

IV

THE MILKY WAY

SINCE the star that varies in light plays a considerable part in the measurement of distances to the star clouds of the Milky Way and to external galaxies I shall describe in this section some of the current investigations of variable stars at the Harvard Observatory.

First it should be noted that the distance of a star is *simply related to its apparent magnitude*, as measured with reference to adopted standards, and to its absolute magnitude or intrinsic luminosity. When the intrinsic luminosity of a star can be determined from some characteristic of its light or behavior, it is a simple matter to measure the star's apparent magnitude and compute the distance. This method is used, as mentioned in Section II above, in the spectroscopic determinations of stellar distances, where the relative intensity of lines in the spectra gives the clue to absolute magnitude. The same procedure is used with variable stars, the intrinsic luminosity being judged on the basis of various observable properties.

For eclipsing variables the dimensions of the components, their relative brightnesses, and their spectral types help to fix the absolute magnitudes; for Cepheid variables the length of the period is the clue to the star's output of radiation, and a serviceable period-luminosity relation has been discovered. Fortunately, the various kinds of variable stars are giants or supergiants—they may be seen at great distances, and therefore become useful for measuring the remotest galaxies that our telescopes can resolve.

There are several important astronomical problems connected with the study of eclipsing binaries. We might mention, for instance, that the analyses of their light variations provide our chief source of direct information on the densities of stars; they tell of the stellar forms in tidally disturbed binary systems; they occasionally give the linear dimensions of stellar bodies, and they furnish much information on the sizes, shapes, and inclinations of the orbits of close double stars. From the light curve of an eclipsing binary we also deduce an estimate of the distance; and it is for this reason that eclipsing binaries become important in galactic explorations, since we frequently find such variables among the faintest objects on the photographic plates.

Orbits of more than a hundred eclipsing binaries have been computed from their light curves. Frequently the solutions are inherently indeterminate; at other times they are indefinite because of the low quality of the photometric observations on which the graphs of the periodic variations are based. In the past most of the light curves of eclipsing stars have been derived from visual observations. Relatively few good light curves have been based on photographic observations.

To improve existing light curves and to add new material for the further photographic study of eclipsing binaries a special research program was recently inaugurated at the Harvard Observatory with the assistance of a grant from the Permanent Science Fund of the American Academy of Arts and Sciences. Several thousand estimates of magnitudes have been made for ten or twelve stars and the computation of their orbits is under way. The light curves obtained from the photographic observations are of relatively high quality; the periods of variation have been accurately determined, sometimes to a millionth of a day. For

