April 4, 1939. H. C. SNOOK 2,153,010

MICROSCOPY

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Fig. 1.

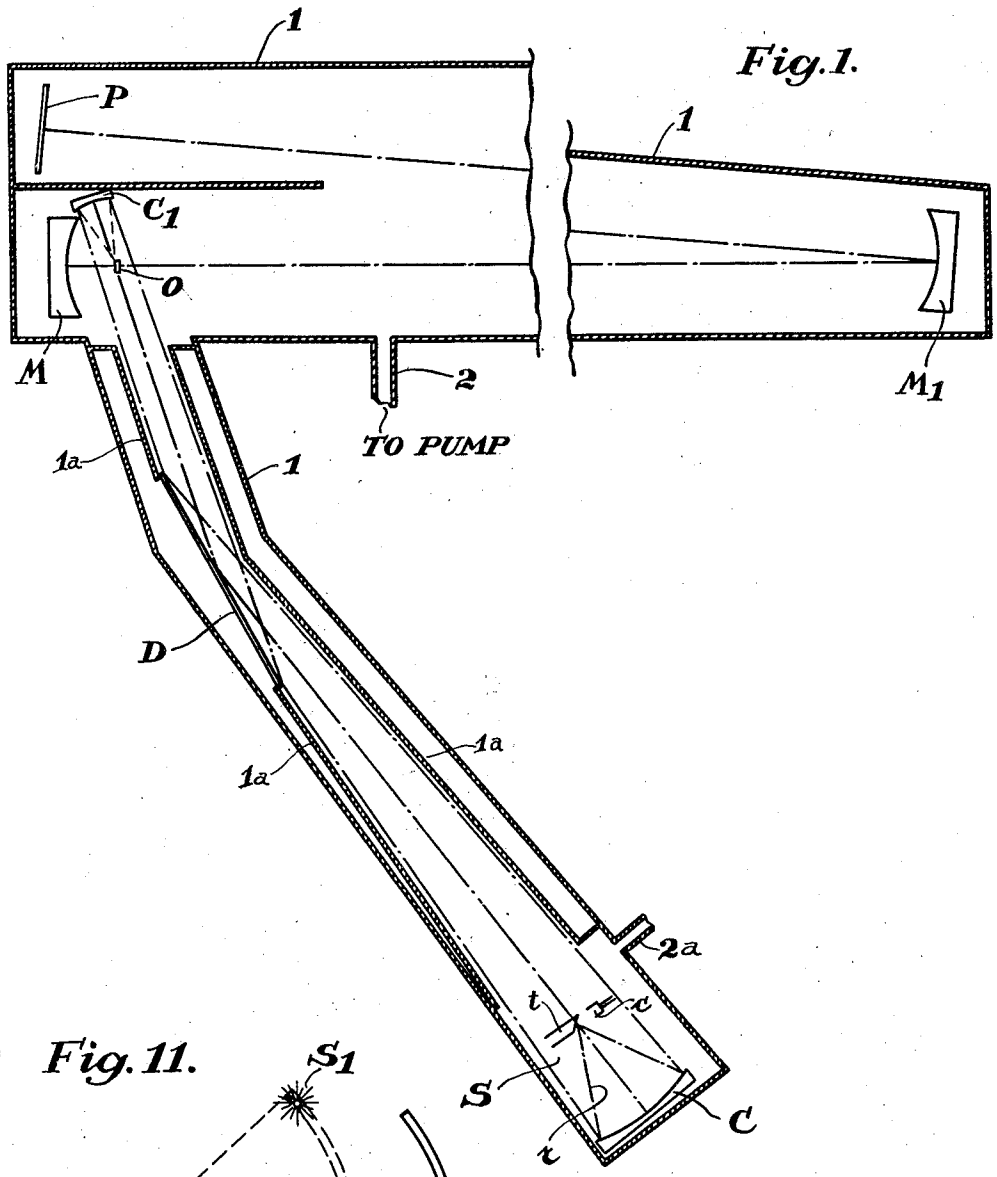
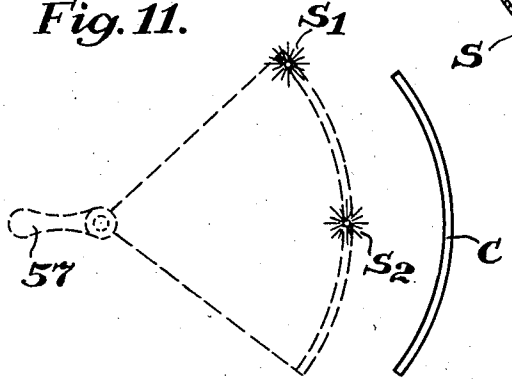


Fig. 11.



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April 4, 1939. H. C. SNOOK 2,153,010

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Filed Nov. 25, 1935 10 Sheets-Sheet 2

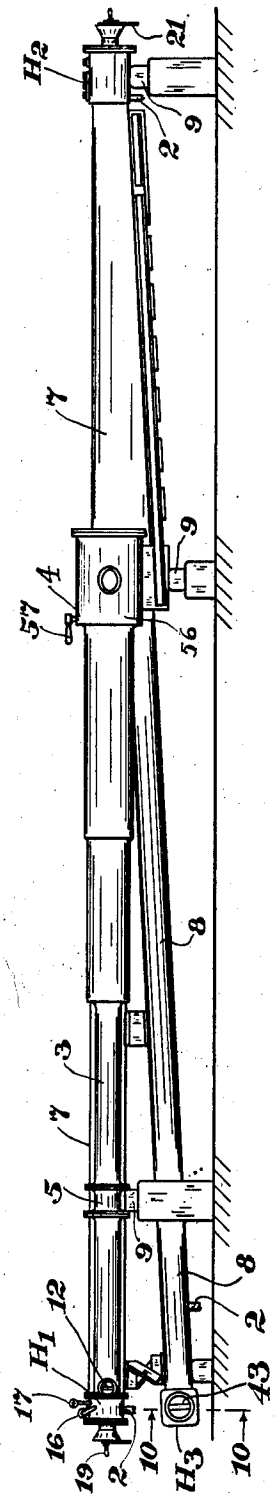


Fig. 2.

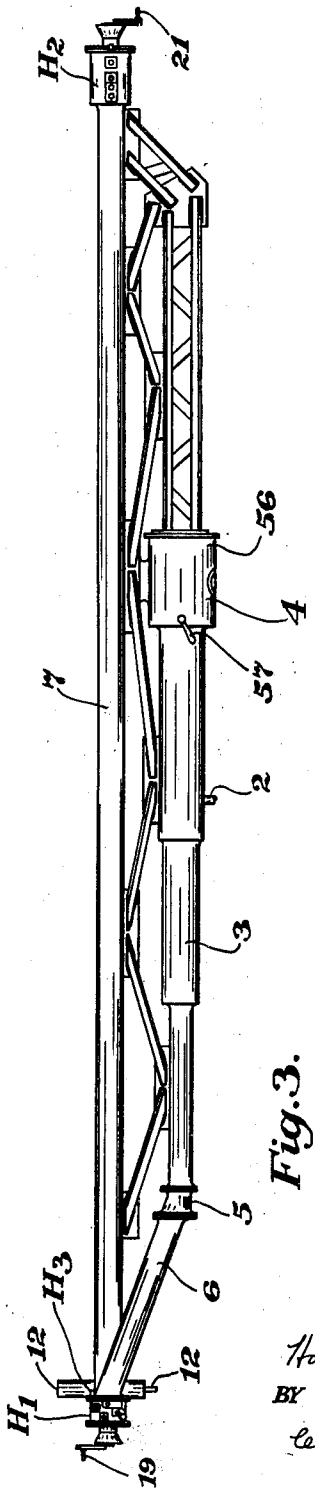


Fig. 3.

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April 4, 1939. H. C. SNOOK 2,153,010

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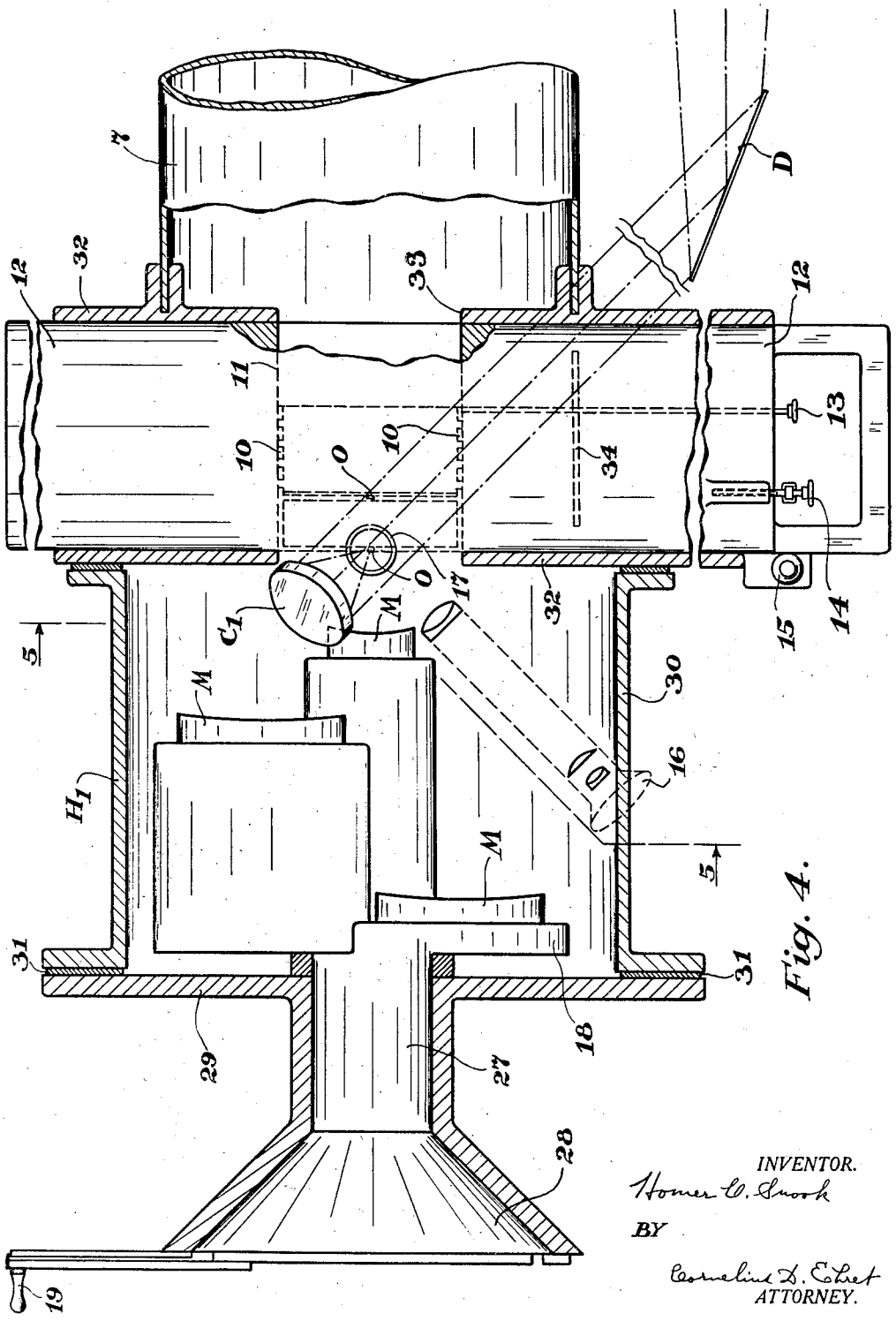


