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STEPS TOWARD THE HUBBLE CONSTANT. II. THE BRIGHTEST STARS IN LATE-TYPE SPIRAL GALAXIES

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ABSTRACT

Identification and photometry of the brightest blue and red supergiant stars are given for the highly resolved galaxies NGC 2366, NGC 4236, IC 2574, Ho I, and Ho II in the NGC 2403–M81 group. The data are based on plates taken with the Hale 5-meter telescope and on new photoelectric sequences, or on photographic transfers to other photoelectric sequences. Brightest stars in the Large Magellanic Cloud, the Small Magellanic Cloud, and the solar neighborhood have been selected by analysis of recent data in the literature. This material, together with less complete data for NGC 6822, IC 1613, and M33, gives a calibration of the absolute blue magnitude of the brightest blue stars in terms of either the luminosity of the parent galaxy or the luminosity class. The absolute magnitudes range from $M_B(1st) = -8.0$ for $M_B(gal) = -14.5$ to $M_B(1st) = -10.0$ for $M_B(gal) = -20.7$. The standard deviation of a single galaxy about the mean correlation line is $\sigma(M_B) \simeq 0.5$ mag. The correlation of M(star) and M(galaxy) is significant at the 2.5 σ level, and can be understood as a consequence of the normalization of a common luminosity function to the total luminosity of each parent galaxy.

A test of the assumption that six galaxies of the NGC 2403 group are closely at the distance of the parent galaxy was made by determining the individual distances by the H II region calibration of Paper I and by the bright-star criterion here. The mean distance to the six galaxies is 3.09 ± 0.13 Mpc (the standard deviation of a single galaxy distance is ± 0.30 Mpc). There are no significant differences (larger than $\sim 1.5\ \sigma$) in our distances to any of the six members of the group.

The brightest red supergiants [chosen such that $(B - V)_0 \gtrsim 2.0$] have a remarkably small dispersion in absolute magnitude, and the magnitudes do not depend on the luminosity of the parent galaxy. The calibration gives $M_v^0(\max) = -7.9 \pm 0.1$ mag. Brighter stars are guillotined either by downward sloping evolutionary tracks from their brighter main-sequence progenitors, or by the sharp onset (at $M_V \simeq -8$) of some physical process that drastically shortens the life of a brighter red supergiant.

Bright blue irregular variables are not so well defined in absolute luminosity. Although they are very luminous at maximum light [$\langle M_B \rangle \simeq -9.4 \pm \sim 0.5$], some members of the class, such as η Car, become so much brighter ($M_B \simeq -14$) at certain times that the stars, as a class, are apparently unsuitable as accurate distance indicators.

Subject headings: galaxies — galaxies, clusters of — luminosities — luminous stars

I. INTRODUCTION

Hubble's extragalactic distance scale depended entirely on the brightest stars in nearby resolved galaxies (Hubble 1936*a*). His expansion rate of $H = 526$ km s^{-1} Mpc^{-1} (Hubble 1936*b*) was obtained from the constant term in the redshift-magnitude equation for these brightest stars, combined with a calibration of their absolute magnitude ($\langle M_{pg} \rangle_s \simeq -6$). The calibration was made using galaxies whose distances were known either from Cepheids (in the Local Group) or with much less certainty from novae and irregular variables (in the M81 and M101 groups) (Hubble 1936*a*, table 1).

Hubble's secondary distance criterion was total galaxian magnitude. But, as the mean absolute magnitude for field galaxies was calibrated relative to the brightest stars (Hubble 1936*b*), the expansion rate determined from such galaxies is not independent of the first method. The agreement of the two methods (Hubble 1936*b*, table 6) tests only the internal consistency of the data.

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There are various problems with the brightest-star criterion. Many were isolated by Hubble (1936*a*, pp. 281–283) himself, and others have come to light by more recent knowledge. The difficulties, as we now understand them, would include (1) errors in the distances to the calibrating galaxies caused by too faint a zero-point to the Cepheid period-luminosity (*P-L*) relation; (2) confusion of groups, clusters, and H II regions with single stars in the distance interval $33 > (m - M) \gtrsim 28$; (3) superposed contaminating stars from our own Galaxy; and (4) scale errors in the magnitude sequences leading to progressive errors in distances for the more remote resolved galaxies.

As part of the redetermination of galaxian distances, begun in 1950 when the Hale 5-meter telescope went into operation, we have reexamined the brightest-star criterion in a program described by Humason, Mayall, and Sandage (1956, Appendix C). The recalibration has now progressed to a stage where a preliminary discussion of results is useful, leading to a revised value of $\langle M \rangle_s$. Improvements over the 1936 results are possible because of (*a*) the revision of the Cepheid *P–L*-third-parameter relation via the photometric parallaxes of Cepheids in open clusters, (*b*) revision of distances to all Local Group galaxies, (*c*) pushing the Cepheid criterion beyond the Local Group to obtain the distance to members of the M81–NGC 2403 group, (*d*) the isolation of stars from H II regions by use of red plates and Hα filters, and (*e*) use of photoelectric magnitude sequences throughout.

New data on the brightest stars in late-type resolved galaxies in the M81–NGC 2403 group are given in § II; the existing modern data for Local Group galaxies are discussed in § III; the resulting calibration of $M_s = f(M_g)$ for the blue stars is set out in § IV; a comparison of distances for all NGC 2403–M81 group members as determined by H II regions and by the brightest stars, and a test for a difference in the distances of group members themselves is given in § V; a model for the luminosity of the brightest stars as a function of M(galaxy) is given in § VI; the calibration of the very red late-type supergiants is discussed in § VII; and a preliminary discussion is given in § VIII of the class of irregular luminous blue variables first studied by Hubble and Sandage (1953) in M31 and M33.

II. PHOTOMETRY IN LATE-TYPE GALAXIES OF THE NGC 2403–M81 GROUP

The number of galaxies that enter the calibration of brightest stars can be increased by including the highly resolved systems of the NGC 2403 group, whose distances are taken to be the same as for NGC 2403 itself (a test of the assumption is made in § V). We have identified the brightest red and blue stars, and have completed preliminary photometry in NGC 2366, IC 2574, Ho II, Ho I, and NGC 4236 in this group (Holmberg 1950).

The clear danger in identifying brightest member stars is the contamination of the face of a galaxy by stars from our own Galaxy. Many such stars exist, especially fainter than $m \simeq 18$, but the galactic contaminants in high latitudes are confined almost entirely to the color range $0.4 < B - V < 2.0$ (cf. Becker 1967, fig. 3; Becker 1972, fig. 4, suitably transformed to $B - V$ by the equations given in Becker 1967). The limit at $B - V \simeq 0.4$ is due to the lack of many main-sequence stars bluer than this value in the galactic halo (the number of white dwarfs and horizontal-branch stars per square degree is negligible for this problem); the red cutoff is due to the asymptotic behavior of $B - V$ for red dwarfs (see especially fig. 2 of Woolley *et al.* 1970). Because of these color discriminants, we have attempted to identify only those stars over the face of the galaxies that are either bluer than $B - V = 0.4$ or redder than $B - V = 2.0$; and the number of field stars mistaken for brightest members should be negligibly small.

Skeleton photoelectric sequences were set up using the Hale 5-m reflector near NGC 2366, IC 2574, and Ho II. These were supplemented and extended to fainter magnitudes by photographic transfers, either to sequences in several Selected Areas or to the photoelectric sequence in NGC 2403 (Tammann and Sandage 1968). No primary photoelectric sequences were determined in NGC 4236, or in Ho I, and the photometric standards there depend solely on photographic transfers.

TABLE 1

PHOTOMETRY OF STARS IN AND NEAR NGC 2366 IDENTIFIED IN FIGURE 1

A. PHOTOELECTRIC SEQUENCE IN NGC 2366

Star	V	B	$B-V$
A..........	12.28	13.17	0.89
B..........	13.03	13.94	0.91
C..........	13.76	14.43	0.67
D..........	15.21	15.79	0.58
E..........	16.87	18.04	1.17
F..........	18.63	19.63	1.00
G..........	19.07	20.16	1.09
H..........	19.28	19.75	0.47
I..........	16.98	17.64	0.66

B. SECONDARY B SEQUENCE

Star	B	Star	B
1..........	17.53	16..........	19.98
2..........	17.55	17..........	20.22
3..........	17.68	18..........	20.30
4..........	18.11	19..........	20.35
5..........	18.15	20..........	20.42
6..........	18.23	21..........	20.50
7..........	18.21	22..........	20.70
8..........	18.90	23..........	20.62
9..........	19.02	24..........	20.76
10..........	19.15	25..........	20.71
11..........	19.28	26..........	20.97
12..........	19.33	27..........	21.21
13..........	19.36	28..........	21.15
14..........	19.78	29..........	21.34
15..........	19.81	30..........	21.40

C. BRIGHTEST BLUE STARS

Star	B	Star	B
B1.........	18.53	B15.........	21.03
B2.........	19.13	B16.........	21.05
B3.........	19.25	B17.........	21.05
B4.........	19.58	B18.........	21.06
B5.........	19.85	B19.........	21.09
B6.........	19.98	B20.........	21.17
B7.........	20.30	B21.........	21.19
B8.........	20.54	B22.........	21.22
B9.........	20.63	B23.........	21.21
B10........	20.72	B24.........	21.23
B11........	20.86	B25.........	21.34
B12........	20.91	B26.........	21.33
B13........	20.94	B27.........	21.37
B14........	20.96	B28.........	21.42

The brightest red and blue stars were found by blinking pairs of 103aO and 103aD plates taken mostly with the 5-m telescope. Because the quality and the extent of the plate material can be substantially improved by future work, the present results are to be regarded as preliminary.

a) *NGC 2366*

A photoelectric sequence of nine stars (A–I) in the interval $12.3 \leq V \leq 19.3$ is identified in figure 1 (plate 17) and listed in the first part of table 1. The sequence was extended faintward by photographic transfer plates to SA 51 (one pair) and to NGC 2403 (two pairs), in blue only. We adopted Baum's unpublished sequence in SA 51 which he kindly made available. Thirty secondary standards were determined from the transfer plates, using the primary photoelectric standards for control of the zero point.

