On Abbe's apochromatic micro-objectives and compensating eye-pieces, made of the new optical glasses in the works of Dr. Carl Zeiss in Jena, with some general remarks on object glasses / by Adolf Schulze.

On Abbe's Apochromatic Micro-Objectives and Compensating Eye-pieces, made of the new Optical Glasses in the Works of Dr. Carl Zeiss in Jena, with some general remarks on Object Glasses. By ADOLF SCHULZE.

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IT is at the request of Dr. M'Kendrick that I come here this evening in order to call your attention to an important advance which has quite recently been made in the construction of microscopical objectives, an advance which is a matter of the greatest possible interest and gratification, not only to the microscopist, but to many others besides; because the means by which this improvement has been attained are equally applicable to the construction of telescopes, photographic lenses, spectroscopes, and, in fact, to the construction of nearly all optical instruments. I refer to the invention of new kinds of optical glasses, which permit, firstly, of the almost complete correction of the spherical aberration of lenses, as far as their curvatures will permit; and, secondly, of the correction of the chromatic aberration by the elimination of the so-called secondary spectrum.

Those of you who have followed the improvements in the construction of the microscope during the last ten years will be aware that they are nearly all due to the genius of Dr. Ernest Abbe, Professor in the University of Jena, now the first living authority on microscopical optics, and who, in the execution of his inventions, is most ably seconded by the eminent optician, Dr. Carl Zeiss. It was Professor Abbe who gave us a few years ago his now famous theory of the formation of the microscopical image by diffraction spectra, a theory which is easily proved by a series of experiments which are among the most interesting and fascinating in the domain of experimental optics; and it was Abbe who introduced lucid mathematical expressions of the relations of aperture, resolving power, and penetration; in fact, it was he who brought light where formerly there had been nothing but confusion and darkness. It was Abbe also who, about seven years ago, invented the objectives for homogeneous immersion; and now we have to thank him for his Apochromatics, by far the best lenses ever constructed, and which are destined to supersede ultimately all other micro-objectives previously made.

The Micro-objective is the most essential part of the microscope. It is that lens or combination of lenses which is nearest to the object, and forms of it an enlarged, inverted, and reversed image, which is again further enlarged by the ocular or eye-piece. The eye-piece, however, cannot bring out or resolve any more details of the object than the objective has transmitted to it; it can only magnify these details still more. A good Micro-objective is a system of lenses, consisting often of as many as twelve, which are composed of crown and flint glasses, and are ground to certain spherical curves. The following are the *relative qualities of a Micro-objective:*—First of all, its *defining power* or *definition*, which depends upon the more or less perfect correction of the spherical and chromatic aberrations; secondly, the *resolving power*, or the power to separate and make visible close structural details, surface-markings, bands of lines and gratings, and this resolving power is, as Abbe has shown us, dependent upon the aperture of the lens, which is the power to collect and transmit a smaller or larger cone of rays from the object to the eye-piece; thirdly, the *penetrating power* or *focal depth*, which consists of the vertical range through which parts of an object of different planes can be seen at the same time. As the penetrating power decreases inversely with the square of the resolving power, it follows that narrow-angled lenses possess far greater penetration than wide-angled ones, which latter possess very little. The *flatness* is that quality of a lens which admits of the image being seen with the same distinctness in the centre as at the margin of the field, without any readjustment of the focus. The *working distance* has no fixed relation to the focal length, because all compound objectives are stated by their equivalent focal lengths—*i.e.*, by the focal lengths of single lenses possessing the same magnification. Wide-angled lenses have shorter working distances than lenses of narrow angles; the working distance for some of the dry high-power objectives, such as the $\frac{1}{50}$-in., being for instance only ·003 inch.

A good objective should combine all the foregoing qualities in the greatest degree compatible, but for special purposes some of these qualities may have to be sacrificed to others, though the definition should never be sacrificed. As I shall have to speak a good deal of spherical and chromatic aberration, I may as well state here that the spherical aberration is that optical imperfection of a spherical lens which brings the rays passing through its marginal zone sooner to a focus than the rays passing through its central part, so that the focus, instead of being a point, becomes a short line. The chromatic aberration arises from the unequal refrangibility of the several coloured rays which make up white or uncoloured light, so that they are not all brought to the same focus even by a lens free from spherical aberration. Lenses act like prisms and disperse the light into a spectrum, the violet and blue rays of which fall within the principal focus, whilst the red being the least refrangible rays fall somewhat beyond it.

