Telescopic vision of an illuminated surface

Fred Vorhies
State University of Iowa

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Telescopic Vision of an Illuminated Surface

by

Fred Vorhies

A Thesis
Submitted to the Faculty of the Graduate College of the State University of Iowa
in partial fulfillment of the requirements for the degree of Master of Science
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Acknowledgment

I wish to take this opportunity to express my appreciation to Dr. G. W. Stewart and the members of the Staff of the Physics Department for the valuable assistance rendered on many occasions. I am especially indebted to Dr. L. P. Sieg, under whose supervision this work carried on.
Telescopic Vision of an Illuminated Surface

An interesting aspect of the subject of telescopic vision has been discussed in a series of articles written by Dr. G. J. Stoney\(^1\). In these articles Dr. Stoney discusses the subject from a theoretical standpoint, but makes some suggestions as to how apparatus could be set up and used in verifying his theories and assumptions. It is the purpose of this thesis to show how this apparatus works in practice and to give the results obtained by its use.

From the standpoint of Stoney's theory, images may be divided into four classes. The first class consists of the natural images in nature, while the last three classes which will be defined later, may be called concentration images, optimum images, and partial images. The advantage in introducing this conception of the concentration image arises from the circumstance that the method of analysis which has proved to be the most efficient in tracing out how ordinary images are actually formed by nature, is the analysis of the light within any space.

\(^1\) Philosophical Magazine vol. 16, 1908.
occupied by a uniform medium, into its constituent vibrations,— an analysis which will be shown to be possible and legitimate. I shall show later how the optimum and partial images are related to the concentration image. We shall learn how a natural image is formed by admission into the telescope, of vibrations that start from different points of the object, and shall see that each of these vibrations is capable of giving some kind of an image. The images in nature then, are formed by the interference of an infinite number of these constituent vibrations. This particular point has been investigated by Mr. A. B. Porter. He found that when a broad light source is used, the geometrical image is really a superposition of coincident interference patterns.

As a basis for his theories Dr. Stoney makes the following assumptions which I have used and proved to be correct. —

(1) In studying an illuminated surface or object, the planet, Mars, for example,— the real object No. 1 can be removed and a substitute, No. 2., can be used in its stead. No. 2. is to be a transparent object with the details of No. 1. delineated upon it.

Wood's Physical Optics p.222.
(2) When No.2. is illuminated from behind with diffused light, the same sort of image will be formed in the telescope as when No.1. is illuminated from in front with diffused light.

(3) A lens can be placed immediately in front of No.2. and by use of a point source of light, the previously mentioned concentration image can be obtained.

(4) The introduction of the lens does not alter the optical conditions.

(5) One method of analysis permits us to consider that the natural images in nature are made up of an infinite number of partial images.

EXPERIMENTAL METHODS

Fig.1. is a photograph of the experimental apparatus in its final form, while Fig.2. is a diagram of the same. M at the right of the drawing is a monochromatic illuminator which gets its light from an arc lamp. Light from M is focused by the lens L, on the pin-hole S which acts as the light source which illuminates the object O. Behind and touching O is the achromatic lens L2 which focuses the light from S upon the aperture A which is made separate from the camera C. This
focused image of the point source with its accompanying diffraction pattern caused by the object 0, is the concentration image which has been mentioned above. The camera is used instead of the telescope because, for my purpose, they are optically the same, and there is the additional advantage in the use of the camera in that a record can be made of all that can be seen in the telescope. The aperture A is capable of rotation and also of lateral motion by means of a micrometer screw, so that it can be moved to one side or up and down as desired.

The object 0 was made by drilling a hole 4.5 cm. in diameter in a plate of copper. Across this was placed wire varying from .08 mm. to .62 mm., in diameter. This wire was placed in such a manner as to form details which could be studied in a photograph. The distance 0A is determined by the focal length of the lens $L_2$. In this case 0A was 120 cm.

If we now suppose that the object 0 is to represent the planet Mars, we can obtain by means of Airy's formula, which gives the diameter of the diffraction rings formed at A by a circular

Wood's Physical Optics p. 237.
aperture of given size at 0, when illuminated by a point source at S, the size of the aperture that must be used at A. Further as I shall now show, the distance from 0 to A, the size of the object at 0, and the size of the aperture at A can be so chosen as to give on the photographic plate, an image of the same optical excellence as that obtained by a given sized telescope at a given distance from a heavenly body which is represented by the object 0. In other words we can duplicate the astronomical conditions in the laboratory.