The transfers were measured by the Argelander method of eye estimates using appropriate step-scales drawn from a library of such scales taken over the years in various seeing conditions. The method largely overcomes difficulties of iris photographic photometry in the presence of crowding and gradients in the background.

The 30 secondary standards are identified in figure 1 and are listed in table 1B. There are no V-magnitudes for the secondary standards because no yellow transfer plates are available.

The mean random error for the secondary standards in B is 0.08 mag, as determined from the repeated measurements. There is no systematic difference in zero point between the photoelectric and the secondary sequence in the range of overlap. From the excellent agreement of all three separate transfers, we expect the systematic error in the secondary sequence to be smaller than 0.15 mag at $B = 20.7$.

The brightest blue stars were found by blinking the best yellow and blue plates; and although no V-magnitudes are available, we believe from our experience in other calibrated galaxies that we did maintain approximately the color limit of $B - V \leq 0.4$ mag for the candidates. The B-magnitudes for the blue stars (B1–B28) are given in table 1C as found from the means of independent estimates on the two best blue plates. The values have a mean random error of about ± 0.1 mag.

Eight very bright red stars (R1–R8) were also found by blinking.[1] The single available V plate is of poor quality, but a preliminary estimate of the magnitude of the brightest red star (R1) is $V = 19.0 \pm 0.5$.

No systematic search for variables on the 17 available blue plates was made, but accidentally one faint star was found to be roughly 1 mag brighter on a 5-m telescope plate taken in 1951 relative to the majority of the other plates. The star is a suspected variable, and is marked VI in figure 1.

b) *IC 2574*

Ten stars of the photoelectric sequence (A–J) are in the range $15.9 < B < 20.3$. They are marked in figure 2 (plate 18), and are listed in table 2A. The sequence was independently tested and extended to other stars using a single photographic transfer with NGC 2403, on blue plates obtained with the 1.2-m Palomar Schmidt. The B-magnitudes of both the photoelectric and secondary sequences were further smoothed by step-scale estimates of two very good Hale reflector blue plates.

[1] They are numbered in order of decreasing brightness and identified in fig. 1.

TABLE 2

Photometry of Stars in and near IC 2574 Identified in Figure 2

A. Photoelectric Sequence in IC 2574

Star	B	V	$B-V$
A	15.92	15.21	0.71
B	16.78	15.34	1.44
C	17.60	16.83	0.77
D	17.96	17.07	0.89
E	18.90	18.10	0.80
F	18.99	17.77	1.22
G	19.52	18.26	1.26
H	19.84	18.96	0.88
I	20.12	18.87	1.25
J	20.25	18.90	1.35

B. Secondary B Sequence

Star	B	Star	B
1	16.80	11	19.71
2	17.01	12	19.87
3	17.40	13	19.87
4	17.45	14	20.12
5	17.70	15	20.15
6	17.93	16	20.17
7	19.19	17	20.28
8	19.22	18	20.36
9	19.53	19	20.41
10	19.61	20	20.48

C. Brightest Blue Stars

Star	B	Star	B
B1	19.48	B11	20.20
B2	19.90	B12	20.21
B3	19.92	B13	20.24
B4	20.06	B14	20.25
B5	20.09	B15	20.27
B6	20.10	B16	20.28
B7	20.11	B17	20.30
B8	20.14	B18	20.30
B9	20.15	B19	20.31
B10	20.18	B20	20.33

The secondary sequence stars (1–20) are marked in figure 2 and are listed in table 2B. The mean random error of a listed magnitude is $\leqslant 0.1$ mag, and the scale error of the secondary sequence should be negligible because it extrapolates the photoelectric sequence by only 0.2 mag.

The brightest blue stars were found by blinking one yellow and one blue 5-m telescope plate. The one available yellow plate is of fair quality only, and is unsuitable for faint magnitude estimates. Hence, it can only be estimated that the color limit of $B - V \leq 0.4$ was kept.

The blue stars of IC 2574 (B1–B20) are identified in figure 2 and are listed in table 2C. These magnitudes have a mean random error of $\leqslant \pm 0.1$ mag, except for those cases on heavy background, where the error will be larger.

The very red supergiants were more difficult to find due to the lower quality of the only available 5-m

V-plate. However, a good red (103aE+RG2) plate exists which was blinked against the blue plate, resulting in the identification of 12 stars (R1–R12 in fig. 2) whose $B - V \geqslant 2.0$. To estimate their V-magnitudes we used the approximate relation

$$B - R = 1.65(B - V)$$

to determine an R sequence for the red plate from the photoelectric standards. The faintest sequence star is H, with $R = 18.4$. The brightest very red supergiant candidate (R1) is 0.5 mag fainter as determined from a step scale. If $B - V = 2.0$, then $B - R = 3.3$, and R1 has $B = 22.2$ and $V = 20.2$. No variables were detected in IC 2574.

c) *Holmberg II*

Ten stars of the photoelectric sequence (A–J), lying between $12.3 < V < 19.8$, are identified in figure 3 (plate 19), and are listed in table 3A. A secondary sequence was established from one transfer in B to SA 68, and two transfers in V (one to SA 68 and the other to NGC 2403); all on plates taken with the 5-m telescope. We are indebted to Henrietta Swope for the excellent extensive sequence in SA 68, based on an unpublished photoelectric sequence by W. Baum in that area.

TABLE 3

THE SEQUENCE STARS IN AND NEAR HOLMBERG II IDENTIFIED IN FIGURE 3

A. PHOTOELECTRIC SEQUENCE

Star	B_{pe}	V_{pe}	$(B - V)_{pe}$	B_{pg}	V_{pg}
A........	13.22	12.35	0.87	...	...
B........	16.64	16.34	0.30	...	...
C........	17.58	16.80	0.78	...	...
D........	19.06	18.61	0.45	19.05	18.67
E........	19.78	18.77	1.01	19.97	18.69
F........	19.93	18.38	1.55	19.94	18.34
G*.......	19.94	19.25	0.69	...	...
H........	20.20	18.33	1.87	20.04	18.41
I.........	20.77	19.80	0.97	20.85	19.76
J.........	20.83	19.48	1.35	20.89	19.40

B. SECONDARY SEQUENCE

Star	B	V	Star	B	V
1........	18.54	18.03	15........	21.48	21.35
2........	18.82	17.91	16........	21.55	20.25
3........	18.93	18.38	17........	21.62	21.30
4........	19.74	18.50	18........	21.74	20.70
5........	19.91	18.38	19........	21.75	21.43
6........	20.02	19.75	20........	21.84	21.40
7........	20.02	19.15	21........	21.84	20.63
8........	20.27	18.53	22........	21.97	21.30
9........	20.70	19.40	23........	22.00	20.47
10........	20.27	19.97	24........	22.24	21.53
11........	20.84	20.12	25........	22.54	20.76
12........	20.86	19.19	26........	22.58	21.56
13........	21.37	20.00	27........	22.70:	20.92
14........	21.40	21.31	28........	22.74:	20.82

* Star G is variable. Range on our plates in B from 20.24 to 20.74; V from 19.18 to 19.75. Because of its position, it is doubtful if it is a member of this galaxy.

The transfers were made by step-scale estimates for each of 69 stars in Ho II (10 photoelectric standards treated as unknown, 28 secondary sequence stars, and 31 brightest blue stars). Each transfer agrees remarkably well with the photoelectric values (the mean systematic differences are smaller than ± 0.05 mag), and no zero-point or scale corrections were applied to the transformed values. The results, listed in table 3, were smoothed by additional measurements of two very good B plates and one very good V plate, all taken with the 5-m Hale reflector.

The secondary sequence extends to $B = 22.7$, $V = 21.6$, well beyond the photoelectric values. Although there is no evidence for scale errors in the transfers, this faint sequence must be considered to be preliminary until a photoelectric check is made.

