ART. IV.—*The Photo-mapper*; by HENRY M. PARKHURST.

It is a remarkable fact that while vision is by far the most accurate of our senses, aiding us almost exclusively in obtaining accurate measures, we have as yet discovered no method of measuring the intensity of light. The method of measuring the brightness of a star by extinction, for example, is in fact merely a method of assisting the eye in estimation. If we were to measure the diameter of a sphere by removing it to such a distance that it should cease to be visible and multiplying that distance by a certain constant; or by subdividing it until we could divide it no longer, or until the atoms should have no appreciable weight, and multiplying by a constant; it would be analogous to determining the brightness of a star by ascertaining what proportion of its light is too small to affect the retina.

The true mode of measurement is by substraction of certain known quantities. To illustrate the advantage of this, were the difference of brightness of Arcturus and Capella but $.01^m$, that difference would be visible to the naked eye; and were it but $.0001^m$, it would be easily visible with telescopic aid. Could we construct a glass which would transmit, not a certain proportion of the whole light of a star, but all its light exceeding a certain absolute quantity, it would afford us a perfect photometer. Or could we construct a glass which should transmit polarized light, but which would not transmit common light, that would accomplish the same result. But in the mean time we may be allowed to designate estimations assisted by mechanical means as measures of the magnitude of a star.

My first experiments in determining by mechanical means the magnitude of stars observed in zones, and recording that magnitude at the time of observation on star-maps taken by the instrument described in the Journal for September, were made in 1865. I then constructed a hexagonal diaphragm so arranged that a series of six plates over the object glass, moved simultaneously by a lever extending the length of the telescope, gradually diminished the aperture until the star ceased to be visible. I connected this lever with the system of levers operated by the star-key, and recorded upon the map, in the same right-ascension with each star, a point whose position indicated the aperture at the moment of extinction, and therefore gave by a prepared scale the magnitude of the star.

My next step was to avoid the long and cumbrous lever by adopting the principle of the apparatus invented by me in 1860, and which I term a Bar Photometer, reducing the cone of light from a star at a point intermediate between the object-glass and its focus, instead of directly reducing the aperture at the object-glass.

At a convenient point, say one-eighth of the distance from the focus to the object-glass, I place in the meridian a straight bar one-eighth of the diameter of the object-glass in width. Clamping the telescope a little to the west of a star, the cone of light is gradually intercepted by the bar, and gradually reappears. The time during which the star is extinguished, or during which it remains of less brightness than a standard artificial star in the field, indicates the brightness of the star by the proportion of the light cut off by the bar at the moments of occultation and reappearance.

A modification of this plan, is to make the bar wider, so that it shall become a diaphragm, with a central aperture of the width of the cone of rays, observing the duration of apparition instead of the duration of occultation of the star.

By either of these methods the scale may be made one of equal parts by a device similar to that which will presently be explained. With or without such a device, this method is well adapted for observations of small variable stars, requiring no apparatus but the bar, whose distance from the focus shall be so determined that photometric accuracy shall not be sacrificed, while there shall be no unnecessary consumption of time. Indeed a plain Bar Photometer can at any time be extemporized in a few minutes. Its adjustment in width or distance is not essential, because its position and width can be determined and the proper connections made without difficulty after the observations.

A further modification of this plan, is to revolve the diaphragm 90° , and make it movable in declination, occultating the star on both sides of the center of the field, the magnitude being indicated by the extent of the motion, which may be conveniently and accurately measured, with a dim light, by a pair of dividers.

By a still further modification, the motion of the diaphragm may be produced, by means of intermediate levers, by the star-key of my star-mapper; and this constitutes the Photo-mapper, which I will now more particularly describe.

The diaphragm is moved parallel to itself in an arc corresponding to that described by the star-point and star-key, being supported and guided by two parallel bars whose bearings are screwed to the east side of the telescope tube. The diaphragm being seven-eighths of the distance from the object-glass to its focus, the length of the supporting bars is seven-eighths of the radius of the star-point. As I use a camera-prism, which slightly shortens the focus, I have, in my instrument, made the proper corrections, but need not here refer to details of that description.

On the same center with the star-point, and star-point-bar, shown in fig. 1 of my article on the Star-mapper, is another bar

placed parallel to the axis of the telescope, pointing toward the object-glass. The further end of this magnitude-bar is connected at right angles by a connecting-rod with universal joints, with the upright arm of a lever, the lower arm of which is the lower supporting-bar. The length of this upright arm and of the magnitude-bar must be equal. In photo-mapping I place the prism always in the meridian, to avoid the complicated adjustments which would be necessary if its position were to be varied.

As the diaphragm will move seven-eighths as fast as the star-point, it is evident that if it is so adjusted that it will not intercept any of the light of a star in the center of the field when the star-point is brought to the declination of that star, then in mapping a northern or southern star in the field its light will be unobstructed. But moving the star-key to the north or south of a star will intercept part of its rays. The light of the star being thus equalized with that of a standard artificial star, or extinguished, as the case may be, a magnitude mark is impressed on the paper. The star is then mapped in its proper position, and the distance upon the map, of the magnitude mark from the corresponding star, will be the measure of the magnitude of that star.

