Stellar Magnitudes and their Determination.

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I.—APPARENT MAGNITUDES: (*a*) VISUAL.

THE magnitude of a star, as determined by direct astronomical observation, is a measure of its *apparent* brightness on a scale which has been precisely defined only within recent years. Hipparchus was, so far as is known, the first to assign magnitudes to the stars, and his results have been preserved for us by Ptolemy in the Almagest. The classification of Hipparchus was a crude one, the stars being divided into six classes, all the brightest stars being assigned to the 1st magnitude, and all those only just visible to the naked eye to the 6th. Ptolemy extended the classification by recognising the gradation in brightness between the stars in a given class, this gradation being indicated by the words μείζων and ἐλάσσων, used to denote that a star was brighter or fainter than the average star of its class. Ptolemy's estimations were adopted almost universally until the time of Sir William Herschel, who developed a plan for representing various degrees of difference in brightness between stars by the use of arbitrary symbols, and made observations of the magnitudes of nearly three thousand stars. It was not until Argelander carried out the great project of the "Bonn Durchmusterung" (1852 onwards) that magnitudes were first estimated to tenths, and even in this great work the scale adopted, though made to correspond fairly closely with the then existing scales, was an arbitrary, and not a uniform, one.

Sir John Herschel was the first to attempt to formulate a numerical relationship between the apparent brightnesses of stars of successive magnitudes, and he concluded that the best representation was afforded by a relationship according to which a decrease in light in geometrical progression corresponds to an increase in magnitude in arithmetical progression. He also estimated that the actual ratio of the light of a star of the 1st magnitude to one of the 6th is at least 100 : 1. Herschel's conclusion is in accordance with a psycho-physical law, enunciated by Fechner, that, as a stimulus increases in geometrical progression, the sensation produced by it increases in arithmetical progression, the law being departed from, however, in the case of very intense or very weak stimuli. According to this law, if I_m denotes the apparent brightness of a star of magnitude m, then $I_m : I_{m+\Delta m} = k^{\Delta m}$, where k is a constant, which is called the "light ratio."

Using this relationship, the value of k (or $\log k$) corresponding to various early series of magnitude determinations, after standardisation by various photometric devices, can be found. These show a somewhat wide variation around a mean of about 0·40 for $\log k$. Thus a few values are:—

Herschel	... 0·407	Argelander	... 0·431
Struve	... 0·383	Groombridge	... 0·388

The values are not, in general, constant within any given series. Thus for the "Bonn Durchmusterung" of Argelander we have:—

For magnitudes	3 to 5	... 0·29
,, ,,	5 to 6	... 0·30
,, ,,	6 to 7	... 0·39
,, ,,	7 to 8	... 0·39
,, ,,	8 to 9	... 0·44

It was, therefore, suggested by Pogson that the value 0·40 for $\log k$ should be definitely adopted as a basis for accurate photometric determinations of magnitude. This value is in sufficiently close agreement with the values derived from the older series of determinations to ensure that the magnitudes derived on this basis will not deviate greatly from the older estimates. Owing to the convenience of this figure, all modern photometry has been based on this convention, which assigns a value to k of 2·512... The convenience of the figure is due to the facility with which it enables estimates of brightness to be transformed into magnitude differences ($\Delta m = 2{\cdot}5 \log I_m / I_{m+\Delta m}$). In the case of two stars one of which is 100 times as bright as the other, we then have $\Delta m = 5$ magnitudes, exactly in accordance with Sir John Herschel's estimate.