The brightest blue stars (B1–B31) found by blinking yellow and blue plates are marked in figure 4 (plate 20), together with the very red supergiants (R1–R10). The colors and magnitudes for the blue stars are given in table 4, and those of the red supergiants (together with their range) in table 5. Many of the red stars (R1, R3, R4, R7, R8, R9) proved to be variable on the three available plates in each color, taken at widely different times. The observed maximum brightness of the brightest (R1) is $V = 20.21$, corresponding to $M_V{}^0 = -7.44$, but the true maximum may be considerably brighter because the V-amplitude for this type of variable is large ($\Delta V \geqslant 1$ mag; e.g., Tammann and Sandage 1968 for similar stars in NGC 2403).

Other variables in or near Ho II include G of the photoelectric sequence (probably not a member), B4, B27?, and one additional star, marked as V1 in figure 3, near the outskirts of the galaxy. The magnitudes of V1 were estimated on 10 blue and three yellow Hale reflector plates. The range in B is from 19.84 to 20.85 and in V from 19.57 to 20.35. The star is clearly blue. If a member, the maximum magnitude reached from our limited material is $B(\max) = -7.9$. The color and high luminosity suggest this star as a candidate for the luminous, irregular blue variables (see § VIII) discussed by Hubble and Sandage (1953).

d) *Holmberg I*

No photoelectric measurements are available for stars near Ho I, but we did obtain one set of good blue transfer plates (Hale 5-m reflector) to take the sequence from NGC 2403 to Ho I. The B-magnitudes of a preliminary sequence of 10 stars (1–10) and of 12 blue member stars (B1–B12) were determined from this transfer by step-scale estimates. The magnitudes were further smoothed by measuring an additional good blue plate. The stars are identified in figure 5 (plate 21), and their magnitudes are listed in table 6. The mean random error of a listed magnitude is less than or equal to 0.12 mag, but the zero point of the sequence could be in error by perhaps as much as ~ 0.3 mag because it is based on only a single transfer.

Twelve bright blue stars (B1–B12) are identified in figure 5 as found from blinking a yellow and a blue plate. Red stars were found from the same pair; but

TABLE 4

THE BRIGHTEST BLUE STARS IN HOLMBERG II IDENTIFIED IN FIGURE 4

Star	B	$(B - V)$	Star	B	$(B - V)$
B1.......	19.58	−0.32	B17.......	20.70	+0.03
B2*......	19.62	+0.19:	B18.......	20.70	+0.16
B3.......	19.71	+0.36	B19‡......	20.74	+0.05
B4†......	19.72:	(+0.07 − 0.36)	B20.......	20.78	−0.01
B5.......	19.78	−0.40	B21*......	20.80	−0.11
B6.......	20.01	−0.09	B22‡......	20.80	−0.05
B7.......	20.05	−0.22	B23.......	20.85	+0.12
B8*......	20.13:	+0.41:	B24.......	20.86	+0.21
B9.......	20.27	+0.03	B25.......	20.97	−0.09
B10......	20.30	−0.23	B26.......	20.99	+0.06
B11......	20.42	−0.16	B27§......	21.00	(−0.09 + 0.14)
B12......	20.51	−0.03	B28.......	21.07	−0.05
B13......	20.64	+0.24	B29.......	21.10	+0.17
B14......	20.65	+0.11	B30.......	21.17	+0.07
B15......	20.66	−0.04	B31.......	21.08	+0.20
B16‡.....	20.69	−0.09			

* Diffuse. † Variable. ‡ Possibly nonstellar. § Variable?

as we have no V-magnitude sequence, we cannot assume that the color limit $B - V > 2.0$ was maintained. The brightest good candidate is marked in figure 5 as R1. Its magnitude remains to be determined.

Our plate material is so scarce for this galaxy that no statement concerning variables is possible.

e) *NGC 4236*

As in Ho I, we have no primary photoelectric magnitude sequence in NGC 4236, nor do we have transfer plates taken with the 5-m telescope. The system is so important, however, that we have made an interim solution by measuring transfer plates made with the 1.2-m Palomar Schmidt, using the sequence in NGC 2403 (Tammann and Sandage 1968). Eight sequence stars (1–8) as well as 18 bright blue stars (B1–B18), found by blinking a good pair of Hale reflector plates, are identified in figure 6 (plate 22). The magnitudes were estimated on the 1.2-m transfer plates. The 26 stars were further smoothed by measuring an available 5-m telescope plate. The values are listed in table 7. The mean random error of the tabulated values is ~0.15 mag, but there may be a zero-point error of several tenths of a magnitude, as transfers using Schmidt plates are subject to large error. The sequence must clearly be strengthened by future photoelectric data.

A few bright, apparently very red stars were found by blinking, but the lack of a V-sequence and their faintness in B made it impossible to decide whether $(B - V) \gtrsim 2.0$. The stars are not identified for this reason.

f) *NGC 2403*

Star counts in NGC 2403 showed that the brightest stars begin at $B \simeq 18.25$, or $M_B{}^0 = -9.55$ (Tammann and Sandage 1968). We adopt this value for the first ranked star in B, and we have further adopted the red irregular variable V41 (Tammann and Sandage 1968) to be the brightest red supergiant at $V(\max) = 19.98$ or $M_V{}^0(\max) = -7.77$, taking the apparent visual (AV) modulus to be $(m - M)_{AV} = 27.75$, as determined from the Cepheids (Tammann and Sandage 1968).

TABLE 5

VERY RED SUPERGIANTS IN HOLMBERG II IDENTIFIED IN FIGURE 4

Star	B(range)	V(range)	Remarks
R1.........	22.43– 22.47	20.21–20.53	Variable?
R2.........	21.34– 22.28	20.22–20.39	
R3.........	21.93– >22.8	20.25–20.53	Variable
R4.........	22.19– >22.8	20.30–20.78	Variable
R5.........	22.17– 22.31	20.34–20.46	
R6.........	21.60– 21.94	20.40–20.56	
R7.........	>22.3– 22.71	20.49–20.85	Variable?
R8.........	21.62– 22.01	20.54–20.60	Variable?
R9.........	>22.6	20.60–21.3	Variable
R10........	21.79– 22.03	20.62–20.66	

TABLE 6

PHOTOMETRY OF STARS IN AND NEAR HOLMBERG I IDENTIFIED IN FIGURE 5

Star	B	Star	B
Photographic Sequence			
1...........	19.70	6..........	20.82
2...........	19.81	7..........	21.55
3...........	20.54	8..........	21.57
4...........	20.69	9..........	21.58
5...........	20.80	10..........	21.67
Brightest Blue Stars			
B1.........	19.52	B7..........	20.81
B2.........	19.86	B8..........	21.10
B3.........	20.10	B9..........	21.27
B4.........	20.15	B10..........	21.47
B5.........	20.45	B11..........	21.54
B6.........	20.54	B12..........	21.57

TABLE 7

PHOTOMETRY OF STARS IN AND NEAR NGC 4236 IDENTIFIED IN FIGURE 6

Star	B	Star	B
Photographic Sequence			
1	17.85	5	19.47
2	18.70	6	19.68
3	18.84	7	20.26
4	18.98	8	20.33
Brightest Blue Stars			
B1	19.15	B10*	19.79
B2	19.19	B11	19.85
B3	19.31	B12	19.86
B4*	19.51	B13	19.94
B5	19.64	B14	19.97
B6	19.68	B15	20.02
B7*	19.74	B16	20.06
B8	19.77	B17	20.16
B9	19.79	B18	20.20

* Possibly nonstellar.

III. THE BRIGHTEST BLUE STARS IN GALAXIES OF THE LOCAL GROUP

Considerable work has recently been published by many authors on brightest stars in the Large Magellanic Cloud (LMC), the Small Magellanic Cloud (SMC), and in the local solar neighborhood ($D \leq 4000$ pc). We summarize these new data in this section, together with the more restricted material available in M33, IC 1613, and NGC 6822.

a) *Large Magellanic Cloud*

The pioneer work of Feast, Thackeray, and Wesselink (1960), based on slit spectra, gave the first modern H-R diagram for the brightest stars in LMC and SMC. This work proved beyond doubt that these stars are exceedingly bright absolutely. The search for brightest members was made more efficient by Fehrenbach's objective-prism technique, and a large number of new A, F, and G-type supergiants were found by Fehrenbach, Duflot, and Petit (1970)—color classes where the galactic contamination is severe. The finding list from the French objective-prism survey was used by Ardeberg *et al.* (1972) in an extensive photoelectric photometry of the member stars, which is an extension of similar work by Wesselink (Feast *et al.* 1960) and by Mendoza (1970). Stars in common among the three lists show excellent photometric agreement.

To plot a color-magnitude diagram for the brightest stars we have used 380 stars brighter than $B = 14$ mag from table 1 of Ardeberg *et al.* (1972, their most probable LMC members), with 27 additional stars from either Feast *et al.* (1960) or Mendoza (1970). The 407 stars are shown in figure 7*a*, in which the observed B-magnitude is used along the left ordinate, and intrinsic colors obtained from the observed color by subtracting $E(B-V) = 0.08$ mag throughout (Gascoigne 1969). This procedure is clearly only approximate because there may be differential color gradients across LMC and random fluctuations in the color excess, but the features of the diagram *for our purposes* are not badly distorted. We believe the present compilation is practically complete for the brightest stars as indicated by the strong overlap in the three lists, and by the fact that all the very brightest stars occur already in the first list of Feast *et al.* (1960) (see table 8 below).

