Photoelectric Photometry in Astronomical Studies

Advances have been made in various fields of astronomy through the use of photoelectric techniques.

Frank Bradshaw Wood

The history of the use of photoelectric techniques in astronomical studies goes back almost to the discovery of the photoelectric effect, but for many years work could be done only on relatively bright objects by persons who were experts in electronics as well as in astronomy. Various factors have changed the picture radically in the past 15 years. The chief of these is the replacement of cells that use gas amplification of the current initially freed at the photosensitive surface by cells that use secondary emission for this purpose. This and other aspects of instrumentation have been dealt with adequately elsewhere. Astronomical photoelectric photometery is some 50 years old, but the facet that concerns us here is that portion of it which might be classified as the modern phase—developments which cover little more than the past ten years. This modern phase is characterized by the use of filters to isolate various regions of the spectrum and by efforts to establish standard color systems; it is characterized by the extension of photoelectric techniques into the infrared region of the spectrum, and by other advances in instrumentation; it is characterized by ingenious spectrophotometric devices in which advantage is taken of the sensitivity and linearity of the photosensitive surface; and, finally, it is characterized by a rapid spread in the number of individuals and institutions that use photoelectric methods, and by worldwide cooperative programs among these.

I shall try to describe briefly the impact of photoelectric photometry upon various fields of modern astronomy; in an article of this length it is, of course, impossible to be all-inclusive.

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Eclipsing Variables

Historically, the first field of stellar astronomy to feel the impact of photoelectric methods was that of eclipsing variables. These are double stars which are much too close together to be seen as anything but a single point of light. In the majority of these systems, the components are even much closer together than the planets of our solar system; in some, the outer envelopes are probably actually in contact. We know that these are double-star systems by the oscillations in the positions of their spectral lines, caused by Doppler displacements as the stars revolve about their common center of gravity, and by the changes in the light caused by successive eclipses as each component passes between us and the other once in each orbital revolution.

A typical "light curve" is shown in Fig. 1. This shows the variation of light with time. When the period has been determined, observations on many nights can be combined to form such a curve, by plotting as abscissa the "phase" or length of time elapsed since the last moment when the greatest loss of light occurred (primary minimum) and as ordinate, the measured difference of magnitude between the variable star and a nearby star of supposedly constant light. In this instance the phase is plotted in terms of the fraction of the period of light variation.

The light changes in this system are caused primarily by two factors. One is the effect of the eclipses as each star alternately passes between us and the other. In this system, the eclipses are nearly equal in depth. This indicates that each star has approximately the same brightness per unit area of its surface and hence that the two components are of nearly the same surface temperature. In systems where one star is much hotter than the other, the hotter component, of course, emits much more radiation per unit area. Since the same area is obscured at each eclipse, in such cases the eclipses are of greatly different depths.

The second main cause of the light changes in this and similar systems is the distortion of each star from spherical form, chiefly by the gravitational attraction of the other. To a rough first approximation, we may say that the stars resemble footballs rather than baseballs, with the long axes pointed toward each other. Thus, near the times of the eclipses we are looking at the smaller ends of the stars, whereas one quarter period later we see much greater areas. In very close systems such as this one, this effect is responsible for a considerable fraction of the total change in light.

Further inspection of the light curve shows that one minimum has a flat bottom, where the light remains constant for an appreciable interval. This shows that this eclipse is total, with the smaller companion behind the larger. A half period later the annular eclipse occurs, and the smaller component passes in front of the larger. We note that the bottom of this eclipse is not flat. The explanation is as follows: If the star were near enough to be seen as a disk, we would notice that it appeared brightest at the center, where our line of sight is perpendicular to the "surface" and thus penetrates more deeply into the star than it does near the edge, where the line of sight is nearly tangential. Since the temperature increases with increasing depth, the star thus appears hottest and brightest at the center—a phenomenon easily observed on the sun. Thus, as the smaller star passes from the edge to the center of the larger, it eclipses successively brighter regions on the surface and loss of light continues, even though the same area is covered at each instant. As it passes from the center to the other edge, the reverse occurs. The exact value of the ratio of the brightness at the edge to that at the center is connected with the process of radiation transfer through the star's atmosphere, and thus it is important to have observational values of this to check predictions made by theory. Yet, with the exception of the sun, no star appears as more than a point of light. Thus, our only observational check (again, apart from the sun) must come from eclipsing systems. Naturally, the more precise the measures the more precise will be our knowledge of the numerical value of this quantity. The increased precision of photoelectric observations as compared to other techniques is obviously of considerable value here.