Having adopted this convention, it becomes necessary, before a magnitude can be assigned to any star, to fix the zero from which the magnitudes are to be estimated, it being agreed that the scale shall be continued in both directions, stars brighter than a star of the 1st magnitude being assigned zero or negative magnitudes. The use of the term "negative magnitude" may be misleading to those who are not astronomers, but the conception is a useful one if the scale of magnitude is to be considered—as theoretically it must be considered—capable of infinite extension at each end. It has the further advantage of not causing a break with the old-established convention that the brighter the star the smaller (algebraically) is the quantity denoting its magnitude. It is convenient so to choose the zero that the modern precise photometric magnitudes shall agree as closely as possible with the older values, which we have seen also corresponded closely with a value of 0·4 for the logarithm of the light ratio. In actual practice the zero has been fixed somewhat indirectly; in the extensive visual photometric work carried out at the Harvard Observatory all the stars were compared with the Pole-star, for which a provisional magnitude was assumed. Thus differences of magnitude only were determined. All the magnitudes were finally increased by a quantity so chosen that the mean of the magnitudes deduced for 100 circumpolar stars between the 2nd and 6th magnitudes agreed with the corresponding mean of the values assigned in the "Bonn Durchmusterung." In the photometric *Durchmusterung* of Müller and Kempf at Potsdam the zero was chosen so that the mean magnitude of 144 selected fundamental stars north of the equator, between magnitudes 4 and 7, should agree with the corresponding value in the "Bonn Durchmusterung." The systems of magnitudes derived in these two investigations are not in absolute accordance, as will be seen later.

For the accurate determination of visual magnitudes, some form of photometer is necessary. The two types which have provided the best results are the Zöllner photometer and the meridian photometer of Pickering. The former is illustrated in Fig. 1, the principle of the instrument consisting in the formation of two images in the focal plane of the telescope, one being the image of the star under observation, and the other that of an artificial star the brightness of which can be varied and brought into equality with that of the real

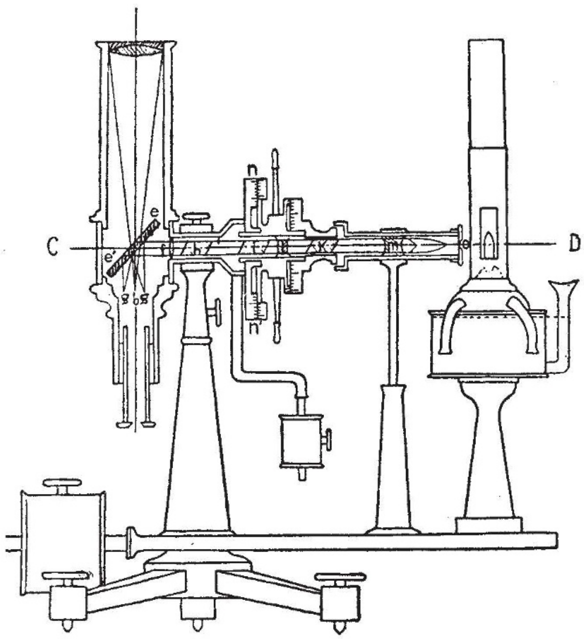

FIG. 1.—The Zöllner Photometer.

star. The light from a standard lamp, giving a constant illumination, passes through a pin-hole in a diaphragm *o*, holes of different sizes being used to simulate stars of different magnitudes. The divergence of the rays passing through the pin-hole is increased by a concave lens, *m*, and it then passes successively through a polarising Nicol, *k*, a thin quartz plate, *l*, cut perpendicularly to its optical axis, a second Nicol, *i*, and a third Nicol, *h*. The Nicol *i* and the quartz plate *l* are fixed relatively to one another, but the Nicol *k* can be rotated, so varying the colour of the light falling on the third Nicol. When the colour agrees as nearly as possible with that of the star under observation, *k* is clamped into position. The Nicol *h* acts as an analyser, and the system *k, l, i* is turned as a whole relatively to it in order to vary the brightness of the artificial star and bring it into equality with that of the real star. The light then passes through a lens, *f*, which focusses it in the focal plane of the telescope, after reflection by the plane glass mirror *ee′*, which forms two images of the artificial star of nearly equal brightness by light reflected from its front and back surfaces respectively, the former being somewhat the brighter of the two. There are four positions of the rotating system in which equality can be obtained between the brighter of these images and that of the star under observation, and the reading corresponding to each is observed. Some observers prefer to make the observation by adjusting the brightness of the images of the artificial star so that the real star image is intermediate in brightness between the two images of the artificial star. As differences in brightness only are measured, it is immaterial which procedure is adopted provided it is adhered to throughout. A standard star is then observed in a similar way. If I_1, I_2 are the angles through which the polarising system is turned in the two cases, from the position corresponding to crossed Nicols, then the ratio in brightness of the two stars is $\sin^2 I_1 : \sin^2 I_2$, and therefore their difference in magnitude is $5 \log (\sin I_1/\sin I_2)$. All the Potsdam observations were made with two photometers of this type, though differing in some details from that illustrated here; 144 fundamental stars were chosen, which were combined into 432 pairs, and intercompared in order accurately to determine their magnitudes. Every zone star was then compared with an adjacent fundamental star.