The upper envelope for the brightest stars shows little color dependence for $(B-V)_0 \lesssim 0.6$, except for the five very brightest stars. Because these have $-0.1 < (B-V)_0 < 0.15$, it is clear that our restriction of $(B-V)_0 < 0.4$ for other galaxies, would *not* have eliminated the brightest member stars of LMC if color had been the chief criteria for membership (as in § II).

Data for the eight brightest stars in LMC according to the present compilation are listed in table 8 using magnitudes that are averaged from Feast *et al.* (1960), Mendoza (1970), and Ardeberg *et al.* (1972). The spectral types are from Ardeberg, except for R136 (the central object in 30 Dor) which was taken from Feast *et al.* (1960). All stars in table 8 have known radial velocities and are certain members of LMC. The absolute magnitudes both in the table and along the right-hand ordinate of figure 7*a* are based on $(m-M)_{AB} = 18.91$ (Sandage and Tammann 1971, table 5), as determined from the Cepheids alone.

b) *Small Magellanic Cloud*

Osmer (1973) has obtained *uvby* photometry for all of Sanduleak's (1968) 169 stars, chosen as probable members of SMC from an objective-prism plate taken with the Curtis Schmidt telescope. Additional *UBV* photometry by Feast *et al.* (1960) exists for six other stars, by Mendoza (1970) for three more, and by Dachs (1970) for two more. The $(b-y)$ colors of Osmer were changed to $(B-V)$ by a transformation based on 29 stars for which colors on both systems are available.

As in figure 7*a*, observed B-values (uncorrected for absorption) are plotted in figure 7*b* against $(B-V)_0$ for all stars with B brighter than 14 mag in the above source lists. The $(B-V)_0$ colors were obtained from

TABLE 8

THE EIGHT BRIGHTEST STARS IN THE LARGE MAGELLANIC CLOUD

Star	$(B-V)_{obs}$	B	$M_B{}^0$	Spectral Type
R76	0.19	9.31	−9.60	A3 Ia-0
R136	0.17	9.32	−9.59	O+WN
R62	0.10	9.76	−9.15	B9 Iae:
R103	−0.02	9.87	−9.04	B5 Ia
R118	0.07	9.94	−8.97	A0 Iae
R105	0.19	10.29	−8.62	Pec
Sanduleak 129-69	0.42	10.32	−8.59	F6 Ia
R75	0.09	10.38	−8.53	A0 Ia

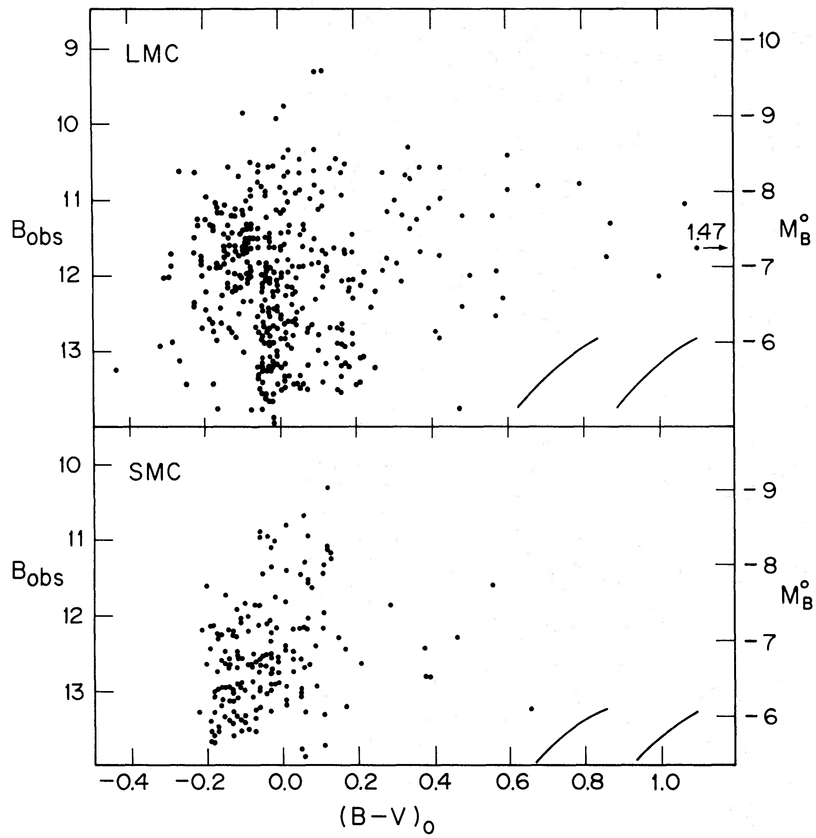

FIG. 7*a*.—Color-magnitude diagram for the brightest photoelectrically measured stars in LMC. Absolute magnitudes on the right calculated with $(m - M)_{AB} = 18.91$. A reddening of $E(B - V) = 0.08$ was adopted. The upper part of the instability strip for Cepheids is also shown.

FIG. 7*b*.—Same as for SMC. Apparent modulus assumed to be $(m - M)_{AB} = 19.35$. Reddening adopted as $E(B - V) = 0.02$ throughout.

the observed colors by subtracting $E(B - V) = 0.02$ throughout, as determined by Gascoigne (1969) using faint main-sequence B stars, and as suggested by the color-amplitude properties of the Cepheids in SMC relative to those in LMC (Sandage and Tammann 1971, table 4). Higher values for the reddening are suggested by the work of Dachs (1970), Osmer (1973), and others.

Also shown in figures 7*a* and 7*b* are the upper parts of the instability strip for Cepheids, as defined elsewhere (Sandage and Tammann 1968, table A1). The absolute magnitudes shown along the right ordinate of figure 7*b* have been computed from the apparent blue modulus of $(m - M)_{AB} = 19.35$, as determined from the Cepheids alone (Sandage and Tammann 1971, table 5).

From figure 7*b* one sees that the brightest stars in SMC lie within the color interval $-0.2 < (B - V)_0 < +0.2$, confirming again the previous indications that the brightest stars in galaxies have $(B - V)_0 \leq 0.4$ mag.

The eight brightest stars in SMC are listed in table 9, using mean magnitudes from Feast *et al.* (1960), Mendoza (1970), Dachs (1970), and Osmer (1973) for the stars in common. Spectral types are from Feast *et al.* All stars are certain members, and were included in the original Radcliffe survey of 1960.

There is a remaining question concerning the reddening, and the listed absolute magnitudes, in table 9. The adopted reddening is $E(B - V) = 0.02$, justified as mentioned by evidence from the Cepheids and from the fainter blue stars. However, the apparent cutoff in figure 7*b* at $(B - V)_0 \simeq -0.2$ and—even more

TABLE 9

THE EIGHT BRIGHTEST STARS IN THE SMALL MAGELLANIC CLOUD

Star	$(B - V)_{obs}$	B	M_B^0	Spectral Type
R45..........	0.14	10.31	−9.04	A0 Ia-0
R40..........	0.06	10.70	−8.65	B8 Ie
R11..........	0.02	10.84	−8.51	B6 Ia
R42..........	−0.04	10.91	−8.44	B2.5 I
R5...........	−0.05	10.98	−8.37	B3 I
R27..........	0.09	10.98	−8.37	B9 Ia
R9...........	0.00	11.03	−8.32	B3 Ia:
R6...........	0.14	11.12	−8.23	B6 I

important—the spectral-type–color relation of stars in table 9, indicates by comparison with figure 7*a* that the mean color excess for the supergiants may be as high as $E(B - V) \simeq 0.13$, in agreement with Osmer (1973). Hence, it would seem that either the supergiants in SMC occur in regions of higher reddening than the Cepheids, or some increased (circumstellar?) reddening may be associated with the individual stars themselves—but not the Cepheids. If the higher reddening applies, all stars in figure 7*b* would be moved blueward by $\Delta(B - V) = 0.11$ mag on the average, and the absolute magnitudes in table 9 should be made brighter by 0.44 mag.

For the present purpose, it does not seem useful to account for the "abnormal" reddening of the SMC supergiants within the parent galaxy, since in general one can correct only for the galactic foreground absorption when dealing with individual stars in external galaxies.

c) The Solar Neighborhood of the Galactic System

Diagrams such as 7*a* and 7*b* are much harder to construct for the galactic system. Individual distances and reddening must be known for the field supergiants chosen as bright star candidates. Such data are nearly always the result of long-term, difficult, and fundamental observational programs. The recent completion of several such programs by others permits a more complete discussion of brightest galactic stars than has been previously possible. In particular, the present discussion supersedes an earlier compilation made 10 years ago (Sandage 1962, table 3) for the distance-scale problem.

A principal list of galactic supergiants has been compiled by Humphreys (1970*a*). She very kindly provided us with a copy, ordered according to membership in associations—an ordering that proved very useful. We have updated her catalog slightly, using newer data of Stothers (1972*a*, *b*). Only supergiants in well-established associations whose distances are known by standard methods were considered. After excluding associations with insufficient data, or whose reality is still doubtful, 56 aggregates remained, containing 343 supergiants, defined as stars of luminosity classes I0, Ia, and Ib.