This is not the only place in which the increased accuracy of photoelectric observations aids in the study of eclipsing systems. Almost half a century ago Stebbins, using photoelectric methods, and Dugan, using visually a polarizing photometer, independently discovered the so-called reflection effect. This effect, produced by the heating of one side of each star by the radiation of the other, causes the light to be brighter just outside of secondary minimum than it is at a corresponding phase near primary; it also affects in a complicated way the brightness at other portions of the light curve. It must be measured in each individual case before either the ellipticity of the stars or the other elements can be computed.

We have seen how the mere inspection of a light curve can tell us much about a given eclipsing system. Detailed analysis yields much more.

The development by Russell in 1912 of computational methods whereby elements of the system could be derived from the light curve gave impetus to the study of eclipsing stars by photometric methods. Combined with spectrographic results, Russell's methods permit computation of masses, radii, and densities of the components—quantities of fundamental importance to the astronomer. For any given system, the accuracy with which these can be determined will depend upon the precision (and distribution) of the observations; the increased precision made available by photoelectric measures made their use in such studies of particular value.

The astronomer working in this field before 1940 was hampered by two factors. The first was the low sensitivity of the photoelectric cells which limited sharply his choice of stars. The second factor arose from the fact that, while the photosensitive surface itself was reliable in emitting electrons, the means of amplification were by no means so reliable; vacuum techniques had to be used, and the photoelectric photometers of the 1930's and earlier were temperamental instruments. Nevertheless, it was largely (although not entirely) photoelectric observations which showed that the eclipse theory, complex as it is, is not able to explain all the observed phenomena. Even when we allow for effects caused by the nonspherical shapes of the components, by reradiation effects, and by such factors as gravity effects and limb darkening, in many cases we find effects in the light curve which cannot be explained without assuming intrinsic changes in the stars themselves or the presence of great circumstellar streams or shells surrounding one or both of the components.

Sometimes these complications are relatively easy to detect through photoelectric observations, and some have even been detected by methods of lower accuracy. The eclipsing system UX Monocerotis, for example, shows almost continuous erratic fluctuations of light. In some instances the brightness has been observed to increase 15 to 20 percent in less than 15 minutes. Independent photoelectric studies have been carried out at three different observatories, and it is clear that the changes are really changes in the light from the star and are not caused by variations in the transparency of the earth's atmosphere. Intrinsic fluctuations have also been reported for DQ Herculis. This is an old nova which was found by Walker to be also an eclipsing binary. A long list of such systems could be named, ranging from such relatively large variations to changes of the order of 1 or 2 percent in the shape of the light curve. When the variations are this small, it becomes extremely difficult to separate real changes in the star from fluctuations introduced by the earth's atmosphere. Indeed, almost every system which has been observed precisely at different epochs shows some changes which seem to be connected with intrinsic changes of at least one of the components. Careful inspection of Fig. 1, for example, shows that in portions of the light curve the observations on 15, 16, 17, and 18 May do not duplicate precisely those on 30 March and 9–10 April. Even larger changes are shown between this light curve and one obtained of the same system in 1955. Perhaps this is not surprising when we consider the conditions which must exist when two stars are moving around their common center of mass with periods of a few days or even a few hours and with their surfaces separated by a distance which often is only of the order of one stellar radius and frequently is considerably less. To account for such changes, we need new treatment, taking into account the presence of circumstellar material and of disturbances on the stellar photospheres.

