X-RAY MICROSCOPY
AND MICRORADIOGRAPHY

PROCEEDINGS OF A SYMPOSIUM HELD AT THE
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The X-Ray Microscope with Catamegonic Roof-Shaped Objective

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Consider a series of mirrors $M_i$ of center $C_i$. The ray perpendicular to the center $O$ of an aperture $D$ is reflected—at points $O_i$, taken as the poles of the mirrors—at glancing angles $u_i$ assumed to be small. This series of segments $O_iO_j$ constitute the "pseudo-axis" of the system. The mirrors are said to be crossed when the planes $C_iO_iO_j$ and $O_iO_jC_j$ ("principal" sections of the beam) are perpendicular, parallel when these planes are coincident, and perpendicular when their axes $C_iO_i$ and $C_jO_j$ are perpendicular. In this terminology, P. Kirkpatrick (1) has shown that a pair of crossed mirrors is stigmatic for a point $A$ on its pseudo-axis, the position of which is related to the geometrical constants of the system by the relation

$$\frac{2}{O_2C_2 \times u_2} - \frac{1}{-O_1A + O_1O_2} = -\frac{O_1C_1 \times u_1 + 2O_1A}{-O_1A \times O_1C_1 \times u_1 + O_1O_2(O_1C_1 \times u_1 + 2O_1A)}$$

J. Dyson (2) has shown that the plane which is the tangential image of a plane perpendicular to the pseudo-axis of a single mirror at a point $E$ is also perpendicular to this axis if the aperture has its center situated at a distance from the mirror $O \Omega = -OE \times OC \times u / (OE + OC \times u)$

Assume that this relation is satisfied for the point $A$ by each of the two mirrors of the pair, and take as reference axes for object and image the directions $AY$ and $A'Z'$, perpendicular to the two planes of incidence of the pseudo-axis. The coordinates $(Y',Z')$ of the point $B'$, the paraxial image of $B(Y,Z)$ are given by

$$Y' = \frac{Y(O_1O_2 + O_2A')}{O_1A}$$

$$Z' = \frac{Z}{O_1A} \left[ O_1O_2 + O_2A' \left( 1 - \frac{2O_1O_2}{O_2C_2 \times u_2} \right) \right]$$
The magnification $G_y = Y'/Y$ is greater than that in the $Z$ direction $G_z$ so that the image displays anamorphisis with axis $A'Z'$.

In order to correct this orthogonal distortion, we have established (3) a relation which connects the inclinations of the object and image planes with the position of the aperture. This relation must be satisfied simultaneously by both mirrors. Instead of imposing on the system these two conditions for conjugation, it is simpler to employ two fine slits, perpendicular to each other, each of which play the role of an aperture in one of the principal sections of the beam. The distortion of the objective can thus be compensated by a distortion of the same form—due to inclination of the image—and of axis $A'Y'$. But the adjustment is sensitive and must be made after every change in the geometrical conditions of the system. The center of the exit pupil (conjugate to $\Omega$ in the image space) is not fixed and the usual classification of the aberrations is no longer valid, but a change of variable (4) allows the re-establishment of the classical expressions for the aberration figures.

Fig. 1. Point imaging by reflection of X-rays from a "catamegonic" objective mirror.

In face of the difficulties of adjusting and focusing a system of separated mirrors, we have devised at the Laboratoire de Chimie Physique a catamegonic * objective, stigmatic for all points on the axis, which gives a homothetic image of the object and which includes only a single aperture. The new objective (5) is based on the following observation:

If we make $O_1O_2$ equal to zero, the correction of the astigmatism becomes independent of the position of $A$ on the axis, the magnifications $G_y$ and $G_z$ are equal and a single aperture suffices to erect the field completely.