To obtain a more complete picture of the bright part of the color-magnitude diagram for less evolved stars, we added 117 O stars of luminosity classes II–V which are probable members of the 56 aggregates. The stars were taken principally from the listing of Ruprecht (1966). A number of Of stars are among these 117 added candidates. Because Of stars have lower surface gravities than O stars of the same temperature (Heap 1971), they should be among the brightest O stars known. We also included a few Wolf-Rayet stars that are members of the associations, although it is known that the brightest such stars are not among the very brightest stars in LMC or SMC (Smith 1968). Known spectroscopic binaries were included because they are naturally ideal candidates for brightest stars in external galaxies.

Finally, we have added two supergiants that are not known members of any association. The star HR 5171 A ≡ HD 119796 is a G8 Ia$^+$ (Humphreys, Strecker, and Ney 1971) with a B0 Ib companion (HR 5171 B) at 9''.7 separation. Judged from the companion, the distance modulus is $(m - M)_0 = 12.5$, which gives $M_B{}^0 = -8.8$ with an absorption of $A_B = 5.3$ mag. HR 5171 A is variable (Humphreys *et al.* 1971; Harvey 1973). At its brightest phase observed by Harvey, the star was 0.6 mag brighter than the above elements; hence the star has reached $M_B = -9.4$ mag, and it belongs to the very brightest galactic stars known—a fact first pointed out by Humphreys *et al.* (We have plotted the star at $M_B = -8.8$ in our final color-magnitude diagram given later).

The data for the 460 stars in the two master lists were converted to $M_B{}^0$ and $(B - V)_0$ by the following straightforward steps.

1. The mean distance to each aggregate was compiled from the literature. The most frequently consulted sources were Hoag and Applequist (1965), Ruprecht (1966), Walker and Hodge (1968), Becker and Fenkart (1971), Humphreys (1970*a*; the mean distance for all stars in a given aggregate was used), Heap (1971), Moffat (1972), Moffat and Vogt (1973), Stothers (1972*a*, *b*), and Vogt and Moffat (1972). In addition, many papers dealing with individual clusters or associations were used.

2. The magnitudes and colors, obtained primarily from Blanco *et al.* (1968), Humphreys (1970*a*), and Lee (1970), were corrected for absorption and reddening by adopting the intrinsic colors from Johnson (1966) for supergiants earlier than F5, and from Kraft and Hiltner (1961) for F6–K7 supergiants. Intrinsic colors for M supergiants have considerable scatter within a given spectral subclass; hence, the mean $E(B - V)$ for all earlier-type stars in the same aggregate was used. The same procedure was used for known spectroscopic binaries. Following Schmidt-Kaler (1965), Lee (1970), and Stothers (1972*a*), we adopted the blue absorptions to be $A_B = 4.0E(B - V)$ for O, B, and A stars; $4.3E(B - V)$ for F–K stars; and $4.6E(B - V)$ for M stars. The F–K stars would be ~0.2 mag fainter, and the M stars ~0.4 mag fainter on the average, than we have put them if $A_B = 4.0(B - V)$ had been assumed throughout.

3. Absolute magnitudes and intrinsic colors follow from the distances of step (1) and the corrected colors and magnitudes of step (2).

The resulting color-magnitude diagram is shown in figure 8. Known variables are shown as crosses; but in view of the limited information on most of these variables, their positions are uncertain to within the limits of their amplitude. The brighter part of the Cepheid instability strip is also shown as taken from the same source as in figure 7.

Comments on stars near the instability strip are set out in Appendix A. Unlike figure 7 where the absolute magnitude scale depends solely on the Cepheid distances to LMC and SMC, the calibration in figure 7 rests on the individual aggregate distances. These have largely been determined by photometric parallax methods that rest ultimately on the calibration of the

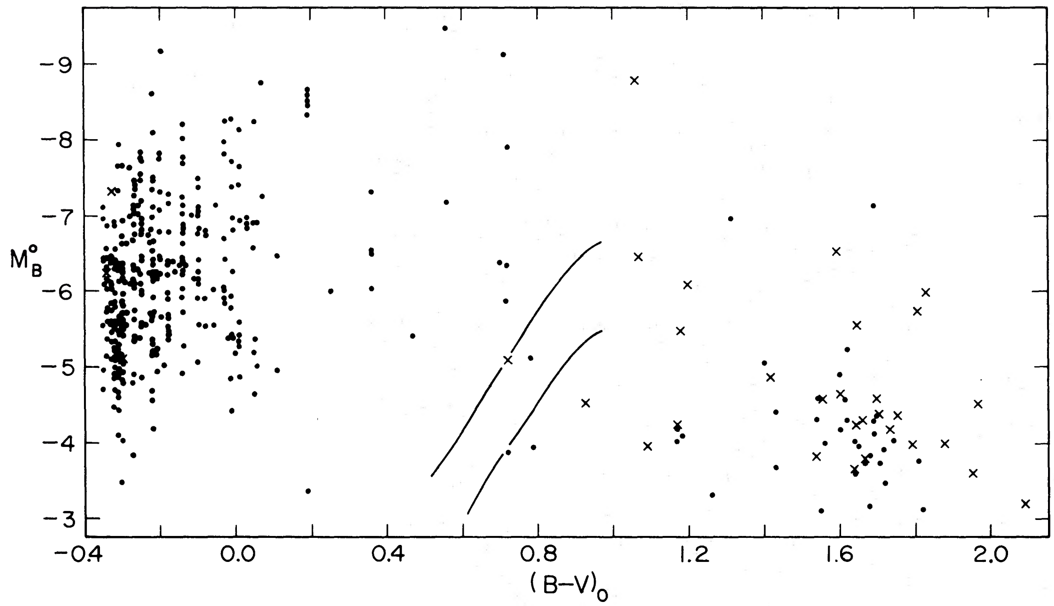

FIG. 8.—Color-magnitude diagram for the solar neighborhood using members of 56 associations and clusters. *Crosses*, known variables. Part of the Cepheid instability strip is shown.

age zero main sequence. But since the calibration of the Cepheids rests upon the same base, the agreement of the upper parts of figures 7 and 8 does not itself provide an independent test of the Cepheid zero point.

Three features of figure 8 are noteworthy:

1) The brightest stars in the solar neighborhood surpass $M_B = -9$ in absolute magnitude. Note again that we have plotted HR 5171 A at $M_B = -8.8$ instead of its "maximum observed amplitude" value of $M_B \simeq -9.4$.

2) The upper luminosity envelope is quite independent of color for $(B - V)_0 \lesssim 1.0$, and the large majority of stars brighter than $M_B = -8$ are bluer than $(B - V)_0 = 0.2$. The brightest stars in LMC and SMC are also bluer than this limit. Hence, our restriction of $(B - V)_0 \lesssim 0.4$ for the external galaxies so as to avoid massive field star contamination (§ II) again seems justified.

3) Supergiants redder than $(B - V)_0 \simeq 1.2$ are usually variable, and are all absolutely fainter than the near-main-sequence stars by about 2 mag. The situation is similar to that known in NGC 2403 (Tammann and Sandage 1968, § VIII and fig. 12).

We list in table 10 the eight brightest stars (in B) in this sample. Besides HR 5171 A, on which we have commented previously, a comment is necessary on star 8 in the galactic cluster Pi 20 (Pismis 1959). According to Lyngå (1968), Pi 20-8 has $M_B{}^0 = -9.9$ if the cluster has a modulus of $(m - M)_0 = 13.2$. It would then be the brightest star in our sample. However, following the rediscussion by Moffat and Vogt (1973), we have adopted $(m - M)_0 = 11.9$ which gives $M_B{}^0 = -8.6$ if $A_B = 4.0E(B - V)$.

We should also comment on our luminosities for ρ Cas and ζ^1 Sco which are higher than generally quoted. The distance values for the Cas OB5 association differ widely in the literature, ranging from $(m - M)_0 = 11.51$ (Becker and Fenkart 1971, not used here because of the many evolved stars used in the solution) to 12.66 (Reddish 1967). We have adopted Stothers's (1972*b*) value which leads to the high luminosity in table 10, provided that ρ Cas is a member.

Our adopted modulus for ζ^1 Sco in Sco OB1 is close to the values obtained by Crawford *et al.* (1971), by Schild, Hiltner, and Sanduleak (1969), and by Schild, Neugebauer, and Westphal (1971). The high value of $M_B{}^0 = -9.2$ in table 10 results from our adopted value of $(m - M)_0 = 11.7$.

Finally, we have not retained star 12 in the highly reddened association Cyg OB2 (Morgan, Johnson, and Roman 1954; Sharpless 1957; Schulte 1958; Reddish, Lawrence, and Pratt 1966) because the absorption is so extraordinarily high ($A_B = 13.2$ mag), and because at least part of this must be circumstellar. Similar stars in external galaxies would be faint in any case. We have, therefore ignored this star and, for the same reason, Becklin's star which may also have a cocoon nature (Penston, Allen, and Hyland 1971).

