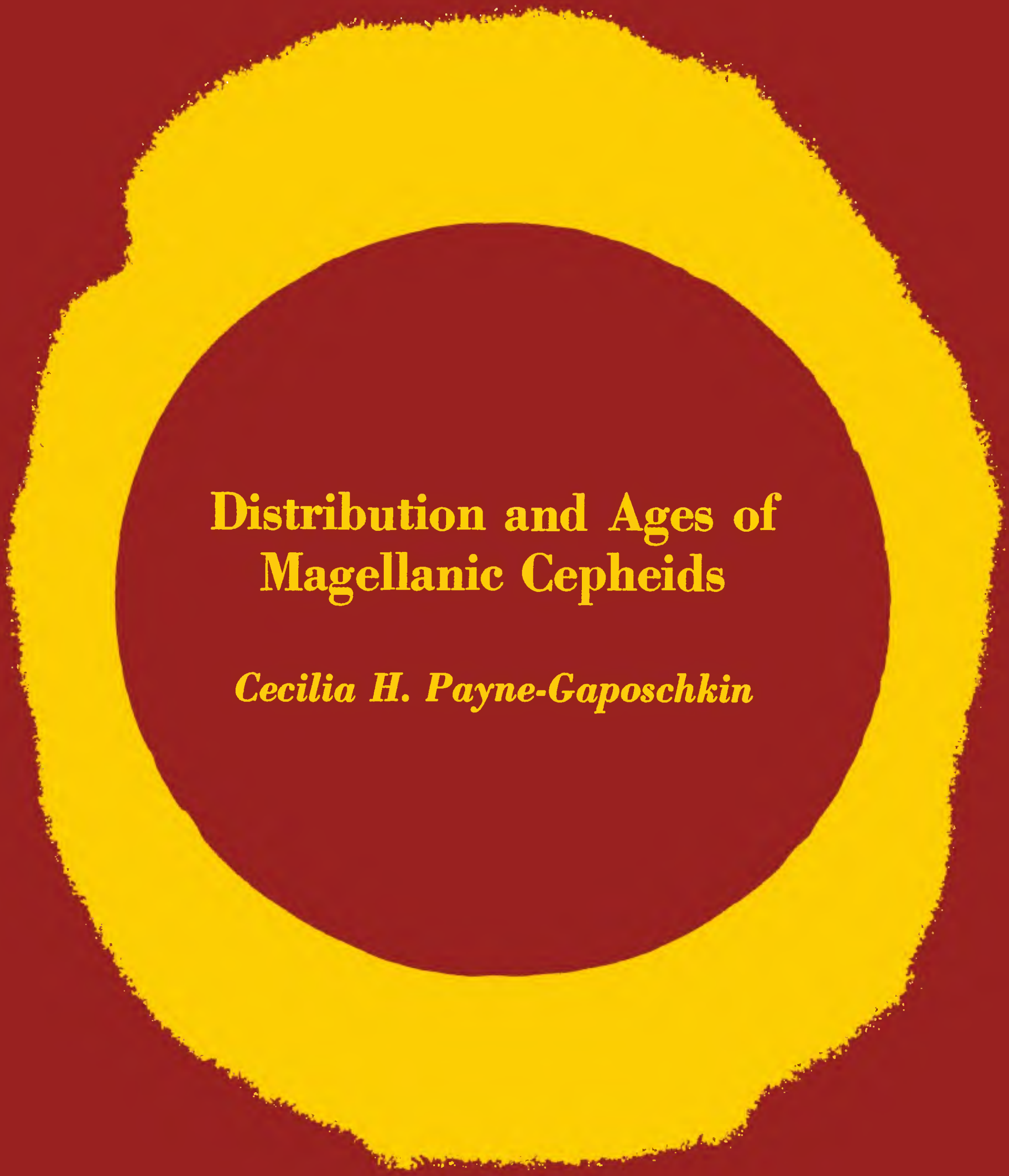

Distribution and Ages of Magellanic Cepheids

Cecilia H. Payne-Gaposchkin

SMITHSONIAN CONTRIBUTIONS TO ASTROPHYSICS • NUMBER 16

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ABSTRACT

Payne-Gaposchkin, Cecilia H. Distribution and Ages of Magellanic Cepheids. *Smithsonian Contributions to Astrophysics*, number 16, 32 pages, 8 figures, 15 tables, 1974.—The distribution and ages of the Magellanic Cepheids are discussed under four major topics:

1. The Large Cloud is shown to contain components with a variety of ages. A time scale is set up by means of the color-magnitude arrays of clusters, the integrated colors of clusters, the luminosities of Wolf-Rayet stars, and the periods of Cepheids. It is suggested that (unlike other components of the Large Cloud) the red globular clusters may constitute a halo.

2. Changes of period for galactic and Magellanic Cepheids are used to test the time scales derived for Cepheids. The computed time scales are seen to be of the right order, and the actual time scales are similar for Cepheids in the Galaxy and in the Clouds. If these time scales are sensitive to composition, the changes of period furnish no evidence for differences of composition in the three systems.

3. Evidence bearing on possible differences of composition is reviewed. So far as Cepheid variables (and stars of similar age) are concerned, there is no good evidence for differences of composition. This conclusion does not apply to the globular clusters, and perhaps not to the intermediate-age clusters; those in the Clouds are probably of similar composition to those of similar age in the Galaxy.

4. The period-amplitude and period-frequency relations, and their differences, are shown to be compatible with differences in the time of formation of stars that are now Cepheids in the two Clouds and in the Galaxy.

The discussion under these four topics suggests that the observed differences between the three systems can be interpreted in terms of differences in the timetable of star formation, without the need to invoke initial differences of composition.

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Distribution and Ages of Magellanic Cepheids

Cecilia H. Payne-Gaposchkin

A Time Scale for Clusters and Cepheid Variables

The color-magnitude diagrams of open clusters furnish a classical basis for a scale of ages. Table 1 contains data on $(B-V)_T$, the intrinsic color at the turnoff, and on $(B-V)_0$, the intrinsic integrated color, for clusters where both have been determined. Successive columns give values of $(B-V)_T$ published by Johnson et al. (1961), Sandage (1963), Gray (1965), and an adopted mean. The next two columns give the logarithm of the age in years, taken from Sandage (1963) for the clusters for which he published it, and the logarithm of the ages of all the clusters in the table, deduced from a smooth freehand curve representing the data of the previous column. The remaining columns give values of $(B-V)_0$ as published by Sandage (1963), Arp (1964), Buscombe (1964), and Gray (1965) and finally an adopted mean. Data for a few clusters, denoted by asterisks in the final column, are from Schmidt-Kaler (1967).

The age is determined from $(B-V)_T$, which sets a minimum for the cluster. The integrated colors, which include measured values of $(B-V)_0$ and summed values of $(B-V)_0$, are less accurate as criteria of age. They will be used later in our discussion of the Large Magellanic Cloud.

We now apply the cluster time scale to an examination of the ages of Cepheid variables. A Cepheid that is a member of an open cluster must of course conform to it in position and in radial velocity. It should also have a similar color excess when the latter is corrected for dependence of color excess on intrinsic color, as described, for example, by Wildey (1963) and Jung (1970). The period of the Cepheid must also be considered in assigning cluster membership.

It has long been recognized that there should be a relationship between the age of a Cepheid and its period. Young (1961) suggested (essentially on the basis of an assumed mass-luminosity relation) a "semitheoretical formula":

$$\log t = -0.714 \log P + 8.57, \qquad (1)$$

where P is the period in days, and t, as before, the age in years. Kippenhahn and Smith (1969) have considered the ages of Cepheids on the basis of the position of the Cepheid strip in the evolutionary tracks of chosen models. By weighting the data given by Kippenhahn and Smith according to the duration of the Cepheid stage for each star considered, Tammann (1969) has obtained a similar relation:

$$\log t = -0.651 \log P + 8.16. \qquad (2)$$

Equations (1) and (2) differ principally in the size of the constant that defines the time scale, the ages deduced by Young's formula being greater by a factor of about 2.5. We shall assume that the Cepheids in clusters have the same age as the clusters and, on this basis, deduce a time scale for Cepheids.

Table 2 examines the credentials of a number of Cepheids that lie near open clusters. Succes-

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TABLE 1.—*Colors of open clusters*

Cluster	$(B-V)_T$				log t		$(B-V)_0$				
	Johnson	Sandage	Gray	Adopted	Sandage	Present	Sandage	Arp	Buscombe	Gray	Adopted
NGC 129	-0.16			-0.16		7.50		+0.61			+0.61
NGC 188		+0.61	+0.65	+0.63	10.08	10.08	+0.84:	+0.78		+0.92	+0.85
NGC 225	-0.11		-0.11	-0.11		7.89				+0.11	+0.11
NGC 457	-0.25	-0.20	-0.27	-0.24	7.10	6.90	+0.12		+0.08	+0.11	+0.11
NGC 581	-0.21	-0.13	-0.21	-0.18	7.95	7.35	+0.05		+0.02	+0.01	+0.03
NGC 663	-0.28	-0.28	-0.24	-0.27	6.60	6.64	-0.10		-0.15:	-0.09	-0.11
NGC 752	+0.35		+0.35	+0.35		9.48				+0.63	+0.63
NGC 744	-0.08		-0.07	-0.08		8.10				+0.08	+0.06
NGC 869	-0.28	-0.30		-0.29	6.50	6.48	-0.15	-0.18	-0.18		-0.17
NGC 884	-0.28	-0.30		-0.29	6.50	6.48	+0.10		+0.06		+0.08
IC 1805	-0.32	-0.32	-0.35	-0.33	6.30	6.12	-0.27		-0.31	-0.33	-0.30
Tr 2	-0.14	-0.14	-0.14	-0.14	7.75	7.66	+0.20		+0.06	+0.27	+0.14:
NGC 1027	-0.02	-0.20	-0.14	-0.12	7.10	7.82	+0.13		+0.09	+0.13	+0.12
IC 1848	-0.29			-0.29		6.48					-0.29
NGC 1245	+0.16		+0.16	+0.16		9.10				+0.01	+0.01
Perseus	-0.20		-0.20	-0.20		7.20				+0.02	+0.02
NGC 1342	+0.05		+0.05	+0.05		8.78				+0.35	+0.35
Pleiades	-0.12		-0.14	-0.13		7.84		-0.10		-0.13	-0.12
NGC 1502	-0.29	-0.33		-0.31	6.00	6.30	-0.27		-0.31		-0.29
NGC 1528	-0.02	-0.09	-0.03	-0.05	8.12	8.30	+0.08		+0.05	+0.13	+0.09
NGC 1545	-0.08		-0.08	-0.08		8.10				-0.21	-0.21
Hyades	+0.10		+0.10	+0.10		8.95		+0.40		+0.49	+0.44
NGC 1647	-0.09		-0.09	-0.09		8.02				+0.07	+0.07
NGC 1662	-0.04	-0.07	-0.04	-0.05	8.20	8.30	+0.19		+0.15	+0.17	+0.17
NGC 1664			-0.16	-0.16		7.50				+0.13	+0.13
NGC 1778	-0.10		-0.09	-0.10		7.96				+0.08	+0.08
NGC 1893	-0.34			-0.34		6.02				-0.16	-0.16
NGC 1907	0.00		-0.09	-0.04		8.35				+0.61	+0.61
NGC 1912	-0.09	-0.17	-0.06	-0.11	7.35	7.89	+0.10		+0.07	+0.07	+0.08
NGC 1960	-0.24	-0.24		-0.24	6.87	6.90	-0.14		-0.16		-0.15
NGC 2099	-0.10	-0.09	-0.13	-0.11	8.12	7.89	+0.26		+0.22	+0.27	+0.25
NGC 2158		+0.30		+0.30	9.40	9.40	+0.65:	+0.66			+0.66
NGC 2168	-0.17		-0.17	-0.17		7.43				+0.03	+0.03
NGC 2169	-0.27		-0.22	-0.24		6.90				-0.02	-0.02
NGC 2251	-0.16		-0.20	-0.18		7.36				+0.13	+0.13
NGC 2264	-0.30		-0.27	-0.28		6.57		-0.18		-0.15	-0.16
NGC 2281			0.00	0.00		8.53				+0.56	+0.56
NGC 2287	-0.20		-0.20	-0.20		7.20				+0.16	+0.16
NGC 2301	-0.14		-0.14	-0.14		7.66				+0.23	+0.23
NGC 2323	-0.19		-0.24	-0.22		7.04				+0.06	+0.06
NGC 2353	-0.25		-0.23	-0.24		6.90				-0.12	-0.12
NGC 2362	-0.28		-0.29	-0.28		6.58		-0.21		-0.25	-0.23
NGC 2422	-0.18		-0.18	-0.18		7.36				-0.06	-0.06
NGC 2539			0.00	0.00		8.53				+0.47	+0.47
NGC 2548			-0.05	-0.05		8.30				+0.26	+0.26
IC 2682	+0.40	+0.50		+0.45	9.87	9.72	+0.74		+0.69		+0.72
IC 2602			-0.25	-0.25		6.80				-0.07	-0.07