In order to use Airy's formula which refers to diffraction rings formed with a point source of light and apply it to an astronomical object seen by reflected diffused light, I was compelled to make use of the five assumptions made in the first part of this thesis. Airy's formula for the fifth maximum diffraction ring is \[ \sin \theta = \frac{2.361 \lambda}{r} \] where \( \theta \) is the angle of diffraction, \( \lambda \) the wavelength of the light used and \( r \) the radius of the lens casting an image of the point. In my work I used blue-green light so that \( \lambda = 0.000055 \) cm. and \( r = 2100 \) mi., the radius of Mars.

Then \[ \sin \theta = \frac{2.361 \times 0.000055}{2100} \]

\[ \sin \theta = \frac{x}{35050000} \]

where 35050000 miles is the distance Mars is away from the observer. From
these two expressions the value of X is found to be 2.138 cm. \( 2X = 4.276 \) the diameter of the fifth maximum ring in the diffraction pattern from Mars. If a 24 in. telescope is used, the value of X is found to be \( \frac{24 \times 2.54}{4.276} = 14.27 \).

This means that the diameter of the telescope is 14.27 times greater than the diameter of the fifth maximum diffraction ring from Mars. This value of X was then used in determining the diameter of A.

If the diameter of O is 4.5 cm. and OA equals 120 cm. \( \sin \theta = 2.361 \times \frac{0.000055}{2.25} \)

\[ \sin \theta = X \]
\[ \frac{120}{2.361} \]

\[ X = 0.006928 \text{ cm.} \]

\[ 2X = 0.013856 \text{ cm. the diameter of the fifth maximum diffraction ring from O.} \]

\[ 0.013856 \times 14.25 = 0.1976 \text{ cm. or about 2 mm., which I used as the diameter of the aperture which represents a 24 in. telescope in my experimental apparatus. I then used this relationship in determining the sizes of the other apertures to be used.} \]
The following table shows the sizes of the apertures used and the diameters of the telescopes which these apertures represented in my experimental apparatus.

<table>
<thead>
<tr>
<th>Aperture</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 mm.</td>
<td>48 in.</td>
</tr>
<tr>
<td>3 mm.</td>
<td>36 in.</td>
</tr>
<tr>
<td>2 mm.</td>
<td>24 in.</td>
</tr>
<tr>
<td>1.25 mm.</td>
<td>15 in.</td>
</tr>
<tr>
<td>1 mm.</td>
<td>12 in.</td>
</tr>
<tr>
<td>.6 mm.</td>
<td>7.2 in.</td>
</tr>
<tr>
<td>.4 mm.</td>
<td>4.8 in.</td>
</tr>
</tbody>
</table>

Returning now to the object 0, if 4.5 cm. equals 4200 miles, the wires on the object which were .62 mm., .36 mm., and .08 mm. respectively, would equal 56 mi., 35.5 mi., and 7.5 mi. on the planet Mars. These calculations were made because a great deal of discussion has taken place between astronomers concerning certain details upon the surface of the planet. So-called canals varying in width from 60 miles to 20 miles have been viewed by different observers. In order to investigate this point, I made
my smallest details represent canals 7.5 miles in width.

Going now from the construction of the apparatus, let us notice how it works. If an incandescent lamp behind a ground glass screen were placed at S, instead of the point source of light, there would be an infinite number of point sources. Each of these points would be capable of illuminating O and would thus give a diffraction pattern at A, or as we have said, a concentration image. The advantage then, in using the point source S is simply to cut down the complexity of the diffraction pattern at A and in turn to simplify the image produced in the camera C. Then again, if this diffused white light were used, there would be a large number of different wavelengths in operation. This is simplified by using the illuminator M. By the use of these two devices the image is greatly simplified and a study of it is much more easily made.

Upon examining the diffraction pattern at A it is found that it consists of a bright central spot surrounded by not only bright and dark rings
caused by the circular form of the object that represents Mars, but also in the field there are colored patches which are spectra caused by the wires used to represent superficial details on the planet. Now any part of this pattern, when admitted into the camera or telescope is capable of giving some kind of an image of the object 0. This fact permits one more step in the analysis and gives a means of obtaining partial images. Under ordinary conditions most of the light is contained in the central bright spot and the first five or six rings of maximum intensity. This being true, if this part of the pattern is admitted into the telescope, a good image should be obtained. If this part of the pattern does not enter the telescope, the image will not be so good; the quality depending on the particular part of the pattern admitted.

