II.—*On High-power Definition: with illustrative Examples.* By
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PLATE XXXIII.

It is well known that the smallest visual angle subtended by a minute spot capable of being appreciated by the eye varies very much with the observer, even after proper adjustments have been made for long or short sight. The writer once tried the following experiment in order to determine the minimum visual angle. Receding from a pole, diameter $1\frac{1}{4}$ inch, elevated on a rising ground against the sky, it vanished at a distance of 1150 yards. The pole was capped with a black ball, to show its locality after the shaft disappeared. The angle subtended by $1\frac{1}{4}$ inch at 1150 yards' distance is about *six seconds of arc*. This occurred in 1834. In youth the eye is in general more sensitive, but the late celebrated astronomer, Mr. Dawes, retained surpassing keenness of sight to the last. To such, "definition" is a comparatively easy task with lower powers than to general observers. At a distance of a thousand yards our volunteers are taught that the head of a man sinks between the shoulders, and an appreciable visual angle is given by the bull's-eye at this distance of about $2\frac{1}{4}$ min. ($2' \cdot 29$). These facts supply us with data for judging of the average power of definition.

Now suppose thirty or forty bull's-eyes in a straight line, painted black, in contact upon a white wall. Though 2 ft. in diameter, at a distance of a thousand yards only a black line would appear; the eye could not, unassisted, in general define the bull's-eyes of which it was composed,—or, in other words, definition of a line of round, black dots, each of about $2\frac{1}{4}$ minutes' visual angle, would fail. Perhaps if each centre were perforated with an inch aperture and illuminated from behind, their definition would be pos-

DESCRIPTION OF THE PLATE ON HIGH-POWER DEFINITION.

- Figs. 1 and 2.—Examples of diffraction and interference, producing a very perfect resemblance of Test-scale Podura markings by the intersecting beaded ribbing of two superimposed azure blue scales.
- „ 3 and 4.—Sketch of Podura seen by direct condensed light and of longitudinal beading, with a few beads of the under-surface glimmering through the upper set.
- „ 5 to 8.—“Admiration Test-scale.” The general beading shows itself in a great variety of forms, according to the state of the illuminating pencils and the focussing upon the upper and under set.
- „ 7.—The most perfect resolution hitherto attained by exceedingly patient and finely-adjusted glasses. The ribbing (*b*), Fig. 8, is here distinctly represented by darker beads of the upper rouleaus; the under-set always appear brighter in colour. Isolated beads, free from collateral interference rays, assume a natural resplendence and focal point.
- „ 8.—*a, b, c, d, e*, different appearances of the test-scale under different conditions of illumination and vision. The ribbing (*b*) is preliminary to the transformation of the spikes of *a* into the rouleaus of *e*.

sible. In the case of double stars visible with Mr. Browning's $8\frac{1}{2}$ -inch silvered specula (on favourable nights with 400 diameters), the closest I believe is Gamma² Andromedæ, $\frac{1}{10}$ seconds apart; this interval with 400 amounts to a visual angle of $400 \times \frac{1}{10}'' = 160''$, the smallest perhaps under which the eye can effectively divide and separate, not merely elongate, fine double stars; and but for the sparkling glory of these suns, so minute and dwindled in an abyss of distance, doubtless much closer stars (with instruments more perfectly free from aberration) should become visible. Only the finest known definition can sever those glittering points.

The healthy human eye, then, consisting of an achromatic combination of refracting media, and of a sensitive recipient of rays whose sensibility is limited to the minuteness of the distribution of its nerves, differs widely in its powers of definition, and particularly in its qualification of distinguishing a line from a string of dots each subtending an angle less than $2'$.

The subject of definition is beautifully illustrated by the whole range of what are termed *line* test-objects, whether as the various pleurosigmata, striated scales, or artificial lines on glass, as Nobert's; the latter, however, being grooves cut or ploughed into glass by a fine, pointed diamond, cannot offer the same characteristics for definition as objects whose lines are caused by small, spherical bodies raised in relief, the complete resolution of which requires besides definition "penetration" (or less angular aperture than is necessary to catch the shadows arranged lineally upon glass). For these and other reasons the distinct definition and portraiture upon the retina of minute illuminated or *shaded* spherical dots, of small visual angle, placed in close contact, may be regarded as the severest known standard test both for the performance of microscopes and telescopes.