TABLE 1.—*Colors of open clusters*—Continued

Cluster	$(B-V)_T$				log t		$(B-V)_0$				
	Johnson	Sandage	Gray	Adopted	Sandage	Present	Sandage	Arp	Buscombe	Gray	Adopted
NGC 3532			-0.04	-0.04		8.35				+0.27	+0.27
Coma	+0.05		+0.05	+0.05		8.78		+0.22		+0.19	+0.20
NGC 4755	-0.20		-0.20	-0.20		7.20				-0.01	-0.01
NGC 6087	-0.17:		-0.15	-0.15		7.59				-0.15	-0.15
NGC 8231				-0.30$^+$		6.45					-0.24*
NGC 6405	-0.18		-0.12	-0.15		7.59				+0.17	+0.17
NGC 6475	-0.10		-0.06	-0.08		8.10				+0.15	+0.15
NGC 6494	-0.06		+0.05	0.00:		8.53				+0.18	+0.18
NGC 6531	-0.30		-0.33	-0.32		6.20				-0.16	-0.1
NGC 6530	-0.32		-0.33	-0.32		6.20				-0.12	-0.12
NGC 6633	+0.15	-0.12	-0.12	-0.03:	7.95		+0.15		+0.11	+0.12	+0.13
IC 4725	-0.20	-0.14	-0.20	-0.18	7.75	7.35	+0.13		+0.21	+0.09	+0.14:
IC 6709	-0.16		-0.20	-0.18		7.35				+0.21	+0.21
NGC 6802	-0.14		-0.13	-0.14		7.67				+0.07	+0.07
NGC 6866	+0.06	+0.01	+0.06	+0.04	8.45	8.72	+0.29		+0.26	+0.41	+0.32:
NGC 6871	-0.24			-0.24		6.90			+0.48		+0.48
NGC 6940	+0.15	+0.10	+0.16	+0.14	9.17	9.06	+0.35		+0.31	+0.39	+0.35
NGC 7063	-0.10		-0.10	-0.10		7.96				+0.23	+0.23
NGC 7092	-0.06	-0.06	-0.12	-0.08	8.30	8.10	-0.02		-0.03	+0.06	0.00
NGC 7142	+0.38		+0.38	+0.38		9.58				+0.60	+0.60
IC 5146			-0.27	-0.27		6.64		-0.21		+0.17	-0.02:
NGC 7160	-0.30		-0.30	-0.30		6.40				-0.25	-0.25
NGC 7209	0.00	-0.05	-0.06	-0.04	8.30	8.35	+0.33		+0.30	+0.30	+0.31
NGC 7261	-0.10		-0.15	-0.12		7.80				+0.19	+0.19
NGC 7380	-0.30	-0.30	-0.33	-0.31	6.50	6.30	-0.19		-0.22	-0.12	-0.18
NGC 7789	+0.30	+0.32		+0.31	9.48	9.42	+0.70	+0.62	+0.65		+0.66
NGC 7790	-0.18	-0.18		-0.18	7.35	7.35	+0.09		+0.04		+0.06
Cep III	-0.25		-0.25	-0.25		6.80				-0.36	-0.36
Lac I	-0.30		-0.30	-0.30		6.40				+0.05	+0.05
Ori I	-0.32		-0.32	-0.32		6.20				-0.12	-0.12

sive columns give the cluster, the Cepheid, the logarithm of its period, the observed color excess of the Cepheid, the observed color excess of the cluster, log t for the cluster (from Table 1), and log t for the Cepheid, calculated from the formulas of Young (AY) and of Kippenhahn and Smith (KS). Data for the Cepheid in NGC 6649 are taken from Tammann (1969), those of S Nor from Breger (1970).

As suggested above, a Cepheid that is a cluster member should have a color excess consistent with that of the cluster, and its age should conform to that of the cluster. The stars whose color excesses and/or ages do not conform to these criteria are placed in parentheses. We reject VY Per, UY Per, SZ Cas, DF Cas, UX Car, and ER Car on the basis of color excess, and VX Per, YZ Car, CF Car, and AQ Pup on the basis of age. The star CV Mon has not been included, because the cluster to which it was once assigned is probably nonexistent. We note that the Cepheids near the double cluster in Perseus, used by Sandage and Tammann (1968) in their calibration of the zero point of the period-luminosity curve, are all excluded on the basis of age, and nearly all on the basis of color excess. As discussed elsewhere, the zero point determined with their aid is nonetheless unaffected.

The acceptable Cepheids in Table 2 permit us to conclude that the empirical determination of cluster ages, based on Table 1 and the Limber-Sandage time scale, is in satisfactory agreement

TABLE 2.—*Classical Cepheids near open clusters*

Cluster	Cepheid	log P	Color Excess		log t Cluster	Cepheid	
			Cepheid	Cluster		AY	KS
NGC 129	DL Cas	0.903	0.59	0.58	7.50	7.93	7.57
NGC 869, 884	(VX Per)	1.040	0.59	0.56	6.55	7.83	7.48
	(VY Per)	0.743	1.06	0.56	6.55	8.04	7.68
	(UY Per)	0.730	1.02	0.56	6.55	8.05	7.68
	(DW Per)	0.562	0.67	0.56	6.55	8.17	7.79
	(SZ Cas)	1.134	0.80	0.56	6.55	7.76	7.42
NGC 1027	(DF Cas)	0.583	0.64	0.40	7.75	8.15	7.78
IC 2581	(UX Car)	0.566	0.13	0.37	(6.30)	8.17	7.79
	(YZ Car)	1.259	0.37	0.37	(6.30)	7.67	7.34
NGC 3496	(CF Car)	0.740		0.50	(8.70)	8.04	7.68
NGC 3532	(ER Car)	0.888	0.24	0.01	8.35	7.94	7.58
Tr 18	(GH Car)	0.758	0.36	0.37	(7.20)	8.03	7.67
NGC 6087	S Nor	0.989	0.18	0.20	7.59	7.86	7.52
IC 4725	U Sgr	0.829	0.52	0.50	7.75	7.98	7.62
NGC 6664	EV Sct	0.490	0.64	0.60	7.96	8.22	7.84
NGC 7790	CE Cas a	0.711	0.62	0.52	7.35	8.06	7.70
	CE Cas b	0.651	0.59	0.52	7.35	8.11	7.74
	CF Cas	0.688	0.64	0.52	7.35	8.08	7.71
Pup I	(AQ Pup)	1.475	0.60	0.54	5.90	7.52	7.20
Vel III	RS Pup	1.617	0.64	0.62	6.80	7.4	7.11
NGC 6649	Anon	0.709	(1.24)	1.24	7.70	8.06	7.70

with the time scale derived by Kippenhahn and Smith on the basis of the theory of evolutionary tracks. The time scale given by Young's approximate formula is too long. We shall accordingly use the scale of ages based on Table 1 for the clusters, and equation (2) for the Cepheids.

The relation between period and age for the accepted Cepheids shows considerable scatter, which might be ascribed to: (1) errors in the Cepheid periods; (2) dispersion in the physical properties of the Cepheids; (3) uncertainty in $(B-V)_T$; and (4) dispersion in the properties of the clusters.

1. Errors in the periods of the Cepheids used can hardly affect the data, but the interpretation of the periods may do so. If a star is pulsating in an overtone, the period appropriate for age determination will be longer, and the age accordingly smaller, with a difference in log P (for the first overtone) of about -0.2. Possibly EV Sct is in overtone pulsation, but in that case the discrepancy would be even greater.

2. This possibility covers differences of composition and also mass loss (which might itself be a function of luminosity and thus of mass). We have no convincing spectroscopic evidence of differences of composition among classical Cepheids, although differences large enough to affect the time scale might not be large enough to affect the spectrum. Mass loss must certainly occur, but the limits calculated by Kippenhahn and Smith would account for only half the observed dispersion.

3. Kippenhahn and Smith (1969, Table 2) used the *luminosities* of the stars at the turnoff point to obtain cluster ages, and their material was more heterogeneous than ours. We believe that it is less circuitous to determine log t from $(B-V)_T$ than from an absolute bolometric magnitude that involves a bolometric correction and magnifies a possible error in color excess by a factor of 3. The uncertainty in $(B-V)_T$ is certainly not greater than $0.^m10$ for the clusters considered. This may still lead to an uncertainty in log t of perhaps 0.5, since we are confined to the region of negative $(B-V)_T$.

4. The clusters, like the Cepheids, may differ significantly in composition and also in other properties, such as the presence of supergiants and numerous red giants. It should be noted that

the most discrepant point in the Kippenhahn-Smith plot relates to the Cepheids in the Magellanic cluster NGC 1866, for which both the turnoff point and the modulus are uncertain. These variables are not discussed in the present section, but will be considered in our discussion of the Large Magellanic Cloud.

Distribution and Affiliations of Large Cloud Variables

Figures 1–4 illustrate the distribution of several types of variable stars, and of Cepheids of various periods and luminosities, within the boundaries of the Large Cloud. The distributions are neither uniform nor similar. Table 3 summarizes conditions in a number of areas, including five sections of the bar, counted from south to north. Column 6 refers to a small region around the Tarantula Nebula 30 Dor. Column 7 gives average values of the tabulated quantities for the whole Cloud.

Successive lines of the table contain: (1) area in square degrees; (2) median log P for the Cepheids in the area; (3) through (8) numbers of Cepheids, irregular variables, long-period (including cyclic) variables, W Virginis stars, Wolf-Rayet stars, and eclipsing stars, all per square degree. Columns (9) through (13) give the ratios of the number of stars of the indicated types to the number of Cepheids in the area.

The periods of the Cepheids in the bar are shortest in Area A and progressively longer toward Area E (south to north). The relative numbers of irregular and long-period variables tend to increase over the same interval. The 30 Dor region is exceptionally rich in irregular variables and Wolf-Rayet stars, whereas the northern end of the bar, rich in irregular variables, is relatively poor in Wolf-Rayet stars.

Several compact blue clusters, notably NGC 1866, 2058, and 2065, seem to be associated with knots of Cepheids, but with few if any variable stars of other types. They will be discussed later. Table 3 illustrates the variety of the Large Cloud population, ranging from that of the 30 Dor region (poor in Cepheids and rich in Wolf-Rayet stars, irregular variables, and eclipsing stars) through the bar (absolutely and relatively rich in Cepheids, and containing other types of variable star) to the blue populous clusters (where Cepheids predominate). There are also, as we shall see, compact red clusters that contain RR Lyrae stars.

The difference in distribution for Cepheids of different periods and its relation to that of other objects to which ages can be assigned suggest that the variety displayed by Table 3 may furnish a way of studying the timetable of star formation in various parts of the Cloud. Arp (1964: 227) has already remarked: "It would be important to pinpoint areas of present star formation and try to discover differences between them and the neighboring areas where star formation has just ceased. . . . By studying color-magnitude diagrams of various regions of the Cloud . . . much can be learned about the age composition of the stars in various regions within the Cloud. In combination with the velocity data a beginning could be made on the problem of how the locus of star formation has moved within the system as a function of time." We explore these possibilities by collecting data on variable stars that appear to be associated with datable components of the Cloud.

The basis of our study is the time scale for clusters (Table 1), which enables us to relate $(B-V)_T$ and $(B-V)_0$ to age. We also make use of equation (2), which expresses the age of a Cepheid as a function of period and which has been shown to be compatible with the Limber-Sandage time scale that has been used for the clusters. We must be mindful of the possibility that the physical properties of both Cepheids and clusters may not be the same in the Cloud and the Galaxy, but while this possible difference might invalidate an absolute time scale, it seems legitimate to expect that the times deduced for the Cloud will be consistent for clusters and Cepheids.