Fig. 4.

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April 4, 1939. H. C. SNOOK 2,153,010

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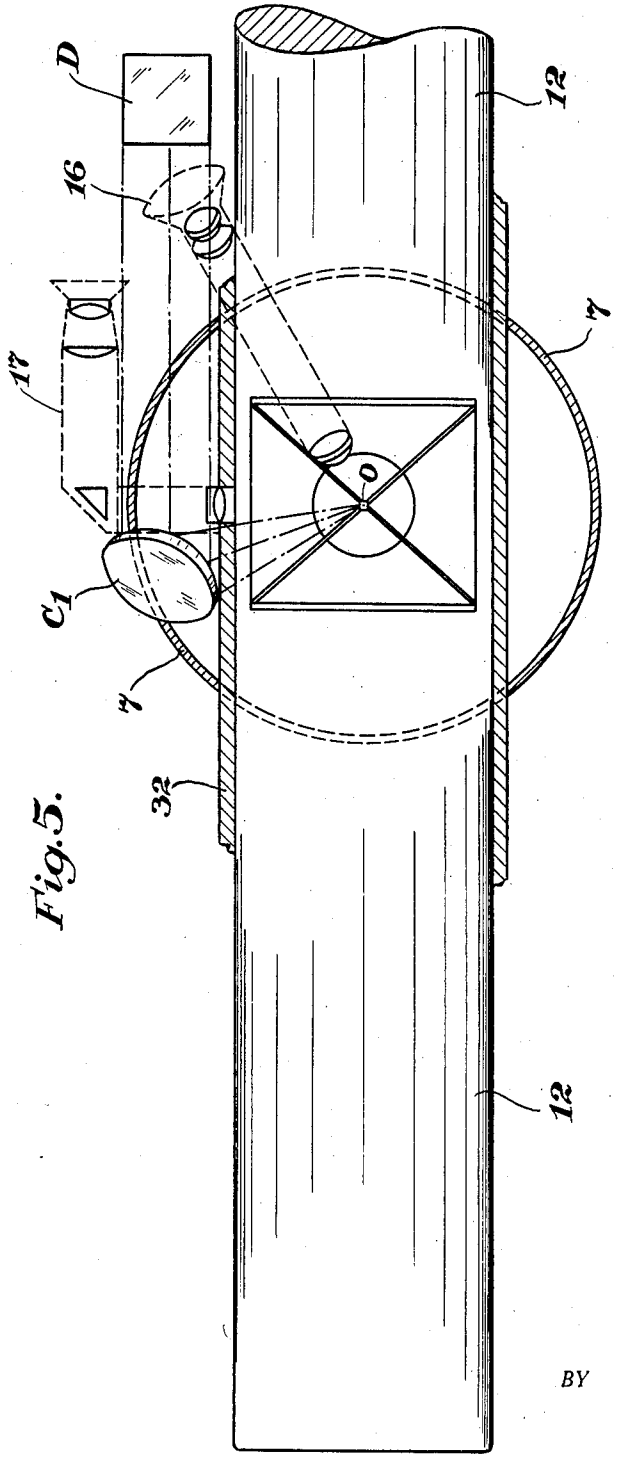


Fig. 5.

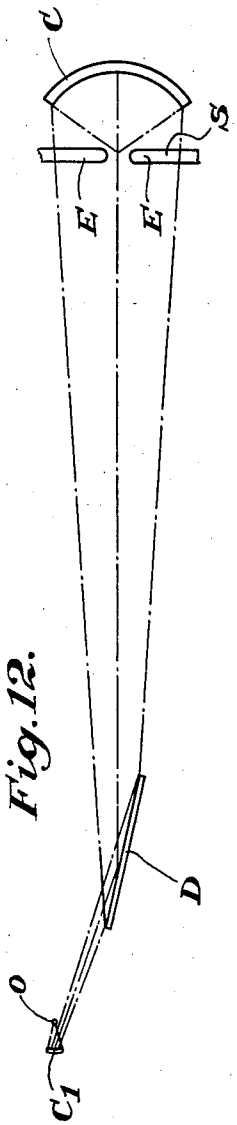


Fig. 12.

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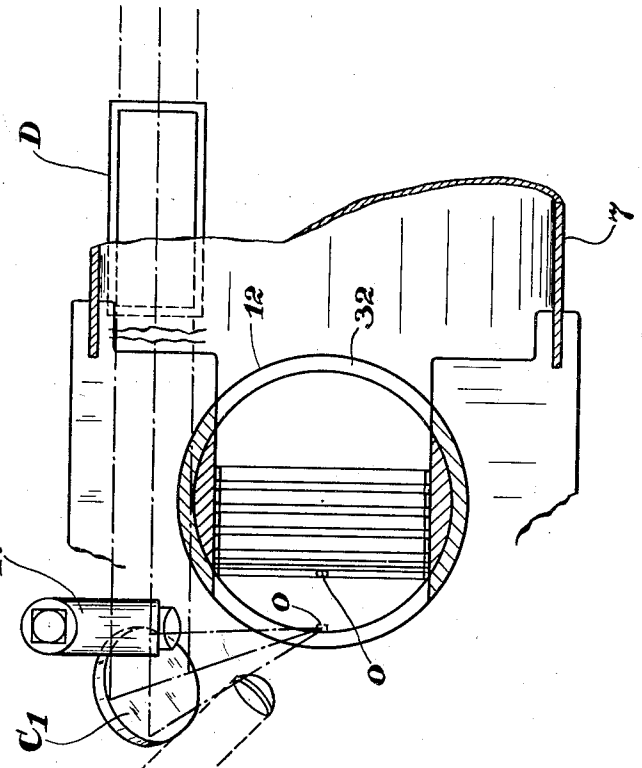


Fig. 6.

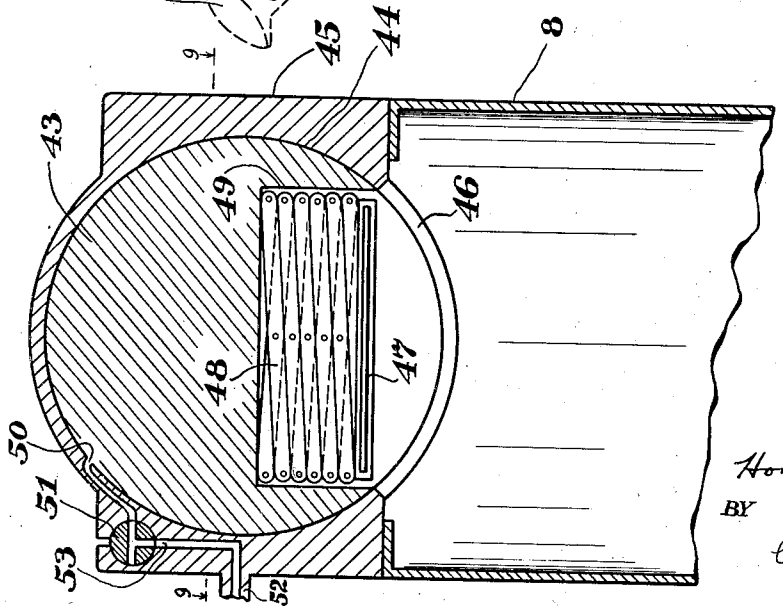


Fig. 10

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April 4, 1939. H. C. SNOOK 2,153,010

