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NEW METHODS IN THE STUDY OF STELLAR SPECTRA[1]

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THIS year marks the one hundredth anniversary of one of the greatest contributions to astronomy: In 1844 Bessel published a paper on the *Astronomische Nachrichten* in which he showed that the slow angular proper motions of Procyon and Sirius are slightly irregular and that in the case of Sirius the departures of the observations from uniform, rectilinear motion are suggestive of a period of fifty years. Eighteen years later Alvan G. Clark discovered a faint companion to Sirius in the place predicted by Bessel's successors. The period of this companion, according to a recent orbit by Volet, is 49.94 years—almost precisely the value deduced by Bessel. The extraordinary physical character of the companion of Sirius—the first white dwarf known to astronomers—has been the subject of many recent investigations on the structure of the stars and on the properties of matter in the degenerate state. These remarkable advances in physical science were possible because Sirius is not a single star, but is a binary pair in which the brilliant primary serves as an indicator of the distance, size and mass of the system. The fundamental contribution by Bessel consisted in the use of a new method: The proper motions were used to reveal the existence of an invisible (until then) companion.

It is appropriate that in view of this anniversary I should devote my address to a description of several new methods which have been of help in our investigations of double stars. We are no longer dependent solely upon visual observations of wide pairs which can be resolved in our telescopes or upon accurate proper motions to infer the existence of invisible companions. Photometric measurements of the brightnesses of certain stars show periodic oscillations which can only be explained if we assume that in a close unresolved pair the plane of the orbit lies in the line of sight and that each component eclipses the other once

[1] Address of the retiring vice-president and chairman of Section D of the American Association for the Advancement of Science (1943).

in every revolution. An even more powerful tool is the spectrograph which permits us to measure the Doppler displacements of the spectral lines and to determine whether these displacements are constant or variable. If they are variable and periodic the presumption is great that we are observing a binary whose velocity component in the line of sight reflects the direction and the speed of the star in its orbit. About one thousand eclipsing variables have been discovered and their periods and minima of light determined. For nearly four hundred stars the spectrographic orbits have been determined. But only about sixty stars are common to the two lists. Every eclipsing variable must, of course, be a spectroscopic binary, but only those spectroscopic binaries whose inclinations are sufficiently close to 90° are eclipsing variables.

On June 23, 1880, Professor V. K. Ceraski, director of the University Observatory at Moscow, Russia, noticed that an inconspicuous star in the constellation Cepheus was very much fainter than on several preceding nights. He noted it as a variable star and soon established that the variation in light repeated itself every two and one-half days. In conformity with the usual practice the star was designated by a capital letter of the Roman alphabet and it is now known as U Cephei. During the past sixty-four years a large number of visual and photographic observations of the light curve have been made at various observatories. The star is of the eclipsing type: The partial phase, when the disc of the larger but fainter star gradually encroaches upon the brilliant disc of the smaller star, lasts about four and one-half hours. During this interval the brightness of the star is reduced to about one tenth of its normal value. The drop in brightness is especially rapid in the later stages of partial eclipse, and it is thrilling to see the light going out as one observes U Cephei in a small telescope. During totality, which lasts two hours, the light comes entirely from the dim and yellow companion. Then during another four and one-half hours the disc of the bluish primary is gradually uncovered and eleven hours after the beginning of the eclipse the light is normal. Thereafter, for forty-nine hours, the light undergoes only minor fluctuations. In particular, when the brilliant primary is in front of the dim companion the total light is reduced by less than one tenth of its normal value. In fact, the depth of the principal eclipse is roughly one hundred times greater than the depth of the secondary eclipse.

In spite of this disparity both eclipses have been observed by a number of competent observers among whom the late Professor R. S. Dugan, of Princeton, and Professor R. H. Baker, of Illinois, deserve special credit. The secondary eclipse occurs almost precisely half-way between two primary eclipses. This information is important. It tells us that the orbit of U Cephei is either circular, so that the motions of the stars are uniform, or if it should be elliptical the periastron must be either at its nearest or its most distant point from the earth. We describe this condition by saying that the product e.cos ω of the eccentricity times the cosine of the angle which measures the longitude of the periastron is close to zero. The photometric observations do suggest a small departure from zero, but this departure is only consistent with a value of the eccentricity not larger than 0.08.

The spectrographic orbit of U Cephei was determined in 1930 by Professor E. F. Carpenter, of Arizona, from photographs taken at the Lick Observatory. The Doppler displacements turned out to be periodic, as they should in a binary, but the shape of the resulting orbit was very unsymmetrical. The eccentricity was almost 0.5 and the periastron occurred near the ascending node of the orbit, that is, about 90° from the nearest point and 90° from the most distant point in the orbit. The angle ω is measured from the node, not from the nearest point of the orbit. Hence, ω was close to 0° and cos ω = 1. The spectroscopically determined value of e.cos ω was, therefore, almost 0.5—completely at variance from the photometric value.