Since Professor Abbe formulated the expression of *Numerical Aperture*—by which is understood the product of the sine of the semi-aperture of a Micro-objective and the refractive index of the medium in which its front lens is immersed, be that medium either air, water, glycerine, or oil,—the vast superiority of wide-angled immersion lenses over the so-called dry lenses of high powers has been at once demonstrated, opinions formerly differing greatly regarding the respective merits of dry and immersion lenses. No dry front lens can collect image-forming rays from a radiant in balsam, or a similar refractive medium, making a greater angle than about 82 degrees; nor can an immersion lens do so if the radiant is in air or mounted dry, because, according to the law of total reflection, no ray of light can pass from air into crown glass and through it if the angle of incidence is 41 degrees or more, but is reflected out again under the same angle, the sum of the angles of incidence and reflection with the normal being about 82 degrees. This is a principle that is made much use of in microscopical illumination, especially for the illumination of objects on dark ground. The power of a microscope is not, as is popularly supposed, its mere magnifying power, but its power of showing surface markings, structural details, and separating or resolving closely-ruled bands of lines with the best definition possible. This power of showing detail, or the resolving power of an objective, is a direct function of the numerical aperture. The greater the angle, or rather the sine of the angle, of the rays proceeding from the radiant or object into the front lens, and the greater the refractive index of the medium intervening between the anterior lens of the objective and this radiant, the greater is the resolving power,—equal corrections of the spherical and chromatic aberration being assumed. A lens magnifying, say, only one-tenth as many times as another may be more powerful than it by virtue of the greater numerical aperture which it possesses, and will be capable of showing details which the more highly-magnifying lens of smaller aperture is unable to resolve. The aim in Microscopy is not to magnify and amplify as many times as possible, but to see minute details clearly with as little magnification as practicable; mere magnification being easily obtained at the other end of the tube by high eye-piecing, provided the objective is so well corrected that it does not break down under the strain of deep oculars.

I referred to the Abbe *diffraction theory of the formation of the microscopical image*, the substance of which is simply this that the diffraction images produced by the passage of the rays of light through closely approximated lines or structures have a most important share in the formation of microscopical images, it being formerly assumed that these were solely produced in accordance with the laws of refraction, or in other words that they were mere dioptric images. This, however, is only the case within a certain limit, and both Professors Abbe and Helmholtz have found by theoretical researches that no amount of magnifying power can separate or resolve markings or details which are more than the $\frac{1}{2500}$th of an inch apart, and that these are solely imaged by their diffraction spectra. The objective has therefore not only to transmit the dioptric beam, but it has also to collect the diffraction spectra, and as these diffraction spectra fall the wider apart the closer the lines are which produce them, it becomes evident that an objective must be capable of collecting a sufficient number of these spectra if the object is to be truly imaged. It is further evident that different objects may produce identical microscopical images, and that the same structure may produce different microscopical images if these objects are viewed with lenses of different apertures. I will give you just one illustration of this theory. Suppose you place on the stage of your microscope a grating consisting of fine parallel lines, every alternate line stopping short in a horizontal line drawn through the centre, in other words, two gratings, of which the upper one has only half as many lines per inch as the lower one, and you focus these gratings with a suitable objective. By removing the eye-piece and looking into the tube of the microscope you will perceive at the back lens two rows of spectra, each having a central circle of bright and colourless light the dioptric beams, and the oval spectra with their blue ends directed towards the centre arranged laterally. The upper row contains twice as many spectra as the lower one, and corresponds with the wide grating; the lower row contains only half as many spectra as the upper one, and corresponds with the narrow grating. By inserting at the back lens of the objective a grate-shaped diaphragm, the bars of which stop out every alternate diffraction spectrum of the line of close-lying spectra, and by replacing the eye-piece, you will find on looking through it that you have altered the appearance of the object, and that those lines which actually stop short in the horizontal diameter of the field appear now as continuous, and that the whole field appears as one grating of close lines. The explanation of this is that you have now two rows containing the same number of identical diffraction spectra which necessarily yield identical pictures in the eye-piece. If, on the other hand, the diffraction spectra are all stopped out, allowing only the two dioptric images to pass, it will be found on looking through the eye-piece that the grating, which must be finer than $\frac{1}{2500}$th inch, has disappeared or become invisible. By manipulating the diffraction spectra and the dioptric beams of more complex structures their appearances may be greatly varied, and no one who has once tried these beautiful experiments can doubt the correctness of Abbe's theory that microscopical structures of greater fineness than the $\frac{1}{2500}$th inch are solely imaged by their diffraction spectra.