Datable components are summarized in the following tables beginning with the youngest. Actually, the smallest ages that have been assigned in the Cloud are those attributed by Westerlund and Mathewson (1966) to three possible supernova remnants, 300 years for 132 D and 3000 years for N 49 and N 63. Neither variable stars nor clusters can be associated with anything so recent. These authors also suggest that Constellation III, and perhaps Constellation I, discussed

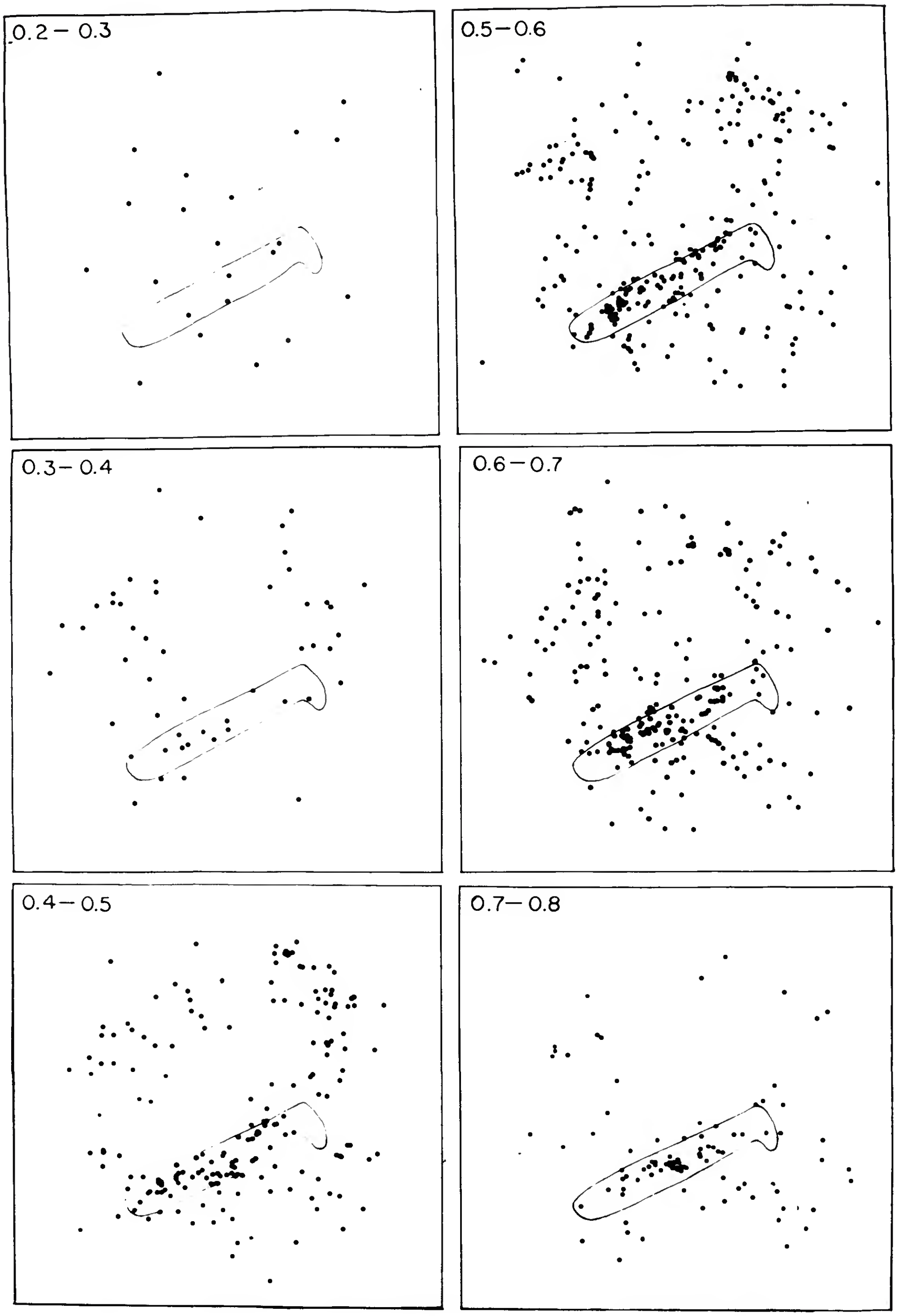

Figure 1.—Large Cloud: Distribution of Cepheids with various values of log P. The outline of the bar is indicated.

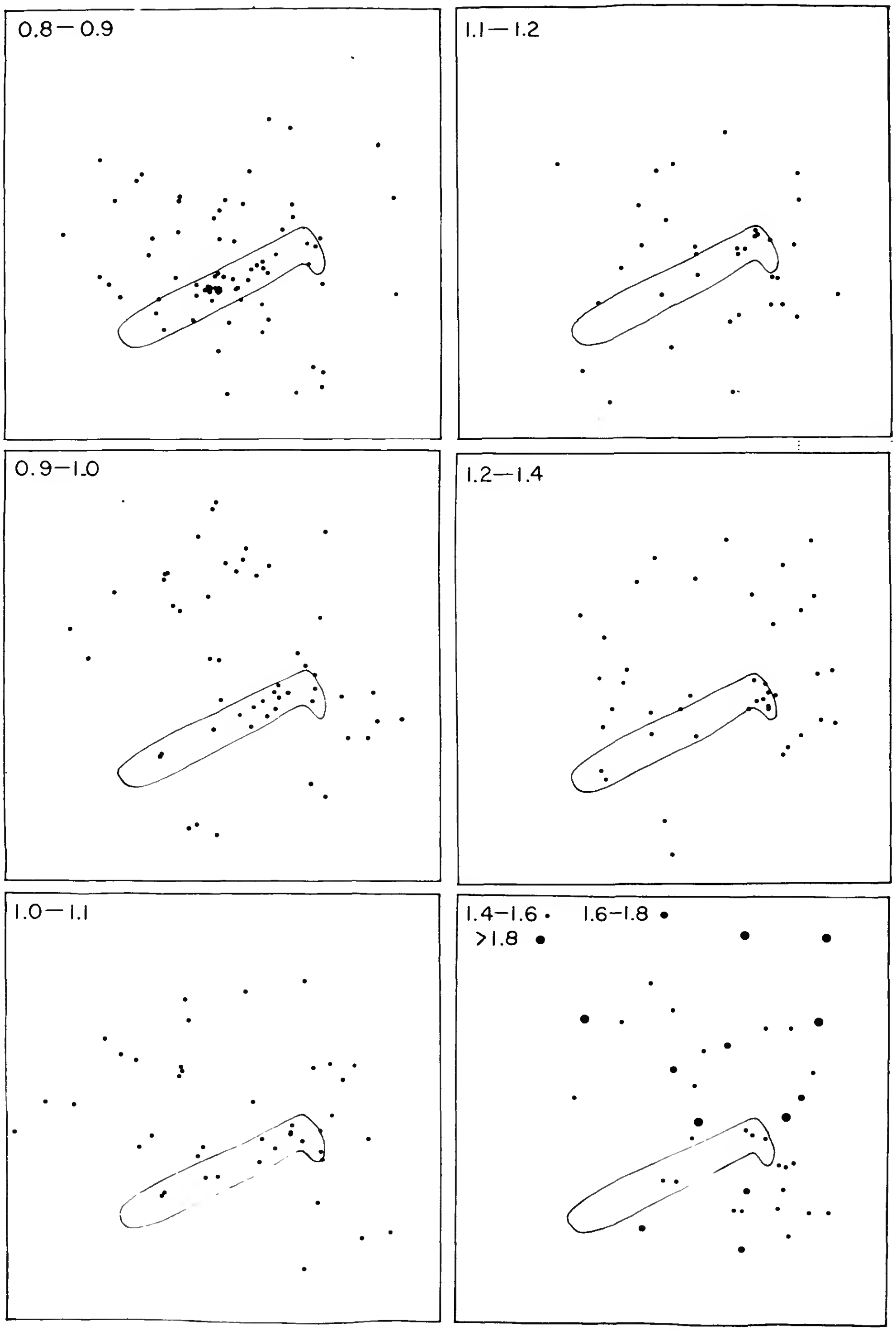

Figure 2.—Large Cloud: Distribution of Cepheids with various values of log P.

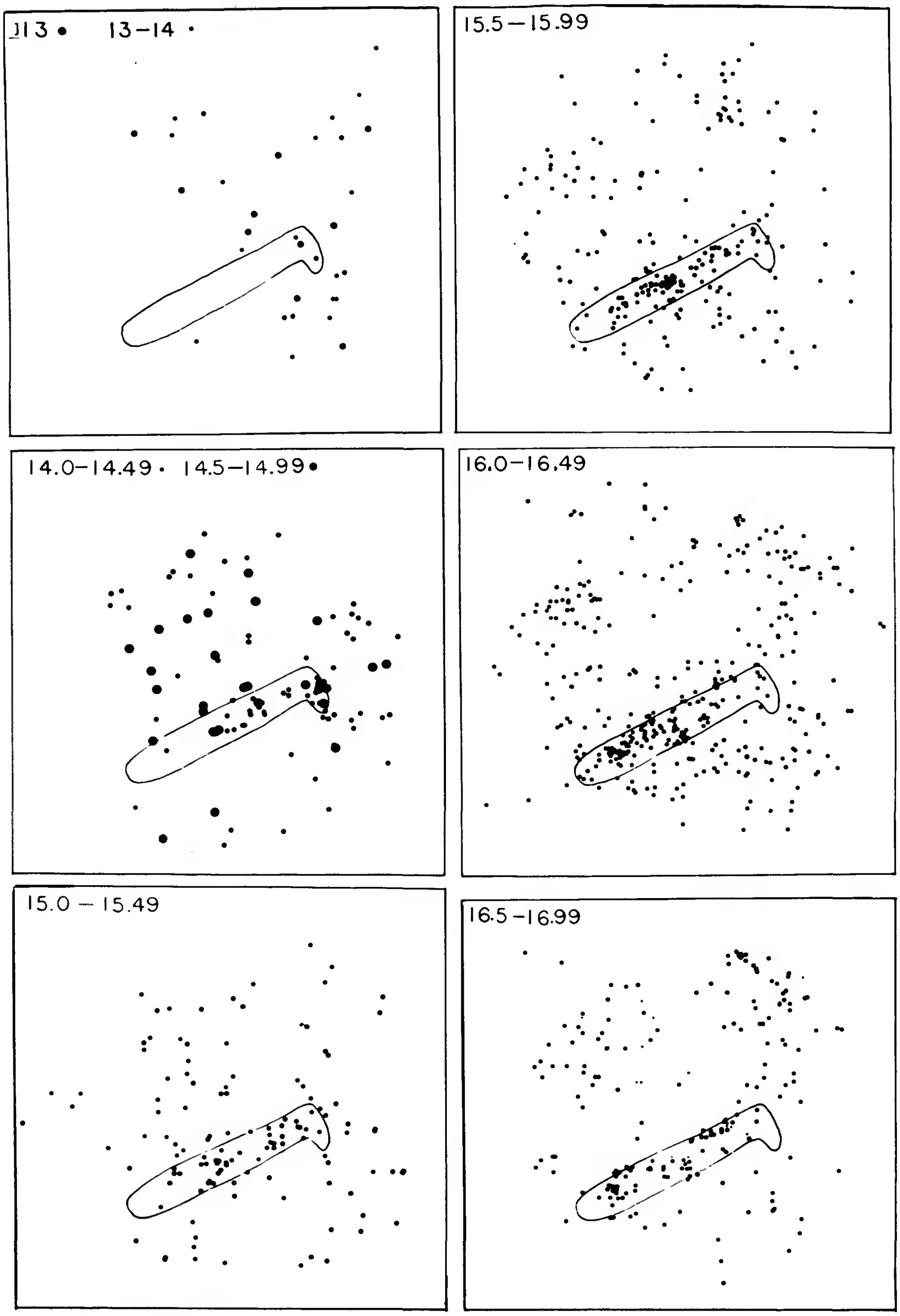

FIGURE 3.—Large Cloud: Distribution of Cepheids with various apparent photographic magnitudes, averaged to mean intensity and uncorrected for absorption.

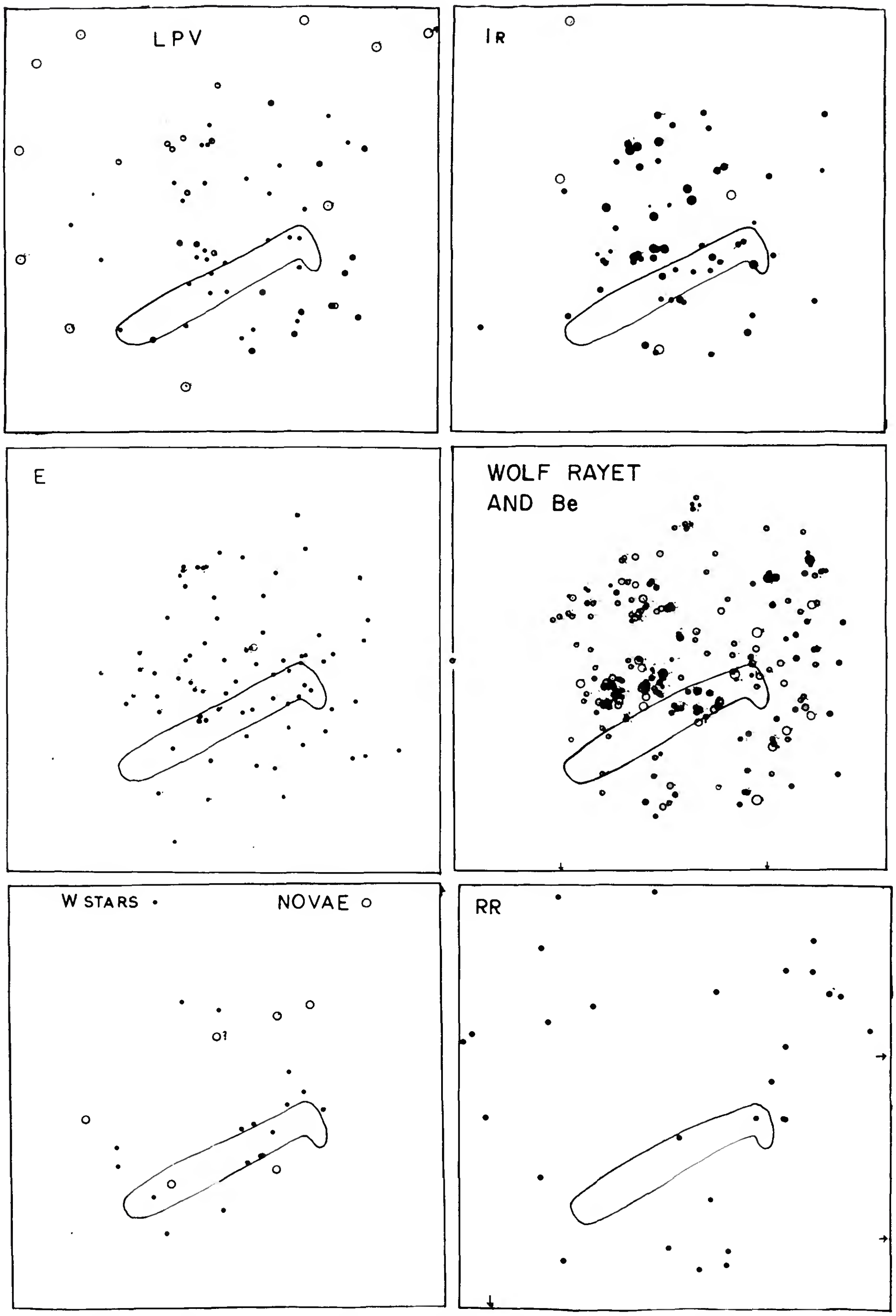

FIGURE 4.—Large Cloud: Distribution of long-period variables (LPV), irregular red variables (Ir). eclipsing variables (E), Wolf-Rayet stars (WR, dots) and Be stars (Be, circles), W Virginis stars (W, dots) and novae (circles), and RR Lyrae stars (RR). Foreground stars among the long-period and irregular variables are indicated by circles; all the RR Lyrae stars are foreground.

by Shapley and Nail (1953), may have had their origin in "super-supernova" explosions about 10^6 yr ago. These constellations are associated with the clusters NGC 1968–1974 and NGC 1962–1965–1966–1970 (see Table 4).