It is an interesting fact that if only the central maximum is admitted by the telescope, we get no image of the object although a large amount of light will be admitted.
The above discussion now permits the insertion of a definition of partial and optimum images, which terms were mentioned in the first part of this thesis. The image obtained when the diffraction pattern from a point source is admitted into the telescope or camera is called a partial image. If the central bright spot falls symmetrically within the aperture of the camera objective an optimum partial image is formed. This seems to be the best image that it is possible to obtain of a given object with a given aperture, and is theoretically better than any image of a similar object taken under similar conditions with diffused light. In other words with this laboratory apparatus we not only can imitate astronomical conditions but can obtain even better images than are possible under natural conditions, because we can control the number of partial images that go to make up the final image. If the aperture A is moved to one side the central bright spot will not be admitted into
into the camera and the image obtained will come from some part of the outer diffraction pattern. This image is one of the inferior images, which along with all of the other partial images, good and inferior, go to make up the natural image of the object. From this it is easily seen that the images in nature are simply the result of an infinite number of partial images, and that instead of having one diffraction pattern falling in the camera, there is an infinite number of theses patterns. So that it is quite obvious that a natural image cannot be as good as an optimum image, because the natural image can be considered to be made up of the optimum and a number of other inferior images. As my results will show, a natural image may approach the optimum in excellence but it cannot equal it.

The above analysis is really an application of the theories of image formation proposed by Ernst Abbe a number of years ago, for the microscope, to the theory of telescopic vision.

Wood's Physical Optics p. 223.
EXPERIMENTAL RESULTS

The experimental results obtained in this work are found in the accompanying photographs. Fig. 3 contains four series of partial images taken with different sized apertures. Series 1 was taken with a 2 mm. aperture and represents what would be seen with a 24 in. telescope. No. 1 was taken with the central bright spot of the diffraction pattern focused in the center of the aperture. This, what I have chosen to call an optimum image and seems to be better than can be obtained in nature under the same conditions. Nos. 2-8 were taken by moving the camera aperture to one side by means of the micrometer screw. The aperture was moved one half millimeter each time. This means that No. 8 was produced by diffraction rings three and one half millimeters out from the central bright spot. Now it can be seen that in nature there would be an infinite number of these partial images, and that the images we observe about us are produced by an infinite number of these partials, interfering as they are brought
to a focus by a lens or by the eye. The in-
creasing infriority of the partial images as we
go from 1 to 8 is to be noted. Now again let me
repeat that it is the addition of such partial
images and many others besides, that go to make
up the natural diffused light image.

The phenomenon of the change in appearance
of the lines from black to white can be account-
ed for by the laws of diffraction. It will be
noticed in the last part of each series that the
horizontal wires almost disappear. This is caused
by the movement of the aperture A to one side.
After it has been moved two or three millimeters
it is in such a position that the parts of the
diffraction rings that enter the camera are al-
most perpendicular lines. This part of the pattern
is not capable of giving images of the horizontal
wires. Investigations along this line have been
made with ordinary wire screens\(^5\).

No.9. is what I have chosen to call the
composite image. It is to be taken as an approx-
imate imitation of a natural image. It is obtained

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A.B. Porter, Philosophical Magazine vol. 11, 1906.
by superposing the exposures 1-8 on the plate, giving equal times of exposure to all eight.

From the discussion above the conclusion would be drawn that this image, No. 9, should not be as good as No. 1. In series 1, very little difference can be seen between 1 and 9. This is because the quality of the good images in the series outweighs the parts contributed by the poorer images. This point is made more clear by the following series. Series 2, 3, and 4 were taken exactly as No. 1. with exactly the same lateral movement of the aperture A, and show the effects of smaller apertures. Series 2 was taken with a 1.25 mm. aperture representing a 15 in. telescope, series 3 with a 1 mm. aperture representing a 12 in. telescope, and series 4 with a .6 mm. aperture representing a 7.2 in. telescope.

It will be noticed that as the aperture decreases in diameter, the number of good images decreases and that No. 9, the composite image, gradually gets poorer than the optimum No. 1. In series 4, the optimum itself is not distinct.
This is on account of the fact that the aperture was so small that the main part of the diffraction pattern was not all admitted. The subject of partial images will be discussed again in connection with Fig. 6.