MICROSCOPY

Filed Nov. 25, 1935 10 Sheets-Sheet 6

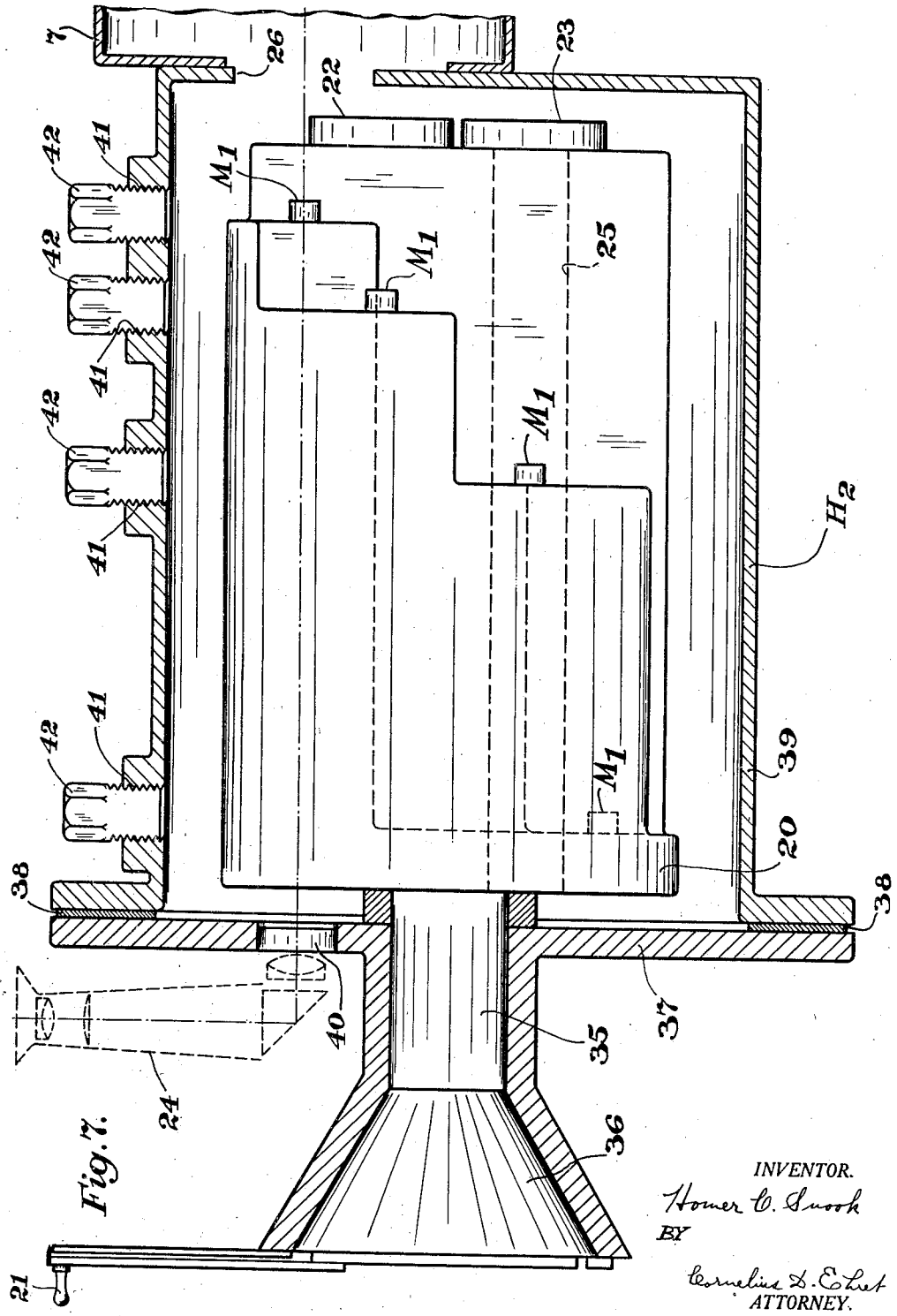


Fig. 7.

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April 4, 1939. H. C. SNOOK 2,153,010

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Filed Nov. 25, 1935 10 Sheets-Sheet 7

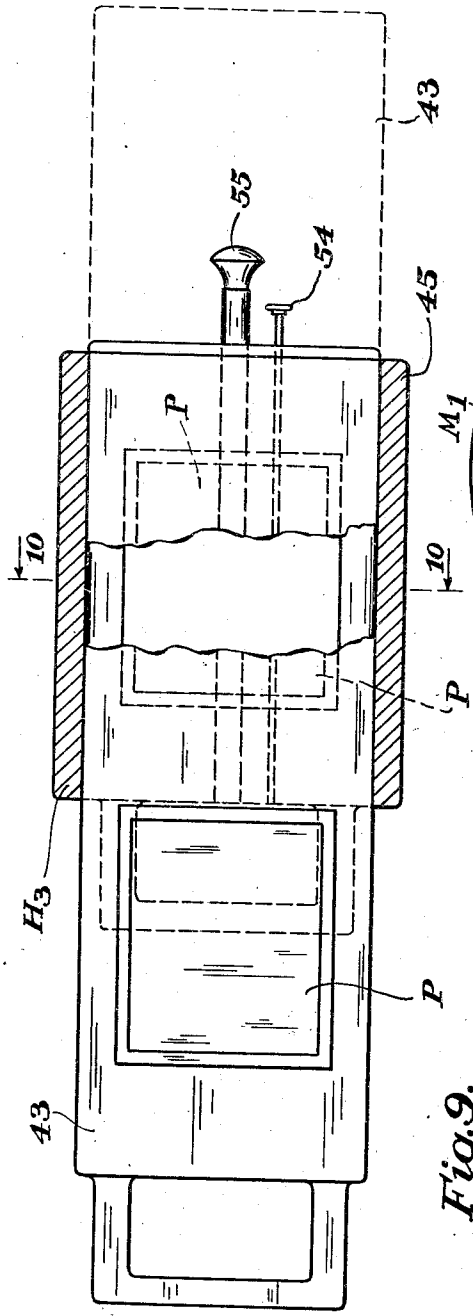


Fig. 9.

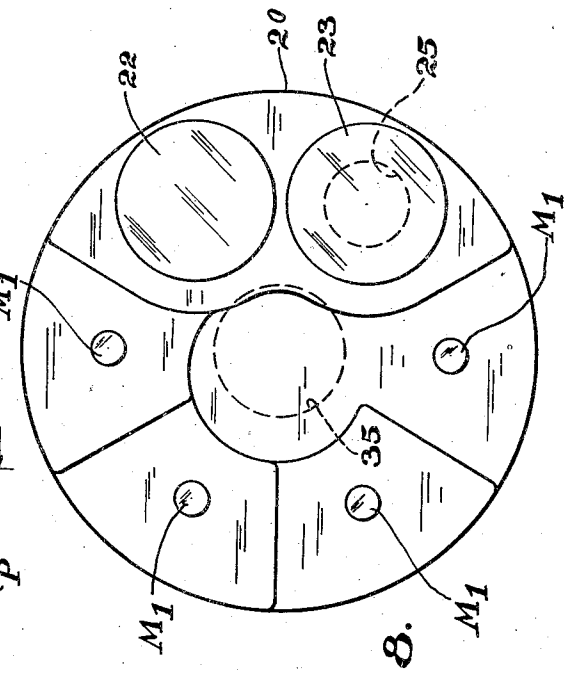


Fig. 8.

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Filed Nov. 25, 1935 10 Sheets-Sheet 8

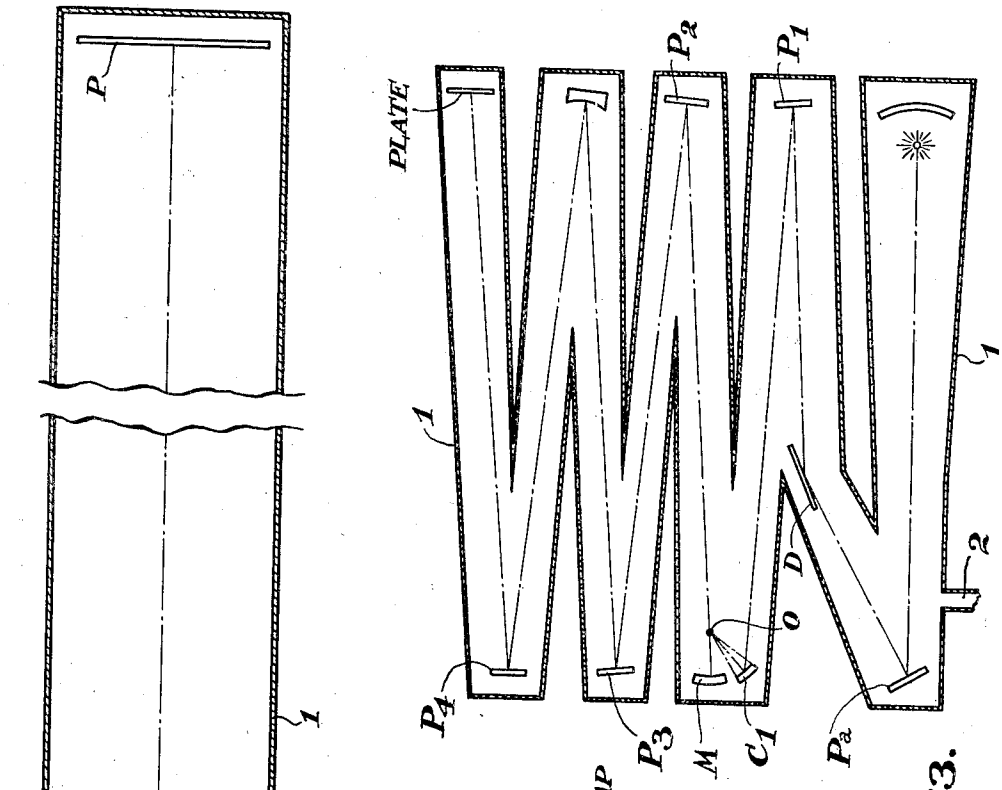


Fig. 13.