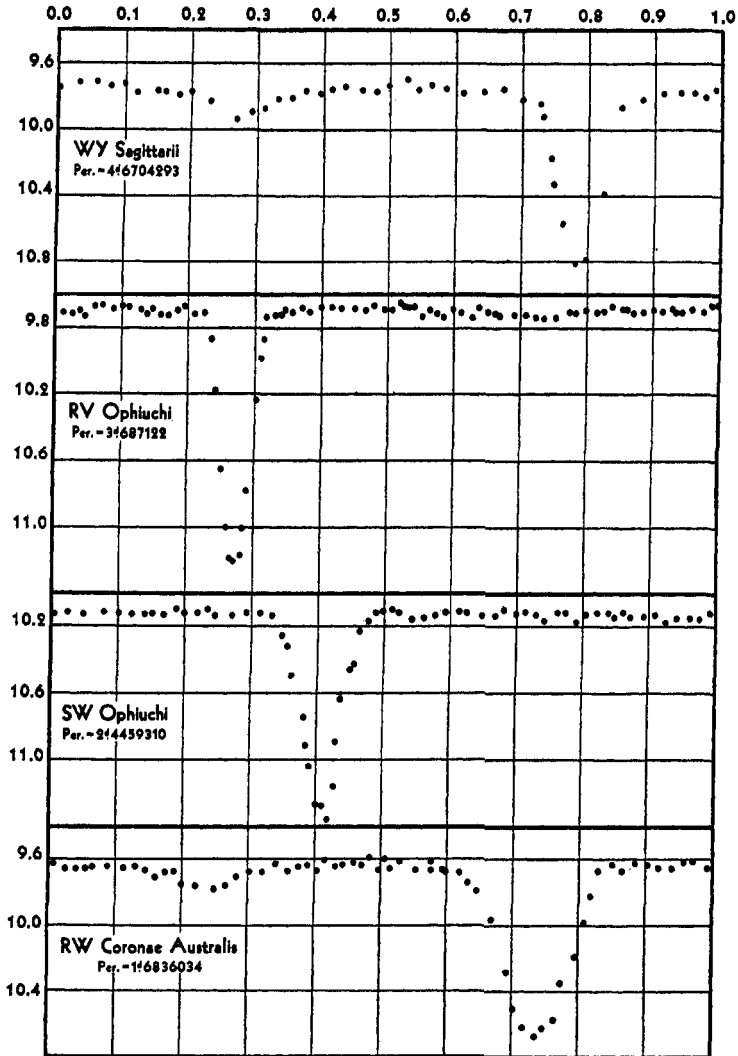


FIGURE 14. Light curves of eclipsing binaries. Ordinates are photographic magnitudes; abscissae are fractions of the periods.

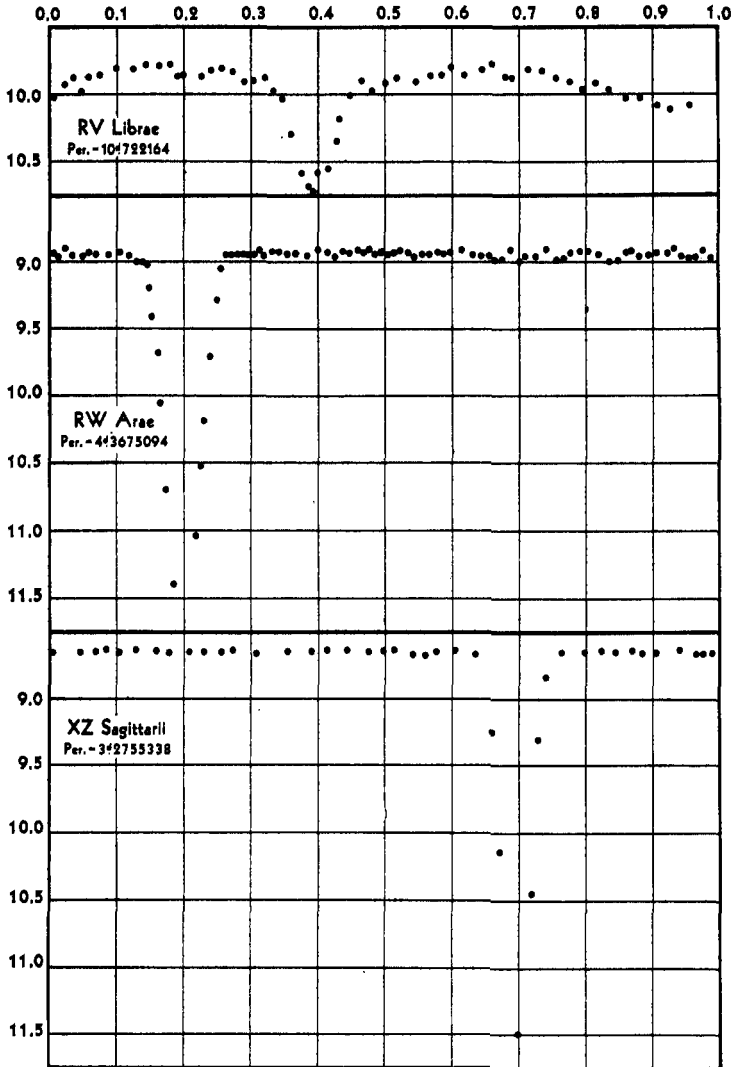


FIGURE 15. Light curves of eclipsing binaries.
 Ordinates are photographic magnitudes; abscissae are fractions of the periods.

some of the stars the observations show shallow secondary minima and the slightly rounded maxima that indicate the gravitational deformation of the component stars of the binary. In Figures 14 and 15 several of the new photographic light curves are shown. Each plotted point represents, in general, the mean of ten observations.

The analysis of these light curves will show that some of the binaries are composed of nearly equal stars, while the components of others are very unequal in size, most of the light coming from the smaller members. Some of the eclipses are only partial, while for others the small companion is completely occulted by the larger at primary eclipse and is projected fully on its disk at the shallow secondary eclipse.