The disadvantages of deepening the eye-pieces in place of exalting the magnifying power of the object-glass or reflector, are at once so appreciable, in the appearance of haze, cloudy definition, and obscurity, caused by the increase of the "least circle of confusion," and the destruction of *aplanatism*, that great genius has been displayed in constructing object-glasses from $\frac{1}{16}$ th to the $\frac{1}{25}$ th and $\frac{1}{80}$ th of an inch focus, whose performance has almost been regarded as beyond mere praise, entitling them to the highest honours which nations in their art exhibitions can confer. Yet in the best glasses there is a certain residuary aberration (chiefly spherical) which obscures the clear definition under a power of 1000* of a string of

* To find the visual angle (θ) of the 80,000th of an inch under a power of 1000 at 10 inches distance (the usual focal distance of the LAST image from the eye of the observer),

$$\text{Sine } \theta = \frac{\text{perpendicular}}{\text{hypotenuse}} = \frac{1000 \times \frac{1}{80000}}{10} = \frac{1}{800}.$$

Hence θ the visual angle = $4\frac{3}{5}$ minutes nearly, or nearly double the visual angle of a two-foot bull's-eye seen at 1000 yards target.

beads less than 80,000 to the inch: whilst a visual angle of 6" would represent an object whose diameter in the field of a microscope magnifying 1000 linear must be $\frac{1}{3,400,000}$ th, or less than the 3,000,000th part of an inch. From this we can form some idea of the exceedingly minute character of objective aberration; even for a good $\frac{1}{8}$ th object-glass it does not exceed the 50,000th of an inch.*

The extreme difficulty of defining a minute row of beads arises from the uncorrected aberrations confusing their images, by which several images overlap and obliterate the form of individual beads; still more is it increased if one set of beads be confused with the images of an underlying stratum of intersecting rows, forming a complicated beaded lattice-work, as in many interesting scales.

The Society will permit me to observe that I have found in the difficult enterprise of resolving the Podura scale into its component beads, the definition may be refined, partly by selecting such pencils of rays as pass through the lenses of the object-glass, so as to form an image with the most perfect aplanatism, or freedom from spherical aberration; all other rays causing haze and nebulous definition, and therefore with the least possible use of excentric pencils of light such as emanate from ordinary condensers. In these high-power researches the integrity or perfection of the illuminating pencil of rays is as important as that of the refractions of the objective. In my experience I have found an oblique central pencil of aplanatic and achromatic cones of light of small aperture (15° to 20°) of the greatest practical utility, the obliquity being varied according to the object in view.

Another circumstance is worthy of note, *viz.* the position of the stigmatic image, or of the distance from the back lens of the object-glass where there is a *real* focus. If a precious stone of refractive index $\mu = 1.6861$ can be found, such as is free from a double image, the equation for aplanatism

$$2\mu^2 - \mu - 4 = 0$$

will be satisfied if the gem be a plano-convex lens with the plane turned towards the object; the image would be formed without aberration. But till this can be found and worked, a search for the real focus or best image should not be neglected along the axis of the instrument.

By elaborate calculation it appears that the variation of the distance between the front lenses of an object-glass produces a

* The aberration of lenses depends upon their general shape, and for illumination, crossed lenses should be formed into bull's-eyes.

Lenses.	Plano-convex.	Convexo- plane.	Equi-convex.	Crossed lens.	Crossed lens reversed.
	405	105	150	96	310
Aberration	100000	100000	100000	100000	100000

change in the aplanatism of the final image viewed by the eye-piece; it not merely makes a convenient adjustment for the errors caused by using different thicknesses of covering-glass, which varies from the $\frac{1}{100}$ th to the $\frac{3}{100}$ ths of an inch, but the index on the screw-collar may be used as a measure of spherical aberration occurring at the final focal image. The aberration sensibly changes for every different distance of the final focal image from the object, and consequently with the same object and covering-glass for differently-constructed eye-pieces.