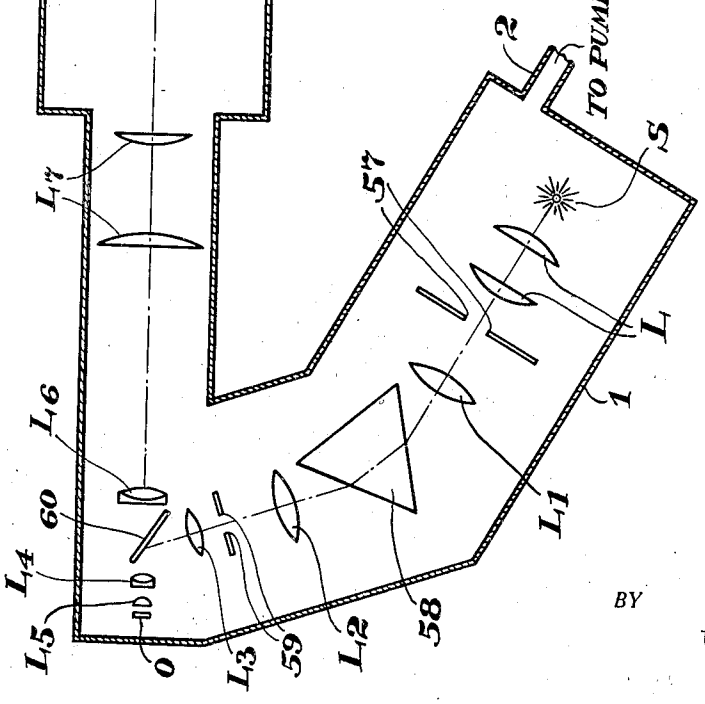


Fig. 14.

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April 4, 1939. H. C. SNOOK 2,153,010

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Filed Nov. 25, 1935 10 Sheets-Sheet 9

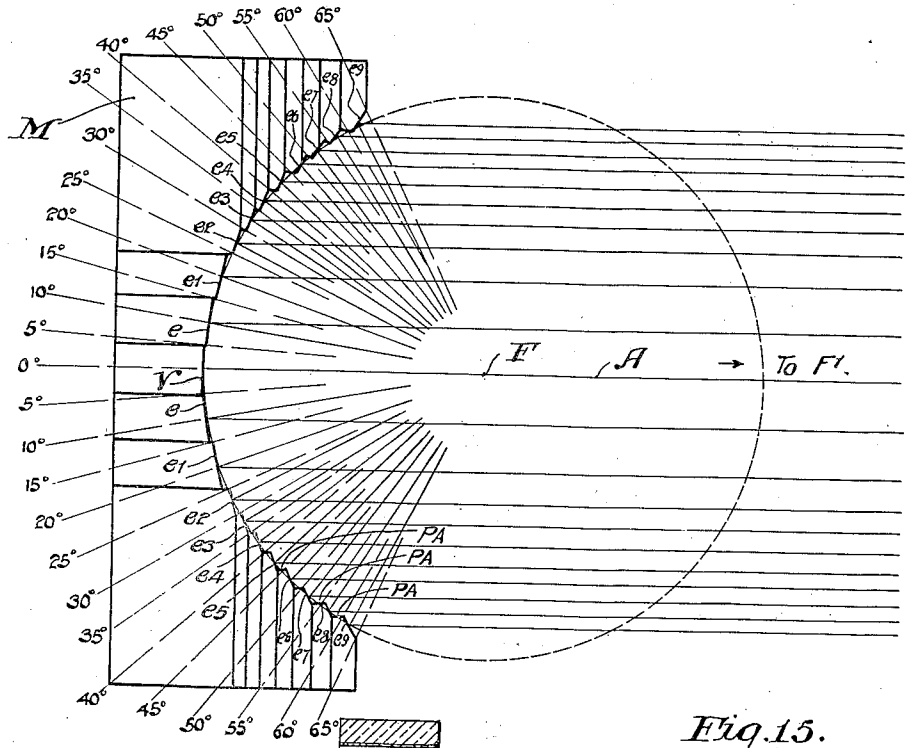


Fig. 15.

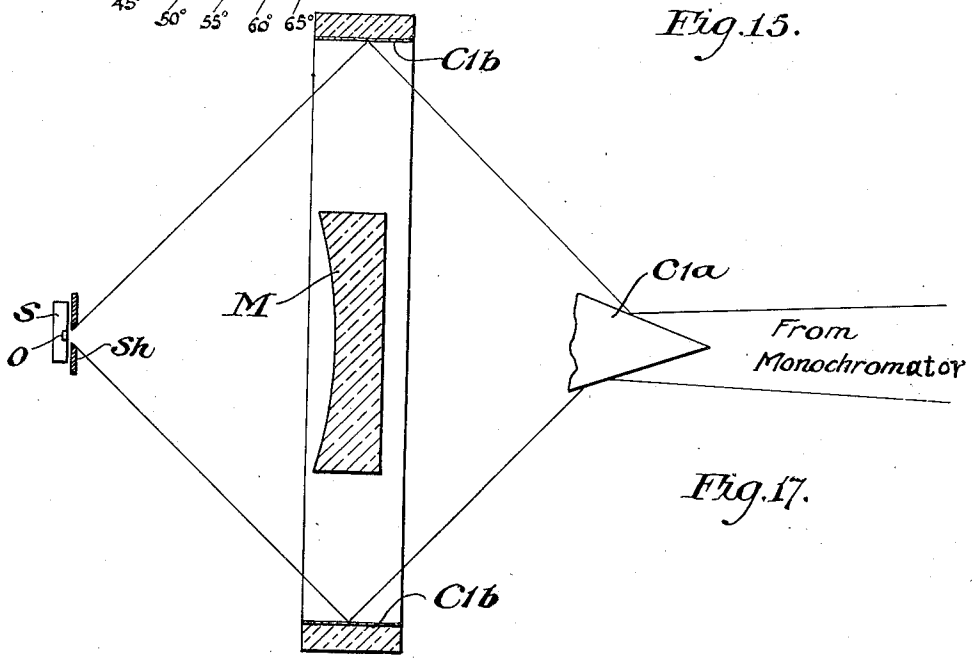


Fig. 17.

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April 4, 1939. H. C. SNOOK 2,153,010

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Filed Nov. 25, 1935 10 Sheets-Sheet 10

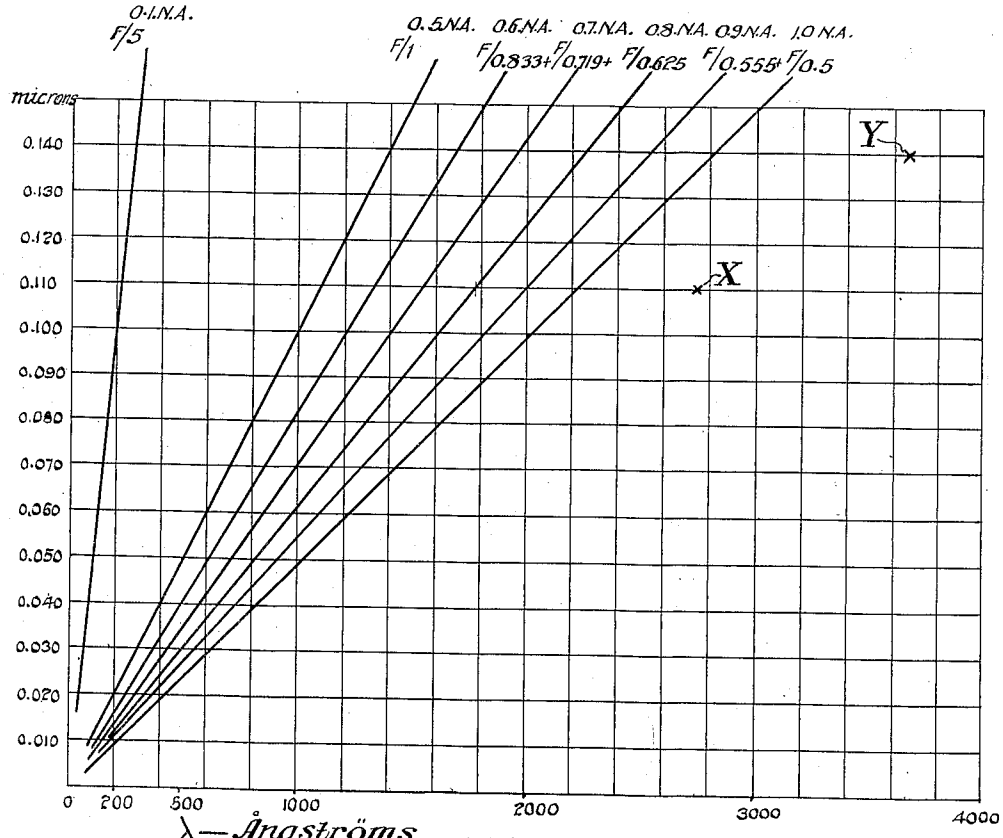


Fig. 16.

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Patented Apr. 4, 1939

2,153,010

UNITED STATES PATENT OFFICE

2,153,010

MICROSCOPY

Homer C. Snook, Summit, N. J.

Application November 25, 1935, Serial No. 51,427

12 Claims. (Cl. 250—53)

My invention relates to microscopy, and particularly to methods and apparatus for increasing the useful magnification by substantially extending the limit of resolution.

In accordance with my invention, for procuring high magnification with materially extended limits of resolution, I irradiate the object or specimen by a selected narrow band of radiation having wavelengths within the range from about 2,000 Angstroms to about 200 Angstroms; and for wavelengths of these orders of magnitudes I utilize an image-producing system comprising, as distinguished from refractors or lenses, reflectors or mirrors having suitably high coefficients of reflection and suitably low coefficients of absorption.