The Cepheid variable star, which now has the distinction of being the astronomer's most important tool in measuring the universe, is found sparingly among the naked-eye stars, infrequently also throughout the local system, but in considerable abundance in and around the Milky Way star clouds, in the globular star clusters, in the Magellanic Clouds, and in the nearer of the spiral galaxies. The periods vary in length from a few hours to a month or more, and the longer the period the higher the luminosity and the redder the spectral class. When the periods are some weeks in length the stars are supergiants and, even when at a distance of a hundred thousand light years, can be recorded with moderate-sized telescopes.

The period-luminosity relation for Cepheid variables gives a simple way of estimating the distances not only of individual Cepheids but of the clusters and star clouds in which they are situated. Many observations must be accumulated, however, to permit the derivation of light curves

and periods. Frequently fifty or a hundred photographs of a Cepheid variable are necessary before the period can be determined, the apparent magnitude satisfactorily measured, and the distance deduced. Hence the work of exploring the Milky Way with the aid of Cepheid variables is a laborious process; but students of the subject are agreed that no method at present known is more satisfactory for estimating great distances.

Among the current or very recent investigations on Cepheid variables at the Harvard Observatory are:

- (1) A new determination of the period-luminosity relation;
- (2) Coöperative studies with a score of other observatories on some fifty selected variable stars of the Cepheid class—studies which involve for Harvard observers work on the periods, the photographic light curves, the magnitudes of comparison stars, the variations in spectral class throughout the period of each variable, and the collection of approximately two hundred special photographs on each star;
- (3) The discovery and cataloguing of eight hundred new Cepheid variables in the Large Magellanic Cloud;
- (4) The systematic investigation of the light curves of more than a hundred variables, and the dependence of the form of light curve on period length;
- (5) Detailed spectral analyses of the brightest Cepheids;
- (6) The change with brightness for many Cepheid variables of the degree of ionization of the calcium in the stellar atmosphere.

Many of these studies of Cepheids are only indirectly related to exploration in the Galaxy. They involve problems of stellar temperature, stellar evolution, and the cause

of Cepheid variability. Others bear directly on the problems of the absolute magnitudes of Cepheids and their distribution in space, and thus lead directly to knowledge of galactic dimensions.

Long period variable stars showing variations considerably larger, in general, than Cepheid variables, and with periods ranging in length from one hundred to five hundred days or more will probably also be of importance in measuring the distance to galactic star clouds. As yet we do not know a great deal concerning their intrinsic luminosities or the dependence of intrinsic luminosity on length of period, spectral class, or shape of light curve.

Certain data on the motions of these stars, examined by various investigators, indicate that at maximum light the variables have between one hundred and five hundred times the luminosity of the Sun. The frequency curve of the maximum magnitudes of long period variable stars in a remote Milky Way field is compared in Figure 16 with the frequency curve of magnitudes of Cepheid variables with periods less than one day. If it is assumed that the stars of the two types are at the same distance, the frequency curves indicate that the long period variables are intrinsically a magnitude brighter photographically than the Cepheids. A further indication of the high luminosity of the long period variable stars is obtained from the Large Cloud of Magellan, in which two long period variables, if they are not superposed stars, have at maximum the luminosity of Cepheid variables with periods of approximately fifty days. A similar indication may be derived from a study of long period variables in the globular cluster 47 Tucanae.

Taken altogether, it appears that the absolute magnitude of long period variables at maximum is high, and will in

time be extensively and successfully used in the estimation of great distances. Meanwhile a vast amount of observational work is carried on, photographically at the Harvard Observatory and visually by several variable star societies, in collecting data on the brighter and nearer long period variables and preparing these stars for the increasingly important rôle they will some day fill.