This discrepancy has worried astronomers for the past fourteen years. No one knew whether Carpenter's results were correct, but every one agreed that the photometric observations could not be in error. Unfortunately, there are in existence only half a dozen spectrographs, at the most, which are sufficiently powerful to record the spectrum of U Cephei with sufficient dispersion to analyze and measure its absorption lines and most of these are overburdened with work. Yet, the question is a rather important one: If we can not trust the spectrographic orbit of U Cephei, how can we be sure that other spectrographic orbits give us the true elements of the hundreds of binaries for which they have been determined?

I have recently obtained a long series of spectrograms of U Cephei at the McDonald Observatory in Texas. The spectrum is that of a star whose temperature is about 18,000° C. and whose spectral lines are very diffuse and shallow. We associate this appearance of the lines with rapid axial rotation of the star; and by comparing its lines with those of other stars we infer that the primary component of U Cephei rotates with a velocity at the equator of about 200 km/sec. This is about one hundred times faster than the rotational velocity of the sun, but it is not unusual among the hotter stars. The spectrum of the secondary component is too faint to be photographed except with the long exposures which are necessary during totality. These long exposures show a spectrum of the solar type, characterized by a temperature of about 5,000° C. The lines of this star are sharp and the equatorial velocity of its rotation is less than 50 km/sec.

Now, the photometric observations give us the ratio of the radii of the two components. This quantity is derived in a very simple manner from the durations of the partial and total phases of the eclipses, and it is one of the most reliable results of the photometric analysis. The observations show unmistakably that the hot star has about one half the size of the cooler star. Yet it rotates more than four times faster. Clearly, the periods of rotation of the two stars are not the same and at least one of these can not be synchronized with the period of revolution of the binary. This is a most extraordinary result which no one had expected: The components are quite close to one another; their surfaces are separated by less than one radius of the larger component. It had usually been thought that in such a close binary pair the periods of rotation and of revolution must coincide and, if they do not, the system will rapidly follow the theoretical scheme of binary evolution with a gradual approach toward synchronization. As a matter of fact, the great majority of spectroscopic binaries do show strong evidence of synchronization, and U Cephei is definitely abnormal.

The velocity curve which I derived from my measures of U Cephei shows another effect of rapid rotation. In the two partial phases of the eclipse, when the disc of the primary is partly covered by the darker disc of the secondary, the lines of the primary are unsymmetrically displaced: Just before totality we observe the receding limb of the primary; immediately after totality we observe the approaching limb. This phenomenon had been previously observed in other stars. But I was not prepared to find that in U Cephei this effect completely distorts the descending branch of the velocity curve, so much so, in fact, that it is difficult to derive reliable elements of the spectrographic orbit.

Nevertheless, I believe that my observations conclusively show that the spectrographic observations are not consistent with the photometric results: The velocity curve is unsymmetrical in the sense found by Carpenter, although the degree of asymmetry is less than was found by him. What, then, is the cause of the discrepancy?

When I carefully examined the spectral lines of U Cephei during the partial phase I noticed that the hydrogen lines looked very unsymmetrical: Before totality they seemed to possess a narrow and well-defined core to the violet of the center and after totality they had a much stronger and broader core to the red of the center of the line. I at first thought that this asymmetry was produced by the Schlesinger-Rossiter-McLaughlin rotation effect, but a more careful study of the theoretical line contours convinced me that in U Cephei the asymmetry would be least just before and after totality, while the opposite was observed on my plates. I decided that the narrow cores before totality and the broader cores after totality must come from two streams of gas; the one receding, the other approaching. The cores gave no indication of Stark effect broadening. Hence, I believe, the streams have very low pressures. They can not be simply the atmospheric limbs of the eclipsing secondary because their displacements are too large to accord with the small rotational velocity of the secondary. It is most probable that the streams flow from the cool star toward the hot star, and from the hot star toward the cool star. In other words, the observations suggest that the two stars are not completely separated, but are joined by a tenuous common atmosphere in which currents may be set up in a manner analogous to those investigated theoretically by Kuiper and observationally by me in the famous binary system of β Lyrae.

It is perhaps not unreasonable to suppose that if gaseous currents can distort the spectral lines in the partial phases of the eclipse, they may do so outside of eclipse, and thereby render the descending branch of the velocity curve steeper than the ascending branch.