Series 1. of Fig. 4. shows eight optimum images represented by Nos. 1-8 inclusive, obtained with apertures of the following sizes.

<table>
<thead>
<tr>
<th>No.</th>
<th>Aperture</th>
<th>Telescope</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4 mm.</td>
<td>48 in.</td>
</tr>
<tr>
<td>2</td>
<td>3 mm.</td>
<td>36 in.</td>
</tr>
<tr>
<td>3</td>
<td>2 mm.</td>
<td>24 in.</td>
</tr>
<tr>
<td>4</td>
<td>1.25 mm.</td>
<td>15 in.</td>
</tr>
<tr>
<td>5</td>
<td>1 mm.</td>
<td>12 in.</td>
</tr>
<tr>
<td>6</td>
<td>0.6 mm.</td>
<td>7.2 in.</td>
</tr>
<tr>
<td>7</td>
<td>0.4 mm.</td>
<td>4.8 in.</td>
</tr>
<tr>
<td>8</td>
<td>0.3 mm.</td>
<td>3.6 in.</td>
</tr>
</tbody>
</table>

Series 2 is taken with the same apertures and under the same conditions except that the object 0 was illuminated with diffused light instead of monochromatic light. This was done by removing the point source S (Fig. 2.) and placing...
in its stead an incandescent light in front of which was a ground glass. This series represents, then, the natural telescope image.

Series 3., Fig. 4., was taken with the same apertures as were used in series 1 and 2, but with reflected light. To accomplish this I placed a white cardboard just back of object 0 and directly against the wires. I then placed four incandescent lights in front and a little to one side of the object. The lens $L_2$ was removed while this series was being taken so that the illumination on the object would be more intense. Nos. 7 and 8 are missing in series 3 because the illumination could not be made intense enough to affect a photographic plate.

The points to be noticed in comparing these three series are as follows.-(1) With the exception of the very small apertures the optimum images are better than the diffused light images. (2) There is very little difference between series 2 and series 3. The lines in series 3 are possibly a little broader, due to the effect
of shadows. This point will be discussed again in connection with Fig. 6.

Realizing that I was dealing with ideal atmospheric conditions I arranged for disturbing the atmosphere while an exposure was being made. To accomplish this, two bunsen burners were placed between the object 0 and the camera C. I do not claim that this gave real atmospheric conditions, but it is quite evident that there would be some similarity between movements of the air in the laboratory and movements of the atmosphere when a telescope is being used in actual practice. Series 4 and 5 show the results obtained. Series 4 is made up of optimum images taken with the apertures used above, while series 5 was taken under the same conditions as 4, except that the burners were lighted and the air was in motion. It is quite evident that motions or disturbances in the atmosphere affect the quality of the image. The final conclusions from these results will be left for the latter part of this paper.
Fig. 5. shows some results obtained in the early part of my research. These photographs were taken of a smaller object than I later used and were obtained by use of a short focus lens. These five series are introduced simply as additional proof of the points made in the last few paragraphs. Series 1 was taken with a 4 mm. aperture representing, in this case, a 24 in. telescope, while series 2 was taken with a 2 mm. aperture representing a 12 in. telescope. No. 10 in each series is the composite image. In series 2 it is quite evident that No. 10 is not as good as the optimum No. 1.

Series 3, 4, and 5 are optimum, transmitted, and reflected images respectively. Nos. 1-5 were taken with apertures representing telescopes ranging respectively through the values 24 in., 12 in., 6 in., 3.6 in., and 2.5 in. As in the previous photographs shown, the optima are better than the diffused light images, while there is very little difference between those taken with the transmitted light and those taken with the reflected light. The broadening of the lines
in series 5 is due to shadow effects. This slight error could be eliminated if the reflected light could be made sufficiently intense.

Realizing that the results obtained by use of the complex object might be questioned, I constructed a more simple object and photographed it under the same conditions as the first. The second object used was a simple wire grating made by winding wire around two screws which were fastened in a frame. The screws were made with fifty threads to the inch. Wire of two sizes (.15 mm. and .37 mm.) was wound upon these screws and soldered. The wire on one side was then cut away and that which was left was tightened by turning two nuts in the frame. This grating was then placed in the position of the original object. The advantage in using the grating with vertical wires came from the fact that its diffraction pattern consisted of a row of horizontal spectra, rather than a confused and promiscuous scattered spectra as was the condition in the case of the first object. As the camera aperture
is moved to one side, nearly all of the diffraction pattern is admitted (a part at a time) into the camera. The composite photograph would be a truer representation in this instance, for more of the pattern is used than in the series already discussed.

