

## REVIEW ARTICLE

# Intratetrad mating as the driving force behind the formation of sex chromosomes in fungi

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### ABSTRACT

In some fungi-ascomycetes and basidiomycetes, the 4 haploid spores formed as a result of meiosis can fuse in pairs, forming a dikaryon or diploid. The consequence of such intratetrad mating is the preservation of heterozygosity of genes linked to the mating-type (MAT) locus. If the MAT is linked to the centromere physically or genetically (as a result of the suppression of recombination), the centromere regions of all chromosomes are preserved in a heterozygous state. Suppression of recombination in the MAT chromosome contributes to the accumulation of lethal mutations and chromosomal rearrangements in it. Two MAT chromosomes cease to be homologous and become analogues of the sex chromosomes of animals and plants.

**Keywords:** intratetrad mating; sex chromosomes; *Microbotryum sp*; *Neurospora tetrasperma*; mating type (MAT) locus

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Several species of fungi, whose genome has been studied accordingly, have a pair of “sex” chromosomes, similar in their characteristics to the sex chromosomes of animals and plants<sup>[1–4]</sup>. The stages of evolution of the sex chromosomes of fungi are discussed in several articles<sup>[5–11]</sup>. In most of these articles, the possible role of a special type of cell mating, intratetrad mating, which, in our opinion, is the driver of the formation of sex chromosomes, is not considered<sup>[9]</sup>.

In ascomycetes and basidiomycetes, the possibility of fusion of cells and nuclei is determined by differences in the loci of mating types (MAT), in some species there are two pairs of such loci, in others—one. In those fungi in which 4 haploid cells formed as a result of meiotic division (asco- and basidiospores) remain in contact for some time, there is a possibility of fusion two products of the same meiosis, which we have called intratetrad mating<sup>[12]</sup>.

The genetic consequences of such mating were considered by us<sup>[12,13]</sup> and it was shown that the probability of homozygote formation in intratetrad mating is lower than in classical self-fertilization (fusion of gametes formed by one organism, but in different meiotic divisions), but higher than in sibling mating. Much later, Kirby’s article was published, which repeated our conclusions<sup>[14]</sup>.

Another consequence of intratetrad mating is the preservation in a heterozygous state of genes closely linked to the mating type locus. At the same time, if the MAT locus itself is linked to the centromere, then in a number of generations the heterozygosity of genes in the

centromeric regions of all chromosomes is maintained, not only the chromosome carrying the mating type locus<sup>[13]</sup>. This has been confirmed experimentally<sup>[15,16]</sup>.

Intratetrad mating has two obvious biological advantages over the random coupling of spores (gametes). Firstly, during the dispersal of fungal cells, individual haploid spores are unlikely to meet a suitable mating partner, but if the connection between the spores persists after meiosis, they can fuse in pairs. This circumstance is critically important, since in many fungi it is the diploid or diheterokaryotic stage that is more viable, or only this stage in pathogenic fungi can infect the host organism.

The second advantage of intra-tetrad mating is the preservation of the heterozygous state of large sections of the genome noted above and, due to this, the manifestation of the effects of heterosis. As it was said, the centromeric regions of all chromosomes are preserved in the heterozygous state, but on condition that the mating type locus is closely linked to the centromere of its chromosome<sup>[13,17,18]</sup>.

The noted two advantages of intratetrad mating have led to the fact that in a number of species of asco- and basidiomycetes, a convergent evolved obligate or facultative intratetrad mating takes place. The fixation of intratetrad mating in the life cycle during evolution was considered in work<sup>[19]</sup>. As obligate (or very frequent) intra-tetrad mating is known in *Saccharomyces ludwigii*, *Microbotryum sp.*, *Neurospora tetrasperma*, *Agaricus bisporus*.

In obligate intra-tetrad mating, and even in cases where this type of spore union is facultative, the mating type locus in most genetically analyzed cases is linked to its centromere (**Table 1**).

**Table 1.** Features of the life cycle and location of the MAT locus in some fungi<sup>[17,18]</sup>.

Organism	Dominant stage in the life cycle	Intratetrad fertilization	Distance (cm) MAT-cen
<i>Saccharomyces ludwigii</i>	Diploid	Obligatory	0.0
<i>Microbotryum violaceum</i>	Dikaryion	Very frequent	0.0
<i>Neurospora tetrasperma</i>	Heterokaryon	Obligatory	0.4
<i>Saccharomyces cerevisiae</i>	Diploid	Frequent	25.3
<i>Schizosaccharomyces pombe</i>	Haploid	Possible	>50
<i>Pichia pinus</i>	Haploid	Possible	1.4
<i>Hansenula wingei</i>	Haploid	Possible	26.0
<i>Neurospora crassa</i>	Haploid	Possible	6.6
<i>Sordaria brevicolis</i>	Haploid	Possible	1.7
<i>Ascobolus immersus</i>	Haploid	Possible	0.0

The close coupling of the mating type locus and centromere may be a consequence of either their physical very close location in the chromosome, or the suppression of recombination at the MAT-cen district. The first may be the result of the transposition of the MAT into the near-centromeric region, the second may be the result of the occurrence of inversions and other chromosomal rearrangements<sup>[9]</sup>.

Since during intratetrad mating and linkage of the mating type locus with the centromere, regions that persistently maintain a heterozygous state in a number of generations appear in the genome, various changes will accumulate in these regions. These are, firstly, lethal and sublethal mutations that will persist without showing their negative effect (in some cases, in a heterozygous state, lethal mutations can have a positive heterosis effect). Secondly, these are chromosomal rearrangements (also in some cases with a lethal effect), which will increasingly “lock” the crossing-over in the near-centromeric area.

The presence of lethals linked to the mating type locus or with centromeres of other chromosomes was shown when studying natural populations of the fungus *Microbotryum sp.*<sup>[20]</sup>.

A careful study of the chromosome where the MAT locus is located showed that two chromosomes with MAT1 and MAT2 loci differ very much, which is the result of many rearrangements and transpositions<sup>[9]</sup>. The presence of loci determining the possibility of cell pairing, morphological differences (in this case, differences in length<sup>[3]</sup>), suppression of recombination while maintaining a small homologous “pseudoautosomal” district<sup>[3,9]</sup>, do the chromosomes of *Microbotryum sp.* analogs of animal sex chromosomes.

This allows us to present the evolution of chromosomes in fungi in the following way (**Table 2**).

**Table 2.** Stages in sex chromosome evolution.

Stages	Selective disadvantages/advantages
Release of haploid spores immediately after meiosis	Difficulty of finding a mating partner
Maintenance of spore connection	Ease of finding a partner
Intratetrad mating	Dikaryon/diploid formation, heterosis effects
Recombination suppression across the MAT locus	Heterozygosity retention in a number of generations
Accumulation of differences between homologous chromosomes	Fixation of recombination suppression in sex chromosomes

So, intratetrad mating in itself, regardless of its genetic consequences, is biologically beneficial, since it guarantees the possibility of fusion of haploid cells (or nuclei) with the subsequent formation of a diploid or a diheterokaryon. Once appearing, intratetrad mating will contribute to the linkage, physical or genetic, of the MAT and centromere locus and the accumulation of rearrangements in the genome. The accumulation of rearrangements in the chromosome with the MAT locus will lead to the formation of sex chromosomes in fungi, in many respects similar to the sex chromosomes of animals.

## Conflict of interest

The author declares no conflict of interest.

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