We believe the most important aspect of figure 8 is the fact that in this small, quite incomplete, and somewhat arbitrary sample of supergiants, most of which are within only 4000 pc of the Sun, stars exist with absolute magnitudes at least as bright as $M_B{}^0 = -9$. There seems little doubt, therefore, that still brighter stars exist, invisible to us, in the Galaxy. The result is remarkable—especially if the Hubble type of the Galaxy is Sb, as data concerning the nuclear bulge (Sandage, Becklin, and Neugebauer 1969; Schmidt-Kaler and Schlosser 1973) have indicated. And because there is no question that the brightest stars in Sb galaxies are fainter than in Sc systems of comparable

TABLE 10

THE EIGHT BRIGHTEST STARS IN THE SOLAR NEIGHBORHOOD ($M_B{}^0 < -8.5$)

Star	Spectral Type	Aggregate	$(m - M)^0$ adopted	$M_B{}^0$
ρ Cas..........	F8 pec Ia	Cas OB5:	12.5	−9.45*
ζ[1] Sco.........	B1.5 Ia-0	Sco OB1 (NGC 6231)	11.7	−9.17
HD 96918......	G0 Ia	Car OB1	12.15	−9.09
HR 5171A.....	G8 Ia⁺	double	12.5	−8.78†
6 Cas..........	A3 Ia⁺	Cas OB5	12.5	−8.72
ϕ Cas..........	F0 Ia	NGC 457	12.2	−8.65
HD 74180......	F0 Ia	Vel OB1	11.0	−8.61
Pi 20-8.........	B1 Ia:	Pi 20	11.9	−8.60

* Membership not certain. † Variable, $M_B{}^0$(max) ~ −9.4 mag.

luminosity (Hubble 1936*a*), the conclusion from figure 8 would be that stars as bright as $M_B{}^0 = -10$ could reasonably be expected to occur in Sc I supergiant spirals. We shall argue for this view on other groups in § IV and in Paper III of this series.

d) *M33*

The brightest star identified in M33 is the first-ranked blue star in the cluster that excites the H II region NGC 604 (Hubble 1926). It has $m_{pg} = 15.75$. But Hubble found, from star counts in about one-fifth of the galaxy, that there must be somewhat brighter stars yet. We adopt conservatively his value of $m_{pg} = 15.5$ for the very brightest. At this level, his magnitudes are still reliable, and no scale correction is necessary. With $B \simeq m_{pg} \simeq 15.5$, and $(m - M)_{AB} = 24.68$, it follows that $M_B{}^0(\text{first}) = -9.18$. A more complete study of the luminosity function over the face of M33 is now in progress with plates taken at the Cassegrain focus of the wide-angle Bowen 1.5-m telescope at Palomar, using a new photoelectric sequence (Sandage and Johnson 1974), but results are not yet available.

e) *NGC 6822*

A color-magnitude diagram for NGC 6822 was given by Kayser (1967). The confusion with foreground stars is apparent, but imposing a color limit of $(B - V) \leq 0.67[(B - V)_0 \leq 0.40]$ avoids this difficulty. One remaining star with $V \simeq 13.6$, $B \simeq 14.1$ is much too bright, and can safely be omitted.

The brightest star in B that we identify with the galaxy has $V \simeq 16.55$ and $B \simeq 15.76$ as read from the C-M diagram. Its intrinsic color corresponds to spectral type ~B7. Its absolute magnitude is $M_B{}^0 = -9.27$ if $(m - M)_{AB} = 25.03$.

For the three brightest stars, the danger of confusion with possible foreground stars is larger because some of the candidates are near the color limit, and the field is very crowded. We choose for the second brightest a star with $V \simeq 15.52$, $B \simeq 16.02[(B - V)_0 = 0.23$ corresponding to ~F2], and for No. 3 a star with $V = 15.47$, $B = 16.04[(B - V)_0 = 0.30$, corresponding to ~F3]. The mean magnitude of the three brightest is then $B = 15.94$, or $M_B{}^0 = -9.09$. Replacing No. 2 or No. 3 by the next brightest and bluer (and hence perhaps somewhat safer candidate; $V \simeq 16.02$, $B \simeq 16.24$, type B7) would make the mean magnitude of the first three only 0.07 mag fainter.

f) *IC 1613*

The brightest star in IC 1613 is 22 A, identified on charts given elsewhere (Sandage 1971), at $B = 17.00$, which at the adopted modulus of $(m - M)_{AB} = 24.55$ corresponds to $M_B{}^0 = -7.55$. The next brightest stars have not yet been discussed adequately, as a revision of Baade's luminosity function is not yet complete.

IV. THE BLUE-STAR CALIBRATION

The adopted data for the brightest blue stars in the 11 calibrating galaxies and in the galactic system are listed in table 11. Listed also are the van den Bergh (1960) luminosity class L_c, the absolute magnitude $M_{pg}{}^0$ (corrected for adopted absorption in our own Galaxy) on the m_{pg} system of Holmberg (1950), the adopted blue distance modulus from Paper I (Sandage and Tammann 1974), and the resulting absolute magnitude $M_B{}^0$ for each galaxy. (We have assumed that $m_{pg} \simeq B$ in this color range.)

Also listed is the mean of the first three brightest stars as determined in the previous sections for all galaxies except M33, IC 1613, and NGC 2403. For the eight systems with available data, $M_B{}^0(3) - M_B{}^0(1) = 0.22 \pm 0.04$, and we have adopted this value in listing $M_B{}^0(3)$ in parentheses for the remaining three.

The correlation of $M_B{}^0(1)$ and $M_B{}^0(3)$ with M_{pg}(gal) is shown in figure 9. Open circles are members of the Local Group, and closed circles are members of the M81–NGC 2403 group. Least-squares solution for the brightest blue star as a function of $M_{pg}{}^0$ [considering M_{pg}(gal) to be the independent variable (it presumably is accurate for the calibrating galaxies)] gives

$$M_B(1) = 0.315 M_{pg}(\text{gal}) - 3.48\,, \qquad (1)$$

with a correlation coefficient of 0.66. The solution suggests that the correlation is significant because such a correlation coefficient from 11 observations requires the probability that M(star) and M(gal) are *not* correlated to be 0.03 (table 3C of Bevington 1969),

TABLE 11

SUMMARY DATA FOR BRIGHTEST BLUE STARS IN THE CALIBRATING GALAXIES

Object	Sample	L	$M_{pg}{}^0$	$(m-M)_{AB}$	m_B	$M_B{}^0$
Solar Neighborhood....	First	...	...	...	...	−9.45:
	⟨3⟩	...	...	...	...	−9.14
LMC..............	First	III–IV	−17.86	18.91	9.31	−9.60
	⟨3⟩				9.46	−9.45
SMC..............	First	IV to IV–V	−16.42	19.35	10.31	−9.04
	⟨3⟩				10.63	−8.73
M33...............	First	II–III	−18.49	24.68	15.5	−9.18
	⟨3⟩				(15.72)	(−8.96)
NGC 6822.........	First	IV–V	−15.82	25.03	15.76	−9.27
	⟨3⟩				15.94	−9.09
IC 1613............	First	V	−14.55	24.55	17.00	−7.55
	⟨3⟩				(17.22)	(−7.33)
NGC 2403.........	First	III	−19.00	27.80	18.25	−9.55
	⟨3⟩				(18.47)	(−9.33)
NGC 2366.........	First	IV–V	−16.34	27.75	18.53	−9.22
	⟨3⟩				18.97	−8.78
NGC 4236.........	First	IV	−17.53	27.58	19.15	−8.43
	⟨3⟩				19.22	−8.36
IC 2574............	First	IV–V	−16.69	27.60	19.48	−8.12
	⟨3⟩				19.77	−7.83
Ho II..............	First	IV–V	−16.53	27.67	19.58	−8.09
	⟨3⟩				19.64	−8.03
Ho I...............	First	V	−14.36	27.63	19.52	−8.11
	⟨3⟩				19.73	−7.90

which corresponds to a correlation that is significant at the 2.2 σ level. The standard deviation of a single observation from the mean of equation (1) is $\sigma(M_{\rm star}) = 0.52$ mag. This should be compared with $\sigma = 0.70$ mag from the straight mean value of $\langle M\rangle_{pg}{}^0 = -8.74$ if no correlation with M_{pg}(gal) is assumed.

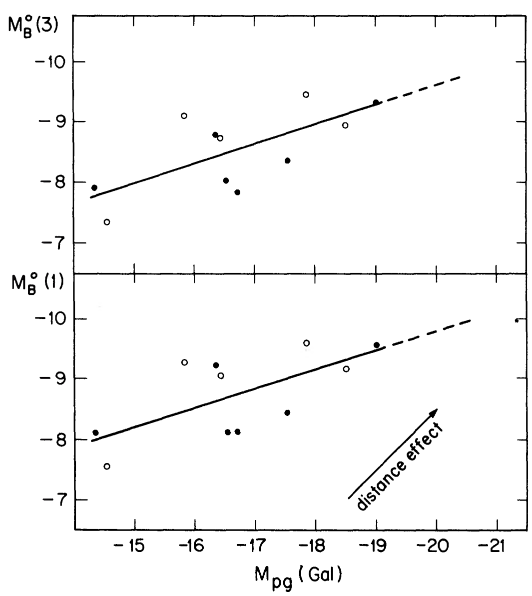

FIG. 9.—Calibration of M_B for the brightest star, and for the mean of the first three brightest stars, as a function of the absolute magnitude of the parent galaxy. *Open circles*, Local Group; *closed circles*, the NGC 2403 group.