Fig. 6. contains four series, showing the different effects obtained with apertures of varying diameters. Series 1 was taken with a 4 mm. aperture representing a 48 in. telescope, series 2, with a 2 mm. aperture representing a 24 in. telescope, series 3. with a 1 mm. aperture representing a 12 in. telescope, and series 4. with a .6 mm. aperture representing a 7.2 in. telescope. It will be noticed in series 1. that as the aperture was moved sidewise across the field, one half millimeter at a step, that six good images were obtained, while series 2. contains four, series 3. two and series 4. only one. It would be expected then, that the composite image would be much better in series 1. than in the others, and this is what is observed when an examination is made of No. 18. in each series.
In series 1. No. 18. is practically as distinct as the optimum No. 1. In studying the series this is what should be expected, for the large aperture admits so much of the diffraction pattern that the good partial images overcome the defects introduced by the inferior partial images. In series 4., even the optimum No. 1. is indistinct. This would indicate that the aperture did not admit enough of the diffraction pattern to give an approximately good image.

Fig. 7. shows the same effects as were shown by Fig. 4. These photographs were taken with the following apertures, - 4 mm., 3 mm., 2 mm., 1.25 mm., 1 mm., and .6 mm. respectively, representing the same sized telescopes as were mentioned in the previous tables. Series 1. was taken with reflected light, series 2. with transmitted diffused light, series 3. with monochromatic light, and series 4. with the same conditions as series 3. except that the atmosphere between the camera and object was disturbed by means of two bunsen burners. There seems to be very little, if any, difference between series 1. and series 2.
This again shows that it makes no difference where the illumination is located. The optimum images in series 3. are better than the corresponding images in series 1. and series 2. This is possibly more evident in Fig. 7. than in Fig. 4. Series 4. shows conclusively that movements in the atmosphere affect the quality of the image to a marked degree.

In passing it might be well to note how the time of exposure was determined for the different apertures. It is generally understood that the intensity of light varies as the area of the aperture. In the use of photographic plates this is not true, however. The following formula gives the method for determining the time of exposure,

\[ C \log t_2 = \log A_1 + C \log t_1 - \log A_2 \]

where \( C \) is a constant depending on the sensitivity of the plates used, \( t_1 \) is the time of exposure for aperture \( A_1 \), and \( t_2 \) the time for aperture \( A_2 \). After experimenting a few times, \( C \) was found to be .7 for the plates used. It was also found that with a 4 mm. aperture and diffused
transmitted light that 2 minutes gave a dense negative. These values were placed in the formula and the time of exposure was determined for the other apertures. The following values were obtained:

<table>
<thead>
<tr>
<th>Aperture</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 mm.</td>
<td>2 Min.</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>5.4</td>
</tr>
<tr>
<td>1.25</td>
<td>10.5</td>
</tr>
<tr>
<td>1</td>
<td>14.5</td>
</tr>
<tr>
<td>.6</td>
<td>30</td>
</tr>
</tbody>
</table>

It was found that when reflected light was used, that these values multiplied by five gave the correct density.

In order to add clearness to the subject of partial images and to further explain the conclusions drawn from the photographs, Fig. 8. is inserted. The dark line in these drawings indicates the relative size of the different apertures used. No. 1. is 80 mm. in diameter and represents a 48 in. telescope; No. 2. is 40 mm. in diameter and represents a 24 in. telescope; No. 3.
is 20 mm. in diameter and represents a 12 in. telescope; while No. 4. is 10 mm. in diameter and represents a 6 in. telescope.

In the first part of this thesis it was shown that the diameter of the fifth ring of maximum intensity in the diffraction pattern from Mars would be approximately 4.276 cm. or 1.68 in. Now if 20 mm. in the diagram represents 12 in. 1.68 in. will be represented by 2.8 mm. The two red circles in each figure were then drawn 2.8 mm. distance from the dark line marked c. We can consider then, that these circles divide the space in and around the telescope into three parts or divisions, a, b, and d. We then see that if the central bright spot of any of the infinite number of diffraction patterns from Mars, falls within the space a, a good image will be formed. If the central bright spot falls within the space b an image will be formed which will not be quite as good as those found in class a. As the central bright spot of the diffraction pattern passes over the edge of the telescope another class of images will be formed which will be much poorer
than those of either class a or class b. I have chosen to call this group of images class c. This corresponds to what has already been said in the previous paragraphs. If the central bright spot is not admitted to the camera, a very poor partial image is formed by the parts of the pattern that are admitted. As the central bright spot falls within the space d only the outer diffraction rings enter the telescope and the images formed by them are poorer than those in either of the other classes. If the central bright spot falls outside of the space d the essential parts of the pattern do not enter the telescope and so we are not interested in them.