Data for very young clusters and associations are collected in Table 4. Successive columns give: (1) name of the group; (2) values of $(B-V)_0$ published by van den Bergh and Hagen (1968) or derived from the data of Bok and Bok (1962), the latter denoted by asterisks; (3) to (6) logarithms of ages, deduced, respectively,

Table 3.—*Typical areas in the Large Cloud*

	1 Bar A	2 Bar B	3 Bar C	4 Bar D	5 Bar E	6 30 Dor Area	7 LMC Average
1. Square degree	0.586	0.651	0.759	0.690	0.427	0.695	39
2. Median log P	0.552	0.600	0.677	0.662	1.020	0.544	0.630
(per square degree)						1.235	
3. Cepheids	73.4	130.6	156.5	111.6	72.6	14.4	20.4
4. Irregular	5.1	9.2	26.4	27.6	14.0	21.6	5.9
5. Long-period	1.7	4.6	5.3	4.3	4.7	2.9	1.1
6. W Virginis			1.3		4.3		0.3
7. Wolf-Rayet				5.5	0.9	15.0	1.0
8. Eclipsing ratio to Cepheids:	1.7	4.6	5.3	4.3	4.7	10.0	1.4
9. Irregular	0.07	0.07	0.17	0.25	0.19	1.50	0.29
10. Long-period	0.02	0.03	0.03	0.04	0.06	0.20	0.05
11. W Virginis			0.01		0.06		0.02
12. Wolf-Rayet				0.05	0.01	1.07	0.05
13. Eclipsing	0.02	0.03	0.03	0.04	0.06	0.71	0.07

Table 4.—*Very young clusters and associations*

NGC	$(B-V)_0$	Logarithm of Age (yr)					Members: Red Supergiants	W Stars	HV	Variable Stars		Color	Reference Color-Magnitude Array
		From C-M Array		From $(B-V)_0$	From W Stars	Adopted				Type	Magnitude		
		Maximum	Turnoff										
1810						6.93	2	0					Woolley (1960)
1818	-0.07			6.93		6.93	3	0					Woolley (1960)
1929–1937	-0.29*			6.12		6.12	0	0					Bok (1964)
1955	-0.21*			6.40	6.57	6.48	0	1					Bok, Bok, and Basinski (1962)
1968–1974	-0.27*			6.18		6.18	2	0					Bok, Bok, and Basinski (1962)
1962–1970	-0.20*	6.30	6.56	6.44	6.43, 6.68	6.53	0	2					Westerlund (1961a)
1983	-0.12*	6.50		6.74		6.72	0	0	5495	Irregular	10.95–11.87	Blue	Westerlund (1961a)
1984		6.34				6.60	2	0	2556	Irregular	14.84–16.35	Red	Westerlund (1961a)
2004	-0.19			6.47		6.47	6	0					Woolley (1960)
2070	-0.22			6.36	6.39, 6.67	6.37, 6.67	1	10					Westerlund (1961a)
2074		6.36	6.68		6.69	6.67	0	2					Westerlund (1961a)
2081		6.56	6.78		6.77	6.78	2	2	1017	Irregular	15.30–15.95	Red	Westerlund (1961a)
									2753	Irregular	15.30–16.70	Red	
									5993	Irregular	15.30–16.25	Red	
2092		7.00				7.26	2	0	6002	Irregular	16.18–17.65	Red	Westerlund (1961a)
2100	-0.12	6.45	6.84	6.74		6.78	18	0					Westerlund (1961a)
Westerlund Area "b"						6.0–7.0	45	0	957	Irregular	13.87–14.84	Red	Westerlund (1961a)
									2565	Irregular	13.43–14.43	Red	
									2567	Irregular	14.44–15.15	Red	
									5870	LP	14.30–17.09	Red	

from the maximum and turnoff of the color-magnitude diagram by Westerlund (1961a), from $(B-V)_0$, and from the apparent magnitudes of the Wolf-Rayet stars; (7) logarithm of an adopted age; (8) number of red supergiants; (9) number of Wolf-Rayet stars; (10–13) name, type, and magnitude color of variable stars; and (14) reference to the source of the color-magnitude array. The ages derived from $(B-V)_0$ were deduced graphically from Table 1. Those in the sixth column are deduced with the help of the observation of Westerlund and Smith (1964) that the brightness of a Wolf-Rayet star seems to be related to its age, the youngest being the brightest. Westerlund (1961a: 44) states: "It appears likely that the turnoff point gives a good estimate of the age of a stellar group. . . . All stars of type Wolf-Rayet found so far are situated *at* the turnoff point." All the Wolf-Rayet stars in the clusters tabulated have composite (W+O) spectra. The average (v_o) magnitudes of those in NGC 1962–1965–1966–1970, 2074, and 2081 are found from the work of Smith (1968) to be 11.14:, 12.48, and 13.31, respectively. These, with the ages of the relevant clusters, lead to the relationship

$$\log t = 0.10 \, v_o + 5.44.$$

The similarity of the color-magnitude arrays for NGC 1810 and 1818 suggests similar ages, and we have assumed them to be equal. Bok (1964) assigns to NGC 1929–1937 an upper limit of 6.3 for log t. We defer discussion of the complex region surrounding NGC 2070.

The striking feature of Table 4 is the absence of Cepheids, though it contains 10 irregular variables. In the Large Cloud as a whole, the number of known irregular variables is 3% of the number of known Cepheids. The upper limit of age for the clusters in Table 4 is about 10^7 yr, and we infer that their members have not had time to reach the Cepheid stage.

The red irregular variables (when present) are brightest in the youngest clusters. The red supergiants (some of which are probably undetected variables) show the same tendency. Their average B magnitudes in NGC 1984, 2081, and 2092 are, respectively, 14.71, 15.32, and 15.72; the corresponding adopted values of log t are 6.60, 6.79, and 7.26. The older the cluster is, the fainter are the evolved stars. An order-of-magnitude estimate of their luminosities, based on a true modulus 18.45, a color excess $0.^m06$, and a color index $1.^m6$, gives -5.6, -5.0, and -4.6 for M_v of the red supergiants in the three clusters.

No red semiregular variables are known in the youngest clusters and associations. The bright irregular variable in NGC 1983 is a blue star, HV 5495 = HD 269582 (P Cyg spectrum). In NGC 2081, there are both Wolf-Rayet stars and red irregular variables, with B magnitudes 13.09 and 15.30 (max.), respectively, but since the W stars are composite, the actual W component may not be much brighter than the red variable. Westerlund's area "b" is a large association whose red supergiants have a spread of 3 magnitudes. This suggests that it contains stars with a variety of ages, as already noted by Westerlund. One long-period variable lies within its probable boundaries. The ages suggested by the brightness of the red variables and supergiants range from about 10^6 to over 10^7 yr. These facts are in harmony with the conclusion of Stothers (1969: 935) that clusters containing supergiants show "decreasing and increasing number of blue and red supergiants, respectively, with age."

Data for the region surrounding 30 Dor (NGC 2070) are given in Table 5. The corresponding entry in Table 3 relates to Westerlund's sampling of stars in a smaller area. Table 5 embraces an area of 0.695 square degree, which contains 15 irregular variables, 10 Cepheids, and 2 long-period variables. Evidently, the region is less homogeneous in population and age than those just discussed. The Cepheids favor two periods; the irregular and long-period variables have average maximal photographic magnitudes 15.11 and 15.36 (corresponding roughly to M_v -5.1 and -4.9). We conclude that the irregular variables point to a value of about 6.5 for log t, but the presence of Cepheids suggests a value of at least 7.0.

The small region within 30 Dor itself (Table 6) suggests a smaller age. Data for the W stars are from Smith (1968); those for the O to F supergiants, from Feast, Thackeray, and Wesselink (1960); those for the red supergiant, from Westerlund (1961a). In obtaining a value of v_o for R 134, 135, 139, and 140, we have adopted the absorption used by Smith for HD 38268.

Unlike the clusters previously noted, the group within 30 Dor contains W stars with a large range in magnitude, from 8.48 to 12.51. Both the brightest (HD 38268) and the faintest (HD 269926) have composite spectra. Even if (as is quite possible) HD 38268 is as multiple as the Trapezium in Orion, there must still be a range of at least 2 magnitudes among the W stars, and HD 38268 would be as bright (and hence as young) as any W star in the Large Cloud. The W stars suggest values of log t from under 6.4 to 6.7, the irregular variables about 6.7, and the Ce-

TABLE 5.—*Variable stars in the 30 Dor area (0.695 square degree)*

	Cepheids		Irregular Variables		Long-Period Variables	
HV	log P	$\langle m \rangle_0$	HV	Magnitude	HV	Magnitude
5940	0.3747	16.78	2626	15.35–16.25	2677	15.26–17.62
5930	0.5376	16.55	2635	14.50–15.50	2763	15.40–17.64
2666	0.6124	15.52	2649	13.91–15.09		
2616	0.6666	15.92	2655	15.75–16.78		
2613	0.6681	15.96	2669	14.35–15.30		
2620	0.6843	16.00	2674	15.55–16.35		
2647	1.1519	15.63	2679	14.53–15.21		
1006	1.1527	15.04	2681	15.26		
1005	1.2721	14.50	2728	15.33–16.00		
2749	1.3637	15.12	2732	15.00–15.75		
			2740	16.00–17.00		
			2753	15.30–16.70		
			2761	15.20–16.22		
			12998	15.72–17.25		
			13044	14.91–15.64		

TABLE 6.—*Young stars in the 30 Dor region*

Star	Spectrum	v_0	$(b-v)_0$	Radial Velocity (km/sec)
HD 269891	OB + WN	10.55	-0.21	
HD 269926	WN 4 + OB	12.51	-0.18	
HD 38282	WN 7	10.79	-0.20	
HD 269928	WN 7	11.24	-0.20	
HD 38344	WN 6:+ OB	12.10	-0.17	
R 134	(WN 7)	(11.40)		
R 135	(WN 7)	(12.19)		
HD 38268	OB + WN	8.48	-0.21	
R 139	WN 7:+ OB:	(10.91)		
R 140	WN 6	(10.86)		
R 131	B9 I			+269
R 132	B-A			
R 133	O8			+235
R 137	B0.5 Ia:			
R 138	AO: I:			
R 141	B0.5:			
R 142	B			
R 143	F5–F8 Ia			+263
Westerlund 8		13.47	(+1.94)	

pheids at least 7.0. Westerlund 8, in the compact region, has an apparent B magnitude of 15.41 (uncorrected for absorption) and thus falls in the same age group as do the irregular variables. The compact group contains no known Cepheids, although R 143 may possibly be one, with an uncorrected B magnitude of 11.36.

These facts suggest a complex history of the 30 Dor region. Stars have been forming in the surrounding area for at least 10^7 yr, but in the compact center there is nothing with log t greater than 6.7, and some of the stars must be even younger. The association around NGC 1962–1965–1966–1970 seems to be similar to the 30 Dor cluster, and so is the association near NGC 1955, described by Bok, Bok, and Basinski (1962) as consisting primarily of blue-white supergiants and containing HD 36402, WC5+OB, $v_0 = 11.38$, which corresponds to log t = 6.58. Neither of these associations contains any known variable stars.