In summary, we may say that current photoelectric work on eclipsing stars is characterized by four main developments: the determination, with such precision as is permitted by the atmosphere and by the stars themselves, of the elements of the system; studies of irregularities in the light curves and of sudden changes of period of revolution; the use of narrow band filters to isolate special regions of the spectrum and the extension of observation in the infrared to as far as the 1.6-micron

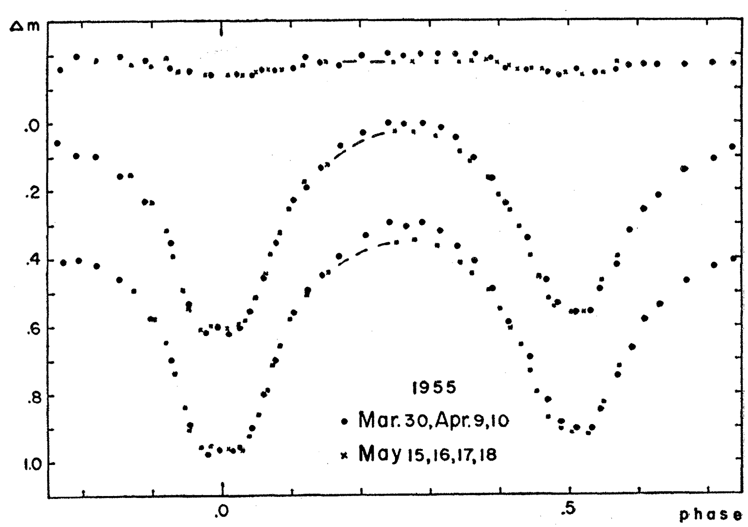

Fig. 1. Light curve of the eclipsing variable AH Virginis. The two lower curves are photoelectric observations in the blue and yellow regions of the spectrum, respectively. They were made by L. Binnendijk at the Flower and Cook Observatory of the University of Pennsylvania. The entire period of light variation is less than 10 hours. The upper curve is the "color curve." This system appears slightly redder at the times of minima than at other parts of the curve. Note that in slightly more than a month, detectable changes occurred in the light curve.

atmospheric window; and international cooperative campaigns in which photometric and spectroscopic observers around the world concentrate for a while on one particular system in an attempt to keep it under extended, continuous observation for a specified interval.

Intrinsic Variables

Studies of intrinsic variables by photoelectric means came later and formerly were less common than work on eclipsing stars, but here too the photoelectric work has had a strong impact on the field. As would be expected, in part its value has been in the detection of details of light and color changes too small or too rapid to be detected by photographic methods. In their authoritative chapter on intrinsic variables in volume 51 of the *Handbuch der Physik,* Ledoux and Walraven remark that perhaps no photometric observations ever made have been used as frequently as the six-color photoelectric observations made by Stebbins and his collaborators on the pulsating stars, δ Cephei, η Aquilae, and RR Lyrae. In a star of this type, the radius alternately increases and decreases as the star expands and contracts in a periodic variation. During contraction the atmosphere becomes hotter because of the compression and hence gives off more light per unit area. It also tends to give off less light because of the decrease in surface area, but this is more than overcome by the temperature effect. During expansion the reverse effects occur. However, simple pulsation of the star as a whole fails entirely to explain many of the observed effects. Modern pulsation theory is extremely complex, making use of such phenomena as shock waves spreading outward through successive layers of the star, but it is still far from successful in explaining all the observed phenomena. Precise observations of light changes, especially the multicolor kind, which take advantage of the relatively long wavelength range over which photoelectric cells are sensitive, frequently bring to light new phenomena to be explained. For example, those of Stebbins and his collaborators showed the maxima arriving at different times in the different wavelength bands. From the light, color, and velocity curves, it is also possible to compute mean radii of these pulsating stars. Other studies have shown differences in the light curves of pulsating variables belonging to different stellar populations and hence presumably of different ages.

Still another use in the study of intrinsic variables lies in the study of stars which show rapid and irregular variations. These fall into various categories. Some, such as AI Velorum or SX Phoenicis, show double or multiple periodicity. An interesting analysis by Walraven of the light curve of the former was possible chiefly because he could follow the variation continuously, using a photoelectric photometer which he had designed for the purpose. In order to study these rapid changes it is necessary to have a continuous record of events rather than the sort of integration provided by photography. SX Phoenicis, for example, on occasion doubles in brightness in less than 20 minutes.

