DISCUSSION

THE PULSATION THEORY OF STELLAR VARIATION

ALTHOUGH pulsation of stars had been suggested some years earlier, its recognition as a probable cause of stellar variation dates from the demonstration by Shapley[1] that the dimensions of Cepheid variable stars were incompatible with an explanation in terms of orbital motion. Eddington[2] developed the mathematical theory, but a serious disagreement with observation was found. The theory indicated that the star should be at light maximum when it was smallest and at minimum when largest, since change of temperature would much more than offset change of size. The radial velocities, however, showed most rapid approach of the stellar surface (most rapid expansion) at light maximum and most rapid collapse at light minimum. In spite of the contradiction, the pulsation theory enjoyed wide acceptance and astronomers hoped that the difficulty would eventually be removed.

In the following discussion, in agreement with the conventional method of plotting the radial velocity curve, we shall use "velocity minimum" to mean greatest velocity of approach and "velocity maximum" to mean most rapid recession. On the pulsation theory, these two phases are most rapid expansion and most rapid collapse, respectively.

Eddington's solution corresponds to a standing wave throughout the star. The theory was modified by M. Schwarzschild,[3] who introduced the postulate of running waves in the outer less dense layers, while the standing wave solution was retained for the interior. For the type star, Delta Cephei,[4] the Schwarzschild theory gave excellent agreement with the observed correlation of light and velocity curves.

For the long-period variable star Mira (Omicron Ceti)[5] the velocity curve based on the absorption lines has its maximum at light maximum, just the opposite of the relation in Cepheids, and also in serious conflict with the older pulsation theory. The radiometric observations[6] by Pettit and Nicholson yield a computed velocity curve almost one half period out of phase with the observed absorption velocities.

The anomalous relative strengths of the bright hydrogen lines of long-period variables had long been recognized as an indication that the absorption may occur at much higher atmospheric levels than the bright lines. R. M. Scott[7] showed that the integration of the velocity curve of the bright lines of Mira gave a variation of the star's diameter that was in good agreement with the radiometric data and with the variation to be expected according to the Schwarzschild theory, since the minimum of emission velocity comes a short time later than maximum light. The absorption velocity lags about 150 days (about 0.4 period), which represents the time of travel of the running wave from the effective emitting to the effective absorbing layer.

We shall now show how several other observed relationships find a logical explanation in the running wave pulsation theory.

In 1923 at the University of Michigan Observatory, J. A. Aldrich[8] found that when absorption lines in the spectrum of the Cepheid variable S Sagittae were segregated according to the level at which the lines occurred in the solar chromosphere, the phases of the velocity curves of higher levels lagged relatively to the lower. The effect was soon found in Eta Aquilae[9] by Rufus and in W Sagittarii[10] by Curtiss. Similar effects have since been found in several other Cepheid variables, chiefly by observers at Michigan.[11] In this lag of phase of the velocity curves of higher atmospheric levels, we have clear observational evidence of the reality of the running waves which emerge from the stellar photosphere at light maximum and pass upward through the atmosphere.

The writer[12] pointed out that Cepheids, semiregular variables of intermediate period and long-period variables exhibit a "period-lag" relation. In the five-day Cepheids the velocity minimum is simultaneous with light maximum, but in Cepheids of longer period the velocity minimum comes about one tenth period later. This lag increases through the semi-regular stars, and in the long-period variable Mira (period 330 days) it is so great that velocity minimum comes at light *minimum*. Confirmation of the lag among the Cepheids was found by Joy[13] from very extensive observational material. The RV Tauri stars[14] as a class show a lag that is comparable to that of the Cepheids of longest period (about 45 days). The most regular example is AC Herculis.[15] The sequence continues

[1] H. Shapley, *Astrophys. Jour.*, 40: 448, 1914.

[2] A. S. Eddington, *Monthly Notices, Royal Astron. Soc.*, 79: 2, 1918; 177, 1919; 87: 539, 1927.

[3] M. Schwarzschild, *Circulars, Harvard Observatory*, No. 429, 1938.

[4] M. Schwarzschild, *Circulars, Harvard Observatory*, No. 431, 1938.

[5] A. H. Joy, *Astrophys. Jour.*, 63: 281, 1926.

[6] E. Pettit and S. B. Nicholson, *Astrophys. Jour.*, 78: 320, 1933.

[7] R. M. Scott, *Astrophys. Jour.*, 95: 58, 1942.

[8] J. A. Aldrich, *Popular Astronomy*, 32: 218, 1924; *Publ. Observatory, Univ. of Mich.*, 4: 75, 1932.

[9] W. C. Rufus, *Proc. Nat. Acad. Sci.*, 10: 264, 1924; *Publ. Observatory, Univ. of Mich.*, 4: 101, 1932.

[10] R. H. Curtiss, *Publ. Ast. Soc. of the Pacific*, 38: 148, 1926.

[11] See several papers in *Publ. Observatory, Univ. of Mich.*, Vols. 4, 5 and 6, by Rufus, D. W. Lee and R. M. Petrie.

[12] D. B. McLaughlin, *Astron. Jour.*, 40: 16, 1929.