Further in accordance with my invention, the absorption by ambient air or other gas is reduced or substantially eliminated by maintaining the elements of the optical system in suitably high vacuum, or high vacua, particularly when there are utilize those wavelengths for which the aforesaid absorption is significant; and also for those wavelengths for which the ambient air or gas, or for which gas occluded or liberated by the object or specimen or the vacuum container during microscopy thereof, introduces refractive or other undesired effects, such as scintillation; as an alternative, for some types of work, the image-producing system is maintained in an atmosphere, at any desired pressure, super- or subatmospheric, consisting of a gas or gases, such as hydrogen or helium, having low coefficients of absorption and refraction at the wavelengths used.

Further in accordance with my invention, one of the mirrors, such as the objective mirror, comprises annuli whose reflecting surfaces are portions of different ellipsoids having common conjugate foci; more particularly, the angular width of each annulus, as viewed from a focus, such as the object-focus, is made sufficiently small materially to reduce aberrations at a conjugate focus, such as the image-focus, to negligible magnitude.

My invention resides in further aspects of method and apparatus hereinafter described.

This application is a continuation-in-part of my copending application Serial No. 10,431, filed March 11, 1935.

For an understanding of my invention, and for illustration of apparatus embodying it, reference is to be had to the accompanying drawings, in which:

Fig. 1 diagrammatically illustrates an image-producing system for producing photo-micrographic or fluoro-microscopic images;

Fig. 2 is a side elevation of apparatus having an image-producing system of the type shown in Fig. 1;

Fig. 3 is a plan view of the apparatus of Fig. 2;

Fig. 4 is a detail view, in plan, on enlarged scale and with parts in section, of the primary head of the apparatus shown in Fig. 2;

Fig. 5 is a view in elevation, taken on line 5—5 of Fig. 4; partly in section and with parts omitted;

Fig. 6 is a side elevation of parts appearing in Fig. 5;

Fig. 7 is a detail view, in elevation and on enlarged scale, of the secondary head of the apparatus shown in Fig. 2;

Fig. 8 is a plan view of the mirror turret shown in Fig. 7;

Fig. 9 is a detail view taken on line 9—9 of Fig. 10;

Fig. 10 is a sectional view taken on line 10—10 of Fig. 9;

Fig. 11 diagrammatically illustrates an arrangement for selectively using different sources of radiation in the apparatus shown in Figs. 2 and 3;

Fig. 12 diagrammatically illustrates a source of radiation specifically different from that shown in Fig. 1;

Fig. 13 diagrammatically illustrates an arrangement for reducing the overall length of an apparatus such as shown in Figs. 2 and 3;

Fig. 14 illustrates another modification of the invention;

Fig. 15 is a cross-sectional view of a preferred form of objective mirror;

Fig. 16 is a graph referred to in explanation of the image-producing system;

Fig. 17 illustrates another modification for obtaining wide-angle irradiation of the object.

In the present microscopic practice, the maximum useful magnification is about 1,000 diameters, and the resolution about 0.11 micron. Although higher magnifications have been employed, the increased magnification actually gives no greater detail because the resolution is no better than aforesaid at 1,000 diameters. At the present time, and with the materials at present known, greater useful magnification cannot be obtained with the refracting type of microscope. Although it is appreciated the resolution obtainable with a microscope increases as the wavelength of the light or radiation used is decreased, there are known no suitable re-

fracting materials which are sufficiently transparent to radiation much below 3,000 Angstroms. Radiation of these short wavelengths can be generated by electronic bombardment of various metals at various voltages or by condensed sparks and arcs in vacuo, but prior to my invention they have not been used to produce real images in either photo-micrography or fluoromicroscopy.

To obtain substantially enhanced useful magnification and resolution far in excess of those possible with a refracting type of microscope now employed, I utilize an image-producing system whose components, as diagrammatically shown in Fig. 1, comprise a suitable source S of radiations within the range below 2,000 Angstroms, and an arrangement for selecting a narrow band of wavelengths and impressing it upon the object or specimen O. Specifically, the monochromator or apparatus for providing radiations within a desired narrow band of wave lengths may comprise, as shown, a source of radiation S, a primary condenser mirror C, a diffraction grating D and a secondary condensing mirror C1. The radiation, generated by the source S, which as shown may be a target T bombarded by electrons emitted by the cathode *c*, is directed by the primary condenser C upon the diffraction grating D which is viewed by the secondary condensing mirror C1 which focuses the narrow band of radiation selected from the spectrum produced by grating D upon the object O. The radiation may also be produced by an electric spark or arc between electrodes E, E of Fig. 12. By suitable selection of the material of the target, or of the electrodes, and of the electric voltage and wave form employed, a band of radiation including the desired narrow band of substantially monochromatic radiation can be obtained.

The selection of different narrow bands of radiation from the source S for irradiation of the object can be effected by varying the angular relation to each other of any one or more of the elements S, D and C, preferably or most simply by adjustment of D, the diffraction grating.

The object O is at one conjugate focus of the mirror M, whose other conjugate focus is located in front of the second mirror M1, preferably ellipsoidal, which views the real image of the object produced by mirror M and impresses a magnified real image upon the photographic or fluorescent plate P.

It is to be noted that the radiation received by the diffraction grating D, instead of emanating from a point source or a slit, as is customary in spectroscopic practice, is collected by the condensing reflector C through the large solid angle or cone of radiation *r*. The irradiation of the object is therefore substantially enhanced. Further, the diffraction grating D, as below stated, is surfaced with material selected to have a high coefficient of reflection at the wavelengths used. This also affords greater intensity of irradiation of the object at the wavelengths desired.

The reflecting surfaces of the mirrors M, M1, C and C1, and of grating D, and of any of the other mirrors herein referred to, are of a material which for the band of radiation used has an appreciable coefficient of reflection and a low absorption coefficient; for example, the surfaces may be of one or more elementary metals such as aluminum, magnesium, beryllium, cobalt, silicon, sodium, caesium, lithium, potassium, nickel or rhodium, or metal alloys, which may be deposited in any suitable manner as by sputtering or evaporation. The support, backing or form for the reflecting surface should be of material having an insubstantial thermal coefficient of expansion, such as fused quartz, invar, Pyrex, etc. The surface of the material of the backing of the mirror is ground, polished and figured after the manner employed in the production of optical mirrors. The metallic coating subsequently applied to the supporting surface may be polished and figured optically, if necessary or found desirable.

For the range between 2000 Angstroms and 200 Angstroms (one Angstrom equals .0001 micron) the effect of air absorption is so great as to preclude transmission of radiation through air at atmospheric pressure. Therefore within this range of wavelengths, or for any wavelengths for which occur refractive or other adverse effects of the air or gas between elements of the image-producing system, whether it employs mirrors as in Fig. 1 or is of a refracting type shown in a subsequent modification, the path of the radiation is in a vacuum preferably high and of the order of 10^{-6} millimeters of mercury, or lesser pressures. As shown in Fig. 1, the entire image-producing system may be enclosed in a housing 1 connected as by the pipe or conduit 2 to a suitable vacuum pump.

As it may be desirable, in some instances, to have a different degree of vacuum where the radiation is produced, there may be provided an inner casing 1*a* which closely fits the path of radiation in the monochromator to provide a gas path of substantial impedance between the source of radiation and the major portion of housing 1 which encloses the mirrors M, M1 and plate P. Separate pumps may be connected to the outlets 2 and 2*a* on opposite sides of the impedance.

The use of mirrors eliminates chromatic aberration, and therefore any narrow band of a wide range of wavelengths can be used to illuminate the object without loss of definition. It is usual practice to correct the lens system of a refracting microscope for usually not more than three different wavelengths of visible light, and at all other wavelengths there is more or less chromatic aberration. The mirror system, therefore, not only obtains results possible with the known refractive systems at the wavelengths for which the refractive elements are sufficiently transparent, but has features of advantage over the refracting type of microscope for still shorter wavelengths. With the lens or refractive system good definition or clarity of the image can be obtained only at the few long wavelengths for which the lens system is corrected, whereas with a given mirror system good photomicrographs are obtainable at a plurality of related wavelengths most of which are in the range of wavelengths shorter than visible light. The reflecting materials mentioned above are suitable for the range of wavelengths including visible light and extending substantially below 2,000 Angstroms. Whereas, with the present types of refracting microscopes the maximum useful magnification is of the order of 1,000 diameters and the resolution obtainable is of the order of 0.11 micron, my method and system afford a wide range of useful magnifications, as to a maximum of upwards of 10,000 diameters and with resolutions better than 0.11 micron.

Figs. 2 and 3 illustrate in greater detail the construction of a microscope system of the type shown in Fig. 1. The tube 3 between the housing 4 for the source of radiation and the housing 5

for the diffraction grating, the tube 6 between housing 5 and the head H1 which contains the object, condensing and reflecting mirrors C1 and M, tube 7 which connects the primary head H1 to secondary head H2 which contains the second mirror M1, and tube 8 between the secondary head H2 and the head H3 which encloses a sensitized plate, such as a photographic or fluorescent plate P, are all interconnected to form a single rigid unit, because even slight relative movements of any of the parts of the image-producing system during exposure would blur the image and thereby prevent realization of the high degree of resolution obtainable with the apparatus. The apparatus as a whole is mounted to be as free from shock as possible as by the damped resilient supports 9 of any suitable type. This is rendered necessary because of the constant seismic disturbances of the earth's crust, as well as other transitory disturbances as caused by railroad trains, automobile trucks, and the like. By making the apparatus as rigid as possible and substantially isolating it from the effect of seismic and other disturbances, relative motion of the parts and consequent distortion of the image is rendered negligible.