As previously stated, the resolving power is a function of the numerical aperture. Mr. J. W. Stephenson has computed a most useful table, which is regularly published on the covers of the *Journal* of the Royal Microscopical Society. This table gives, for 130 different numerical apertures ranging from ·05 to 1·52, the corresponding angular apertures of dry, water, and homogeneous-immersion lenses, and the number of lines per inch which objectives of these numerical apertures can resolve by white and by monochromatic light, as also the number of lines which these lenses will photograph, this latter number being about 30 per cent. in excess of the lines they can resolve by white light. By measuring the aperture of any objective, which is done with an apertometer such as Abbe's, and by referring to Stephenson's tables, one can find at a glance the number of lines this lens is theoretically able to resolve or to photograph, and in our best objectives the actual result falls very little short of the theoretical limit.

The greatest improvements in the construction of Micro-objectives during the last six years, that is to say, since the introduction of the homogeneous-immersion system, have nearly all tended in the direction of the increase of the numerical aperture, which has been advanced from 1·2 to 1·5 in homogeneous-immersion lenses, and we have thus almost reached the theoretical limit. It is, however, very doubtful whether by going beyond 1·3 or 1·4 with the numerical aperture anything further can be gained; certain it is, on the other hand, that by going beyond these values the working distances of lenses become reduced to impracticably short dimensions, and consequently the range of objects upon which such lenses can be brought to bear is very limited, whilst the difficulties of construction and the expense connected with the production of lenses of extreme apertures become greatly enhanced. The loss of penetrating power, which decreases with the square of the numerical aperture, is also a very serious drawback in lenses of extremely wide apertures. Professor Abbe long ago recognized that by pushing the aperture of objectives beyond its legitimate limit, no adequate advantages could be obtained; and he therefore directed his attention to the attainment of superior definition, or the better corrections of the spherical and chromatic aberrations. Unfortunately, with the means at the command of opticians—viz., with the crown and flint glasses then in use, this was not possible, and new optical media had first to be found before further improvements could be attained. In 1881, Dr. Abbe induced Dr. O. Schott, of Witten in Westphalia, a chemist of great experience in the manufacture of glass, to make for him numerous small quantities of experimentally-produced glasses, and, as these experiments bore germs of promise, Dr. Schott removed in 1882 to Jena, to establish there a melting laboratory in order to repeat his experiments on a larger and more practical scale. More than a thousand different glasses were compounded, and prisms were ground out of them, which were examined by means of the spectroscope and the refractometer, in order to establish the relations of their optical properties to their chemical composition, with the result that a number of new optical vitreous media were obtained which possessed the properties aimed at, viz.:—

(1.) Crown and flint glasses, in which the dispersion for the different regions of the spectrum shows approximately the same ratio, and which admits consequently of the almost complete elimination of the so-called secondary spectrum in achromatic combinations.

(2.) The increase of the number of optical media, in such a way that with the same refractive index a dispersion, or with the same dispersion a refractive index can be obtained, not, as hitherto, only in combination with flint glass of high dispersive powers, but also with lower dispersion, as in crown glass.