The Zöllner photometer is convenient and accurate in use. The colour compensation reduces the subjective errors of personality which are liable to occur when two images of different colours are compared. The colour match can be made much more accurately, however, for yellow and red stars than for white or yellowish-white stars. The principal objection raised against it is the employment of an artificial star—not on the ground of possible variations in its magnitude, for there are types of standard lamps which give very constant illumination, but owing to the fact that the image of the artificial star may not be exactly similar to that of a real star under all conditions of seeing. It is stated by Müller that the tendency is to make bright stars too bright and faint stars too faint, but, provided that the diaphragm or the aperture of the telescope is so chosen that the magnitude of the artificial star does not differ greatly from that of the star under observation, the errors possible on this account are very small. One of the Potsdam photometers was provided with three object glasses which were used in conjunction with three diaphragms. It was found best to use an aperture of 30–40 mm. for stars of magnitudes 2 to 4, of 60–70 mm. for stars of magnitudes 4 to 6, and of 130–140 mm. for stars of magnitudes 6 to 8.

The meridian photometer, devised by Pickering and used at the Harvard Observatory for the very extensive photometric work carried on there under his direction, is illustrated in Fig. 2. It consists of a horizontal telescope pointing to the west and provided with two similar objectives, A and B, in front of which are placed right-angled prisms, C and D, which reflect the light from two stars into the telescope. The prism D is used only for observing the Pole-star, and can be turned about two perpendicular axes by rods E and F.