Referring to Figs. 4, 5 and 6 which disclose in detail the internal construction of the primary head H1, the radiation from the reflecting mirror C1 is focused upon the object O which is carried by the adjustable support 10, preferably a lazy tongs device mounted within the opening 11 in the object carrier 12. The object can be moved axially of the tube 7 by the lazy tongs 10 which are adjustable externally of the apparatus as by the knob 13, and is adjustable transversely of tube 7 as by the knob 14, and can be moved angularly about the axis of the object carrier 12 by adjustment of the knob 15. These adjustments are made while the object is being observed through the view telescopes 16 and 17, while the object is illuminated either with visible light from the monochromator, as in Fig. 12, or by means of fluorescense of the object when irradiated by ultra-violet light, wavelengths shorter than 4,000 Angstroms, also supplied by the monochromator. When the object is adjusted to proper position with respect to the cross hairs of the view telescopes 16 and 17, it is then known to be located at the correct conjugate focus of mirror M so that the real image will be located at the correct corresponding conjugate focus of mirror M properly to be viewed by the second mirror M1 of the head H2.

A plurality of mirrors M may be provided for attainment of different orders of magnification. The mirrors M are mounted on a common rotatable support or turret 18 which is adjustable externally of the apparatus, as by the handle 19, to bring any selected mirror to operative position. The mirrors M are so mounted that each, in turn, when brought into axial alignment with the tube 7 is at approximately the correct distance from the object O; i. e. at the position which will produce a real image always at the same position within tube 7.

As shown in Figs. 2 and 3, the head H2 is at the other end of tube 7. Its internal construction, as shown in Fig. 7, comprises a turret 20 for supporting a plurality of mirrors M1 of different focal lengths each of which is at such distance from the position of the real image produced by the mirror M that when brought into axial alignment with tube 7 the other conjugate focus of mirror M1 is on a photographic plate or fluorescent screen P at the other end of tube 8. The turret 20 is adjusted externally of the apparatus as by the handle 21, thus allowing the operator by various permutations of the mirrors M and M1 to obtain different desired magnifications. For certain low magnifications the turret 20 is located to bring the optical flat 22 axially of the tube 7 and the object is adjusted so that the focus of mirror M conjugate with the object is on the photographic or fluorescent plate located in the head H3, and thereby the final real image is placed on the plate.

The proper position of the real image produced by mirror M for location in front of any one of the mirrors M1 is ascertained by rotating the turret 20 so that the fluorescent, or focusing, plate 23 is brought axially of tube 7. The opening 25 extending from the focusing plate 23 through the turret permits the image on the plate to be observed through the view telescope 24.

It is to be noted with this construction the positions of the object, of the real image and of the photographic or fluorescent plate are fixed. The mirrors in use at a given time have fixed image-producing positions, and the various magnifications are obtained by selecting the desired combinations of mirrors. Each mirror is called upon to perform the single task of making a real image for but one set of conjugate foci. This fixation of conjugate foci is of advantage as the mirrors can be corrected for the positions at which each of them is used, avoiding errors which would occur if different magnifications were sought by changing the relative distances of the mirrors and object.

To ensure that the distances between the various elements of the image-producing system and their alignment remain constant, at least during the time of use or exposure, the tubes 3, 6, 7 and 8 and their cooperating parts should be of material having a low temperature coefficient of expansion. Alternatively, or in addition, the apparatus may be enclosed in a housing which is maintained at a constant temperature during the period of operation.

Since the tubes 3, 6, 7 and 8 are of fixed length, the maintenance of a vacuum, or a desired atmosphere, is facilitated since there is avoided any need of telescoping or sliding joints to change the lengths of these tubes. The selection of the different mirrors at the primary and secondary heads can be effected without any loss of vacuum or change in the gas pressure or composition in the image-producing system by the features of construction now described.

Referring to Fig. 4, the shaft 27 of the turret 18 and the conical sealing extension 28 thereof are ground to fit the plate 29 of the head which is clamped to the head housing 30, the interposed seal or gasket member 31 preventing leakage at this point. The bearing surfaces are preferably lubricated with an oil or grease having a very low vapor pressure, such as Apiezon oil or grease, or N-dibutyl phthalate, or butyl-benzyl phthlate.

The insertion and withdrawal of the object carrier is accomplished with minimum loss of vacuum or gas, because movement of the carrier to the position affording access to the object moves a solid portion of the carrier to block communication between the tube and the outer atmosphere. Specifically, the cylindrical object carrier 12 is ground to fit the tubular casing 32 which is interposed between the tube 7 and the primary head. These bearing surfaces are also lubricated with a lubricant having a low vapor pressure. To with-

draw the object the slide is moved downwardly, as viewed in Fig. 4, or towards the observer, as viewed in Fig. 2, until the upper edge of the aperture 11, as viewed in Fig. 4, passes beyond the edge 33 of casing 32, thus sealing the end of tube 7. For this position the enclosure now defined by the hole 11 in the object carrier and the inside of casing 32 is in communication, through port 34, with suitable means for introducing air into this space. The slide then may be fully retracted to bring the object space within the opening 11 so that it is external to the apparatus, allowing insertion or replacement of the object O. The slide may be then returned to the position bringing the upper edge of the opening 11 somewhat below the edge 33 of the casing so that the object space is again in communication with the port 34 allowing the object space either to be evacuated or filled with gas at a desired pressure corresponding to composition and pressures within the image-producing system. The slide is then moved to bring the object to proper position axially in tube 7 for making of another photomicrograph or visually observable image.

The construction of the secondary head is generally similar to that of the primary head. Referring to Fig. 7, the shaft portion 35 for the turret 20 and the conical extension 36 is ground to fit the cooperating portions of the plate 37 which closes the secondary head. The joint is preferably lubricated by one of the low pressure lubricants above mentioned. As indicated, the gasket 38 is clamped between plate 37 and the cooperating flange of the head housing 39. The window 40 in plate 37, which permits use of the view telescope 24, as above described, is also suitably sealed in the plate. The several openings 41, sealed by the plugs 42, are to permit insertion of suitable tools for adjusting the several mirrors M1 when initially installed. The different combinations of mirrors in the primary and secondary heads afford desired different degrees of magnification, and the movement of the handles 19 and 21 to effect a desired combination also brings the mirrors to such positions that the real images produced are at substantially correct positions.

The construction for permitting removal and insertion of the photographic or fluorescent plate P in the head H3 without loss of vacuum or gas is in general similar to that used in the primary head for allowing removal and insertion of the object O.

Referring to Figs. 9 and 10 the cylindrical plate carrier 43 is ground to fit the opening 44 extending through the casing 45 which is provided with an opening 46 in alignment with tube 8. When the plate carrier is in the retracted position shown by full line in Fig. 9, the photographic or fluorescent plate P can be removed from or placed upon the plate holder 47 which is preferably carried by a lazy tongs arrangement 48. The carrier 43 may be moved to the extended position shown by dotted line in Fig. 9, thereby bringing the plate P in its holder central with the axis of the tube 8, but with the carrier 43 in a position which is so angularly displaced from the position shown in Fig. 10 that the recess 49 in which the plate holder is disposed is brought into communication with the port 50. The valve 51 is then in position to effect connection to a vacuum pump connected to the pipe 52, or, if desired, the passage 53 may extend to tube 8. After the recess 49 is exhausted or filled with suitable gas, depending upon the condition under which the image-producing system is to be used, the carrier 43 is then rotated to bring the plate holder to the position shown in Fig. 10. To remove the plate, the reverse sequence of operations is performed. First, the holder 43 is rotated to bring the space 49 into communication with port 50. The valve 51 is then operated to effect communication of this space with atmosphere, and then the holder 43 can be withdrawn bringing the solid portion to the right of the holder, as viewed in Fig. 9, to block the end of tube 8. The exposed plate may then be replaced by an unexposed plate. This construction is also useful in oscillographs of the type using a photographic plate to record the path of a cathode-ray beam.

With the plate in position to receive the image, it may be uncovered by moving the shutter actuating knob 54, and is of course recovered before removal of the plate carrier by the same knob. The shutter and its actuating mechanism are not shown as any of various known arrangements may be used. The desired position of the plate axially of tube 8 can be obtained by adjustment of knob 55 which is connected to the lazy tongs, preferably through a suitably calibrated reduction mechanism.

As indicated diagrammatically in Fig. 11, there may be disposed within the head 56 of the apparatus shown in Figs. 2 and 3 several sources of radiation for producing different wavelengths. The handle 57 external to the head 56 can be adjusted to bring a selected one of the sources in front of the condensing reflector C. One of the sources may be an incandescent lamp, an electric arc between metallic electrodes, a disruptive spark discharge between metallic electrodes, as in Fig. 12, or other source of visible light, and the other sources (Fig. 1) may be for producing radiation having a wavelength substantially shorter than visible light.

Assuming that a photo-micrograph of a particular object is to be made, the desired source of radiation is brought before the condensing mirror, as above described, and the selected narrow band of wavelengths is brought to focus at the position of the image by adjustment of the monochromator. The adjustments may be made with the object in position when visible light is employed, or when the object will visibly fluoresce at the wavelengths used. Adjustments may also be made by use of a calibrated fluorescent screen in the position of the object which is observed during adjustment of the monochromator to bring the desired narrow band of wavelengths to the position which the object will occupy. The monochromator may be calibrated, and one or more of the elements adjustable, the scales cooperating with the adjustable elements being calibrated so that when the parts are in predetermined positions the desired narrow band of wavelengths will be focused upon the object.