In order to bring together the poles $O_1$ and $O_2$, it is necessary to section the mirrors along planes passing through these points. The portion of the beam corresponding to the part of the one mirror that is removed will fall on the other mirror (Fig. 1). There are thus two orders of reflection possible, and therefore a priori two images. Consider a ray

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* Catamegonic = operating by reflection at large angle of incidence.
incident on $O$. The mirrors are equivalent, for this ray, to a system of two plane mirrors tangent at $O$ to the two spheres. Geometrical optics shows that the image will be unique if the two planes are mutually perpendicular. The two spheres must be orthogonal; i.e., the mirrors are "perpendicular" and not "crossed." It is readily seen, and detailed calculation proves (6), that the system must be symmetrical; that is to say that the section must be made of two spheres of equal radius and in a plane making an angle of $45^\circ$ with the normal. The sections complement each other and the perpendicularity of the tangential planes is preserved along the whole length of the section, so that every ray falling on the "ridge" gives only one reflected ray.

![Fig. 2. The mirror block of the catamegonic objective, compared in size with a matchbox.](image)

However, even for a median ray situated in the plane of symmetry, the planes of incidence are not exactly perpendicular. They make an angle of $\frac{u}{\sqrt{2}}$, which introduces a residual term of astigmatism of the second order, but this term is practically negligible compared with the other aberrations when the mean angle of attack is less than $10^\circ$.

The objective is analogous to a ridge prism with spherical lateral faces, for which reason we have described it by the expression "catamegonic roof-shaped objective" (Fig. 2).

The technique of constructing this objective is very complicated (7). It is practically impossible to make a precise measurement of the angle of the sphere and of the plane of section by means of an angular scale, so that we have had to employ an indirect method. We take as reference surface the polished rear face of the block of glass in which the spherical mirror is formed. We identify by interference the point where the plane tangential to the sphere is parallel to the plane of reference, and then we cut the sphere in a plane passing through this point and making an
angle of 45° with this plane. The plane surface of the section is subsequently polished to a twentieth of a fringe and the two mirrors are fixed to each other by simply utilizing the force of adhesion. The mounting obtained in this way is absolutely rigid, and during three years of use we have never been able to detect on the negatives any modifications which we could ascribe to a deformation of the system. It is obvious that all the operations must be made with the greatest care; in particular, the circle of intersection of the plane and of the sphere should be as perfect as possible, the optical role of the ridge being fundamental. The radius of curvature of the mirrors is 19,623 mm (measured by interference) and their diameter is 5 cm. Once mounted, the mirrors are coated with gold by cathodic evaporation in vacuum. This operation requires very careful adjustment, as the position of the sources has a great influence on the uniformity of the deposit and on the sharpness of the ridge. In order to obtain a sufficiently firm coating, we have improved the adherence by putting a layer of chromium between the gold and the glass.

The mechanical mounting of the objective aims above all at achieving great simplicity of adjustment while realizing the "optical" independence of the two mirrors (Fig. 3). We arrange them to turn about two perpendicular axes that are coincident with their axes of revolution. It is at once clear that rotation around one of the axes does not affect the mean angle of attack of the beam on the sphere which is perpendicular to this axis.

The apparatus (Fig. 4) comprises a field aperture, a platinum object
holder, a selector (which differentiates the four beams), the objective
and its mounting (with focusing system and means of centering in
the X-ray beam) and an apodisé aperture diaphragm (adjustable in posi-
tion with respect to the objective in order to erect the field). In order to
diminish the absorption of X-rays in the air between the objective and
the photographic emulsion, we have placed in the path of the rays a
cylindrical tube, which is closed at one end with a thin window of
aluminum, and at the other end by a container which holds the
photographic film and in which the pressure is reduced to a few milli-
meters of mercury.

Fig. 4. General view of reflection X-ray microscope.