A perpendicular plate, with a circular hole through which the connecting-rod passes, furnishes a convenient point from which to measure with dividers when the instrument is used without the mapper.

Thus far I have spoken of the "cone" of rays, as if the aperture were circular. If it were so, the scale of magnitudes would not be one of equal parts. It may be made one of equal parts by placing over the object-glass an outer diaphragm with an aperture of suitable form, and making the aperture of the inner diaphragm of corresponding form.

Let $x=2.5[y]$ be the equation of a logarithmic curve. Then, the area between any two ordinates of that curve will be $2.5M\Delta y$; M being Modulus. Constructing for the object-glass of 6 inches aperture a diaphragm bounded by four such curves, with values of x ranging from -1.5 inches to $+1.5$ inches, laying off x vertically, above and below the center, and y to the right and left, and a similar inner diaphragm of one-eighth the lineal dimensions, neglecting for the present the portion of the curve which will pass outside of the circle, it will be seen that the motion of each one-fourth of an inch of the inner diaphragm will leave an area corresponding to stars exactly one magnitude smaller. The motion of the star-point will be one-seventh greater, and of the star-key still greater, according to the scale of the map.

But while the object-glass is limited, the inner aperture may

extend beyond the corresponding circle of one-eighth the diameter. If therefore an area equal to twice the omitted portion of the curves above and below is added to the inner diaphragm, it will be almost immediately available, and the omission from the outer aperture will cause an error of less than $\cdot 1^m$, and that only at the commencement of the scale. The proper form of this added portion is the inversion of the last $1^m \cdot 2$ of the curve within the circle, the final value of y being exactly three times its value at the margin of the disk.

With the diaphragms thus constructed, the scale runs through $3^m \cdot 0$ as a scale of equal parts. Beyond that point the star may still be extinguished, if not too near the center of the field; but the scale will be condensed.

The stars occurring in any zone may be divided into three classes: those above the $6^m \cdot 5$ being approximately measured by the condensed scale, and being so few in number that they may be conveniently, as well as more accurately, measured by a different method, to be explained below; those between the $6^m \cdot 5$ and the $9^m \cdot 5$, which may be equalized in brightness with an artificial star in the field previously brought to an equality with a $9^m \cdot 5$ star; and those fainter than the $9^m \cdot 5$, which may be extinguished. The outer diaphragm will so diminish the aperture that $12^m \cdot 5$ stars will be the smallest which can be seen.

The Disk Photometer.—For the brighter stars I employ an entirely different apparatus, based upon a more accurate method. I expand the stars into disks by drawing out the eye-piece beyond the focus, until a portion of the disk shining through an aperture in the field of view shall either be exactly equal in brightness with an adjacent luminous disk, or be imperceptible. The extinction of a disk by expansion is only practicable with a small aperture or with telescopic stars, and is not much, if any, more accurate than extinction by reducing the aperture. But comparison of disks, especially for the stars visible to the naked eye, is the most accurate means of measurement known to me, the error of the comparison being in my experience less than the inequalities of the artificial disk, and the latter much less than those of the sky.

The star and the disk can be compared, if desired, by the aid of polarization, by the use of a double-refracting prism to combine the two disks into one, and a selenite plate and another double-refracting prism to form new colored disks; but instead of producing the final adjustment by further polarization, the bundle of plates may be dispensed with, and the disks rendered colorless by the motion of the eye-piece.

For convenience I have made a slide with six equal openings, to shade the disk with neutral shades, and a slide to shade the star. I ascertained that one shade was equivalent to $1^m \cdot 03$,

and that, although I admit the rule would not be accurate with colored shades, five neutral shades were equivalent to $5^{\text{m}}15$. It is therefore convenient to compare directly stars differing as much as α and λ Ursæ Minoris. In order to neutralize the yellow color of the artificial disk, and to make it appear indistinguishable from the visible portion of the disk of a star, I have found it necessary to use a blue shade. I have extended the telescope by various tubes, sometimes nearly two feet; but with the use of the slides I find that a tube five inches long to hold the eye-piece, usually gives sufficient extension to the telescope and sufficient range of brightness. The amount of the extension I measure with dividers, using a prepared scale which gives directly, in magnitudes, the difference in brightness between the observed star and a standard depending on the brightness of the disk.

The disk photometer is especially useful for observing the brighter variable stars. It is inapplicable for determining the brightness of stars so close together that the space between them is not sufficient for a disk; but in this case it may be used to determine the aggregate brightness of the two stars. It may be used for measuring the brightness of planets, small nebulae and comets, probably of the moon, and possibly of the sun.

The same apparatus may be used to determine the comparative brightness of different portions of the sky, but requires a different process.