The form of the caustic or curve whose successive tangents represent the aberrating rays passing through the last or back lens is exceedingly acute, almost approaching a straight line. If F be the focus for parallel rays passing through the lens L , and intersecting the axis at F ; let Sq be the course of an aberrating ray intersecting the axis at q ; and let it touch the caustic curve RPF at P ; let $FN = X$ and $PN = Y$. Then the square of PN is proportional to the cube of FN or Y^2 varies as $X^3 = NX^3$. And the aberration consists of two distinct dimensions. The lateral aberration is, in this case, represented by PN , and the longitudinal by Fq ; it has therefore breadth and length. But lenses may be so combined that for a certain distance of q from L these aberrations can be reduced almost to nothing.

And it is possible to compensate practically one aberration by introducing another equal and opposite.

On these principles the investigation of the circumstances requisite for enhancing, clearing, or sharpening high-power definition may possibly be successfully carried out.

For a given distance of the object from the object-glass, the aberration caused by refraction through a plate of glass of thickness t is doubled or trebled, &c., by making the covering-glass twice or thrice, &c., as thick: but it also varies in a high ratio as the angle of aperture of the objective increases. In other words, the confusion of the final image is represented by multiplying the aperture by the thickness.

To define some of the most minute lines of diatoms fine definition is often sacrificed to enlarged aperture, which however gives the additional advantage of increased light.

It was only by very oblique and most skilful illumination that black-lined shadows could be obtained in the finest specimens and also by an aperture large enough to admit such oblique rays, that the lines could be seen at all: without this aperture, definition was of no avail with the power employed. Perhaps until a more exqui-

site standard for definition is realized than Nobert's lines and "lined diatoms" no great improvement will be made in the best object-glasses. The writer however ventures to express the opinion that a new standard for high-power definition will be found in the minute structure of the Podura scale, which affords the most severe trial for the correction of residuary aberration with which he is acquainted. And having given much leisure to the use of this interesting object in estimating definition and the possibilities of improvement, he prefers it to all others.

This extraordinary object, dating as a test from the jewel-microscopes of Pritchard and Dr. Goring to the splendid glasses of our eminent makers of the present day, has accomplished more towards the perfection of defining power than any other. It has done for the microscope what Sir William Herschel's close double stars and the rings and satellites of Saturn have done for the development of the charming and exquisite revelations of the telescopes of the time present.

The American Government has lately authorized the exhibition of photographs of several microscopical objects, taken by means of Wales' and Powell and Lealand's glasses: these sun-pictures, especially those by Powell's $\frac{1}{4}$ th, $\frac{1}{5}$ th, and $\frac{1}{50}$ th, agree remarkably with the *accepted* appearances beautifully delineated in Dr. Carpenter's work and that of Messrs. Smith and Beck.

These photographs, taken by an American artist* and exhibited in England—might fairly be accepted as a challenge to English microscopists. But for this circumstance, the writer having awaited seven years for confirmatory evidence of his own results, now ventures to bring before the notice of the Society these observations: and in doing so he begs to remark that he believes they are capable of two kinds of demonstration, the *synthetic* and analytic, as far as the eye is concerned. But in order to obtain similar results, particular attention must be paid to the following conditions:—

- (a.) Illuminating pencil.—A cone of light achromatic and *aplanatic*; angle of apex about 20° ; inclination of axis of cone to plane of stage about 20° to 30° . The size of the condensing lenses employed is of no consequence, the other conditions remaining the same.
- (b.) The scales which are darkest and smallest and with the longest diameter towards the light should be carefully chosen first with a good $\frac{1}{2}$ -inch at 120 diameters.
- (c.) The most patient *corrections* should be applied as to the object-glass, chosen distance of the secondary focal image, and the lenses for the eye-pieces; and lastly, the foci of the object-glasses and depth of the eye-pieces (so as to correct as much as possible the residuary aberration of the object-glass) should be most carefully selected.