In U Cephei this hypothesis remains without confirmation. It is a possibility, but we lack other observational data to verify it. We, therefore, turn our attention to another remarkable eclipsing variable, SX Cassiopeiae. This binary consists of a small, hot primary and a large, cool and dim secondary. The period is 36 days and the secondary eclipse is exactly halfway between successive principal eclipses. Photometrically $e \cos \omega = 0$. The spectra secured at the McDonald Observatory show $e = 0.5$, $\omega = 10°$, so that approximately $e \cos \omega = 0.5$. The results are incompatible and we have precisely the same situation as in U Cephei.

But SX Cassiopeiae shows in its spectrum a series of emission lines of hydrogen and other elements. Such lines are not present in U Cephei because the size of the latter's system is much smaller than that of SX Cassiopeiae, and the intensity of an emission line depends upon that part of the volume filled with gas, which is not projected upon the apparent disc of either component star, as seen from the earth. The emission lines are double, showing that there exist two streams of nebulous matter, one receding, the other approaching. Before totality the violet emission lines become weaker, while after totality the red emission lines become weaker. This undoubtedly represents the eclipse of an approaching stream before totality and of a receding stream after totality. The existence of the streams is proved beyond doubt; they flow from the cool star along the following side of the hot star and return along its preceding side, after making a complete circuit.

The interesting thing about SX Cassiopeiae is that we can actually link these streams with the anomalous velocity curve and attribute to the streams the distortion of the spectral lines which makes the velocity curve unsymmetrical and appears to give us a large eccentricity. We are making use here of a very new and interesting tool of astrophysical research, which has already produced valuable results in a number of problems. This tool is designated as the dilution effect. It permits us to determine whether an absorbing mass of gas is on the surface of a star, or at some distance above the surface. The relative intensities of certain spectral lines—Mg II, Si II and He I—in a source whose dilution we wish to determine are compared with those produced in an ordinary stellar atmosphere. The ratio of the total intensities is inversely proportional to the square of the height of the source above the photosphere of the star. In SX Cassiopeiae the dilution test showed that at the time of secondary eclipse we are observing not the pure, undisturbed spectrum of the hot star, in front of the cool star, but a composite spectrum consisting in part of lines produced in an approaching stream—that is, in a stream receding from the hot star—at a considerable height above the photosphere. The measured radial velocities were not those of the hot star alone but were in part those of the moving stream. The velocity curve, in consequence, was greatly distorted and did not represent the orbit of the binary system.

The advances which I have described were possible because we had at our disposal two new methods: the method of stellar rotation and the method of the dilution effect. When a star rotates as a solid body (which it probably does not, though the approximation may be good enough for most purposes) around a fixed axis, all points on the apparent disc which are located at the same distance from the projection of the axis have the same radial component of rotational velocity. The broadened spectral line, therefore, serves in the nature of a spectroheliograph: Each point on the line-profile comes from a definite vertical strip on the disc of the star. If the star's atmosphere is not everywhere the same, in temperature or density, the shape of the broadened line should reveal the difference. An effect of this kind has been observed in U Cephei. The spectral lines of U Cephei prior to totality are systematically weaker than after totality. This must mean that the receding half of the star as seen at principal eclipse has weaker lines than the approaching side. We already know that the hot companion of U Cephei rotates very rapidly. Hence (as was long ago suggested by Dugan from photometric inequalities in the light curve) the tidal bulge of the star may be carried forward by the rotation and is seen before totality. We do not know why the lines originating above the bulge are weaker than those coming from other parts of the star's atmosphere. But we have isolated an interesting astrophysical phenomenon and made it susceptible of theoretical treatment.

The methods of rotation and dilution were helpful in the solution of another recent puzzle. In 1928, Dr. M. L. Humason and Dr. S. B. Nicholson of the Mount Wilson Observatory determined the period and the spectrographic elements of a new spectroscopic binary designated as HD 163181. In 1938, Dr. S. Gaposchkin at Harvard found that this star is also an eclipsing variable, the period in light agreeing exactly with the period of the spectrographic orbit. The spectrum shows absorption lines of one star only; the other component registers no absorption lines in the spectrum. The radial velocity of the brighter star is variable. As it recedes from the earth and gradually reaches the most distant point in the orbit it reaches the time of superior conjunction. At this time the star may undergo an eclipse if the inclination is suitable. Gaposchkin found two eclipses: a slightly deeper one when the star is at inferior conjunction; the secondary when it is at superior conjunction. This result appears paradoxical because the spectrographic results predict the principal eclipse at superior conjunction and also make it probable that the secondary eclipse should be very shallow.