The attention of the Prussian Government having been directed to the researches of Drs. Abbe and Schott, who were enthusiastically and materially assisted by the Messrs. Zeiss, it granted to these gentlemen a subsidy of £3,000 on the most liberal terms possible. A not inconsiderable manufactory has now been established in Jena for the production of glasses for optical and other scientific purposes, under the name of the Glastechnische Laboratorium, Schott und Genossen, which has issued an interesting catalogue compiled on a strictly scientific basis. This catalogue contains a list of 44 glasses, of which 19 are quite new. The list gives the specific gravity, the refractive indices (which vary from 1·5151 to 1·9626, the latter for the heaviest silicate flint glass), and the mean dispersion, which varies from 0·00737 to 0·04882. There is also a price list of discs for telescope objectives up to 20 inches diameter. These new vitreous media contain many elements, some of them as many as 14, but the chief constituents seem to be silicates, borates, and phosphates.

Mr. Zeiss is the first optician who has made Micro-objectives of these new optical glasses, and these lenses have been beautifully made according to the formulæ and data given to him by Professor Abbe. In these lenses Zeiss has been able to overcome the greatest defects of objectives, the optical glasses hitherto available forming an insurmountable barrier to further improvements. In consequence, namely, of the great disproportion of the dispersion of the various colours of the spectrum, our best so-called achromatic lenses have up to now been only corrected for two colours of the spectrum, and the unavoidable residue of unachromatism—the so-called secondary spectrum—was always more or less perceptible. In the new lenses it has been possible to bring three colours to one focus. The optical glasses formerly used in the construction of Micro-objectives likewise did not permit of the correction of the spherical aberration for more than one colour. Objectives, although fairly-well corrected for the middle of the spectrum, showed, nevertheless, a spherical under-correction for the red and a spherical over-correction for the blue and violet rays, which imperfection appeared as a more or less great inequality of the achromatic correction between the central portion and the peripheral zones of an objective. These defects caused an imperfect combination of the image-forming rays, and the result was that objectives, especially those of large apertures, did not stand high eye-piecing, because the defects of spherical and chromatic aberration became more apparent with them than with the lower magnifying ones. In the new lenses the spherical aberration has been completely corrected for two different colours of the spectrum, and therefore practically for all.

Dr. Abbe has called his new lenses *Apochromatics* or *Apochromatic Objectives*, owing to their superior spherical and chromatic corrections, which represent a higher order of achromatism than that hitherto attained.

The *practical advantages* which these Apochromatics possess over other Micro-objectives are the following:—

(1.) Owing to their superior corrections, the full value of their large apertures becomes now only apparent. Indeed, the images formed by the new dry and water-immersion lenses are scarcely distinguishable from those formed respectively by the old water and homogeneous-immersion lenses of even perceptibly larger aperture.

(2.) The largest magnifications for a certain aperture may be obtained by high eye-piecing and by objectives of relatively long foci, thus obviating the necessity for objectives of extreme short focal lengths. The apertures of the old lenses are estimated to stand profitably eye-pieces magnifying from four to six diameters, whilst those of the apochromatic objectives, even those of the largest aperture, will stand an amplification of at least 12 to 15 diameters, and hence a very much larger range of useful magnification can be obtained with them.

(3.) By the correction of the secondary spectrum, and the (for all practical purposes) perfect correction of the spherical aberration, the visual and the actinic foci of these objectives coincide, rendering them especially suitable for photo-micrography.

(4.) The increased spherical and achromatic corrections of the new objectives produce a much larger concentration of light in the images produced by them.

(5.) The objects viewed by them appear in their natural colours.

Special eye-pieces, however, are required, in order to utilize to their fullest extent the capabilities of the new lenses, and Dr. Zeiss has constructed suitable eye-pieces, which he designates Compensating Oculars. The front lenses of objectives of short focal lengths are single crown glass lenses, which are therefore unachromatic. All objectives of wide aperture in which the front lens of the system cannot be achromatized itself, although well corrected for their chromatic aberrations in their centres, show yet a considerable difference of magnification for the different colours in the marginal zone, which appears as coloured outlines. The picture produced by the blue and violet rays is larger than the one produced by the yellow rays. The so-called compensating eye-pieces are designed with a view to correct this residue of peripheral aberration, or to balance or compensate these chromatic differences of magnification. But to make these compensating oculars available not only for the objectives of wide aperture, but also for those of moderate aperture, or for the low powers—these latter had to be so constructed that their marginal zone should possess practically the same aberrations as the objectives of great aperture. The compensating eye-pieces may also be used with wide-angled objectives of older construction.