* Colonel Dr. Woodward.

It is impossible within the limits of this paper to describe further in detail the arrangements found to be most successful.

It is well known that under a low power, as 80 or 100, the Podura is remarkable for its wavy markings (these are a safe guide in selecting the scale), aptly compared to "watered silk." It is here that the *secret* of their cause and nature is to be sought for: hitherto one which has baffled the most famous glasses of modern times. As a simple fact sometimes leads to a suggestion; view carefully against the light two pieces of the silk woven with the finest weft and warp placed one over the other: accordingly as one is lightly *stretched* more than the other or as the weft of one is inclined more or less to the weft of the other, instantly an endless series of waves are developed by the lines of optical interference: mesh intersecting mesh with infinitely varied effect: but always *waves*. Can the waves of the Podura be similarly caused?

Raising the power to 200 or 250 and using a side light upon our scale athwart its length, all waviness disappears, and in its place is seen a longitudinal *ribbing*, shaded very darkly; with a less oblique side light, lucid rhomboid chequers glitter brightly: the rhomboidal sides, crossing at acute angles, may be seen with a low power of 500. With 1200 these ribs have divided themselves into a string of longitudinal beads. But with 2300 they appear to lie in the same plane, and terminate abruptly on the basic membrane: upon focussing for the strings of beads attached to the lower side the beading appears in the intercostal spaces. The upper beads are best seen either green upon a pink ground or pink upon a greenish ground, which phenomena may possibly arise from the different dispersive powers or refraction of the various structures or the correction of the glasses; or even more recondite causes.

When the light is much more oblique, yet achromatic, the beads appear shaded as roughly represented in the diagram, the intervening spaces showing fine traces of intersecting lines.

Using now an adjusting $\frac{1}{2}$ -inch at 250, and rotating the scales, some of the most favourable positions, with oblique light, inclined about 15 degrees to the axis of the scale, show a double set of longitudinal lines forming a lattice-work. These lines are the markings existing on the other side of the scale.

With 300 to 500 the celebrated "spines" appear, according to the size of the scale, as very dark short tapering marks (like "notes of admiration" without the dots!!!). To see these clearly with 2500 has been considered the *ne plus ultra* of microscopical triumphs, and it is consequently with no little diffidence that the writer ventures to traverse the belief of twenty-five years. The object of this paper is to show that definition can be further improved under the use of high powers, and if he should succeed in accomplishing this, the leisure of some years will not have been

spent in vain. It may be here observed that the adjustment of the correcting screw of the object-glass plays an important part in refining the definition, independently of the thickness of the covering-glass. I may observe that the first *six* illustrations accompanying this paper were effected by the anastatic process from drawings made direct from the microscope, in 1863, by a talented lady who is an excellent amateur painter, and who had no previous knowledge of the subject, and therefore wholly unbiassed.

Fig. 3. Is a rough sketch of the Podura spines illuminated by direct condensed light.

Fig. 4. Podura spines resolved into longitudinal striæ of beads with the lower striæ on the under-side of the scale partly visible.

Fig. 5. A rather exaggerated drawing illustrative of the size of the beads, but correctly giving the appearances of interlacing lattice-work formed by the upper and under ribs of beading crossing each other.

Fig. 6. Shows the careful resolution into beading by using a long-drawn tube: on the left the waviness of the beading is remarkable; next are seen rows crossing at an acute angle, and on the right side a more regular display of beading running in straight lines.

Distrusting at this time (1863) this novel appearance, I repeated experiments hundreds of times on different scales, and sought earnestly for some synthetic proofs, which were finally found in the appearances (drawn by the same lady) caused by the intersections of the ribs of the finest and most transparent scales of "azure blue" in Fig. 1, and a coarser intersection shown at Fig. 2. The beads to be seen brightly and clearly in the fine scales of Fig. 1 require very careful adjustments, and the spurious spines *there* shown, counterfeit, in every particular, the behaviour of the spines (which I shall also venture to call *spurious*) of the Podura scale.