The young populous ("blue globular") clusters that contain variable stars are given in Table 7. Successive columns give the name of the cluster, $(B-V)_0$ from van den Bergh and Hagen (1968), ages estimated as described above from the color

TABLE 7.—*Variable stars in and near young populous clusters*

				Variable Stars				
		log t (yr)		Cepheids			Irregular	
NGC	$(B-V)_0$	$(B-V)_0$	Cepheid	HV	log P	m_0	HV	m
1850	0.07:	7.45	7.20	904	1.483	13.57		
			7.46	905	1.073	14.28		
1854	0.13	7.70					5626	17.24–18.18
1856	0.26	8.18	7.66	2349?	0.763	15.70	11988	17.93–(18
			7.85	11985	0.483	17.00	11989	17.59–18.22
1866	0.20	7.95	7.92	12192	0.366	15.99		
			7.81	12193	0.540	16.54		
			7.83	12194	0.506	16.40		
			7.84	12196	0.493	16.36		
			7.84	12197	0.498	16.69		
			7.80	12198	0.547	16.24		
			7.89	12199	0.422	16.89		
			7.88	12200	0.435	16.71		
			7.81	12201	0.537	16.35		
			7.84	12202	0.492	16.80		
			7.85	12203	0.470	16.93		
			7.81	12204	0.536	15.89		
			7.83	12205	0.506	16.10		
			7.90	12206	0.399	16.58		
2058	0.17	7.85	7.74	2706	0.646	15.49		
			7.81	2713	0.538	16.43		
			7.69	2714	0.728	15.61		
			7.84	2717	0.499	16.53		
			7.76	2720	0.615	15.29		
			7.83	5975	0.502	16.47		
			7.69	5978	0.729	16.01		
			7.84	13042	0.487	15.34		
2065	0.17	7.85	7.82	1008	0.534	15.31		
			7.83	1009	0.513	15.43		
2136	0.14	7.72	7.59	2868	0.883	15.29		
2156	(0.05)	7.47	7.49	12078	1.029	15.22		
SL 204			7.72	W 49	0.677	16.03		

of the cluster and the periods of the Cepheids, and data on the associated variable stars. A query indicates that the variable is far from the cluster and may not be a member. For NGC 1866, we include only stars within 10′ of the cluster center. All these stars are in the list of Shapley and Nail (1951); we have determined a period for HV 12192. Several of these stars have also been studied by Arp and Thackeray (1967). The integrated spectral class for NGC 2156 is from the Henry Draper Extension. No integrated color has been published for this cluster, and we have adopted a mean of the published colors for three clusters also classed as A3 in the Henry Draper Extension (NGC 1774, 0.00; NGC 2134, 0.10; NGC 2136, 0.05). The star W49 was discovered by Woolley and Epps (1963) in Cluster No. 204 of the list published by Shapley and Lindsay (1963).

The clusters have a moderate range of ages, log t ranging from 7.45 to 8.08. The ages deduced from the periods of the Cepheids are in general agreement with those deduced from the colors of the clusters, except for NGC 1856, for which we note that the Cepheid membership is doubtful on account of distance.

The known variables associated with "red globular clusters" are collected in Table 8. Values of (B−V) are from van den Bergh and Hagen (1968); the clusters for which no color is given were taken from the list of Hodge (1959). Most of the variables in the list were discussed by Hodge and Wright (1963) in connection with the clusters; they regarded those marked with asterisks as probable members. Data for three known globular clusters that contain RR Lyrae stars (NGC 1466, 1978, and 2257) are not included.

The data of Table 8 are not readily understood in terms of previous tables. Most of the stars are Cepheids, and except for the one near NGC 1953, they fall near the period-luminosity curve for normal Cepheids in the Clouds. Hodge and Wright discussed the possibility that these stars are Population II Cepheids, in recognition of their proximity to red globular clusters.

It is now known from the work of Gaposhkin (1972) and Payne-Gaposchkin (1971) that the

TABLE 8.—*Variable stars in red globular clusters*

NGC	B-V	Cepheids			Irregular	
		HV	log P	m_0	HV	m
1751		12904	0.290	16.00		
		12910?	0.504	16.33		
1783[*]	0.63				5 unnamed	
1786	(0.67)	880	1.067	14.72		
1846	0.74	2315?	0.382	15.93	12973:	17.95–
1953		12905*	0.820	16.29		
		12911?	0.262	16.49		
1978[†]	0.78		1.322:	(15.8)		
2019	0.77	5910	0.402	16.32		
2121		12908*	0.756	15.20		
		12909*	(0.344)	(16.81)		
		12656?	1.127	14.80		
SL 363		2439*	0.682	16.19		
SL 569		12906	0.242	17.14		
		12907	(-0.002)	(17.5)		
HS 83		13015	-0.178	16.56	13017	15.75–16.33
		13016	-0.236	16.64:		

[*] NGC 1783: Three variables (two red, one blue) are recorded by Gascoigne (1962) and two more (both red) have been noted in Harvard plates. The mean blue magnitude for Gascoigne's red variables is 17.54. He suggests that the blue variable may be an eclipsing star.

[†] NGC 1978: The data are from Hodge (1960a). Four variables, two probably of RR Lyrae type, are mentioned by Thackeray (1959).

Large Cloud does contain some Type II Cepheids about 2 magnitudes below the period-luminosity relation. In addition to 16 such stars in the Large Cloud, there are 3 in the Small Cloud. The likelihood that the Cepheids of Table 8 are of Type II seems to be reduced. If these stars are actually normal Cepheids, we shall have to assume that their membership in the clusters must be rejected on grounds of age (since log t for all these clusters must be between 9 and 10). However, it is hardly justifiable to assign Cepheids to blue clusters on the basis of proximity and then reject stars that lie equally close to globular clusters. We must therefore examine the possibility that they are actually associated with the clusters.

Hitherto, we have treated all the Cepheids, the young clusters, and the blue globular clusters as though they were at the same distance from us, although we should note that Arp (1967) considered it possible that NGC 1866 itself might lie as much as 18 kpc beyond the center of the Large Cloud.

The clusters of Table 8 were all given by Hodge (1960b) in his list of red globular clusters, and his (uncalibrated) color-magnitude arrays for all (except HS 83, which he did not study) show a strong red-giant branch. The detailed calibrated color-magnitude arrays for NGC 1783 by Sandage and Eggen (1960) and by Gascoigne (1962), for NGC 1846 by Hodge (1960c), and for NGC 1978 by Hodge (1960a) all display giant branches that contain their brightest stars. Moreover, the colors of van den Bergh and Hagen (1968) exclude the possibility that the clusters they observed belong to the blue group. However, they display enough variety to suggest that they may not be identical in age, or makeup, or both. The bluest in the table, NGC 1783, is described as "unclassifiable" by Gascoigne. It has some features in common with NGC 361 and NGC 419 in the Small Cloud, and these he regards as of "intermediate age." We note that "intermediate age" is a somewhat loose term and was applied, for example, to the considerably younger cluster SL 204 by Woolley and Epps (1963).

Gascoigne (1966) considered that NGC 1466, 1841, and 2257 resemble galactic halo clusters; they are distant from the Large Cloud and contain RR Lyrae stars. "In the absence of further evidence," he says, they "must be considered old and metal-poor." Some other clusters in the Large Cloud, such as NGC 2209 and NGC 2231 (not in Table 8, since they contain no known variable stars), have, according to Gascoigne (1966: 80), "no galactic counterparts, and *a priori* it is difficult even to say whether they are young or old." If, as he points out, their blue stars belong to the upper end of a main sequence, their distance moduli would be 19.5, and NGC 2231 and Hodge 11 would be 25 kpc beyond the Large Cloud. ". . . this hypothesis," he adds, "seems unlikely, and we would need further evidence before accepting it."

There is, in fact, some evidence that the Large Cloud has a halo of globular clusters. The three that are known to contain RR Lyrae stars (NGC 1466, 1841, and 2257) are far from the Cloud; NGC 1841 is 13 kpc from it, a third of the distance that separates the Large Cloud from the Galaxy. If the Cepheids of Table 8 had the luminosities of W Virginis stars, then NGC 2121, SL 363, and SL 569 would be halfway between the Cloud and the Galaxy. This suggestion could be tested by a search for RR Lyrae stars in these clusters, because most galactic globular clusters that contain W Virginis stars contain RR Lyrae stars too. The "mini-cluster" HS 83 does in fact lie about halfway between the Galaxy and the Large Cloud, as pointed out by Gaposhkin (1967), who discovered two RR Lyrae stars connected with it.

The variable in NGC 1978, regarded by Hodge (1960b) as a W Virginis star, would resemble the galactic W Virginis stars in luminosity if it were at the distance of the main body of the Cloud. The irregular variables in NGC 1783 present no anomalies; no Cepheids are known in that cluster.

The information contained in Tables 4 to 8 is summarized in Table 9, which arranges the material in order of adopted age. The youngest objects are probably in the 30 Dor association. Wolf-Rayet stars are found in the youngest groups; the younger the group is, the brighter is the Wolf-Rayet star. The same is true of the red supergiants (which are not, however, found in the very youngest groups) and the red irregular variables. Cepheids appear in clusters over 10^7 yr old, their periods being on the average smaller for older clusters. Data for the globular clusters NGC 1466, 1841, and 2257, which contain RR Lyrae stars, are from Gascoigne (1966).

Table 9 reinforces the belief expressed by Tifft (1964: 349): " . . . the relative *numbers* of stars formed in the various stages of the history of the systems [the Magellanic Clouds and the Galaxy] have been quite dissimilar." Hodge (1960b, for example) has repeatedly emphasized this point. Woolley (1961) describes the Large Cloud as composed of a mixture of an old population and a new one. Tifft and Snell (1971) describe the makeup of the "bar": ". . . a very strong old component. Superimposed upon this is an irregular scattering of younger stars." In this region they find no evidence of "a specific intermediate age giant branch like that found by Arp in the . . . SMC globular cluster NGC 419."

We can now apply our results to dating the features on the face of the Large Cloud. We compare first the distribution of Cepheid variables of different periods in the Large Cloud (Figures 1 and 2). For stars with log P up to 0.8, corresponding to log t = 7.64, the area north of the Bar, which we may call the "desert," is nearly bare of Cepheids. We can infer either that stars in this extensive region (which contains the dynamical center of the Cloud) are inhibited from Cepheid behavior or that potential Cepheids in the area are too young or too old to be in the Cepheid stage. The former alternative seems unlikely. The second is made probable by the distribution of the ages of the clusters,

Table 9.—*Summary of clusters and associations, Large Cloud*

Cluster	Adopted	Mean Magnitude			Cepheids Mean log P
		Wolf-Rayet v_0	Red Supergiants B	Red Irregular Variables m_{pg} (max.)	
NGC 1929	6.12				
NGC 1962–1970	6.44	11.14:			
NGC 2004	6.47		14.7		
NGC 1955	6.48	11.38			
NGC 1984	6.60		14.71	14.84	
NGC 2074	6.67	12.48			
NGC 1983	6.74				
NGC 2100	6.74				
NGC 2081	6.79	13.31	15.32	15.30	
NGC 1810	6.93		15.50		
NGC 1818	6.93		15.15		
NGC 2092	7.26		15.75	16.18	
NGC 1850	7.47				1.27
NGC 2156	7.47				1.03
NGC 1854	7.70			17.24	
NGC 2136	7.74				0.88
SL 204	(8.06)				0.68
NGC 2058	7.85				0.59
NGC 2065	7.85				0.52
NGC 1866	7.96				0.51
NGC 1856	8.19			17.76	0.62::
HS 83				15.75	-0.20
NGC 1466	>9		17.8		RR Lyrae
NGC 1841	>9		17.9		RR Lyrae
NGC 2257	>9		17.8		RR Lyrae
30 Dor	6.0–8.0	10.5:–12.5	15.41	15.11	0.59–1.35
Westerlund "b"	6.0–7.0		13.5–16.4	13.91	

shown in Figure 5. The ages have been deduced from the intrinsic colors published by van den Bergh and Hagen (1968), including those of some clusters not entered in our tables, because they contain no variable stars. It is seen that within the same roughly elliptical area avoided by the Cepheids, there are no observed clusters with values of log t greater than 7. Outside this area, all the ages exceed this value. As we noted earlier, the ages of Cepheids lie between 10^7 and 10^8 yr. We can then conclude that the potential Cepheids in the "desert" area are too young to have reached the Cepheid stage and that star formation dates there from less than 10^7 yr ago. There might, of course, have been another epoch of star formation more than 10^8 yr ago whose products are too old to be Cepheids now; but if so, it has left no obvious relics in the shape of intermediate-age clusters. When we look at the distribution of Cepheids with longer periods, we find them still sparsely represented in the "desert," and only for log P greater than 1.4, corresponding to log t = 7.25, do we find a good proportion of them encroaching on the region. On the other hand, the bright irregular variables (all very young, as shown by Table 4) and the similarly young Wolf-Rayet stars are practically confined to the area; the long-period variables (also bright and very young) are well represented there, and so are the eclipsing stars, most of which, as blue supergiants, also belong to the very young population.