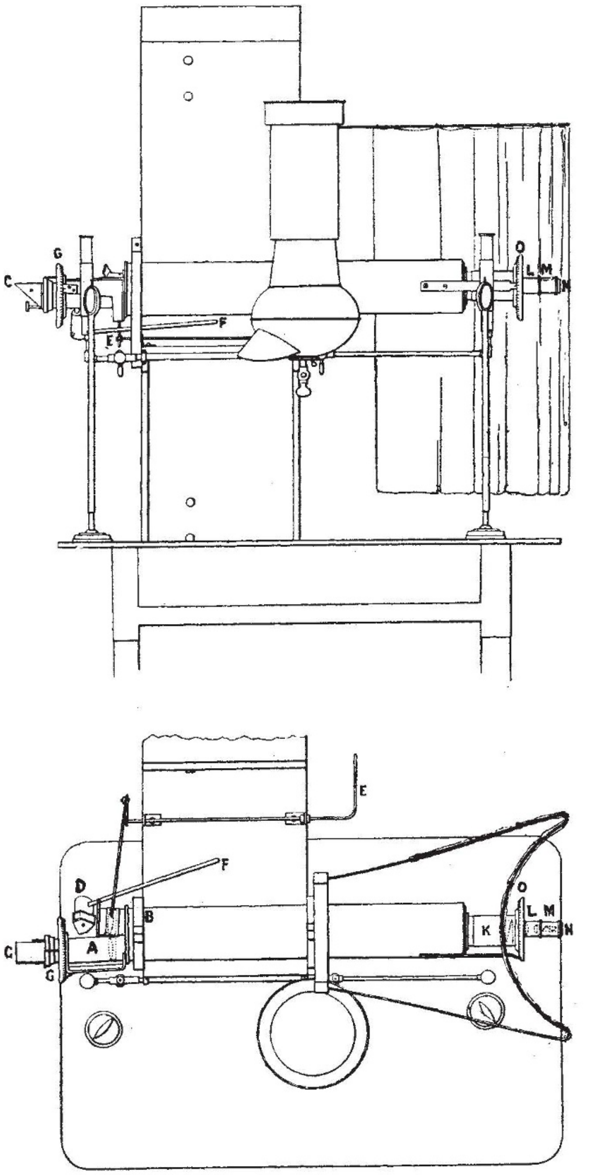

FIG. 2.—The Meridian Photometer.

The prism C can be turned around the axis of the telescope, and its position read by a circle, G, so that a star of any given declination can be observed on the meridian; there is also a slight adjustment for enabling it to be viewed for about one-quarter of an hour before or after meridian passage. A double-image prism, K, made of Iceland spar compensated by glass, is placed near the focus of the objectives, and divides each pencil of light into two; the angles of the spar and glass prism are so adjusted that the two central pencils (one ordinary and one extraordinary pencil) are made to coincide and to pass nearly through the centre of the eyepiece L. In this way errors which might result from having two emergent pupils or from the pencils passing through different parts of the eyepiece are avoided. In front of the eyepiece is placed a Nicol, M, and an eye-stop, N, cuts off the two outside pencils. A graduated circle, O, is attached to the eyepiece and Nicol, and the four positions of the Nicol are observed in which the two images are equal in brightness. Since the beams from the two stars are polarised at right angles, if I is the angle counted from the position where the image of Polaris disappears, then the ratio of the brightness of the star under comparison to that of Polaris is $\tan^2 I$. In taking the observations, readings are obtained with the image of Polaris first on one side and then on the other side of the star. This photometer is accurate in use, and has the advantage over the Zöllner type that similar images are compared. It has several disadvantages; the two stars are compared through different object glasses which cannot in general be interchanged. Stars of low declination are compared with a star at a very different altitude, so that appreciable errors may occur on account of the variations to which the transparency of the atmosphere is liable; with the Zöllner photometer, on the other hand, a star can always be compared with another of about the same altitude. The optical combination also does not permit of very good images, and there is no provision for matching the colours of the two images. It is also limited in its application to stars near the meridian. At the time the Harvard observations were made the variation in brightness of Polaris had not been discovered. After its discovery, the variation was detected in the residuals, although its total range is quite small.

In another type of photometer which has been greatly used, a neutral wedge of uniformly graduated absorption is employed, and the reading is taken of the position of the wedge when the star under observation just becomes invisible. Owing to the strain on the observer's eyes caused by these observations, which are liable to give rise to personal errors of variable amount, and to the impossibility of obtaining an absolutely neutral-tinted wedge, this type of photometer does not give results of the same order of accuracy as the two described above.

Although the theory of the determination of visual magnitudes is very simple, there are many possible causes of error, mainly of a physiological nature, arising from the necessary use of the human eye. Most of these are more important when very faint stars or stars differing much in colour or brightness are observed, though in the Zöllner photometer difference in colour can be compensated to a certain extent. Errors arising from the observation of stars near the threshold of visibility should be avoided by reserving them for an instrument of larger aperture. A few causes of error may be referred to briefly: (i) The Purkinje phenomenon is well known; if two lights of different colours—say, a red and a green—appear equally bright to the eye, then, if the intensity of each is increased in the same ratio, the red will appear the brighter; if reduced in the same ratio, the green will appear the brighter. Thus the relative magnitudes of two stars of different colours depend upon the aperture and power with which they are observed. (ii) Connected with this phenomenon is the difficulty of comparing the brightness of two stars when their colour is different with any type of photometer which does not compensate for colour difference. Some observers will estimate a red star as relatively much brighter than will other observers—errors of half a magnitude on this account are not at all uncommon. The use of a red screen has been suggested, but this and similar devices introduce the Purkinje phenomenon. The most satisfactory solution is to use the smallest aperture which gives no perceptible colour. (iii) Errors are possibly due to the two stars being observed on different parts of the retina; two stars which appear equally bright when side by side will not in general appear so when one is above the other. It is advisable always to view the two stars side by side and then to interchange their positions. (iv) There are various errors possible owing to varying accommodation of the eye, particularly when the colours of the two stars differ. The observer should therefore be screened by a dark curtain, and all readings and settings performed by a second observer outside the curtain.