As has already been shown the image formed in a telescope is the result of the superposition of the images from these four classes. If class a predominates the resultant image should be a comparatively good one, while if the poorer or inferior classes predominate, the resultant image will be of an inferior quality and thus will be indistinct.
By finding the areas of the different sections in each of the drawings of Fig.8 some interesting comparisons can be made. The following table shows the relative values.-

<table>
<thead>
<tr>
<th>No.</th>
<th>Area</th>
<th>Area</th>
<th>Area</th>
<th>Area</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sec.a</td>
<td>sec.b</td>
<td>sec.d</td>
<td>total</td>
<td>a+b</td>
</tr>
<tr>
<td>1.</td>
<td>435</td>
<td>65</td>
<td>78</td>
<td>578</td>
<td>500</td>
</tr>
<tr>
<td>2.</td>
<td>93</td>
<td>32</td>
<td>40</td>
<td>165</td>
<td>125</td>
</tr>
<tr>
<td>3.</td>
<td>16</td>
<td>15</td>
<td>20</td>
<td>51</td>
<td>31</td>
</tr>
<tr>
<td>4.</td>
<td>1.5</td>
<td>6.3</td>
<td>11</td>
<td>20.8</td>
<td>7.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Per cent a is of total area</th>
<th>Per cent a+b is of total area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>75</td>
<td>86</td>
</tr>
<tr>
<td>2.</td>
<td>56</td>
<td>75</td>
</tr>
<tr>
<td>3.</td>
<td>31</td>
<td>60</td>
</tr>
<tr>
<td>4.</td>
<td>7</td>
<td>37</td>
</tr>
</tbody>
</table>

Now if we remember that the images formed by class b are fairly good partials and that those formed by class a are optima images, we can make use of the above table. When a 48 in telescope is used, 75% of the partial images making up the actual image are found in class a, while 86% of the total are included in classes a and b. This would indicate that a 48 in telescope should give a very good image of the disk of the planet Mars. These calculations, are of course, based on the
image of the disk of Mars. The excellence of the image of the smaller details of the planet will be dependent on the relative size of these details as compared with the size of the disk of the planet. No. 2 shows that when a 24 in telescope is used, that 56% of the partials that make up the image are included in class a and 75% in classes a and b. When we remember that the light from class a and class b is more intense than that from the other classes, we might expect a 24 in telescope to give a reasonably good image. Nos. 3 and 4 indicate how far the quality of the image falls off when a 12 in or a 6 in telescope is used. In the latter case the aperture is so small that nearly all of class a is excluded. This is also in accord with experimental results, for it is found that when the aperture would not admit the whole of the bright part of the diffraction pattern, the image obtained was very indistinct.

Before turning to the conclusions to be drawn from this investigation, one more point may be discussed. In taking all of these photographs with the exception of those shown in Fig. 5 the same lens was used. It will be advocated by some that when the aperture was changed that the size
of the lens should also have been changed. This criticism, however, is not in line with the facts of the matter. In an ordinary telescope the aperture has one function and the lens another. The aperture admits a certain amount of light, or a certain part of the diffraction pattern, and the lens forms an image with this light. The quality of the image will not depend upon the size of the lens when the lens is larger than the aperture used, but does depend upon the aperture. In other words, by using a large corrected lens with these different apertures I have the same optical conditions as if I had used a separate lens for each aperture. The size of the image on the other hand will be independent of the aperture, but will depend upon the focal length of the lens. It must be remembered that the quality of the image depends upon the optical excellence of the lens used. The lens I used was a good achromatic telescope objective. The quality of the image, then, depends, with a given wave length, upon two things, the size of the aperture and the correctness or
quality of the lens. The size of the image depends upon the magnifying power of the lens, which is determined by the focal length.