When the light is almost direct, that is, the axis of the illuminating cone of rays is nearly perpendicular to the plane of the stage, the beads sometimes exhibit black dots, crescentic shadows, and brilliant points of light, according to the action of the transmitted rays upon their spherical surfaces. Similar dots may be seen upon the beads of the Pleurosigmata. Had we no visual direct proof of their sphericity, the symmetrical shifting of the crescentic shadows according to the direction of the light would prove their shape.

I may remark that the higher the power can be raised by lengthening the tube and deepening the eye-piece, consistently with a fine definition, the better chance will be afforded for distinguishing the upper and lower sets of beads crossing each other at an acute angle upon the upper and lower surface of the intervening basic

membrane; whilst on the other hand deepening the objective to gain power limits the focal depth or penetration; the amount of this depth even of a $\frac{1}{8}$ th being exceedingly small.

By estimation comparing these beads with those of the *P. formosum* of $\frac{1}{300000}$ inch in diameter, the observed Podura beads may be reckoned at $\frac{1}{500000}$ th to $\frac{1}{1500000}$ th of an inch in diameter. The "spines" usually drawn really embrace in general three or four beads, whilst the intervening spaces abound with beads seen through the basic membrane, and very difficult of observation without special management.

750 diameters will show with fine definition and a long-drawn tube and good penetration, beaded striæ upon both sides of the scale when coarsely marked.

1800 with a $\frac{1}{8}$ th and nearly direct light (which should be formed as free from colour and astigmatism as possible) will show in favourable cases chains of beads lying upon the upper surface.

I cannot here too strongly call attention to the beautiful phenomenon, which I have always endeavoured to obtain as a fine and reliable test of approaching aplanatism and heralding a fine definition. In examining striated bodies—longitudinal bands glisten with a ruby tint upon a green or yellowish green ground. The bands appear like pellucid semi-transparent cylindrical ribs, and the flashing of these bodies with a ruby glow is a signal in my experience that the aberration approaches its minimum; when the beading dispels the mist and haze always accompanying the spurious "spines."

With a power of 2500 the beading may be seen to terminate abruptly, and commence abruptly near the edge of the scale.

The most difficult definition is that of the substratum of beads glimmering through the membrane nearest the light; on the other side they are generally of a very bright yellow-green colour, contrasting prettily with the deep ruby colour of the upper beads.

Availing myself of the aplanatic test above described, and focusing carefully the upper surface of the following tests, I have had the rare pleasure of seeing the manner in which the structures of several beautiful objects are arranged.

A. Battledore scales of azure blue.

The whole surface is beaded over: the large beads seen with a $\frac{1}{2}$ -inch are formed of a mass of strings of beads crossing and recrossing.

B. Fine transparent and smallest striated scales of azure blue.

The upper ribs appear as distinct ruby-coloured beading; between and beneath which are seen *partly obscured* longitudinal rows parallel to and immediately behind the upper set.

- C. The translucent ribbing of *Lepisma Saccharina* is formed of regular beads, and beneath these and radiating from the *quill* are lines of smaller beading crossing the upper set in straight lines. I see these yellow-green, whilst the upper set are brownish red.
- D. By gas-light I observed rows of red spherical beads, placed upon the surface of the test-object, marked by the preparer of the scale *S. Hippocampus*,* alternating with yellow-green rows, somewhat encroached upon by the upper sets; all running parallel to the axis of the scale. 4000 diameters.
- E. The surface of metals and alloys, with a power of 1000 diameters, shows, under reflected light, particles apparently spherical, agglomerated together, with dark lines separating the particles.

N.B.—Diffraction-rings similar to those observed about minute stars are abundant for single particles (scattered on paper by gilding) in proportion as the spherical aberration is less perfectly corrected, but which disappear when the aplanatism is established.

Query.—Are the diffraction-rings of stars due to the undulatory theory of light, or to the residuary uncorrected aberration of telescopic object-glasses?