By the study of these and similar types of errors and the best means of avoiding them, the influence of the human element has been reduced as far as possible. With these precautions, the magnitudes having been finally determined with the photometer, it is necessary to apply a correction for atmospheric absorption, which increases with increase of zenith distance. Careful investigation has been made, both at Harvard and at Potsdam, of the amount of this correction at various altitudes, and the effects of differential atmospheric absorption have been allowed for with relatively small uncertainty. But even after all precautions have been taken it is found that there remain systematic differences between different series of observations, and that these occur not only in the case of series made by different observers and with different instruments, but even between different series made by the same observer with the same instrument. In general, the errors are not large, but they cannot be neglected in comparison with the accidental error deduced from the inner agreement between the observations in any one series. The comparison of the brightness of two images in a photometer is a subjective one, and it seems impossible altogether to eliminate errors. In the observations at Potsdam every star was observed an equal number of times by the two observers in order to make the whole series internally consistent; but another observer observing with the same photometer would probably obtain results differing systematically according to colour. Different results are also obtained from different instruments. Thus Müller and Kempf find, from a comparison of the "Revised Harvard Photometry" with the "Harvard Photometry," in which the observations were made with different photometers, the following relative differences between white and yellow stars in the two series:—

Magnitude *m.*	Mean differences (R.H.P.–H.P.) for white stars *minus* differences for yellow stars *m.*
Brighter than 2·0	−0·23
2·0–3·0	−0·17
3·0–4·0	−0·10
4·0–5·0	−0·10
5·0–6·0	−0·01
6·0–7·0	+0·05
Fainter than 7·0	+0·21

The Potsdam observations made with the different photometers were intercompared, and corrections derived by which all the observations were reduced to a mean system. The differences, in part, were probably due to differences in the absorptions in the several object glasses used.

The comparison between the final Potsdam results and the Harvard results reveals differences which appear surprisingly large in view of the care devoted to the observations themselves. The differences are mainly dependent upon the colours of the stars; to a much less extent they vary with their brightness. The following mean differences in the sense Potsdam *minus* Harvard are found for the Potsdam colour-classes W (white), GW (yellowish-white), WG (whitish-yellow), G (yellow):—

W, +0·25*m*; GW, +0·22*m*; WG, +0·10*m*; G, 0·00*m*.

The differences show continuous variation with brightness for the range 2*m* to 8*m* as follows:—

W, +0·23*m* to +0·37*m*; GW, +0·20*m* to +0·30*m*; WG, +0·12*m* to +0·07*m*; G, +0·07*m* to −0·08*m*.

When it is recalled that a difference in magnitude of 0·1*m* corresponds to an error in apparent brightness of nearly 10 per cent., the magnitude of these errors can better be realised. It is also apparent that there is much scope for improvement in the accuracy of magnitude determinations.

The Potsdam visual *Durchmusterung*, comprising all stars in the "Bonn Durchmusterung" down to a limit of 7·5*m* on the "Bonn Durchmusterung" scale, is probably the most accurate series so far as inner consistency is concerned, the same two observers having observed every star, and instrumental differences having been so far as possible eliminated. If any series of visual photometric observations can be regarded as fundamental, it is this series; but any other fundamental series may be expected to show slight systematic discordances. There is a parallel in the case of meridian observations, in which there are several fundamental systems, and it is customary to reduce any series of observations to one or other of these fundamental systems. If further series of observations are reduced to the Potsdam system, any future revision of this system can easily be extended to all the observations based upon it. At present no series has been generally accepted as a standard, and if two determinations of magnitude of a star agree within one-tenth of a magnitude, astronomers now feel very satisfied.