[13] A. H. Joy, *Astrophys. Jour.*, 86: 363, 1937.

[14] D. B. McLaughlin, *Astrophys. Jour.*, 94: 94, 1941.

[15] R. F. Sanford, *Astrophys. Jour.*, 73: 364, 1931.

through R Scuti[16] (an RV Tauri variable with period 140 days), SX Herculis[17] and R Virginis[18] and ends with Mira.

The period-lag relation can be explained in terms of increased time of travel of the compressional wave from the photosphere to the effective absorbing layer. In five-day Cepheids the absorption takes place close to the photosphere; in long-period variables it occurs possibly 8×10^7 kilometers above the photosphere. In a series of stars from the five-day Cepheids to the long-period variables, the radii of the stars increase from about 20 to 500 times that of the sun, and the acceleration due to gravity at the photosphere decreases from about 500 to 2 cm/sec^2. Correspondingly lower density and greater volume of atmosphere is to be expected about the larger stars.

From measures made near the time of light maximum in the spectra of a large number of long-period variables, Merrill[19] established a relation between the period and the amount of displacement of the emission lines towards the violet relative to the absorption spectra. With increased period of variation, the emission shows an increased difference of radial velocity, in the sense that it is approaching, relatively to the absorption. This effect also finds a plausible explanation in terms of the running wave theory and the Scott model of a long-period variable with the emitting layer far below the absorbing layer. In the long-period variables of shortest period (about 120 days), the distance between the emitting and absorbing layers is relatively small; the travel-time of the wave, the difference of phase, and hence the difference of velocity, will also be small at any instant. For the larger stars of longer period, the difference of phase and hence the difference of velocity at light maximum will increase. This is because the minimum of emission velocity comes shortly after maximum light, but the minimum of absorption velocity is delayed long after maximum. A fluctuation of the correlation near a period of 250 days remains unexplained.

The radiometric measures by Pettit and Nicholson and the infra-red photographic observations by Hetzler[20] showed a marked lag of the date of light maximum of long-period variables for long-wave radiation as compared with the curves for visible light. A similar effect has just been announced by Stebbins[21] for Delta Cephei; light curves measured in six wave-lengths show a progressive delay of maximum for the longer wave-lengths. These observations are entirely compatible with the present pulsation theory, at least qualitatively. At light maximum and for more than a quarter of its period thereafter, the variable star is expanding. After maximum it is cooling. Two opposing tendencies are then in operation: expansion tends to increase the brightness, but cooling tends to decrease it. The cooling is the more effective in all wave-lengths, so that the star fades. According to the Planckian law, the cooling causes the most rapid fading in the shorter wave-lengths; this has the effect of making the maximum earliest in the short wave-lengths, latest in the long.

The more detailed explanation of the forms of light and radial velocity curves of different variables is not so readily forthcoming. But it can now be said that the pulsation theory of stellar variation has reached such a stage of development and of agreement with observation that we no longer need apologize for its remaining shortcomings.

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16 D. B. McLaughlin, *Publ. Observatory, Univ. of Mich.*, 7: 57, 1938.
17 A. H. Joy, *Astrophys. Jour.*, 75: 127, 1932.
18 P. W. Merrill and A. H. Joy, *Astrophys. Jour.*, 69: 379, 1929.
19 P. W. Merrill, *Astrophys. Jour.*, 93: 383, 1941.
20 C. W. Hetzler, *Astrophys. Jour.*, 83: 372, 1936.
21 J. Stebbins, *Astrophys. Jour.*, 101: 47, 1945.

THE PRESENCE OF ALLOXAN IN NORMAL LIVERS

ALLOXAN is readily prepared *in vitro* by the action of certain oxidizing agents on uric acid; since it is known to cause experimental diabetes in animals it was of interest to examine the organs of normal animals for its possible presence. To date, the only such observations, made many years ago, appear to be its detection in the gelatinous mucus from an intestinal catarrh[1] and in the urine of a heart patient.[2] In the vegetable kingdom it has been found (as the "half-reduced" form, alloxantin) in the hydrolysates from crude beet juice,[3] broad (fava) beans[4] and vetch seeds.[4]

A test which has been generally accepted for the identification of alloxan is based on the fact that on stepwise reduction it gives first alloxantin (a 1:1 compound of alloxan and dialuric acid) and then dialuric acid; if barium hydroxide is added to this reduction product, a purple color or purple precipitate is formed. Unfortunately, in the form described in the literature, this test is not well suited to the study of biological materials. We have now devised conditions under which, using as little as 1 cc of 0.01 per cent. alloxan monohydrate solution, this purple color is readily detectable by the naked eye; we have employed ascorbic acid or, preferably, cysteine hydrochloride as the reducing agent.

We next proceeded to examine a variety of animal

1 J. von Liebig, *Ann.*, 121: 80, 1862.
2 G. Lang, *Z. anal. Chem.*, 6: 294, 1867.
3 E. O. von Lippmann, *Ber.*, 29: 2645, 1896.
4 H. Ritthausen, *Ber.*, 29: 894, 2106, 1896; H. J. Fisher and T. B. Johnson, *Jour. Am. Chem. Soc.*, 54: 2038, 1932.