The classification of the compensating oculars has been carried out on Abbe's plan, and they are designated by their magnifying power at a tube-length of 250 mm., which carries at its other end the apochromatic objective. Thus, instead of naming the eye-pieces A, B, C, D, etc., or 1, 2, 3, 4, &c., we have—

Eye-pieces 1, 2, 4, 8, 12, 18, 27—

magnifying 1, 2, 4, 8, 12, 18, and 27 times respectively, under the conditions stated. Both the focal length and number or magnifying power are engraved on each eye-piece, and the magnification of the microscope can therefore be easily calculated by simply *multiplying* the number of the ocular with the initial magnifying power of the objective at the conventional tube-length of about 10 inches, or 250 mm. Thus, for instance, an objective of 2·5 mm. focus magnifies 250 divided by 2·5, or 100 diameters, and in combination with No. 18 eye-piece, 1800 diameters.

The eye-pieces are made in two series—one for the Continental stand, having a tube of 160 mm., and the other for the English stand, having a tube of 250 mm. length; but both series are so arranged that they give the same magnifying powers. The settings of these oculars are so constructed that the lower foci of all those belonging to one series are lying in the same plane when inserted in the body of the microscope, so that no alteration of the focal adjustment is required when interchanging them.

The compensating eye-pieces are of three kinds, viz.:—

(1.) *Search oculars or finders* of great focal length. No. 1 for the Continental stand does not magnify the image projected by the objective at all, whilst No. 2, which is made both for the Continental and English stands, magnifies this image only two diameters. I have found these oculars a very great boon when searching for a certain object on a slide, as they can be instantly exchanged for another eye-piece, and that without requiring a re-adjustment of focus, whilst the double nose-piece—which generally carries besides a high-power system, also a low-power one as a finder—is cumbersome and prejudicial to the centricity of the optical system, and necessitates invariably a readjustment of the focus. A great saving of time, labour, and inconvenience can thus be effected by these search oculars, especially when using immersion lenses.

(2.) *The ordinary working oculars*, magnifying 4, 8, 12, 18, and 27 diameters, respectively; their focal lengths varying from 45 to 10 mm. for the Continental tube, and from 67 to 10 mm. on the English 10-inch tube. These working oculars have all relatively large eye-lenses, whose foci lie so much above their upper surfaces that the usual inconvenience of working with Huyghenian eye-pieces of short foci is not felt, and the camera lucida can also be used with all of them except with No. 27.

(3.) *Oculars for projection*, magnifying two and four diameters for a tube of 160 mm., and three and six diameters for a tube of 250 mm., or 10 inches long, respectively. These oculars have two diaphragms each to reduce the effective apertures of the high-power lenses, should such appear desirable. They are constructed for photo-micrography and for the lantern microscope, and yield an evenly-illuminated flat field and a well-defined image at any screen distance; they can also be used advantageously with ordinary high-power achromatic objectives.

The apochromatic objectives made in Dr. Zeiss' establishment are comparatively few, because, owing to the great range of magnifications they are able to bear, fewer objectives than formerly are now required to form a complete and effective working series.

The following is a list of the new Apochromatics:—

Num. Apert.	Equivalent focal length in mm.	Theoretical limit of resolving power of lines per inch.	
		For white light. Line E.	On the photographic plate. Near line N.
Dry system, . *0·30	24·0	28,963	38,099
,, . 0·30	16·0		
,, . *0·60	12·0	57,846	76,199
,, . 0·60	8·0		
,, . *0·95	6·0	91,590	120,648
,, . 0·95	4·0		
Water immersion, 1·25	2·5	120,513	158,747
Homog. ,, 1·30	3·0	125,333	165,097
,, ,, 1·30	2·0		
,, ,, 1·40	3·0	134,974	177,797
,, ,, 1·40	2·0		

* These are manufactured only for the English tube.