(To be continued.)

The Development and Spread of Civilisation.

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RECENT research suggests that the various forms of human culture are the result of a process of organic growth. Continuity is apparently the key-note of the study of the history of civilisation. But, because it is not possible in each case to supply the missing links, it is incumbent on those who believe in continuity to construct a mechanism of the development and spread of civilisation in all ages and places. The following generalisations suggest how this process has been effected.

It would seem that civilisation—that is to say, the possession of the fundamental arts and crafts necessary for settled corporate life—first appeared in the Near East. There, at some time before 3700 B.C., had apparently been discovered the crafts of agriculture, irrigation, stock-breeding, carpentry, metal-working, stone-working, pottery-making, weaving, and so on. All the rest of the world, so far as can be seen, was at that time peopled only by hunting tribes very low in the scale of culture. These were not long left in possession of their hunting-grounds, for civilisations began to appear in outlying parts of the earth, such as Turkestan, Siberia, China, India, the valley of the Wei in China, the valleys of the Usumacinta and Motagua in Guatemala, Lake Titicaca in Peru, etc. The cultural level of these early centres never exceeded, and rarely approached, that of the Near East. Around these centres appeared later other civilisations, usually progressively lower in cultural level as they became more remote from the centre in space and time. For example, the earliest known civilised settlement of North America was that of the first Maya cities of Guatemala. All the later Maya cities, and the tribes that afterwards occupied the same region, display a definite inferiority of technique in the arts and crafts as compared with these earliest settlements. Northward from Mexico there is a steady drop in the level of culture. Similarly with South America. It is claimed that negro Africa derived practically all its culture, directly or indirectly, from Egypt. As one goes south from Egypt there is, speaking generally, a steady decline in cultural level, the most southerly people of all, the Hottentots and Bushmen, being the lowest. The study of the beginnings of European civilisation reveals a similar condition of affairs. The earliest centre was in the eastern Mediterranean. In no other region of the continent did ancient civilisation attain to so high a level, and the various stages of development of culture appeared later in time in the outlying parts than in those nearer to this region.

It is natural to seek to interpret these and similar facts. In only one region in the world—the Near East—can progressive development of culture be established in ancient times. In that region civilisation probably first appeared, and there it reached the highest level of antiquity. Everywhere in the world outside the area directly and continuously influenced by this region, the story from the beginning is one of uninterrupted degeneration in arts and crafts. In many instances it is possible in these outlying regions to establish direct filiation of culture, and it is invariably found that the process is accompanied by degeneration in the arts and crafts. Since in any one region, such as America, it is found that, wherever direct cultural sequence can be established, the earlier is the more advanced, and that the earliest known culture is the most advanced of all in the technique of the arts and crafts, it is difficult to account for the facts otherwise than by postulating that the earliest civilisation in such a region was derived from one that preceded it in some other part of the world. Carried to its conclusion, this amounts to claiming that everywhere outside the Near East, even in cases where it cannot be established by direct proof, culture exists by reason of direct filiation—in short, it amounts to postulating continuity in culture. In that way it would be claimed that the civilisations surrounding the original culture centres were derived from them, and that the culture centres themselves were derived from those that preceded them on the earth. The chronological argument would thus lead us to derive all the outlying culture centres from the Near East, and the whole process of cultural development would be one of growth outward from the Near East. This solution would satisfy both the spatial and chronological conditions of the problem.

The indication of a motive will tend to facilitate belief in such a world-wide movement of culture in antiquity. The ancient civilisations in different parts of the earth are fundamentally similar—they are all founded on irrigation—and in their economic, social, political, and religious organisa-