CONCLUSIONS FROM EXPERIMENTAL WORK

It may be explained that the conclusions drawn in the following paragraphs are not based alone, upon the results as shown in the accompanying photographs. Not more than half of the photographs taken are shown in this thesis. Over four hundred twenty-five exposures were made in connection with this work. Sometimes a plate was able to show more that the print did. Again, some of the prints shown have to be studied with a magnifying glass in order to get all of the points of contrast. There is a chance for error, also, in making the prints. This point has been kept in mind and no print was mounted until I felt that it was the best that could be obtained. Over two thousand prints were made in order to secure the ones shown here. I feel that the errors in this respect have been eliminated as much as it is possible to do so.
The conclusions are as follows:-

(1) The assumptions made at the beginning of this thesis have been proved to be correct. This is first shown in Figs. 3 and 4 and later by Figs. 6 and 7. There seems to be no difference between the photographs taken with transmitted diffused light and reflected light. The sum of the partial images gives a composite image which seems to be of the same quality and shows the same details as the images obtained with diffused light. This point is of great importance because it shows that the resolution of the image into its different partials is permissible. It also shows that the introduction of the lens in front of the object did not alter the optical conditions. If there is any difference between the composite image and the diffused light image, it may be accounted for when we remember that the composite image was taken with light of one wave length, while all the wave lengths were present when the diffused light images were obtained.
(2) In order to obtain a good image the aperture of the telescope must admit all of the brighter parts of the diffraction pattern from the object. The essential part of the pattern would usually consist of the central bright spot and the first five or six maximum diffraction rings. This conclusion is based on series 4. Fig. 4. and series 3. of Fig. 7. No. 6. in each of these series shows the effect of using an aperture that would not admit all of the brighter parts of the pattern.

(3) Airy's formula can be used in making an estimate of the size of a telescope necessary to give a distinct image of a heavenly body. This was shown particularly in Fig. 8. The calculations and estimates made by use of this formula agree quite closely with the experimental results.

(4) The quality of the image is not greatly improved by increasing the size of the telescope aperture indefinitely. Smaller details may be seen, however, with the larger telescopes. This is shown especially in series 3. Fig. 7. It will
be observed that Nos. 1 and 2 are equally good. No. 1 was taken with a 4 mm. aperture and No. 2 with a 3 mm. aperture. No. 1, however, might have been able to show details that would not appear in No. 2.

(5) Under ordinary conditions in nature perfect images are not obtained. It has been shown that better images can be obtained with this experimental apparatus than can be obtained under normal conditions. In every case it was found that when an aperture large enough to admit the essential part of the diffraction pattern was used, that the optimum images were better than those secured by the use of diffused light. This is shown in Figs. 4 and 7.

(6) If atmospheric conditions were perfect, details as small as seven miles across, on the planet Mars, could be detected with a 24 in. telescope. This seems to be in agreement with the contention that Professor Lowell holds. He has detected certain details upon the surface of the planet as readily with his 24 in. telescope, as
other astronomers have seen with the larger instruments. This was due, very probably, to the good atmospheric conditions found in Arizona.

(7) Movements in the atmosphere affect the quality of the image to a marked degree. While real atmospheric conditions were not produced in the laboratory, yet the results obtained can be relied on to a certain extent. The effects of the movements of the atmosphere are shown by series 4. and 5., Fig. 4. and series 3. and 4., Fig. 7. Noticing Fig. 7. for example, it is seen that in every case the image in series 3. is better than the corresponding image in series 4. The corresponding numbers in these series were taken on the same plate under the same conditions exactly with the exception that the air was in motion in series 4. It is generally understood that movements in the atmosphere affect the images in larger telescopes more than those obtained with the smaller. This point is not brought out in these experimental results. This is possibly because all of the apertures used were comparatively small.
PRACTICAL APPLICATIONS OF EXPERIMENTAL APPARATUS

(1) The apparatus as set up in this experiment can be used in obtaining a photograph of any transparent object, such as lines on a glass plate. A better photograph can be obtained in this way than can be secured in the ordinary way with diffused light for illumination.

(2) This apparatus may be used in studying the partial images from any transparent body, and the contribution of each of these to the total image formed naturally with diffused light.

(3) As advocated by Dr. Stoney and as shown in the results obtained, this apparatus can be used as a practical check on the work of astronomers, and in fact on any persons who view or photograph distant or minute objects.
Fig. 1.

Fig. 2.
Fig. 5.
Fig. 6.
Fig. 8.

No. 1.

No. 2.

No. 3.

No. 4.