In order to resolve this difficulty new spectrograms were obtained at the McDonald Observatory. The velocity curve clearly shows the rotation effect before and after superior conjunction. Hence, there can be no doubt that the principal star is actually eclipsed when it stands behind the secondary component.

The spectrum of HD 163181 is not especially remarkable, but it does show several points of interest. The lines of hydrogen and helium have red emission borders; these disappear or become very weak at inferior conjunction, and are relatively strong at superior conjunction. The absorption lines, on the other hand, are strengthened at inferior conjunction and are weakened at superior conjunction.

We first examine the variation of the absorption lines. The dilution effect shows at once that the absorbing gases are on the surface of a normal star; they are not produced in a nebulous shell or stream. We infer that they are weakened at superior conjunction because the primary component is then eclipsed. They are strengthened at inferior conjunction because at that time the continuous spectrum of the eclipsed secondary component is invisible and the lines are free of blending with continuous light of the secondary. Similarly, the emission lines are strong at superior conjunction because they must belong to the secondary component and these lines are weak at inferior conjunction because at that time the secondary component is eclipsed.

The result of this study is the discovery of an unusual kind of star. The secondary component of HD 163181 has a strong continuous spectrum with weak emission lines, but without perceptible absorption lines. The interpretation of the spectrographic observations would have been easier if there had not been another complication: The emission lines of the secondary show a permanent red shift of some 100 km/sec. with respect to the absorption lines of the primary. This phenomenon had previously been found in two or three other stars, but its origin is unknown.

OBITUARY

DAVID EUGENE SMITH

(AN APPRECIATION)

IN the passing of Dr. David Eugene Smith, who died in New York on July 29, the world has lost a profound scholar and a distinguished teacher. Dr. Smith's accomplishments were so unique and varied that he not alone enriched his own life but also the lives of thousands of his pupils and admirers the world over. His life is worthy of a full volume of many pages, instead of a few pages as here permitted. Others undoubtedly will express appreciation of Dr. Smith's mathematical accomplishments in research and teaching, but this sketch will take the more special phases of his life work into consideration. He made, of course, no distinction in his life's activities; that is, he did not overemphasize one activity against the other. He was equally energetic as teacher, research worker, book collector, connoisseur of portrait prints and manuscripts, bibliographer, traveler and genial host to his many fortunate friends. If ever a man enjoyed a full life, surely Dr. Smith accomplished that.

In reviewing these many and varied activities and their results, one is sure to find only one theme or subject controlling his life. This subject was mathematics in its many ramifications. It received the full benefit of his keen analytical mind, although his method was synthetical in producing results. These results are well known to scholars, particularly in the form of books and special monographs. He may not be famous as a great mathematician in the technical aspect, but to the world of scholarship he will ever be known as the "Great Humanist in Mathematics."

May we not say, in his own words which he spoke concerning Newton at the bicentenary celebration in 1927, as chairman of the program committee and as presiding officer in the opening address: "When we review his life, his idiosyncrasies, his periods of contrast, . . . may we not take some pleasure in thinking of him as a man—a man like most other men save in one particular—he had genius—a greater touch of divinity than comes to the rest of us. Few men have ever lived who explored so successfully as wide a range of human activities and few who could so justly have used the well-known phrase, *Homo sum, et nihil humani a me alienum puto.*" Dr. Smith too had genius in a degree, though of another kind.

(a) He had capacity for friendship and hospitality.

(b) He had capacity to inspire and aid scholars.

(c) He had appreciation of the works of others.

(d) He had capacity for recognizing beauty in mathematical prints and instruments and in Oriental art books.

(e) He had capacity for organization and administration.

Dr. Smith was not a Newton scholar in the technical aspect, but a Newton in the discovery of the humanistic and in the interpretation of the very abstract thoughts of mathematics. His range was from the elementary to the advanced, for he could teach the child to understand numbers as well as discuss abstract formulas with the graduate student. The classroom was not his only sanctum for teaching; his home—his country—and in fact the world, for he lectured whenever called upon, in New York, Paris, Arabia or Yokohama.

His historical writings are authoritatively manifested in his well-known "History of Mathematics" (Vol. I, "General Survey of the History of Elementary Mathematics"; Vol. II, "Special Topics of Elementary Mathematics"). And again, a more advanced treatise was his "Source Book of Mathematics." His little volume, "History of Mathematics in America before 1900," with Dr. J. Ginsberg, will always remain a standard source book. The constant use of these source books is revealed in the teaching research in our mathematical courses. A large number of smaller books and monographs on phases of teaching and history of mathematics are listed in a very complete bibliography of Dr. Smith's writings issued in the first volume of *Osiris,* presented to him to commemorate his seventy-sixth birthday in 1936.