The mean magnitude of the three brightest stars are correlated with M(gal) as

$$M_B{}^0(3) = 0.326M_{pg}{}^0(\text{gal}) - 3.09\,, \qquad (2)$$

which again is significant at about the 3 σ level. The standard deviation of a single observation from equation (2) is $\sigma(M_{\rm star}) = 0.49$ mag.

The sense of equations (1) and (2) is that the brightest stars become brighter as the absolute luminosity of the parent galaxy increases. Hubble (1936*b*, pp. 286–287) found the same effect, but with a coefficient of $\Delta M(\text{star})/\Delta M(\text{gal}) = 0.22$. Holmberg (1950) also found the same sense, and in an elaborate discussion believed the effect extended over the large range in absolute luminosity from $M(\text{parent}) = +0$ to -18, with a slope of 0.60.

Although the slope we have obtained from the modern data is considerably shallower than Holmberg's, the sense of the correlation is still unfavorable for distance determinations for the same reason discussed in Paper I for H II regions (Sandage and Tammann 1974, fig. 9 and § V). The "distance effect" line is shown in figure 9*b*; and although its intersection with the correlation line is steeper than for the H II regions, the iteration required to obtain distances from figure 9 is still moderately unsatisfactory. Therefore, as in Paper I, we have correlated the data with luminosity classes L_c, assigning numerical values of 2.5, 3 to classes II–III, III, etc.

A least-squares solution gives

$$M_B{}^0(1) = (0.588 \pm 0.216)L_c - 11.16 \pm 0.90 \qquad (3)$$

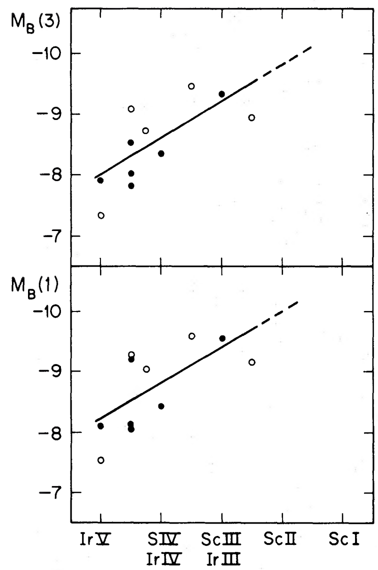

FIG. 10.—Same as fig. 9 plotted against the luminosity class of the parent galaxy.

with $\sigma(M_{\rm star}) \simeq 0.56$ mag, and

$$M_B{}^0(3) = (0.604 \pm 0.202)L_c - 11.01 \pm 0.84 \quad (4)$$

where $\sigma(M_{\rm star}) \simeq 0.51$. The correlations are shown in figures 10*a* and 10*b*, and have the same significance at about 2.5 σ as figure 9.

As in Paper I, there are no Sc I galaxies in the calibrating sample. From the results of simple extrapolation, compromised with knowledge from Paper III using the distance to M101 found by other methods, we adopt provisionally $M_B{}^0(1) = -10.0 \pm 0.2$ for Sc I galaxies, and only note that we believe this to be a highly conservative value in view of the results from the solar neighborhood (§ III) where $M_B{}^0(1) \simeq -9.4$ is apparently reached in even the small sample we have available there.

A very important problem for the future is the extension of figures 9 and 10 to $M_{\rm pg}{}^0({\rm gal}) \simeq -21$ and to L_c = Sc I, not only for the determination of distances but also as a source of observational data on the possible upper limit to main-sequence luminosities. Recent work has made it questionable whether the conventional upper mass limit of $\sim 60\ \mathfrak{M}_\odot$ does in fact terminate the upper main sequence. Pulsational instability does not seem to prevent an even more massive star from living through its nuclear energy consumption without disruption (cf. Ziebarth 1970; Appenzeller 1970; Talbot 1971*a*, *b*), and observational data would be of interest here.

V. TESTS OF THE MEAN DISTANCE TO THE M81–NGC 2403 GROUP AND THE ASSUMPTION OF EQUAL DISTANCE TO THE MEMBERS

a) *The Mean Distance*

The data on H II regions that were assembled in Paper I showed less than a 2 σ difference in H II linear size for galaxies in the M81–NGC 2403 group compared with the Local Group (Paper I, § V*d*). This is illustrated in figures 9 and 10 of Paper I by a systematic separation of the open and closed circles. The effect amounts to $\Delta \log D = 0.169$ as calculated from data in Paper I (L_c from table 2 combined with eq. [7] of Paper I, and thence differenced with the "observed" $\log \langle D_{\rm H}, D_C\rangle_3$ from table 6 of the same paper). To make the regions identical in size (after accounting for the L_c dependence) would require that the mean distance to the M81–NGC 2403 group members be decreased by $\Delta(m - M) \equiv 5\Delta \log D = 0.85$ mag, which would require $(m - M)_0 = 26.71$ for the group mean.

However, we believe this to be an impossible value because (1) the evidence from the brightest stars in figures 9 and 10 of this paper does not show the effect (what slight difference does exist is, in fact, in the opposite sense from the H II region data), and (2) the Cepheid photometry in NGC 2403 cannot be that much in error, and there is no theoretical reason to expect that the Cepheid zero point of the period-luminosity-color (*P-L-C*) relation can differ between galaxies by such a large amount. We believe, then, that the apparent difference in H II region sizes between the Local Group and the M81 Group is due to fluctuations caused by the smallness of the sample. The conclusion is consistent with the size of the effect; it is of the same order as the cosmic dispersion of the $\langle D_{\rm H}, D_C\rangle_3 = f(L_c)$ relation for the Local Group and the M81 Group members taken together [Paper I, figs. 9 and 10, where $\sigma(\Delta \log D) \simeq 0.10$].

We see, then, no clear ground that is statistically significant for changing the adopted mean distance to the M81–NGC 2403 Group. Therefore, we shall continue to adopt the Cepheid modulus of NGC 2403, which is $(m - M)_0 = 27.56$ (Tammann and Sandage 1968).

b) *Equal Distance to the Members*

Because of lack of data on Cepheids in all other members of the NGC 2403 group, we have been forced in the present series to hypothesize that each galaxy of the group is at the distance of NGC 2403. It is clearly necessary to eventually test the assumption by more work on the Cepheids, especially because of the large angular extent of the group (NGC 4236 is 28° from NGC 2403), but such data will take many years to accumulate and analyze. In the interim, we can only proceed by analyzing the scatter about the mean relations to test for systematic deviations.

To make the test, we have treated distances to each of the six group members as unknown, and have determined them from H II regions by using equation (7) of Paper I with the angular diameter data listed in table 4 of that paper, and from brightest stars using equation (4) with the data of table 11 of this paper. The resulting distances are listed in table 12 as $D_{\rm H\,II}$ from the first method, and $D_{\rm BS}$ from the bright stars. The mean distance $\langle D\rangle$, based now on the mean of the calibrations of Papers I and II, is $\langle D\rangle = 3.09 \pm$

TABLE 12

DISTANCES TO MEMBERS OF THE NGC 2403 GROUP FROM THE H II REGIONS AND THE BRIGHTEST STARS

Galaxy	L_c	$(m - M)_{\text{H II}}^0$	$(m - M)_{\text{BS}}^0$	$D_{\text{H II}}$ (Mpc)	D_{BS} (Mpc)	$\langle D \rangle$ (Mpc)
NGC 2403.....	III	27.51	27.43	3.17	3.06	3.12
NGC 2366.....	IV–V	27.07	27.07	2.59	2.59	2.59
NGC 4236.....	IV	26.93	27.79	2.43	3.61	3.02
IC 2574........	IV–V	27.41	28.02	3.03	4.02	3.52
Ho II..........	IV–V	27.22	27.82	2.78	3.66	3.22
Ho I...........	V	27.16	27.65	2.70	3.39	3.04
$\langle D \rangle$..........						3.09 ± 0.12 (σ)

0.12(σ) Mpc [or $(\Delta D/D) = 0.04$] for the six galaxies. The rms deviation of a single galaxy from the mean is $\sigma \simeq 0.30$ Mpc which corresponds to a σ in the modulus of a *single galaxy* of only $\sigma(m - M) = 0.21$, which we consider to be satisfactorily small.

Comparison of $\langle D \rangle = 3.09 \pm 0.12$ with the value derived from Cepheids alone of $\langle D \rangle = 3.25 \pm \sim 0.2$ shows again that the present calibrations of the three criteria (1) do not differ significantly among themselves, and (2) our first step in the distance scale beyond the Local Group out to NGC 2403 appears to be consistent when the three criteria are considered in concert.