The error of the determination of the magnitude of a star by the method of equalizing disks, may be divided into four parts:

I. The error of the assumed magnitude of comparison stars. In my series of observations, instituted to determine the relative amount of the several errors, this error hardly exceeds $^{\text{m}}01$.

II. The error of observation, or inaccuracy of judgment as to the exact point where the disks are equalized. Not only according to the statements of Arago, Silliman, and Crookes, reduced by myself, but according to my own results, the error of observation—I refer to the *mean* error—does not exceed $^{\text{m}}02$, in a series of stellar observations averaging forty to the hour. For fainter stars than I observed in my series, the error of observation is greater. There are three limitations:

1. One disk cannot be distinguished in brightness from another, unless one-sixtieth brighter or fainter, according to Arago.

2. One disk cannot be distinguished as brighter than another, if the subtraction of the light of the fainter disk from the other would leave a disk too faint to be visible by itself. The same principle is applicable to points of light. Unless, therefore, the disk is at least sixty times as bright as is necessary for visibility, the error of observation will be greater.

3. If the disk is small, the accuracy of comparison is impaired. Hence points of light cannot be as accurately compared as disks. I have used a disk of an apparent magnitude of at least 1^o, and have not investigated the amount of error with a smaller disk.

III. The error from the variation of the artificial disk during observation. I have made many and careful experiments to render this error as small as possible, and to avoid ascribing to the irregularity of the sky discrepancies which might be owing to variations of the artificial disk. The brightness of the artificial disk may vary from four causes:

1. The illuminating quality of the gas may vary. Hence observations on different evenings cannot be compared directly. But the change of the gas will be so slow, excepting probably from the heating of the apparatus when it is first lighted, as not to appreciably affect the results.

2. From variation of the pressure the flame may be made larger and brighter. I first partially corrected this by forming upon the screen an image of a circle of the flame $\cdot 05$ in. in diameter. I afterwards made a gas regulator, admitting the gas into an inverted receiver suspended at one end of a lever, the other end of which gradually shut off the gas as the receiver rose; so that whatever the pressure of gas in the mains there should be no variation in the flame.

3. The flame varies in different parts. Hence, if on turning the telescope upon a new star the lantern is not accurately adjusted to a horizontal position, a brighter or fainter portion of the flame will come opposite the aperture. The flame as a whole having been made uniform by the regulator, I have introduced a smoothly ground glass at the aperture nearest the flame, and reduced the flame and moved it further back, so as to use the whole flame.

4. The light from the star is a sharp cone, wholly entering the eye even if withdrawn several inches from the eye-piece. The light from the illuminated screen is a hemisphere. Unless therefore the eye-piece renders the rays parallel, which it will not if the observer is either near-sighted or far-sighted, a difference in the distance of the eye will greatly affect the results. I have therefore turned the plane glass in the eye-piece so as to throw the light directly into the eye, reducing the aperture of the lenses so that the cone of rays from the artificial disk nearly corresponds with that from the star. It is necessary that the eye should be held so that both cones shall completely enter it at once, which can be easily accomplished but requires care.

The error from the variation of the artificial disc, without the gas regulator, I ascertained not to exceed $\cdot 04$. How much this has been reduced by introducing the regulator and ground glass screen, I have no means of estimating.

IV. After allowing for the previous errors, amounting in the aggregate to less than $^m0.5$, the remaining discrepancies of observation of invariable stars must arise from variations of the apparent brightness of the stars from atmospheric obscuration. I divide this into two parts:

1. The general and permanent obscuration depending on the altitude of the star. I have ascertained that this follows the law of refraction; but the coefficient varies in amount on different evenings, sometimes equalling $^m.50$ for an altitude of 20° , and at other times not exceeding one-third that amount. I apply the correction for obscuration to each star, in reducing the observations, so as to eliminate this; and I therefore regard it as no part of the error of observation. The correction may be easily applied without directly determining the altitudes, by a prepared scale.

2. The temporary and local obscuration, from various atmospheric causes. By more than 400 observations of 18 stars of the 2nd to the 4th magnitude, α Persei and γ Arietis being the extremes, I found that the average mean error of an observation, from all causes, amounted to $^m.11$; so that the mean error from the temporary and local obscuration alone is on the average $^m.10$. There is a great difference between different days; the average mean error of all the stars being sometimes as low as $^m.07$ for a whole evening, and at other times for an evening apparently equally clear, as high as $^m.20$. The difference between the stars is no less conspicuous. The stars ϵ and γ Persei are near each other, and nearly of the same brightness. Yet the mean error of an observation of γ Persei, assuming it to be an invariable star, is nearly three times as great as of ϵ Persei.

It is evident therefore that if the results I have reached are even approximately correct, the errors of observation and of the instrument, if ordinary care is used, are of no material consequence; and accurate results can only be obtained by multiplying observations on different evenings, so as to eliminate as far as possible the errors arising from the variations of the sky.