With the source of radiation deenergized the photographic or fluorescent plate can now be inserted and uncovered, as above described. With both the object and plate in position the source of radiation is then energized for a predetermined length of time; the plate is then covered and removed from the apparatus without loss of vacuum. It is desirable that a series of photomicrographs be taken with the plates at slightly different positions axially of tube 8 because the focus, particularly for radiation of short wavelengths, is sharper than can be determined visually. It may also be of advantage to take a series of photomicrographs at somewhat different wavelengths

to obtain enhancement of contrast between diverse constituents of a heterogenous surface, as in metallography. It is to be understood, of course, that my invention is not limited to metallography, but comprehends bacteriology, histology, botany, biology, crystallography, and, in general, the determination of the fine microscopic structure of all materials.

In many instances it is desirable to hold the temperature of the object under observation at a magnitude higher or lower than room temperature. This control can be effected by means included in or associated with the object carrier. For example, the object carrier may support adjacent the object a tube provided for circulation of a heating fluid, or a refrigerating fluid such as liquid air.

The physical dimensions of the apparatus will be determined largely by the magnifications desired and the construction of the optical system. For example, the apparatus shown in Figs. 2 or 3 may be of the order of 20 to 30 feet long. In some cases it may be desirable to reduce the overall length of the apparatus by folding the optical paths, as indicated in Fig. 13, by use of plane reflecting mirrors between some of the optical elements hitherto described. For example, as shown in Fig. 13, the plane reflecting mirror P*a* may be interposed between the source of radiation and the diffraction grating D; the plane reflecting mirror P1 may intervene between the diffraction grating and the secondary condensing mirror C1; and the plane reflecting mirrors P2, P3, P4 may be disposed at other points in the optical path.

The entire system, as in the modification above described, is preferably maintained in a vacuum or suitable gaseous atmosphere. For microscopy at the wavelengths below 2,000 Angstroms the surfaces of the plane mirrors, as well as others of the system, should be of material having insubstantial absorption coefficient and appreciable coefficient of reflection.

In Fig. 14 is diagrammatically shown the optical parts of a microscope of the refracting type modified to obtain some of the advantages of my invention. Briefly, the radiations from the source S are focused by the condensing lenses L upon the slit 57. The collimator lens L1 collects the light from this slit and sends parallel rays to the prism 58. The lens L2 on the other side of the prism focuses the desired narrow band of the spectrum produced by the prism upon the slit 59. The lens L3 parallelizes the monochromatic light issuing from the slit upon the transparent plate 60 which reflects light through the objective lenses L4, L5 upon the object O. The light from the object passes through L5, L4, 60, and the last lens L6 of the objective to produce a real image of the object in front of the projection eye-pieces consisting of lenses L7 which produce a real image on the photographic, fluorescent or visual focusing plate P. The entire optical system, including the source, monochromator, microscope objectives, projection eye-pieces, and the optical path through the plate to the photographic plate, is enclosed by housing I, as in the system of Fig. 1, to permit maintenance of a vacuum or a suitable gaseous atmosphere, as above described, to avoid such adverse effects of air, as absorption, scintillation, etc.

A suitable and preferred construction for the objective mirror M of the modifications of Figs. 1 to 13 is shown in cross-section in Fig. 15. The curved reflecting surface or vertex mirror V has a circular periphery and in the particular objective mirror shown extends about 5° on each side of the axis A. The reflecting surface V, concave toward F, is a portion of an ellipsoid whose first conjugate focus is at F, three inches from the vertex of mirror M, and whose second conjugate focus is thirty feet from the vertex. The reflecting surfaces *e*—*e*9 are annular and are portions of different ellipsoids which have the same common conjugate foci; F, the object focus, three inches from the vertex of mirror M and F1, the image focus, thirty feet from the vertex of mirror M. For the conjugate foci F and F1, no spherical aberration is produced by the ellipsoidal reflecting surfaces V, *e*—*e*9, and under the conditions of use spherical aberration is negligible in the produced images.

For sharp images free of spherical aberration, the object and image fields should not be greater than about ½°. Since the chord of ½° at a radius of three inches is 0.0261 inch, whereas the size of the object under investigation is usually of the order of 0.001 inch to 0.002 inch, the size of the object field is well within the limit of tolerance. Furthermore, the image field of mirror M, for an object field of .001 inch diameter, has a diameter of 0.120 which, located at F1, thirty feet from the vertex of mirror M, has a diameter which is a small fraction of the chord of ½° and, therefore, the size of the image field is also well within the limit of tolerance. Moreover, the image field possesses negligible spherical distortion not only longitudinally at F1 but also laterally over the angular extent of the image field.

As a condition precedent for negligible coma, each annular zone of the echelon objective mirror M should produce magnifications from the different extremes of its own surface that differ from each other by a negligible amount. In the mirror specifically shown in Fig. 15, the first focal distance for each annulus is 3''±0.0625 and the maximum difference in the magnifications is

$$2.075\%\left(\frac{.0625}{3.0000}\right)$$

which is negligibly small.

The variation in magnification due to different distances from the axis of various parts of the object is caused by a variation in radial object distance from F of ±.002''. This variation superimposed upon the focal distance 3''±0.0625'' produces a total maximum variation of ±0.0645'' giving ±2.15% as the total percentage change of the magnifications. Coma is, therefore, negligible.

Coma may still further be reduced by making the width of the annular zones of the echelon mirror angularly smaller with respect to F. Each annular element may be made to correspond to "F" numbers of any suitable relative aperture as follows:

F/5=1/5=chord of 11°29'—angular width of annulus

F/10=1/10=chord of 5°44'—angular width of annulus

F/15=1/15=chord of 3°47'—angular width of annulus

F/20=1/20=chord of 2°52'—angular width of annulus

In the mirror of Fig. 15 the vertex mirror and two of the reflecting annuli are each 10° in angular width, corresponding to F/5.737+, and each of the remaining reflecting annuli is 5° in angular width and corresponds to F/11.46 for each annulus.

As previously stated, the reflecting surfaces of the objective mirror are, for wavelengths shorter than the wavelengths of visible light, of a material, which for the band of radiation used, has an appreciable coefficient of reflection and low coefficient of absorption. The paraxial surfaces PA of the echelon mirror may, if desired, be of non-reflecting material to avoid diffusion of the radiation from the object.

The mirror M1 is ellipsoidal with its conjugate foci f=12 inches and f1=30 feet (at the plate P). Because the mirror is ellipsoidal, it is free from spherical aberration at its foci. The object for mirror M1 is the real image produced by mirror M and which, as above stated, is about 0.0120'' in diameter. At focus f, the real image subtends an arc of about ½° towards mirror M1, and at f1, the real image produced by mirror M1 on the plate is about 3.6'' in diameter, which subtends an arc of about ½° towards mirror M1. Therefore, the longitudinal and lateral spherical aberration with respect to mirror M1 is negligible.

To obtain negligible spherical aberration, the relative apertures of the mirror elements should not be too great. This condition is satisfied by mirror M which, as above stated, has a relative aperture for three elements near the axis corresponding to F/5.737+, and for the remaining elements a relative aperture corresponding to F/11.46. The relative aperture of mirror M1 also satisfies this condition; since f1=12'', the effective aperture is 0.3125'' and the total aperture is 0.75''. Therefore,

$$\frac{.3125}{12.000}=F/38.5 \text{ and } \frac{0.75}{12.00}=F/16.$$

It is appreciated that even when the angular aperture is very small, the focal surface is, nevertheless, a sphere of radius equal to twice the focal length. However, the second focus of each of mirrors M and M1, at which the produced images are located, is about thirty feet from the mirror, giving a focal surface with a radius of about sixty feet. Since the produced image, in the case of mirror M, is only about 0.120'' in diameter and, in the case of mirror M1, is only about 3.6'' in diameter, it is, in both instances, sensibly flat.

Furthermore, since the image and object fields employed extend only relatively small angular distances from the mirror axis in each case, astigmatism, which is produced by sagittal, or non-meridional rays, is negligible.

When the echelon objective mirror makes real images from objects illuminated by "white" light, destructive interference is produced at the real image of certain wavelengths, while, with other wavelengths which form the luminous image, there is cumulative interference. The effect of the destructive interference is to decrease the brightness of the image.

If the microscope is to be used with monochromatic radiation, in addition to the foregoing conditions, the mirror M must be constructed to meet the requirement that the various rays of radiation from F which are reflected by all the elemental areas of all the annuli, and of the vertex mirror shall arrive at F1 in phase with each other; otherwise, the destructive interference at F1 may destroy the image.

Since the vertex mirror and each of the annuli are parts of ellipsoids, all of the rays reflected by each of the individual elements of any one ellipsoid arrive at F1 in phase with each other, so that the requirement is met, considering any two adjacent annuli, when the rays reflected from the anterior edge of the posterior annulus are in phase with the rays reflected from the posterior edge of the anterior annulus.

This condition may be fulfilled whether or not the radial distance, or the paraxial distance between the adjacent edges of adjoining annuli is equal to a whole or integral number of wavelengths. These radial and paraxial distances may each be some different integral number plus or minus different fractions of a wavelength provided that the focal distances, F, for the two adjacent edges are in proper relation to these fractional numbers to ensure that the radiation from the edges are in phase at the posterior edge of the anterior annulus.

This result may be obtained by polishing, or by removal of of material from each annulus (or by addition of material) after its plate has been cemented to the vertex mirror, or to the assembly of previously added annuli. The result of the polishing, or other work upon the surface of each annulus may be observed, the progress of the work controlled, and the correct condition finally verified by observing the interference fringes in the monochromatic light from F that may be reflected by restricted zones at the two adjacent edges of adjoining annuli.