With this series nearly up to 135,000 lines per inch can be made visible, and up to 178,000 lines per inch can be photographed, whilst objects far smaller than the $\frac{1}{200,000}$th part of an inch can be seen with the highest power, for the resolution of close lines must not be confounded with seeing isolated small objects. The homogeneous-immersion lenses are constructed without screw collars for the adjustment for covering glasses of different thicknesses—the invention of Andrew Ross,—and they have to be used with thickened cedar wood oil of the refractive index 1·5128. In spite of their large apertures they will work through covers nearly $\frac{1}{100}$ inch thick. These oil-immersion lenses are generally called homogeneous-immersion lenses, because the immersion fluids with which they have to be used, such as thickened cedar wood oil or some other essential oils and solutions of certain salts, have the same refractive index as crown glass, of which the front lens of the objective and the covering glass are made, and all of which form, therefore, optically a homogeneous whole.

The apertures of Micro-objectives are measured at their back lenses, because the same angular aperture of a dry and an immersion lens is quite a different thing, for the angle of an immersion lens is equivalent to a larger cone of rays in air which has been contracted by the refractive power of the immersion fluid into the same angle as that of the dry lens. The reflection and consequent great loss of light on the plane surface of a dry lens is another point constituting a drawback to high dry powers. This loss of light by reflection does not occur in immersion lenses. The greatest angular aperture which a dry front lens can possess is, of course, 180 degrees, and as the refractive index of air and the sine of 90 degrees are 1, it follows that the numerical aperture for such a lens is 1, which corresponds to an angle of 90 degrees for a water-immersion lens, and to one of 82 degrees for a homogeneous-immersion lens. The angular aperture of a water-immersion lens of 180 degrees is equivalent to a numerical aperture of 1·33, and the angular aperture of a homogeneous-immersion lens of 180 degrees is equivalent to a numerical aperture of 1·52. From these values of numerical aperture it is evident that if the greatest amount of resolving power which a dry lens can possess be stated as 1, then the greatest resolving powers of water- and homogeneous-immersion lenses are 1·33 and 1·52 respectively.

The following diametrical magnifications may be obtained with the apochromatic objectives and compensation oculars:—

Equivalent Focal Length in mm.	Search Oculars.		Working Oculars.				
	1	2	4	8	12	18	27
24·0	...	21	42	83	125	187	281
16·0	15·5	31	62	125	187	281	...
12·0	...	42	83	167	250	375	562
8·0	31	62	125	250	375	562	...
6·0	...	83	167	333	500	750	1125
4·0	62	125	250	500	750	1125	...
3·0	83	167	333	667	1000	1500	...
2·5	100	200	400	800	1200	1800	...
2·0	125	250	500	1000	1500	2250	...

Dr. Zeiss has sent me four of these Apochromatics for inspection, viz.:—those of 16, 4, 2·5, and 2 mm. focus, which I have carefully tested and compared with the older forms, and I find that they surpass by far any objective I have previously examined. Their definition is exquisite, their resolving power is very great, and the pictures yielded by them are most brilliant and free from colour; they possess, further, a very notable increase of illuminating power and give great flatness of field I have also tested these Apochromatics for their photographic capacity, and as a proof of their perfect suitability for this purpose I have brought a few negatives of diatoms and other objects, among them one of *Amphipleura pellucida*, which shows the striæ quite distinctly resolved. The *Amphipleura pellucida* is a microscopic shell, $\frac{1}{225}$-inch long and $\frac{1}{3500}$-inch broad, and bears on its surface cross-marking of the utmost regularity counting at the rate of about 100,000 per inch. To see those lines on a photograph plainly with the unarmed eye, the diatom requires to be magnified nearly 2,500 diameters, or about 6,250,000 times superficially. All these negatives were taken by ordinary lamp-light.

Thanks chiefly to the labours of Professor Abbe, the microscope is to-day perhaps the most perfect optical instrument which we possess, for it appears, both from theoretical and practical considerations, that with it we have as good as reached the limit of microscopical vision, and that no further important improvement is possible, until suitable media of far greater refractive power than any we possess at the present time have been discovered and placed at the service of the optician.