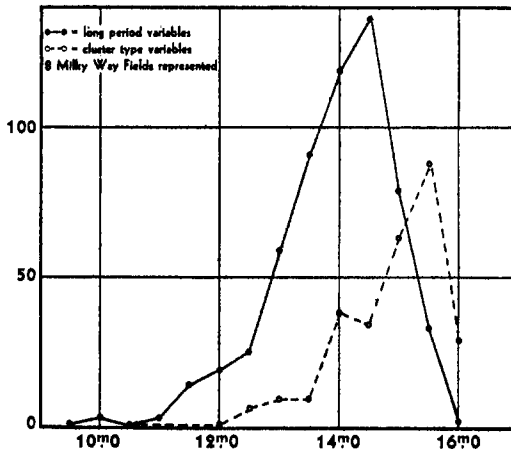


FIGURE 16. Frequency of long period and of Cepheid variables in the Milky Way. Coördinates are numbers of stars and photographic magnitudes.

A fourth kind of distance-indicating variable star is the nova. Many of these intrinsically very luminous objects appear on the Harvard plates and their distribution in the sky has contributed to our knowledge of galactic dimensions and has indicated, for instance, the probable existence of a massive nucleus of the Milky Way system in the direction of the constellation Sagittarius. At maximum brightness the average nova, according to Lundmark's extensive investigations, has more than ten thousand times the Sun's luminosity. Novae became important, therefore, in the determination

of distances of external galaxies, and Hubble has used them most effectively, along with the giant Cepheid variable stars, in studying spiral nebulae that lie at a distance of a million light years.

From the foregoing paragraphs we see how four types of variable stars—eclipsing binaries, Cepheid variables, long period variables, and novae—are useful in measuring space. Such variables can be studied satisfactorily even when so distant and faint that spectroscopic methods are quite impossible and trigonometric and proper motion measures are hopelessly inadequate. They provide an easy entry to the Milky Way star fields in which they are embedded.

About seven years ago a program for the systematic photography of Milky Way variable stars was inaugurated to supplement the plates of the Harvard sky patrol. The patrol supplies ample material for variables brighter than the twelfth magnitude but contributes too little on variable stars associated with the Milky Way star clouds. In this new variable star program the whole of the galactic belt is covered systematically by the photographic telescopes assigned to the problem. In three lines along the galactic circle a total of 196 centers were chosen in such a manner that adjacent fields overlap. The arrangement of the fields is shown in Figure 17, which is a map of the sky, showing the equatorial coordinate system with the galactic circle and the ecliptic traced in. For comparative purposes 72 variable star fields in various high galactic latitudes, as shown on the map, have also been selected for study.

Several thousand photographs have been taken on the program with the telescopes at Bloemfontein and at Cambridge. Particular emphasis has been given to the southern Milky Way, not only because of the greater richness in