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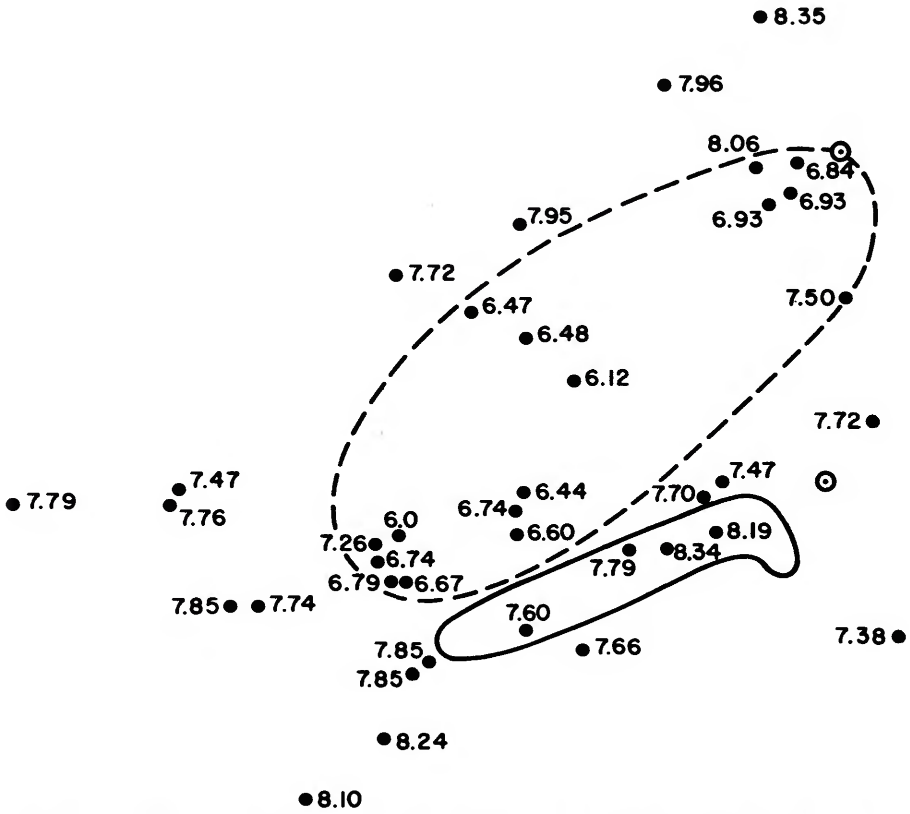

Figure 5.—Ages of clusters, expressed as log t in years. Circled dots denote globular clusters.

Along the northern edge of the region, there are concentrations of Cepheids with log P between 0.4 and 0.7, corresponding to log t from 7.70 to 7.90. Such clusters as occur in the region have similar ages. On the extreme northern edge lies NGC 1866, the nucleus of a knot of Cepheids of comparatively short period and an inferred log t of 7.96.

The greatest concentration of Cepheids is in the "bar" itself. As can be seen from Figure 1, the highest density of Cepheids seems to move up the bar from south to north with advancing period; for log P 0.4 to 0.5, it is at the southern end; for log P 0.7 to 0.8, it is in the center; and for log P 1.2 to 1.4, it is concentrated at the northern end. The progression is illustrated in Table 10.

Data for the 30 Dor area are included in Table 10. The area of the Tarantula Nebula lies just north of Area A and on the edge of the "desert." We can infer a progression of star formation along the bar from south to north, including the contiguous 30 Dor area, beginning with log t = 7.81 and growing more recent as we proceed northward along the bar. A second and much more recent era of star formation is indicated around 30 Dor and extends, as shown above, through the desert region. A similar progression can be noted in the ages of the star clusters in and near the bar. As pointed out by Tifft and Snell (1971), the bar has also been the seat of a much earlier era of star formation, but we may suppose that it is poor in components of ages 10^8 to 10^9 yr.

The very oldest stars evidently occupy extensive regions of the Large Cloud. Red globular clusters are found as far as 25 kpc from it. In fact, the situations of NGC 1466 and 1841 suggest that the two Clouds form an extensive binucleated system.

The evolutionary history of the Small Cloud seems to have been quite different from that of the Large Cloud. The youngest stars are found in progressively more concentrated areas, and the brightest Cepheids of longest period are almost all found in the "axis," as shown by Payne-Gaposchkin and Gaposchkin (1966). All these stars are probably still not far from their point of birth. The axis of the Small Cloud seems to have been producing stars continuously since about 4×10^8 yr ago, though not necessarily with a constant mass spectrum or at a constant rate. The "wing" area of the Small Cloud has, however, a different history from that of the body of the system. It contains no Cepheids with log t greater than about 7.5, and few with log t less than about 7.3; it also possesses many bright blue stars that date back only about 10^6 yr. It is in fact by far the youngest part of the Small Cloud, as was pointed out by Westerlund (1961b).

It is interesting to compare these distributions with the seemingly more orderly arrangement that prevails in the spiral galaxy Messier 31 and in our own system.

The work of Baade and Swope (1963, 1965) and of Gaposchkin (1962) shows a progression of properties in four areas. Table 11 reproduces their results. The angular distances have been converted to kiloparsecs with a distance of 674 kpc. The values of log t have been calculated as before.

Our own Galaxy displays a similar progression, as pointed out by van den Bergh (1958) and others. Table 12 represents the relation recently deduced by the writer from a rediscussion of all available galactic Cepheids.

In both Messier 31 and our Galaxy, these numbers, taken at face value, indicate that the youngest Cepheids are nearest to the center. In the Small Cloud (except for the "wing"), we can say with confidence that the oldest Cepheids are at the edges. The Large Cloud is less simple. The paucity of Cepheids near the dynamical center,

Table 10.—*Cepheid variables in the bar*

Area	A	B	C	D	E	30 Dor	
Median log P	0.552	0.600	0.677	0.662	1.020	0.544	1.235
Corresponding log t	7.80	7.77	7.72	7.73	7.50	7.81	7.36

TABLE 11.—*Cepheids in Messier 31*

Region	I	II	III	IV
Distance from nucleus	15′	36′	50′	96′
kpc	2.96	7.01	9.77	14.76
Medium log P	1.14	0.85	0.91	0.59
log t	7.42	7.61	7.57	7.78

TABLE 12.—*Galactic Cepheids*

Distance from Galactic Center (kpc)	Mean log P	Number of Stars	log t
6–7	1.334	7	7.29
7–8	1.158	24	7.41
8–9	0.956	46	7.54
9–10	0.842	142	7.61
10–11	0.877	62	7.59
11–12	0.799	52	7.64
12–13	0.780	62	7.65
13–14	0.728	23	7.69
14–15	0.643	14	7.74
15–16	0.691	1	7.71
16–17	0.671	2	7.72

and the fact that the youngest clusters are found in that area, might be interpreted in the same sense. But the youngest Cepheids in the Large Cloud seem to concentrate toward the northeast border.

From the distribution of Cepheids, we can evidently obtain some information about the history of star formation in a galaxy, but this information pertains only to an interval from 10^7 to 10^8 yr ago. Clusters do indeed provide data for times before and after this interval, and it is encouraging to note that these data are not contradictory for times where the scales overlap, at least in the Large Cloud.

Evolutionary Patterns for Cepheid Variables

We consider that data presented in the preceding section establish that the stars in recognizable areas (clusters and associations) were formed at different times. We suggest that the differences between the properties of the Cepheids in various areas are results of these differences in age, and that this conception can be extended to areas of the Clouds and our own Galaxy that have not been shown to contain otherwise datable components. We further suggest that the differences between the variable stars of the Large and Small Clouds, and of our own Galaxy, can be similarly interpreted. We now examine the consequence of differences of age on the basis of current theory of evolutionary tracks to see whether (or how far) they are adequate to produce the observed differences in the properties of the variable stars in the systems considered. In the present section, we shall not consider the effects of possible differences of composition, whose reality we shall explore in a later section.

Recent work, notably of Hofmeister, Kippenhahn, and Weigert (1964a, b, c), Kippenhahn, Thomas, and Weigert (1965), Iben (1966a, b, c), and Hofmeister (1967a, b), has shown that an evolving star becomes a Cepheid when its evolutionary track crosses a certain domain in the luminosity—effective-temperature plane. This domain, the "Cepheid gap," lies farthest to the red for the stars of highest mass (and luminosity). Tracks relevant to classical Cepheids are those for masses between 3 and 9$\odot$. The tracks may cross the gap as many as five times, and on each pass the star should be a Cepheid. The general course of the tracks is well established, but as the calculations are still subject to refinement, the results differ in numerical detail. Therefore, it seems best to keep the argument qualitative as far as possible. The theoretical results harmonize qualitatively with the observed period-luminosity and period-color relations. But the predicted tracks are sensitive to composition, as well as to the adopted physical parameters such as opacities and mixing lengths, so exact numerical comparison with observation seems premature.

Figure 6 shows schematically the theoretical tracks for stars of masses 3, 5, 7, and 9$\odot$ in the period-luminosity plane. A track labeled 7,1 de-

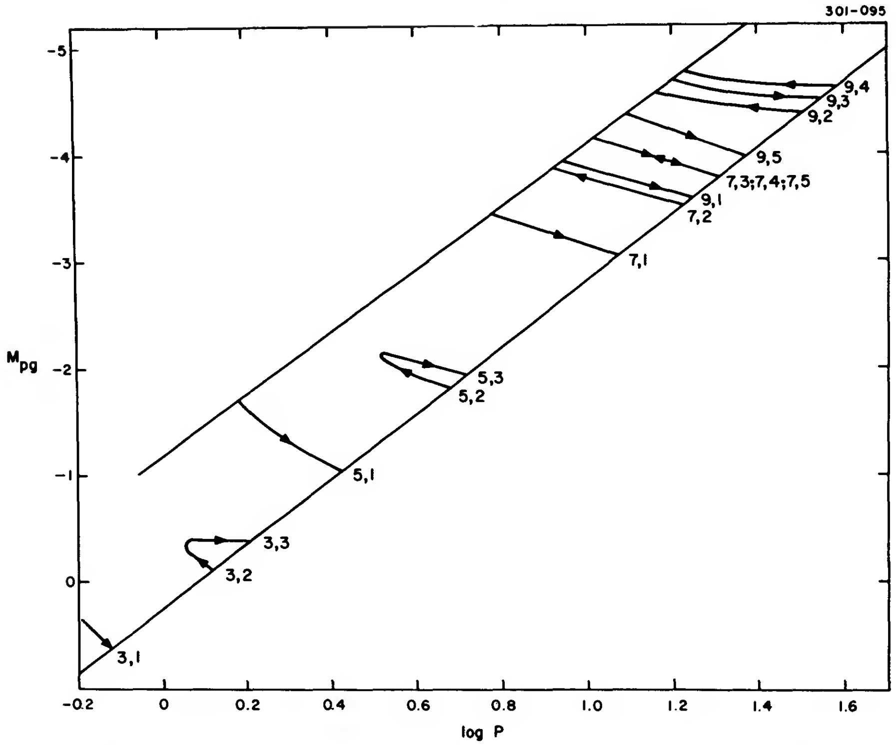

FIGURE 6.—Passes in the period-luminosity plane for several solar masses. The parallel lines indicate the approximate bounds of the instability strip. Each pass is identified by two numbers, the first indicating the solar mass, and the second, the number of the pass. For example, 7,1 indicates the first pass for a star of 7 solar masses. Arrows indicate the direction of the pass. Ordinates are logarithms of period in days, and abscissae, absolute photographic magnitudes.

notes pass no. 1 for mass $7\odot$, and so forth. The bounding lines are defined by the width, in effective temperature and color, of the Cepheid gap; they define the limits of the period-luminosity relation. The actual values are uncertain, since they depend on the model chosen, but the general picture is representative. It shows that there will be a dispersion in luminosity for stars of a given period, and a dispersion in period for stars of a given luminosity. It also shows that stars of given period and luminosity can have a variety of masses.

Changes of period have been calculated by Hofmeister (1967b) for various masses. They are positive (period increasing) for passes 1, 3, and 5 and negative for passes 2 and 4. On account of different rates of development during different passes, the changes are smallest, in general, for passes 2 and 3, larger for pass 4, and largest for passes 1 and 5, for stars of a given mass. For the same reason, the chance of observing a star of given mass as a Cepheid is largest for passes 2 and 3, less for pass 4, and least for passes 1 and 5 (assuming, of course, that stars of this mass have been supplied at a steady rate). Hofmeister's predictions show an order-of-magnitude agreement with observation for some galactic Cepheids, as she herself has pointed out.

If there is a secular change in period, the period P can be expressed as

$$P = P_0 + x \cdot P_0E,$$

where P_0 is the period at an initial epoch, E the number of epochs elapsed since the initial epoch, and x a constant. After E epochs, the time at which the star reaches a certain phase (e.g., maximum) will deviate by $\propto P_o E^2/2$ from the time predicted for constant P_0.

Table 13 presents, for 23 galactic Cepheids, data taken from the compilation by Parenago (1958), from Walraven, Muller, and Oosterhoff (1958), and from Oosterhoff (1960). The change of period is expressed as the logarithm of the change per century, in terms of the period, because Hofmeister expresses her results in this form. The passes are tentatively identified. Table 14 gives similar data for 13 Magellanic Cepheids.

The expected change of period depends on the following: (1) the mass of the star, being greater for larger masses; (2) the pass being traversed, as noted above; and (3) the composition. In Figure 7, we compare the observed values of $\Delta P/P$ per century with those predicted for stars of initial masses 5, 7, and $9\odot$ having Hofmeister's "extreme" (= metal-rich) composition; the periods used are those she has calculated for maximum excitation at the respective masses.

The observed changes of period are of the predicted order of magnitude, and there is no great difference between the galactic and Magellanic Cepheids. Of the 36 stars in the tables, only 3 are assigned to pass 1, which reflects the relative brevity of that pass and the rarity of the stars found to be performing it. For the Magellanic Clouds, where over 2200 Cepheids have been studied, only one can be assigned to pass 1.