In addition, photoelectric methods are important in studying so-called flare stars of the UV Ceti type. While such stars can be detected by other means (indeed, the variation of UV Ceti itself was first observed by Joy in 1948 on a spectrogram), photoelectric methods are needed to record changes accurately and in detail. In these stars, increases of more than a magnitude take place in 5 minutes or even less. The known stars of this type are late type dwarfs of extremely low luminosity. The rapidity of the changes implies that only a small part of the surface is involved. It has been pointed out that we cannot be certain whether such flares are confined to these stars or whether the low intrinsic brightness of the stars makes the flares more easily detectable than in brighter stars. It would be interesting, although tedious, to follow carefully somewhat brighter dwarfs in the hope of detecting changes similar in form but smaller relative to the star's luminosity.

These are only a few examples of the advances made possible in the study of intrinsic variables by the precision of photoelectric methods and by the fact that, by using appropriate filters, it is possible to observe color changes as well as light changes. In addition to aiding greatly in studies of well-known types of systems, photoelectric techniques have made possible the discovery of hitherto unsuspected types of variable stars—those whose variations of light are very small, so that they may be detected only by the most precise measures. For example, some stars, in addition to other peculiarities, show evidence in their spectra of very strong magnetic fields. In most of these stars the magnetic field varies very rapidly, sometimes in a period of a few days. These variations are accompanied by light variations, and the study of these can be of great importance in determining whether the variation is periodic or irregular and, if periodic, in determining the value of the period. Actually, relatively little photoelectric work has been done to date in this field in comparison with many others, but it is an important one and we may hope for increased activity in the future.

Stars of still another type—the β Cephei or β Canis Majoris variables—show small light changes (and associated spectral changes) occurring in a space of 5 or 6 hours. Some of these changes are periodic; in others, two periods seem to be presented, and the resulting light changes are a beat phenomenon. It would be easy to continue at length, but the preceding paragaphs should show the importance of photoelectric methods in studies of intrinsic variables.

Our Galaxy

In addition to analysis of individual variable stars, we find photoelectric techniques now widely used in studies of the structure of our own galaxy. Our solar system is located within this great assemblage of roughly 100,000 million stars, and the problem of discovering details of the size and structure of the galaxy is a difficult one.

In this work, variable stars again appear, because in addition to being of interest as individual objects they are useful for determinations of distances within our own galaxy and between other galaxies and our own. The distances to globular clusters, for example, are determined chiefly through the study of RR Lyrae variables in these clusters. While there is still discussion as to the precise value, the intrinsic luminosity of these variables is known to a reasonable degree of precision. Thus, by measuring the apparent brightness of these stars, the distances to the clusters can be computed by simple application of the inverse-square law, and the more accurate our observations are, the more precisely are the distances known. The inverse-square law, of course, ignores the fact that some light may have been absorbed by interstellar dust clouds near the plane of the Milky Way, but here again the photoelectric method comes to our aid. Because of the size of the particles, the blue light from the distant stars is scattered more strongly than the red, and an initially blue or white star will appear red. The observed color of the star can be measured with precision by photoelectric cells and appropriate filters. Since we know the normal colors of the RR Lyrae stars by studies of nearby samples, we can compute the amount of reddening. There is a known relation between this and the total absorption, so that we can allow for the latter and compute the correct distance.

While this method applies to the distant clusters, much of our knowledge of the structure of the Milky Way system in the neighborhood of the sun has come from star counts—that is, counting the number of stars in given areas brighter than a certain apparent magnitude, repeating for one magnitude fainter, and continuing the process. The method goes back to the time of Herschel, but its chief application came from the development of photography and through methods introduced by Kapteyn. One of the chief weaknesses of the photographic method lay in the uncertainties in the magnitude scale. These uncertainties can now be greatly reduced by the establishment of sequences of standard stars whose brightness has been measured photoelectrically. Astronomers in many places are now busy establishing such sequences for various regions. Further, as first shown by W. Becker, measures in three colors allow us to eliminate the reddening effects just described and to determine the true color of the star. Indeed, Stromgren's six-color photometry, with narrow-band interference filters centered in carefully selected critical regions of the spectrum, gives both luminosity and spectral class to a high degree of precision. Thus, while we will probably have to rely on radio waves for studies of more distant portions of the galaxy, photoelectric methods promise a great deal of help in studying details of interstellar material and star distribution in the neighborhood of the sun.