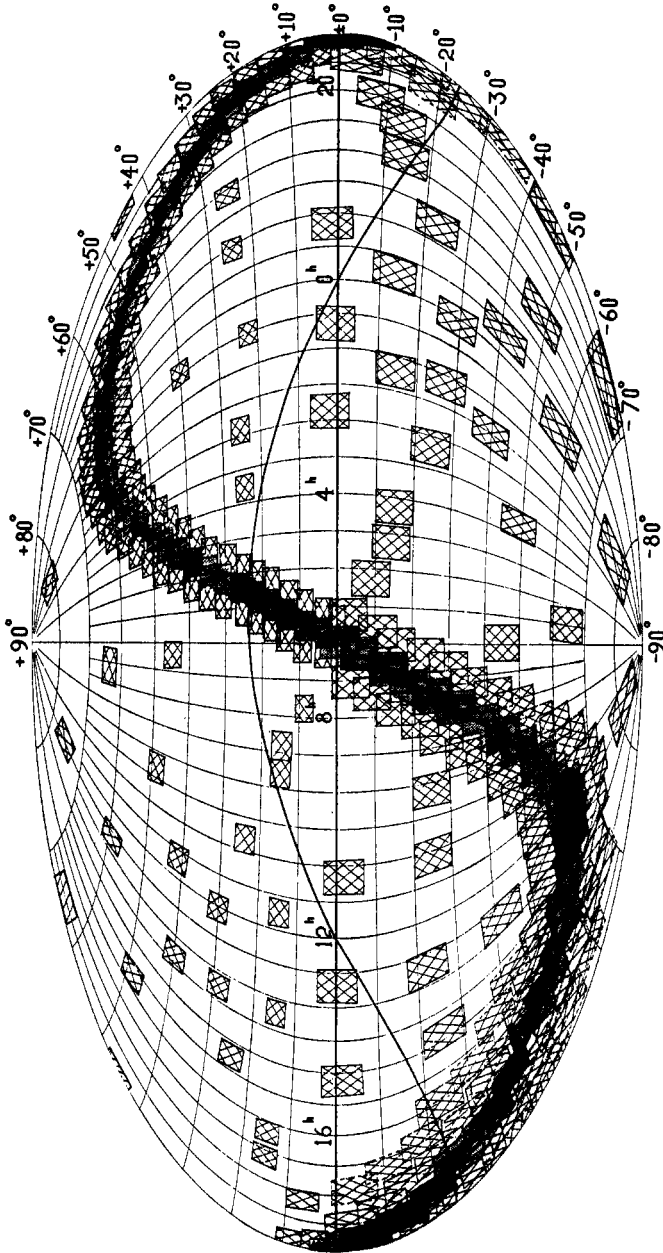


FIGURE 17. Distribution of Milky Way Fields for the variable star program.

variable stars and in other objects of interest, but because the northern sky is being more completely studied at other observatories than the regions in the south. On only a few of the 268 variable star fields have a sufficient number of photographs been collected as yet to permit a thorough study of the variable stars. The regions under closest investigation at the present time are in the southern Milky Way from Centaurus to Aquila. It is in this quadrant that the "galactic nucleus" lies, and here we find the greatest frequency of stars for the whole galactic system.

The photographs of the southern Milky Way are made principally with the 10-inch Metcalf triplet, with which an 8 by 10-inch plate covers approximately one hundred square degrees. Stars fainter than the sixteenth magnitude are shown, and in general the number of variable stars found increases steadily with decreasing brightness. Some fields, however, are much richer than others; and in a very preliminary way we have evidence that certain types of variables favor different regions of the Milky Way. In high galactic latitudes, for instance, Miss Hughes has found an unexpectedly large number of faint eclipsing binaries and faint Cepheids of the cluster type (periods less than a day), but none of the high luminosity Cepheids of longer periods.

A recent tabulation of numbers of new variable stars discovered in the course of the Milky Way survey is given in Table IV.

The Milky Way variable star survey is currently producing much interesting material concerning individual variable stars and the relative numbers of the different types; but the long range goal of the Harvard survey is a determination of the distances and arrangement of the various sections of the Milky Way system. The Leiden, Berlin-Babelsberg, and Sonneberg observatories are also contributing

actively to the study of variable stars and the related problems.

One of our first contributions from the faint variable stars to knowledge of galactic structure is the provisional

TABLE IV
VARIABLES DISCOVERED IN THE MILKY WAY
(in percentages)

Milky Way Field	Long Period	Cluster Type	Short Period	Eclipsing	Irregular and Unknown	Total Numbers
167	30	22	19	21	8	151
169	46	20	10	15	9	135
173	35	26	11	13	15	54
175	35	24	13	16	12	270
184	45	15	27	4	8	350
185	41	29	16	2	12	385
187	45	14	20	2	19	700

VARIABLES IN FIELDS OUTSIDE THE MILKY WAY
(in percentages)

Milky Way Field	Long Period	Cluster Type	Short Period	Eclipsing	Irregular and Unknown	Total Numbers
213	14	42	8	36	0	36
215	5	35	20	40	0	20
217	0	80	20	0	0	10

determination of the distance of the star cloud on which Milky Way Field 185 is centered. Miss Swope and the writer have concluded that the cluster type Cepheids found in great numbers for that particular field are connected with the star cloud and are, in the mean, nearly fifty thousand light years distant. The variable stars in the neighboring

field 187 are of similar magnitude and distance, and we are led to the tentative suggestion that the dense star clouds in the Sagittarius-Scorpio-Ophiuchus region of the Milky Way form something of a nucleus of the whole galactic system. These star clouds are badly marked up with intervening dark nebulosities, and it is possible that the magnitudes of the variables and the distances are disturbed by partially obscuring dust clouds. Further study of the variable stars throughout the region will throw light on the effects of the obscuration; but meanwhile we note that it is the globular star clusters rather than the Milky Way star clouds which indicate that the center of the galactic system lies in the Sagittarius region of the Milky Way.