The computed tracks suggest that at a given period (mass loss being disregarded) a star would become progressively brighter in going from pass 1 to pass 5. A rough test for this tendency can be made by comparing values of $m_0 + 2.5 \log P$ (a measure of deviation from the period-luminosity relation) for the assigned passes. The results are as follows for the Magellanic Cepheids:

Pass	*$m_0 + 2.5 \log P$*	*No. of stars*
1 (5)	17.61	1
2 (4)	17.49	7
3	17.37	5

The number of stars is too small for conclusions; if the passes are indeed 1, 2, and 3, the tendency is in the direction expected.

Not all changes of period, however, are secular. Seventeen Cepheids in the Large Cloud and two in the Small have shown discontinuous changes of period, and with two exceptions, these changes are increases, ranging from about 0.001 P at 3 days to nearly 0.01 P at about 100 days and showing a rough correlation with period.

The fact that some stars show apparently secular changes of period, others show discontinuous changes, and some show no changes at all dis-

TABLE 13.—*Changes of period of galactic Cepheids*

Star	log P	Sign of x	log ΔP/P per Century	Pass
AX Vel	0.41	+	-2.71	1
WZ Pup	0.70	+	-2.14	1
δ Cep	0.73	-	-4.82	2
η Aql	0.86	+	-4.47	3
ζ Gem	1.01	-	-3.45	2
TW Nor	1.03	+	-2.32	1?
SZ Cas	1.13	+	-1.78	1
RW Cas	1.17	-	-3.11	2
XX Car	1.20	-	-2.41	2?
YZ Car	1.26	+	-2.66	3
VY Car	1.28	-	-1.70	4?
RU Sct	1.29	+	-2.36	3
WZ Car	1.36	+	-1.70	1
SW Vel	1.37	-	-1.53	1
X Pup	1.41	+	-1.40	1
T Mon	1.43	+	-3.19	3
l Car	1.55	+	-2.09	3
EV Aql	1.60	+	-0.62	1
RS Pup	1.62	+	-2.62	3
SV Vul	1.65	-	-1.97	2

TABLE 14.—*Secular changes of period for Magellanic Cepheids*

HV	System	log P	Sign of x	log ΔP/P per Century	Pass
12697	LMC	0.388	+	-3.81	3
12534	LMC	0.464	-	-3.32	4
2795	LMC	0.592	-	-3.84	4
2584	LMC	0.670	+	-2.40	1
1695	SMC	1.164	-	-2.95	2
1003	LMC	1.388	-	-2.38	2
902	LMC	1.421	-	-2.45	2
2251	LMC	1.447	-	-2.30	2
1002	LMC	1.484	+	-2.61	3
909	LMC	1.575	+	-2.49	3
2257	LMC	1.594	+	-2.77	3
834	SMC	1.867	+	-2.30	3
829	SMC	1.947	-	-1.26	2

turbs the clarity of the picture. Perhaps we should consider that all changes are discontinuous: the star maintains a constant period for a time and then changes more or less abruptly to another period. If such changes are frequent and observation is intermittent, the impression of a secular change is produced. If they occur at long intervals, a discontinuous change is inferred. If these intervals are comparable to the baseline of observation, the period appears to be constant. Apparently, secular changes show increases and decreases in roughly equal numbers, but discontinuous changes are almost all increases.

Table 15 summarizes change of period of all types for Magellanic Cepheids. The percentage of stars with observably variable periods increases almost uniformly from short to long periods, despite the fact that the number of elapsed epochs in a given time interval (over 50 yr for the Harvard material on the Magellanic Clouds) is greater for a star of short period.

Our study of period changes permits four conclusions: (1) the observed secular changes are of the order predicted by Hofmeister; (2) they do not differ appreciably between the Magellanic Clouds and the Galaxy; (3) some stars show secular changes of period, others show discontinuous changes, and others (in the same period range) show none; and (4) the percentage of stars with inconstant periods increases with period.

The most realistic statement is probably that the theoretical changes of period (predicted at maximum excitation for the relevant masses) coincide roughly with the *upper limit* of the observed changes of period. But (as illustrated in detail later) stars of a given mass should theoretically show a variety of periods, and stars of a given period should accordingly possess a variety of masses. The rate of development and hence the rate of change of period are very sensitive to mass. The stars that show the largest changes of period will be those of the largest mass in the range of period considered. From this point of view, we should expect to find what is actually observed: upper limits to the rate of change at any one period, corresponding to the stars of highest mass. On any probable assump-

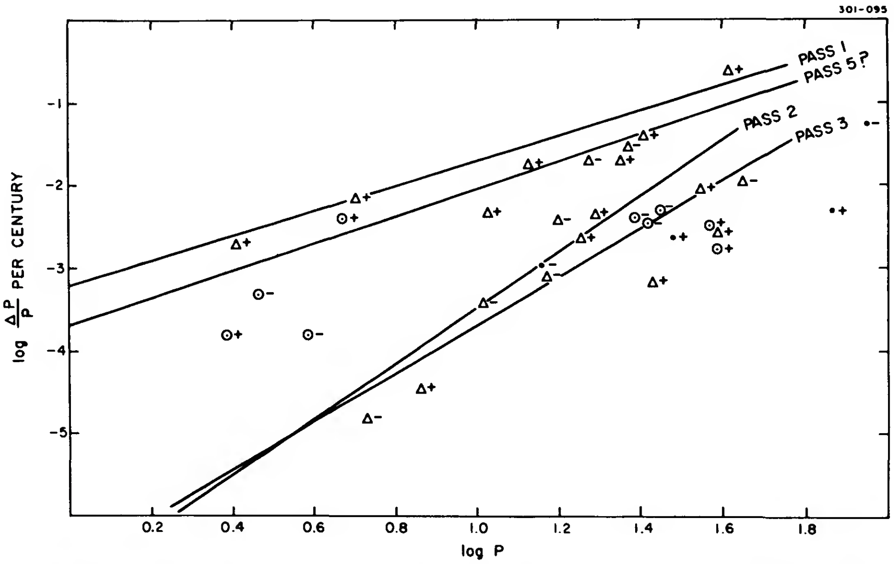

Figure 7.—Change of period, in logarithms of $\Delta P/P$ per century, plotted against log P, for galactic and Magellanic Cepheids. Triangles refer to galactic stars, circles with dots to Large Cloud stars, and dots to Small Cloud stars. The + and − signs beside the symbols indicate whether the period is increasing or decreasing. Theoretical lines calculated by Hofmeister are shown for passes 1, 2, and 3, and a possible course for pass 5 is indicated. On passes 1, 3, and 5, the period is increasing; on passes 2 and 4, it is decreasing.

Table 15.—*Changes of period for Magellanic Cepheids*

log P	Large Cloud				Small Cloud				Combined	
	Increase	Decrease	Erratic	Cepheids	Increase	Decrease	Erratic	Cepheids	%	Cepheids
-0.1 –0.099				0				39	0	39
0.10–0.299				19				293	0	312
0.30–0.499	2	1		233				321	0.6	554
0.50–0.699		2		485				248	0.3	733
0.70–0.899				169				116	0	285
0.90–1.099	1			92			1	57	1.3	149
1.10–1.299	5	1		57		1	1	46	7.7	103
1.30–1.499	4	3		36				16	13.4	52
1.50–1.699	5		1	13				12	24.0	25
1.70–1.899	1			2	1		1	3	40.0	5
1.90–2.099	1		1	2		1		2	75.0	4
2.10–2.299				1				1	0	2

tion as to the mass-frequency function, such stars would be a minority. We therefore feel justified in regarding the rough correspondence between theory and observation, for stars whose changes of period have been observed, as evidence that the time scales that have emerged from the calculations are of the right order.

We are not yet in a position to anticipate what effect composition will have on the rate of change of period. The most we can say is that *if composition has an appreciable effect*, the similarity of the changes of period for galactic and Magellanic Cepheids does not point to an appreciable difference of composition.

The computed times derived from the tracks of Hofmeister (1967b) and of Iben (1966a, b, c) are not identical. The Iben time scale would lead to

$$\log t = 8.34 - 0.717 \log P,$$

and the Hofmeister time scale to about

$$\log t = 8.14 - 0.717 \log P,$$

a formula that would give results very little different from those deduced from Tammann's formula (equation (3)).

The predicted position and width of the Cepheid strip are compatible with the observed dispersion of the period-luminosity relation. As pointed out by Payne-Gaposchkin and Gaposchkin (1966), 50% of the Cepheids in the Small Cloud lie within $0.^{m}22$ (photographic) of the line defined by a linear least-squares solution for the period-luminosity relation. Sandage and Tammann (1968) admit a *total* spread of $\pm 0.^{m}6$ at any one period. Figure 7 suggests $\pm 0.^{m}5$.

The slope of the period-luminosity relation also seems to agree fairly well with prediction. The values deduced from Hofmeister's maximum-excitation points and expressed for photographic magnitudes give

$$M_{pg} = -0.96 - 2.44 \log P,$$

if a linear relation is assumed. This relation falls within the limits of the nonlinear relation favored by Sandage and Tammann (1968).

In summary, the theoretical tracks conform reasonably well with observation, and their form will therefore be accepted in principle.

Evidence Bearing on Composition

In the preceding sections, we have attributed the differences between the two Clouds, and between the Clouds and the Galaxy, to differences in *history*. We must now examine the evidence for another widely acclaimed source of difference —chemical composition. It seems, from the evidence that has been presented, that differences of age and history are inescapable. Is there also evidence as to differences of composition?

Within our Galaxy, the recognized differences of composition embrace the extreme metal poverty of some members of the halo population and the metal richness of the young Population I stars. The range is illustrated by an excerpt from the compilation of Aller (1961: 203).

Population	*Halo* II	*Intermediate* II	*Disk*	*Old* I	*Young* I
Fraction of heavy elements by weight	0.003	0.01	0.02	0.03	0.04
Age (10^6 yr)	6000	5000 to 6000	1500 to 5000	100 to 1500	under 100

From Table 9 we see that the oldest variable stars that we have studied in the Clouds have ages of about 10^8 yr; thus, they fall within the age limits of young galactic Population I stars, or exceed it only slightly. The globular clusters associated with the Large Cloud, some of which contain RR Lyrae stars, must of course be older, and Walker (1972) has shown that NGC 2257 is either of "extremely low metal content like M 92 but with an abnormally low red-giant branch," or a cluster of intermediate metal deficiency like M 3 or M 13.

We are concerned, however, with differences between the LMC, the SMC, and the Galaxy that depend on studies of variable stars and young clusters, and if differences between these are results of composition, we must suppose that the material that was available in the Clouds for star formation 10^8 yr ago was of different atomic makeup from the contemporaneous material in our Galaxy. We can test this possibility only by examining the current composition of young stars and nebulae in the Clouds.

Several sources of information are available: (1) direct analysis of stellar spectra; (2) direct analysis of nebular spectra; (3) UBV photometry of stars; (4) ubvy photometry of stars; (5) color-magnitude arrays of clusters; (6) colors of Cepheid variables; and (7) period frequency of Cepheids. Conclusions based on (1), (2), (3), (4), (5), (6), and (7) are progressively less direct.

1. There are no obvious differences between the spectra of luminous Magellanic and galactic stars. Code and Houck (1956, 1958) found the stars they examined in the Large Cloud "essentially similar to the OB stars of our own Galaxy." Studies by Feast et al. (1958, 1960) were based on direct spectroscopic comparison, on comparison of H–R diagrams, and on UBV photometry. They stated that "We have found no evidence . . . that there is a difference in chemical composition," and further that "Peculiarities have been found in certain stars, most of which can certainly be attributed to causes other than metal-poorness." A more detailed result is the coarse analysis of the spectrum of HD 33579 in the Large Cloud by Przybylski (1965), who found the value of log (metals/H) smaller in HD 33579 by -0.2 ± 0.2. Feast (1964) found no evidence of metal weakness in his study of the SMC cluster NGC 330.

2. The He/H ratio has been studied for 30 Dor by Hugh Johnson (1959) and by Faulkner (1964). The former derived a ratio 0.13, nearly the same as for the Orion Nebula. The latter gives the values 0.074 for 30 Dor, 0.117 for the Orion Nebula, and 0.114 for the Eta Carinae Nebula, and O/H ratios of 2.5×10^{-4} for 30 Dor and 3.4×10^{-4} for the Orion Nebula; the differences seem marginally significant. The He/H ratio for NGC 346 (Small Cloud) was found by Aller and Faulkner (1962) to be 0.11.

3. The application of UBV photometry to the blue supergiants in the Clouds is complicated by the difficulty of determining the intrinsic colors. Not only are the intrinsic colors given by Johnson (1963) for luminosity classes Ia and Ib in the Galaxy too red, as shown by Serkowski (1963) and tabulated by Schmidt-Kaler (1965: 297), but also they are functions of luminosity, as could be deduced from the work of Mendoza (1971) and as specifically pointed out by the Walravens (1971). We note, however, that Dachs (1972) does not take account of this effect. It seems that, except for the excessive luminosities of some Cloud supergiants, the conclusions of the Walravens (1964: 328) still stand: ". . . no real difference can be detected between the Galaxy and the Magellanic Clouds." Insofar as intrinsic color is an index of composition, we conclude that no real difference in the latter is established by these data.

