability, having no apparent selective advantage, has provided a fertile ground for theories and speculation. It seems logical to link meiotic drive with the

evolution of postmating reproductive isolation. Our data, however, show that a proximate connection between drive and hybrid sterility is unlikely for at least the *D. simulans* and *D. sechellia* pair.

We thank JERRY COYNE, STEVE FRANK and LAURENCE HURST for supplying copies of their manuscripts in press. The *Stellate* plasmid clone was kindly provided by ANDREW CLARK. We also thank JIM BULL, ERIC CABOT, JERRY COYNE, JIM CROW, LAURENCE HURST, AVIS JAMES, ALLEN ORR and MIKE PALOPOLI for their valued discussions and comments on the manuscript. This research has been supported by National Institutes of Health (NIH) grant GM39902 (C-I.W.). C-I.W. is also supported by a Research Career Development Award from the NIH and an award from the National Down Syndrome Society. N.A.J. was supported by a Genetics Training Grant from the NIH (5 T32 GM 07102-14).

LITERATURE CITED

CHARLESWORTH, B., and D. HARTL, 1978 Population dynamics of the segregation distorter polymorphism of *Drosophila melanogaster*. Genetics **89:** 171–192.

COBBS, G., 1986 An investigation of the genetics of "male-sex-ratio" phenotype in *Drosophila pseudoobscura*. Genetics **113:** 355–365.

COBBS, G., L. JEWELL and L. GORDON, 1991 Male-sex-ratio trait in *Drosophila pseudoobscura:* frequency of autosomal aneuploid sperm. Genetics **127:** 381–390.

COYNE, J. A., 1985 The genetic basis of Haldane's rule. Nature **314:** 736–738.

COYNE, J. A., 1989 A test of the role of meiotic drive in fixing a pericentric inversion. Genetics **123:** 241–243.

COYNE, J. A., and B. CHARLESWORTH, 1986 Localization of an X-linked factor causing sterility in male hybrids between two closely related species of *Drosophila*. Heredity **57:** 243–246.

COYNE, J. A., and B. CHARLESWORTH, 1989 Genetic analysis of X-linked sterility in hybrids between three sibling species of *Drosophila*. Heredity **62:** 97–106.

COYNE, J. A., B. CHARLESWORTH and H. A. ORR, 1991 Haldane's rule revisited. Evolution **45:** 1710–1714.

COYNE, J. A., and H. A. ORR, 1989 Two rules of speciation. pp. 189–211 in *Speciation and its Consequences,* edited by D. OTTE and J. ENDLER. Sinauer Press, Sunderland, Mass.

CROW, J. F., 1979 Genes that violate Mendel's rules. Sci. Am. **240:** 134–146.

DENELL, R. E., and G. L. G. MIKLOS, 1971 The relationship between first and second chromosome segregation ratios from *D. melanogaster* males bearing *Segregation Distorter*. Mol. Gen. Genet. **110:** 167–177.

DOBZHANSKY, TH., 1936 Studies on hybrid sterility. II. Localization of sterility factors in *Drosophila pseudoobscura* hybrids. Genetics **21:** 113–135.

ESHEL, I., 1985 Evolutionary genetic stability of Mendelian segregation and the role of free recombination in the chromosomal system. Am. Nat. **125:** 412–420.

FRANK, S. A., 1991a Divergence of meiotic drive suppression systems as an explanation for sex-biased hybrid sterility and inviability. Evolution **45:** 262–267.

FRANK, S. A., 1991b Haldane's rule: a defense of the meiotic drive theory. Evolution **45:** 1714–1717.

GERSHENSON, S., 1928 A new sex-ratio abnormality in *Drosophila obscura*. Genetics **13:** 488–507.

HALDANE, J. B. S., 1922 Sex ratio and unisexual sterility in hybrid animals. J. Genet. **12:** 101–109.

HAMILTON, W. D., 1967 Extraordinary sex ratios. Science **156:** 477–488.