Note.—The perfect definition of a broken surface of metal is a more severe test of aplanatism than artificial globules of mercury.

I may now, perhaps, be permitted to present to the Royal Microscopical Society synthetic evidence of the structure of the Podura, which appears to me to satisfactorily account for the peculiar, and I may say, embarrassing phenomena attending the study of the minute structure of this precious scale.

I beg particularly to call attention to Figs. 1 and 2. A careful search with a power of 150 among the scales of *Polyommatus Argus*, or Azure Blue, always found among the Battledore scales, of which, indeed, there are several kinds, will be rewarded with appearances which present the characteristic waviness or watered-silk appearance so peculiar to the Podura scale under low powers. These drawings, made in 1863, elucidate the cause of the Podura markings. With high powers, as 1000 to 2000, these scales show similar beading, and we have here a perfect example of a spurious spine being formed by lines of interference and diffraction; the beading being obliterated in the blank spaces, and dark markings or spines presented, precisely as is the case in the celebrated Podura scales. To my own mind this synthetic formation of the Podura markings is perfectly satisfactory and conclusive.

* This diatom is a specimen of *Pleurosigma Strigosum*.

I wish to add here that Mr. Browning pointed out to me that the beading of the Podura was rather unequal, some of the beads being larger than others. This is exceptionally the case; but I have found in numerous observations a great regularity in the size of the beads on the same scale.

They are most perfectly seen when the axis of the cone of light coincides with that of the objective, and the cone of light from the radiant is of very small aperture.

Extract from a Letter to the President.

October 1.—I feel firmly convinced that within a few months the Podura beadings, such as I have described them, will be thoroughly established. I purposely delayed publishing my results in 1862, hoping that further advances might be made in improving definition, and this has unquestionably been done by the *immersion lens*, which I have used this year with a Powell and Lealand's $\frac{1}{16}$ th. With this lens I have been able to confirm the observations of former years in scales and objects of extreme difficulty. Before using this lens, I had succeeded in gaining a new intensity of definition in the *dry way*, and in balancing the uncompensated residuary aberrations; and I have used the Podura scale as a very exquisite test of the lenticular corrections, though there are other tests of a higher order still.

I have endeavoured also to improve the definition of the immersion lens by extraneous compensation.

Beck gives a very beautiful steel engraving of the test-scale under 1200 diameters. The spines are precise, and exhibited, as he saw them, and as thousands still see them, and as Colonel Woodward photographs them actinically with Powell and Lealand's $\frac{1}{32}$ th and $\frac{1}{64}$ th. But very curiously, in the middle of Beck's work, there is an engraving of the Podura, described "*out of focus*," being a series of parallel bands, which Mr. Aldous has drawn for me with the camera lucida under 4000 and 2500 diameters. These bands, as I see them, are wholly composed of beads of the diameter of the band, the under-beads being out of sight.

The extraordinary difference between the performance of the Hydro-objective and of the Pneumo-objective (the plate of air or water making *enormous differences* in the aberrations of the glasses) must make it apparent to ordinary common sense that our old-fashioned glasses are *wrong somewhere*, and if not in failing to converge the image of a point to another point, I know not where to find it, *i. e.* in aberration,—chromatic aberration being more easily compensated. I know it is very difficult to throw aside the creed and belief of forty years, and I have hesitated a long time to bring forward my views, being perfectly convinced that there would be a *battle of*

the glasses to be fought, and the manner in which the subject of aberration has been treated amply justifies my apprehensions.

I point to the immersion lens as an irrefragible proof of the deficiencies of the corrections of old-fashioned glasses to grapple with some of the exquisite difficulties of microscopic research, and if my poor efforts shall in any way advance the excellence of defining power, especially in the higher range of investigations, I shall in the end feel amply rewarded. The work has been earnest and sincere.

NOTE.—Dr. Pigott desires to have it stated that this paper was sent to the Royal Microscopical Society on the 21st of May last.—ED. M. M. J.