4. Using four-color intermediate-band photometry, Williams (1961) reached the conclusion that the metal/H ratios "do not differ by a large factor, if at all," between the Clouds and the Galaxy, at least for the long-period Cepheids to which the study was confined.

5. The color-luminosity arrays of clusters have received conflicting interpretations. From his careful photometry of cluster stars in the Small Cloud, Arp (1958a, b, 1959a, b) has argued that the clusters considered are metal poor. Feast (1960) considers that the same data do not require metal poverty. These clusters fall into the group described by Gascoigne (1966: 81) as of "intermediate age," unlike the true globular clusters such as NGC 2257, which have been shown by Walker (1972) to be metal poor. These intermediate-age clusters are certainly older than any of the variable stars with which we have been concerned.

6. The colors of the Magellanic Cepheids have been extensively discussed, and I shall not here deal with the subject in detail, as I have treated it elsewhere (*Smithsonian Contributions to Astrophysics*, no. 17). Here I will state the bare outline: the difference in color between the LMC Cepheids and those of the Galaxy is barely significant. When light amplitude is taken into account, there is a definite difference in color *at minimum* between galactic Cepheids and those of the Small Cloud; at maximum the colors do not differ sensibly. At minimum the difference is about $0.^{m}1$, which seems significant. However, it is found primarily for the Cepheids of shortest period and faintest magnitude and may be an effect of background light on the B magnitudes. It is not certain, even if the difference in color at minimum is real, that it points to metal poverty for Magellanic Cepheids. Why is it inconspicuous or absent for the maximal colors?

7. The argument based on differences of period frequency is even less direct. In the next section, we shall examine the effects of age on the period-frequency and period-amplitude relations. If the differences can be attributed to age alone, it would seem unnecessary to invoke differences of composition in interpreting them, unless this has been rendered inescapable by more direct arguments.

In summary, our discussion of evidences for composition differences suggests that these data do not compel us to conclude that such differences exist between the young stars and clusters of the Clouds and our Galaxy. A similar view is expressed by G. Burbidge (1971): ". . . the bulk of the matter which is easily studied in the Magellanic Clouds . . . contains elements with similar total and relative abundance to that in the disk of our Galaxy." He adds that "there may very well be a range of element abundances in the Magellanic Clouds similar to that in our Galaxy."

The Period-Frequency and Period-Amplitude Relations

In examining the effects of the age of a stellar group on the period-frequency function and the period-amplitude relation of the associated Cepheids, we find the crucial consideration is that the time taken for a star of given composition to reach the Cepheid stage is exceedingly sensitive to mass. Hofmeister (1967b) has tabulated the times spent on the main sequence and in the Cepheid stage for stars of masses 5, 7, and $9\odot$. The transition from main-sequence to Cepheid stage is so rapid that the time spent on the main sequence is approximately equal to the whole age of a star that has become a Cepheid. Therefore, the ratio of these times gives a measure of the fraction of its lifetime that a star spends as a Cepheid. We select for comparison the "extreme" composition ($X = 0.602$, $Z = 0.044$), since "normal" composition seems ruled out by the observed changes of period. Extreme and normal compositions differ both in H/He ratio (greater for normal) and in metals/He ratio (greater for extreme). Kippenhahn (1965: 14) has remarked: "It seems clear that the appearance or disappearance of the loops depends on the ratio of the speed of the helium burning phase to some kind of adjustment time of the outer layers. . . . Although we do not yet understand what actually caused the disappearance of the loops [for normal composition], it seems empirically that the loops are a good indication for chemical composition."

The times given by Hofmeister, and their ratios, are as follows:

Mass (⊙)	5	7	9
Time on main sequence (yr)	5.07×10^7	2.61×10^7	1.66×10^7
Cepheid stage (all passes) (yr)	2.82×10^6	5.4×10^5	2.1×10^4
Ratio	0.0555	0.0218	0.0013

Accordingly, in a group of stars that are similar in age but different in mass, those that are

Cepheids at any one time will have an extremely small range in mass. Coeval stars whose masses differ by more than a few percent cannot be Cepheids at the same time. But stars with this very limited range of mass will, if of the same age, display a considerable range of period, depending on their current position in the Cepheid strip.

Hofmeister has calculated "stability coefficients" for all five passes of a star of mass 9. Maximum value of the stability coefficient η is associated with the model of maximum pulsational excitation for the corresponding mass. It seems reasonable to suppose that this model will correspond to maximum light amplitude and that amplitude will be related in some way to η. Figure 8 shows the values of η for the five passes of a star of mass 9. A coeval group of stars with masses very close to 9$\odot$ will display a variety of periods. The amplitudes should be small for the shortest of these periods, should rise to a maximum for log P rather greater than the average, and should fall more abruptly on the long-period side. This would follow even if the expected amplitudes were weighted in inverse proportion to the speed at which stars traverse the strip at the corresponding pass (greatest weight to passes 2, 3, 4, less to pass 5, and least to pass 1).

If stars of other masses have a similar relationship between η and period at the various passes, a similar result would be valid for each

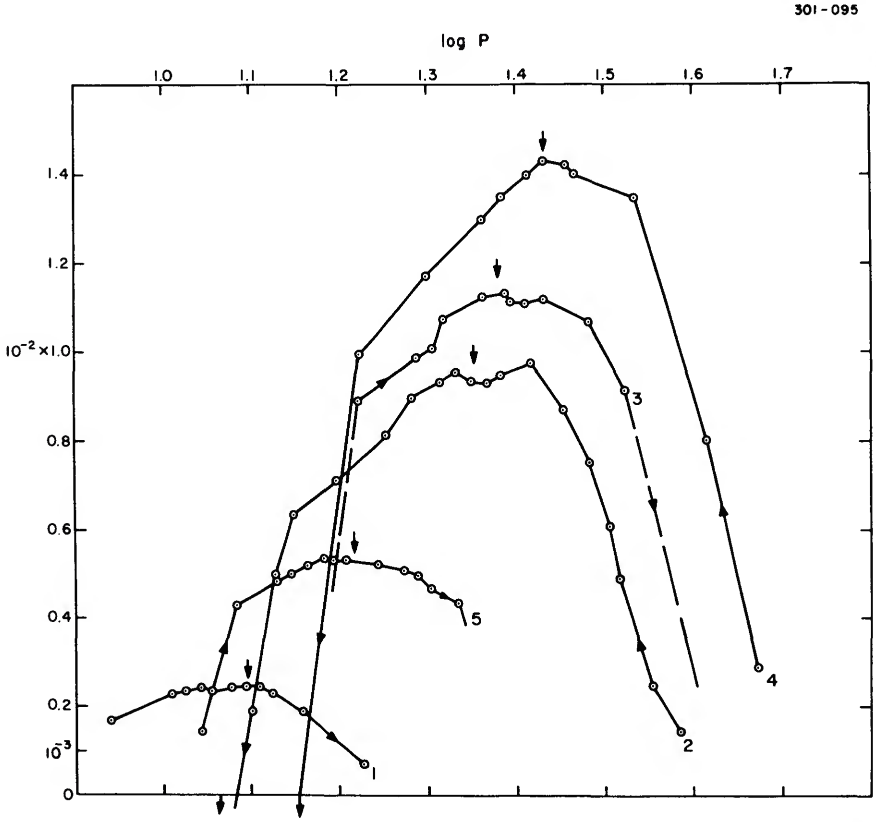

Figure 8.—Hofmeister's "stability coefficient" η plotted against log P for all five passes of a Cepheid of 9 solar masses. The number of the pass is indicated at the right-hand end of the line; arrows on the line show the direction in which the period is changing. Vertical arrows indicate the point of maximum stability. The relative durations of passes 1 to 5 are, respectively, 10, 55, 97, 37, and 11.

mass. Each coeval group would show its own period-amplitude function over a limited range of periods.

If the stars in a system are not coeval but are being produced continuously, their period-amplitude functions will be superimposed. The lower limit of period will be set by the interval since the oldest stars that have reached the Cepheid strip were produced; these will be the Cepheids of lowest mass, which develop the most slowly. *At a given time*, these stars will be joined by more massive stars, born more recently, that have reached the Cepheid strip. These stars will have a period-frequency function that produces maximum amplitude at a somewhat longer period than the oldest group. At the same time, stars still more massive will contribute period-amplitude functions with maximum amplitudes at still longer periods. A group in which stars are being continuously supplied will show a period-amplitude function that is the sum of the period-amplitude functions of all the stars massive enough to have reached the Cepheid strip. One can see that this function will reach a plateau at the period corresponding to the period of maximum excitation of the least massive stars that have reached the Cepheid stage. This would be true (on account of the different rate of development of stars of different masses) even if stars of all masses were produced in equal numbers; actually, the less massive stars are probably always the most numerous, and the maximum will be accentuated.

In the Small Cloud, the Large Cloud, and the Galaxy, there is a close relationship between the period-amplitude and the period-frequency relations: they tend to peak at the same period. The foregoing suggestion is in harmony with this fact. At the long-period side of the frequency distribution, the overlapping stability coefficients would lead to a rather abrupt fall in the period frequency and a concomitant diminution in amplitude; this also is observed.

An alternative interpretation of the differences of period frequency rests on the possibility that within the Cepheid strip the situation of the loops in the evolutionary tracks may differ from star to star, perhaps as a consequence of composition. Hofmeister's "normal" calculations (relatively poor both in helium and in metals) show almost complete suppression of the loops, so that the Cepheid stage would be confined to pass 1. If this result is valid, a population of "normal" composition would contain less than 1% as many Cepheids as an "extreme" population with the same distribution of masses and the same history. If the Small Cloud is metal or helium poor compared to the Galaxy, it should be far poorer in Cepheids, whereas it appears to be far richer. Thus, even if the difference between the Galactic and Magellanic Cepheids is a result of composition, this argument cannot be used to show that the Clouds are poorer in metals.

A period-frequency function has been predicted by Smak (1962) with simplified assumptions: (1) Cepheids originate from an initial main sequence that has the Salpeter initial luminosity function; (2) the Cepheid stage follows closely after the main-sequence stage at the same (visual) absolute magnitude; (3) the Cepheid lifetime is proportional to mass/luminosity. The frequency function thus predicted falls sharply with increasing period and thus agrees (at least qualitatively) with the observed period-frequency functions of the Galaxy and the Clouds for periods greater than that corresponding to the maximum frequency. But the deficiency of short periods is not predicted; Smak inclines to attribute it to observational incompleteness, a consequence of small amplitudes at short periods. However, as shown by the writer (1971), it is undoubtedly real.

Hofmeister (1967b) refines the approach. Assumption (1) is retained, (2) is somewhat modified, and (3) is replaced by the lifetimes cited earlier, which deviate greatly from Smak's assumption. The resulting function shows an abrupt rise to maximum and a slower fall toward long periods, numerical agreement being best for the Small Cloud. She attributes the differences between systems to slight differences in the location of the loops within the Cepheid strip: ". . . we may suspect that different metal-to-helium ratios in the Galaxy and the Small Cloud might lead to a shift of maximum."

The alternative interpretation now put forward is that the supply of stars has not been continuous and that star formation (producing stars that are now Cepheids) became important at different times in different systems—earliest in the Small Cloud, later in the Large, and latest in the part of the Galaxy with which we have compared these systems. It has also differed in different parts of the same system, as the distribution of Cepheids of different periods in the Cloud, the galaxy, and Messier 31 seems to show. If the difference of period frequency between the center and the edge of Messier 31 were a result of differences in composition in different regions of that galaxy, a much larger range in composition would be required than would be needed to account for the differences between the Magellanic Clouds and our Galaxy. The same is true of the difference of period within our own system (Table 12). This statement is independent of any numerical estimate of composition in any of the four systems: if period frequency is an index of composition, the range of composition within our own Galaxy and Messier 31 is greater than the difference of composition between the solar neighborhood and either of the Clouds.

We shall recall that all attempts to predict a period-frequency function have assumed that there has been a continuous supply of stars, and that their masses are distributed according to the Salpeter function. From what has been said above, we have little reason to feel confident about the former assumption.

Another uncertainty is introduced by the tacit assumption that the stars have developed at constant mass. Mass loss, however, is almost certainly taking place. Christy (1967) suggested that β Dor has sustained mass loss during the red-giant stage on the basis of his calculations of velocity and light curves for a star of this period. If mass loss takes place, a Cepheid reaches passes 2 and 3 (the slowest, and those with which most Cepheids must accordingly be associated) with a lower mass than at pass 1. Mass loss would, qualitatively, have two effects. The period-luminosity relation would become less steep, and the frequency of long periods would be increased. All the attempts to predict a period-frequency function have resulted in fewer long periods than are observed. This discrepancy might be removed, or at least reduced, by considering mass loss; however, it could also be removed by a modification of the assumption that the stars have been produced at a constant rate.

The conclusions that we have reached are supported by the opinion of Thackeray (1971): "... the predominance of 2-day Cepheids in the SMC ... very probably points to some difference from LMC and galaxy in its stage of evolutionary development. ... The whole picture of the LMC suggests to us that the system is one of very active star formation, while in the SMC apart from the wing there appears to have been a decline in star formation." We also quote the evaluation of E. M. Burbidge (1971): "The Clouds may owe their barred and asymmetrical distribution, including departure of the centre of rotation from the geometrical centre, to local fluctuations in H I density and rate of star formation at different epochs."

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