Stellar Evolution

Finally, the precise measurement of magnitudes and colors of stars in clusters has provided important observational evidence concerning stellar evolution. From the measured color-magnitude array (a plot of absolute magnitude or intrinsic luminosity against color) it is actually possible to determine the age of the cluster.

When such a plot is made for the stars in the neighborhood of the sun, most of the stars lie on a band which comprises the familiar "main sequence." This runs progressively from very hot, extremely bright blue stars to very cool, extremely faint red stars. We can measure the amount of radiation from the hot, bright stars and compute the rate at which they are using up their fuel (hydrogen) by converting it into helium plus energy. This rate is very high indeed and for the hotter stars ranges up to many thousands of times the rate at which the sun is exhausting its hydrogen. Yet the masses of these stars, and hence the amounts of fuel available, do not exceed the mass of the sun by anything like this amount. With a very few possible exceptions, 40 times the solar mass is an exceedingly generous estimate for the mass of such a star. Simple arithmetic based on the amount of hydrogen available and the rate at which it is being consumed gives us the upper limit of the age of such a star. In extreme cases this may be of the order of only 10 million years or so. At the end of this time, the hydrogen in the core of the star will have been converted into helium, and changes will begin to take place deep in the interior. It is not in order here to follow in detail these changes and their results upon the visible surface of the star; suffice it to say that the star will evolve rather rapidly and will move from its place on the color-luminosity diagram.

Now we find such stars in the neighborhood of the sun only because the sun is in or near one of the great spiral arms of our galaxy which contains immense clouds of gas and dust. It is from such clouds that the stars must be born. But the globular clusters, for the most part, are singularly free from gas and dust. Thus, it is not surprising now (although it was when the discovery was first made) that, when we plot the color-luminosity diagram of a globular cluster, such bright blue stars are absent.

Detailed computation of stellar interiors, such as those which have been carried out by Schwarzschild and his collaborators, tell us the rate at which a star exhausts the hydrogen in its core. This rate depends on the mass of the star and proceeds very much more rapidly for the more massive stars. For a star of any given mass (and hence, in general, of a known related luminosity) there can be computed the length of time which must elapse before the star in the course of its evolution moves away from the main sequence. When we observe the globular clusters, we find that a large part of the upper main sequence is absent, since the stars originally there have moved elsewhere. Comparison of the observed results with the theoretical computations gives us the age of the cluster. Further, observation of the position on the diagram of the cluster stars which are no longer on the main sequence gives us a clue as to what happens to the stars in the course of their later evolution.

We can apply the same treatment to galactic clusters, but here we get a greater variety of results. One or two show a color-magnitude diagram resembling the globular clusters and thus appear to be of almost the same age. In most of them, however, much less of the upper main sequence is missing; just how much gives us the age of the cluster. In the very youngest, the entire main sequence is present, including the bright blue stars. In these youngest clusters it is the lowest part of the main sequence which does not fall in the normal position. Since the rate of contraction depends on the mass of the star, this finding seems to indicate that these stars of low mass have not yet had time to complete their contraction stage and to attain the combination of radius and surface temperature which they, spending their hydrogen slowly, will have for many billions of years.