HARTL, D. L., and Y. HIRAIZUMI, 1977 Segregation distortion, pp. 616–666 in *The Genetics and Biology of Drosophila,* Vol. 1b, edited by M. ASHBURNER and E. NOVITSKI. Academic Press, New York.

HAUSCHTECK-JUNGEN, E., 1990 Postmating isolation and modification of the Sex-Ratio trait in *Drosophila subobscura* induced by the sex chromosome gene arrangement $A_{2+3+5+7}$. Genetica **83:** 31–44.

HAUSCHTECK-JUNGEN, E., and B. MAURER, 1976 Sperm dysfunction in sex ratio males of *Drosophila subobscura*. Genetica **46:** 459–477.

HEDRICK, P. W., 1981 The establishment of chromosomal variants. Evolution **35:** 322–332.

HENNIG, W., 1977 Gene interactions in germ cell differentiation of *Drosophila*. Adv. Enzyme Regul. **15:** 363–371.

HIRAIZUMI, Y., 1990 Negative segregation distortion in the SD system of *Drosophila melanogaster:* a challenge to the concept of differential sensitivity of *Rsp* alleles. Genetics **125:** 515–525.

HURST, L. D., and A. POMIANKOWSKI, 1991 Causes of sex ratio bias may account for unisexuality in hybrids: a new explanation of Haldane's rule and related phenomena. Genetics **128:** 841–858.

MULLLER, H. J., 1940 Bearing of the *Drosophila* work on systematics, pp. 185–268 in *The New Systematics,* edited by J. HUXLEY. Clarendon Press, Oxford.

NAVIERA, H., and A. FONTDEVILA, 1986 The evolutionary history of *Drosophila buzzatii*. XII. The genetic basis of sterility in hybrids between *D. buzzatii* and its sibling *D. serido* from Argentina. Genetics **114:** 841–857.

NOVITSKI, E., W. J. PEACOCK and J. ENGEL, 1965 Cytological basis of "sex-ratio" in *Drosophila pseudoobscura*. Science **148:** 516–517.

POWERS, P. A., and B. GRANETZKY, 1991 On the components of Segregation Distortion in *Drosophila melanogaster*. V. Molecular analysis of the *Sd* locus. Genetics **129:** 133–144.

ROHLF, F. J., and R. R. SOKAL, 1981 *Statistical Tables,* Ed. 2. W. H. Freedman, New York.

SOKAL, R. R., and F. J. ROHLF, 1981 *Biometry,* Ed. 2. W. H. Freedman, New York.

TOKUYASU, K. T., W. J. PEACOCK and R. W. HARDY, 1972 Dynamics of spermiogenesis in *Drosophila melanogaster*. I. Individualization process. Z. Zellforsch. **124:** 479–506.

VOELKER, R. A., 1972 Preliminary characterization of "sex ratio" and rediscovery and reinterpretation of "male sex ratio" in *Drosophila affinis*. Genetics **71:** 597–606.

WU, C.-I, 1983 The fate of autosomal modifiers of the Sex-Ratio trait in *Drosophila* and other sex-linked meiotic drive systems. Theor. Popul. Biol. **24:** 107–120.

WU, C.-I, and A. T. BECKENBACH, 1983 Evidence for extensive genetic differentiation between the Sex-Ratio and the Standard arrangement of *Drosophila pseudoobscura* and *D. persimilis* and identification of hybrid sterility factors. Genetics **105:** 71–86.

WU, C.-I, and M. F. HAMMER, 1990 Molecular evolution of ultra-selfish genes of meiotic drive systems, pp. 177–203 in *Evolution at the Molecular Level,* edited by R. K. SELANDER, A. G. CLARK and T. S. WHITTAM. Sinauer Press, Sunderland, Mass.

ZOROUS, E., 1986 A model for the evolution of asymmetrical hybrid male sterility and its implications for speciation. Evolution **40:** 1171–1184.

Communicating editor: M. J. SIMMONS