For convenience, visible radiation is used in testing and adjusting the paraxial distances between the adjacent edges of the reflecting annuli; for example, 6003.039 Å., one of the spectrum lines of iron, or 6438.47 Å., one of the spectrum lines of cadmium. Assuming, for example, that the adjustment has been made at 6003.039 Å., it is also correct for wavelengths 3001.519 Å., 2001.013 Å., 1500.759 Å., 1200.608 Å., 1000.596 Å., 857.577 Å., 750.380 Å., 667.004 Å., etc.; i. e., the wavelengths whose relation to the chosen wavelength can be expressed by whole numbers. At any of these wavelengths, the cumulative interference at F1 will there produce a real image. Similarly, if the adjustment is made at 6438.47 Å., images are produced at wavelengths of 3219.235 Å., 2146.156 Å., 1609.617 Å., 1287.694 Å., 1073.078 Å., 919.78 Å., etc.

The annular reflecting surfaces of the echelon mirror M are employed to increase the effective numerical aperture of the mirror as an objective.

N. A. (numerical aperture) $=n \sin u$
where $n=1$ (approx) for a vacuum
$\sin u=\sin$ ½ angular aperture

The objective mirror specifically shown in Fig. 15 has an effective numerical aperture of about 0.8; other suitable numerical apertures are

Table A

NA	Total aperture
0.5	60°
0.6	73° 44′
0.7	88° 50′
0.8	106° 14′
0.9	128° 18′
1	180°

In general, as appears from Fig. 16, the larger the numerical aperture, the greater the resolving power for a given wavelength. However, the in-

crease in numerical aperture is attended with increased difficulty in satisfying the other conditions above discussed.

The limit of resolution with the best refractor type of microscope at present known is shown by the cross x, Fig. 16. At a wavelength of 2750 Å., the smallest object that can be resolved has a diameter of 0.11 micron. Shorter wavelengths cannot be used because of the opacity or absorption of the quartz-fluorite lens system at the shorter wavelengths. The limit of resolution with another high-grade refractor type microscope is shown by cross Y, Fig. 16. At a wavelength of 3650 Å., the shortest wavelength used, the smallest object that can be resolved has a diameter of 0.140 micron. Shorter wavelengths cannot be used because of the opacity or absorption of the glass lens system at shorter wavelengths.

With my reflector type of microscope, the limit of resolution is greatly extended, as shown by the curves of Fig. 16, which show the resolutions obtainable with the mirrors of table A, for a range of wavelengths from about 2000 Angstroms to about 200 Angstroms.

As above stated, high magnifying power is useless without correspondingly high resolving power. With any microscope having an optical system capable of working at a numerical aperture (N. A.) of 0.5, the limit set by diffraction to obtain photographic resolution is the same as the wavelength; that is, the diameter of the smallest object resolved equals the wavelength of the radiation used. In the case of larger numerical apertures, the diameter of the smallest object which may be resolved is variously less than the wavelength, as is seen from inspection of Fig. 16. It is, therefore, of interest to ascertain whether the magnification necessary to make the smallest resolvable object visible to the human eye is within reason. That it is so, is shown by the following table.

Limit of photographic resolution with a numerical aperture of 0.5	Diameters of magnification necessary to make photographic resolution just visible to—		
	Acute eye	Average eye	Poor eye
At 2000 Å=0.2 micron	381	571.5	762
At 1000 Å=0.1 micron	763	1143	1526
At 500 Å=0.05 micron	1,524	2286	3048
At 300 Å=0.03 micron	2,540	3810	5080
At 200 Å=0.02 micron	3,810	5715	7620

The mirror system which I have specifically described affords a magnification of 3600 diameters which, as appears from the table above, is suitably high to render visible the smallest object that can be resolved at wavelengths approaching 200 Angstroms.

For certain classes of work, for example, in metallurgy, the diameters of the specimen containing the object may be large, for example, of the order of 0.5 inch. In such case, the optical diameter of the object is limited to about 0.001 or 0.002 by a suitable stop coated with material which is substantially non-reflecting at the wavelength used. Preferably, in such cases, wide angle illumination of the object is used. A suitable arrangement is shown diagrammatically in Fig. 17. The radiation from the monochromator is reflected by the conical mirror C1*a* onto the reflecting surface of the ring mirror C1*b* which, in turn, transmits the radiation to the object O. The stop S*h* prevents the radiation from impinging upon the remainder of the specimen S. The object O is at one conjugate focus of the objective mirror M. The reflecting surfaces of conical mirror C1*a* and ring mirror C1*b* are of material which, for the wavelengths used, has low absorptive power and suitably high reflective power.

The remainder of the image-producing system may be the same as above described.

Certain features of my invention which are herein disclosed but not claimed, for example the rotatable heads H1, H2, and the construction of the objective mirror M (Fig. 15), are claimed in my copending application Serial #229,491, filed September 12, 1938.

What I claim is:

1. In the art of microscopy, the method of procuring high magnification with materially extended limits of resolution which comprises irradiating the object with a selected narrow band of substantially monochromatic radiation within the range of from about 2,000 Angstroms to about 200 Angstroms, and producing solely by reflection a magnified real image of the object.

2. In the art of microscopy, the method of procuring high magnification with resolution better than 0.11 micron which comprises irradiating the object with a selected narrow band of substantially monochromatic radiation, within the range of from about 2,000 Angstroms to about 200 Angstroms, and producing a magnified real image of the object solely by reflection from one or more surfaces having suitably high coefficient of reflection and suitably low coefficient of absorption at the wavelengths of said substantially monochromatic radiation.

3. In the art of microscopy, the method of procuring high magnification with materially extended limits of resolution which comprises irradiating the object with a selected narrow band of substantially monochromatic radiation within the range of from about 2,000 Angstroms to about 200 Angstroms, producing a magnified real image of the object solely by multiple reflections from surfaces having suitably high coefficients of reflection and suitably low coefficients of absorption at said wavelengths, and providing for the radiation to said object, from the object to said surfaces, and from said surfaces a path devoid of media having substantial coefficients of absorption and refraction at the wavelengths of said substantially monochromatic radiation.

4. A microscope for producing a real image of an object comprising means for producing radiation within the range of from about 2,000 Angstroms to 200 Angstroms, means for selecting therefrom a narrow band of wavelengths of substantially monochromatic radiation and directing it upon said object, and means for producing a magnified real image of the object solely by reflection comprising a reflector having a reflecting surface of material having a suitably high coefficient of reflection and suitably low coefficient of absorption at the wavelengths of said monochromatic radiation.

5. A microscope affording magnifications in excess of 1,000 diameters with resolutions substantially better than 0.11 micron comprising means for producing radiation having wavelengths within the range of from about 2,000 Angstroms to about 200 Angstroms, means for selecting a narrow band of wavelengths of said radiation for irradiation of the object, and means for producing a real image of the object solely by

reflection comprising a reflector whose reflecting surface is of material having suitably high coefficient of reflection and suitably low coefficient of absorption at said selected wavelengths.

6. A microscope affording magnifications in excess of 1,000 diameters with resolutions substantially better than 0.11 micron comprising means for producing radiation having wavelengths within the range of from about 2,000 Angstroms to about 200 Angstroms, means for selecting a narrow band of wavelengths of said radiation for irradiation of the object, means for producing a real image of the object solely by reflection comprising a reflector whose reflecting surface is of material having suitably high coefficient of reflection and suitably low coefficient of absorption at said selected wavelengths, and means for maintaining the optical path substantially free of gas or gases having substantial refractive or absorptive power at said selected wavelengths.

7. A microscope affording magnifications in excess of 1,000 diameters with resolutions substantially better than 0.11 micron comprising means for producing radiation having wavelengths within the range of from about 2,000 Angstroms to about 200 Angstroms, means for selecting therefrom a narrow band of wavelengths of substantially monochromatic radiation for irradiation of the object, and means for procuring a magnified image solely by reflection comprising a reflector for producing a magnified real image of said object, and a second reflector for producing a magnified real image of said first real image, said reflectors having reflecting surfaces of material whose reflection coefficient is suitably high at said selected wavelengths.

8. A microscope affording magnifications in excess of 1,000 diameters with resolutions substantially better than 0.11 micron comprising means for producing radiation having wavelengths within the range of from about 3,000 Angstroms to about 200 Angstroms, means for selecting therefrom a narrow band of substantially monochromatic radiation for irradiation of the object, means for producing a real image of the object solely by reflection comprising a reflector whose reflecting surface is of material having suitably high coefficient of reflection and suitably low coefficient of absorption at the wavelengths of said monochromatic radiation, means for maintaining the optical path substantially free of gas or gases having substantial refractive or absorptive power at the wavelengths of said selected radiation, and means permitting insertion and withdrawal of the object into and from the optical system without substantial effect upon the gas composition or gas pressure in said system.

9. The method of obtaining resolution of objects smaller than 0.11 micron which comprises illuminating the object by a narrow band of substantially monochromatic radiation within the range of from about 2000 Angstroms to 200 Angstroms and producing a magnified real image of the object solely by reflection in an optical system including a mirror having a numerical aperture in excess of 0.5.

10. A system comprising a housing, a source of radiation in said housing and for which radiation air has a low transmission power, means for evacuating said housing, a photographic plate for receiving an image produced by radiation from said source, and means for introducing said plate into said housing and for removing it therefrom without substantial loss of vacuum.

11. In the art of microscopy, the method of procuring magnifications in excess of 1000 diameters with resolutions substantially better than 0.11 micron which comprises, in the absence of visible light, irradiating the object by radiation of a selected narrow band of wave lengths within the range of from about 2000 Angstroms to about 200 Angstroms, and producing upon a photographic plate solely by reflection a magnified real image of the object so irradiated.

12. In the art of microscopy, the method of procuring magnifications in excess of 1000 diameters with resolutions substantially better than 0.11 micron which comprises producing radiation having wave lengths within the range of from about 2000 Angstroms to about 200 Angstroms, selecting a narrow band of said radiation, irradiating the object solely by said selected band, and solely by reflection, producing upon a photographic plate a magnified real image of the object at the wavelengths of said selected band.

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