Other Applications

This has been a rather brief survey of some of the ways in which the use of photoelectric cells have aided in modern astronomy. Any astronomer reading this will note many omissions. I have not discussed photoelectric measures of either the nearby planets or of the distant external galaxies. Photoelectric cells used as aids in guiding or in measuring photographic plates have not been discussed, nor have photoelectric cells used in conjunction with prisms or gratings. Photoelectric work in the infrared has been omitted, and no attention has been given to the development of image intensifiers and various other developments. Even the topics treated have been treated sketchily. Comprehensive coverage is no longer possible in an article of reasonable length. But before closing I do want to mention one possible development of the future which may have considerable impact in the field of eclipsing and intrinsic variables and that is the entry of intelligent and enthusiastic amateur astronomers into the field of photoelectric astronomy.

Amateur Astronomers

For centuries, amateurs have made worth-while contributions to astronomy. Among them have been a few great names such as Herschel, Goodricke, and Lord Rosse and, in addition, a host of other individuals who have spent their free time in making and reporting observations. Today amateurs are organized in groups large and small, and a great many cities have their astronomical units. On the national scale the organizations include the American Association of Variable Star Observers (AAVSO) and the Astronomical League. Such organizations are by no means confined to this country. The Southern Hemisphere has the Royal New Zealand Astronomical Society and the Astronomical Society of Southern Africa, as well as various groups in South America. England has produced active amateur astronomers for centuries and has, like almost every country in Western Europe, organized associations of amateur astronomers.

Further, the contribution of amateurs to the field of variable stars has been particularly great. Some organizations, such as the AAVSO, the New Zealand Society, and the amateurs in Berlin, issue their own publications. In other cases (R. Weber in France and G. Romano in Italy are examples), amateurs publish their discoveries in professional journals. To date, the bulk of such work has been done almost entirely by visual and photographic means. But there is no reason why amateurs cannot now build simple photoelectric photometers and use these with telescopes of moderate size to observe the brighter variable stars. Indeed, the *Publications of the Astronomical Society of the Pacific* have carried light curves of variables observed by an amateur, J. J. Ruiz, with equipment built by himself, and a handful of other amateurs are engaged in taking similar measures. If any appreciable number of amateurs become thus engaged, they can by sheer force of numbers do what all the professional astronomers in the world cannot do—keep under reasonably constant surveillance a considerable number of the more interesting of the brighter variable stars.

Conclusion

In closing I should probably try to predict what studies made with instruments that take advantage of the photoelectric effect may be expected to accomplish in the future, but the potential advances in instrumentation are so wide that it is not possible to predict with any confidence what the most useful applications will be, and a list of possibilities would be unduly long. Perhaps the most obvious field is the development of image intensifiers. Experimental work, which began with Lallemand at Paris and has now spread to several observatories, shows that image intensifiers are indeed practical and that, by greatly increasing the quantum efficiency of the receiver, they can indeed for many (but not all) purposes make large telescopes out of small ones—that is, permit telescopes of very modest aperture to do work which was previously possible only with the larger ones. Scanning devices, such as those developed by McGee at London, may also play their part. Whatever the details, it is certain that much of the future of observational astronomy will be written by astronomers making use of equipment which takes advantage of the photoelectric effect.

Integration of Circuit Functions into Solids

The trend in electronic circuit construction is toward microminiaturization and molecular electronics.

S. W. Herwald and S. J. Angello

The development of electronics has, since the beginning, featured progress in reducing the size and weight of equipment required to perform a given function. Substantial progress was made during World War II with the introduction of miniature and subminiature tubes. Unfortunately, mere reduction in size often leads to problems in component handling and assembly which result in increased costs and in less reliability than is found with the larger circuit function. The problem of reliability has become of such importance that recent developments have put this item ahead of size reduction in the list of objectives.

In this article we discuss the techniques which have been developed over the last decade to accomplish reduction in size and, at the same time, increase reliability, with a future potential for cost reduction. Emphasis is placed on circuit functions in solids, for this technique is in the earliest stage of research and development and shows great potential for the future.

Why Make Circuits Smaller?

One straightforward answer to the question "Why make circuits smaller?" may be found in Fig. 1. The complexity of systems is becoming very great. Pre-1940 electronic techniques will not satisfy the space requirements of the B-58 airplane. Even in ships, where one might imagine there would be no limitation on space, the problem of the size of electronic equipment is receiving attention. Space and weight restric-

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