The advantages of this microscope (8) are the following:
1. The adjustments are simple, the axes of the two mirrors being
perpendicular to each other by construction.
2. Astigmatism is corrected for all points on the axis and the correc-
tion remains adequate over a field of 0.1 mm \(M = 100\).
3. Distortion is suppressed without the necessity of inclining the
photographic emulsion or of using a third mirror.
4. The field is erected by means of a single aperture.
5. Finally, as we have indicated elsewhere (9), the existence of a
plane of symmetry insures that a considerable number of aberration
coefficients vanish, so that for the same number of mirrors, our system
has a performance superior to that of systems of separated mirrors. The
actual gain, however, is only about \( \frac{2}{3} \) of the theoretical gain, since it is
impossible to construct in an absolutely perfect manner the ridge of
intersection. The residual aberrations remain appreciable, and in order
to improve the limit of resolution, it will undoubtedly be necessary to
place, after the first system, a similar system which is divergent.

The applications of the total reflection of X-rays, and in particular
of the microscope, are well known. For our part, we have recently re­
viewed three of them (10) and prefer not to return to the subject here.

![Fig. 5. Reflection microradiograph of 28-\(\mu\) platinum wire. \(\times 600\).](image)

We have restricted ourselves at present to using the \( K\alpha \) emission from
a tube with a copper target and to the study of grids, in order to deter­
mine the performance of our instrument. The need to introduce a salt
of an absorbing metal into biological preparations, in order to get ade­
quate contrast, has precluded us hitherto from examining this type of
specimen. In our first picture (Fig. 5) of a platinum wire 28 \(\mu\) in
diameter, a transparent inclusion can be seen on the axis of the wire.
This defect is internal, since it cannot be seen under the optical
microscope, and it cannot be a phenomenon which has some other cause
because it moves with displacement of the wire. The second picture
(Fig. 6) is of a metal grid of bar width 29 \(\mu\) and repeat distance 61.2 \(\mu\).
The nature of the wire gives poor contrast. The field is erected but
curvature remains.
As we do not possess grids fine enough and sufficiently absorbing, we have had to determine the limit of perception on the evidence of this second image and of others of the same nature. We have taken microphotometer traces (I and II, Fig. 7) along similar paths on two negatives taken in the same experimental conditions, one with and the other without the grid present. Subtraction of the two traces (III) reduces the background of the image to a uniform value. We then identify the position of the axis of the grid bars on the resultant curve, and we superimpose the theoretical density curves (IV) on these axes; the latter curves are deduced from the optical measurement of the diameter of the bars in the field and from knowledge of the energy distribution of the radiation obtained by reflection from the mirrors (11). Comparison of the curves shows: (1) The density of the background of a picture taken with grid present has a value slightly higher than the value predicted; this is because of diffusion of the radiation by the grid. (2) The theoretical curve is broader than the experimental curve. As halo is negligible in our experimental conditions, the difference of the abscissas of the two curves represents the enlargement of the image due to the aberrations.

We have taken as criterion of the limit of perception twice the maximum of the curve obtained by subtraction of (III) and (IV). The limit of perception thus obtained is equal to 1 $\mu$. It is obvious that this method is open to many objections, so that we are making attempts at direct measurement with powders which provide tests of both resolution and perception; but it is difficult to obtain uniform surfaces of sufficiently fine grains. The limit of resolution is very dependent on the
size of the object examined; when this is of the order of the limit of perception, the two limits are identical. The values obtained do not appear to depend on the diameter of the wires, which is in favor of the method employed.

Fig. 7. Microphotometer traces across photographic image of (I) grid bar, (II) background, (III) difference between I and II, (IV) calculated intensity distribution.
We have also used a simpler method: the experimental value for the width is compared with the true value. The difference is roughly constant for regions of the same density, and it is of the same order of magnitude as the value given by the other method.

The magnification is 100 times in the conditions used, and we do not think it will be necessary to increase it, since, under these conditions, an object of 1000 A gives an image of size 10 μ, which is above the limit of resolution of some photographic emulsions. The time of exposure is from 10 to 30 min on Kodak Définix film.

We have thus succeeded, with a limited number of spherical mirrors, in obtaining a limit of resolution of 1 μ. This value should certainly be reduced to 8000 A by employing a second mirror system, but it does not seem possible to do better, on account of striations caused by faults in the mirror surface.

References