Finally, inspection of the individual entries in table 12 shows no differences in distance that are significant at the 2 σ level between the group members. NGC 2366 is listed to be closer than NGC 2403 by $\Delta D = 0.52$ Mpc, but this is clearly not significant. The equality in distance between NGC 2403 and NGC 4236 is well shown in table 12, and suggests that the two galaxies are indeed associated in space, separated by only about 1.5 Mpc, which is only slightly larger than the size of the Local Group.

VI. NATURE OF THE CORRELATION BETWEEN M(STAR) AND M(GALAXY)

Can the correlation of M(star) with M(galaxy) of equations (1)–(4) be understood as a statistical effect caused by renormalizing a common luminosity function by the total luminosity of a given galaxy? As long as the luminosity function $\phi(M)$ does not have a vertical cutoff at the bright end, it is clear that the brighter the aggregate, the brighter will be the value of M^* for which

$$\int_{-\infty}^{M^*} \phi(M) dM = 1 , \qquad (5)$$

i.e., the absolute magnitude of the first brightest star. [The common notation is kept here that $\phi(M)$ is the differential luminosity function; that is, the number of stars between M and $M + dM$; hence the integral $\int_{-\infty}^{M^*} \phi(M)dM$ is, by definition, the number of stars equal to or brighter than M^*.]

By a straightforward analysis, Holmberg (1950) showed that a correlation between M of the brightest star and M of the parent galaxy was expected, and would be of the form of equations (1) and (2), i.e.,

$$M(\text{star}) = aM(\text{galaxy}) + b \qquad (6)$$

if a common form to $\phi(M)$ exists of the type $\log \phi(M) = cM + d$, where d is appropriately chosen so that

$$\int_{-\infty}^{+\infty} 10^{-0.4M} \phi(M) dm \qquad (7)$$

is normalized to be integrated luminosity of the parent galaxy. The assumptions appear eminently reasonable, and lead directly to the condition that

$$d = 0.4/a . \qquad (8)$$

If this condition is met, the sense and strength of the correlation of figures 9 and 10 could be explained by this purely statistical effect. Is the condition even approximately realized? Our value of a from equations (1) and (3) is $a = 0.32 \pm 0.11$, which requires $d = 1.25(+0.56, -0.30)$ for the explanation. Hence, in the region near the high-luminosity cutoff at $M_B{}^0(\text{star}) \simeq -9$ we require the luminosity function to be of the form

$$\log \phi(M) \simeq 1.25M + b . \qquad (9)$$

This requirement is remarkably close to what is independently known of the bright end of $\phi(M)$. For the solar neighborhood between $M_{\text{pg}} = -5$ and -6 van Rhijn's (1936, table 6) function gives $d = 0.93$. Furthermore, the function is known to steepen toward brighter magnitudes as shown, for example, by the change of d in table 6 of van Rhijn.

Hence, if equation (9) is applicable to all galaxies in the sample, it not only "explains" the observed mean dependence of the brightness of the brightest star on the luminosity of the parent galaxy, but requires just such a dependence (to within the scatter caused by small-number statistics). (We believe the problem of fluctuations is important for a true understanding of the correlation and the observed scatter, but do not consider it here).

We have made a further test of the statistical model

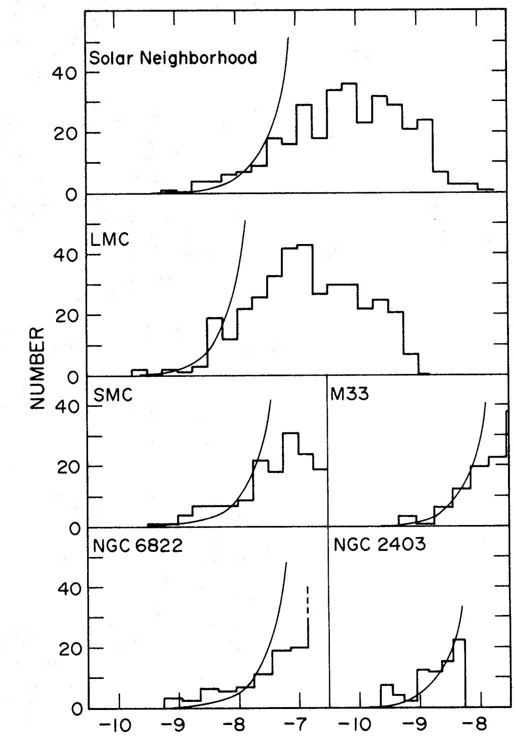

FIG. 11.—Bright end of the luminosity function for five galaxies plus the solar neighborhood compared with the predicted bright end by the model of § VI. The observed functions become rapidly incomplete toward fainter magnitudes.

by normalizing equation (9) by the ratio of the total luminosity of the parent galaxy to that of LMC [by noting that $\Delta b = 0.4\Delta M$(galaxy)], thereby predicting the value of b for all galaxies once its value for LMC is adopted. Equation (9) has, then, no free parameter and can be compared with directly determined luminosity functions from counts in the program galaxies.

Empirical luminosity functions are shown in figure 11. The histograms for the solar neighborhood, LMC, and SMC were obtained by appropriately summing the data in figures 7 and 8 (which are clearly progressively incomplete at the fainter magnitudes). The data for M33 and NGC 6822 are from Hubble (1925, 1926); those for NGC 2403, from Tammann and Sandage (1968), where foreground stars in the three galaxies have been accounted for statistically. The value of b for LMC was found by eye at the bright end for a plausible fit shown by the line (given by $b = 12.118$). The "predicted" curves for SMC, M33, NGC 6822, and NGC 2403 are shown in figure 11 for $b = 11.541$, 11.972, 11.147, and 12.574, respectively, which were calculated from the ratio of the luminosities to LMC.

A better fit of the predicted and the observed functions at the bright end could hardly be expected from our elementary assumptions if only for the reason that we have taken the total galaxian luminosity as a direct measure of the number of very luminous Population I stars, where again we are quite vulnerable to small-number statistics. For intrinsically faint galaxies, another source of the observed scatter in M^* in equation (5) (or fig. 9) could come from the flushing-region model of Searle, Sargent, and Bagnuolo (1973), which is itself a model for fluctuations of the number of bright stars produced.

We conclude that the present data can be understood by assuming that there is a common luminosity function for the brightest stars, and that their numbers are linearly related to the total luminosity of the galaxy. If this is so, there is no need to invoke chemical differences between galaxies to explain why big galaxies make bright stars as proposed by van den Bergh (1973). Indeed, the uniqueness of the luminosity function which *we* need, is also a requirement in the model by Searle (1972) which explains the surprising uniformity of the metal-to-hydrogen ratio from galaxy to galaxy.

VII. THE BRIGHTEST VERY RED SUPERGIANTS

Contrary to the situation for the brightest blue stars, the absolute magnitude of the brightest red supergiants does *not* depend on the luminosity of the parent galaxy. This had already been shown from data assembled for a discussion of NGC 2403 (Tammann and Sandage 1968, § VIII), and it is confirmed by new data discussed here.

The very red stars are important for galaxian distance determinations because of their constant upper luminosity and of the great ease of finding them by blinking blue and yellow or red plates. The difficulty is that all such stars are probably variable; hence either the sample must be large, or many data must be obtained to find magnitudes at the brightest phase, which is our criterion.

a) *The Galaxy*

The three brightest M supergiants in the lists of Humphreys (1970*a*), Lee (1970), and Stothers and Leung (1971) are α Ori, RW Cep (BD 55°2737), and PZ Cas (BD 60°2613). The details for these stars are given in Appendix B. The data show that, despite some uncertainties, it appears justified to assign $m_v(\max) = -8.0 \pm 0.2$ mag for the brightest very red supergiants in the galaxy. Fainter values have been generally quoted in the literature, but primarily because we have used maximum magnitudes here.

b) *Large Magellanic Cloud*

Many of the brightest red stars will be contained in the survey of variables by Payne-Gaposchkin (1971). The two brightest irregular variables listed there have data shown in table 13.

The M_v values follow by *adopting* $B - V = 2.0$. In addition to these two stars, one semiperiodic variable (cycle $\simeq$ 850 days) reaches $m_{pg} = 12.80$ (HV 888), but nothing is known about the color. The brightest long-period periodic variable (HV 2360, $m_{pg} = 13.85$, $P = 790$ days) is 1 mag fainter, but again nothing is re-

TABLE 13

THE TWO BRIGHTEST RED IRREGULAR VARIABLES IN THE LARGE MAGELLANIC CLOUD

Star	m_{pg}(max)	Color	Δm_{pg}	$(m - M)_{AV}$	M_v
HV 2450.......	12.88	"Very red"	1.12	18.83	−7.95
HV 5914.......	13.00	"Very red"	2.37	18.83	−7.83

ported about the color, so any conjecture about M_v is uncertain.

c) *Small Magellanic Cloud*

The four brightest irregular variables in SMC are HV 813 ($m_{pg}{}^0 = 12.40$), HV 1475 ($m_{pg}{}^0 = 12.56$), HV 11423, and HV 11546 (both with $m_{pg}{}^0 = 12.59$) (Payne-Gaposchkin and Gaposchkin 1966). However, these magnitudes have been corrected for variable and unknown amounts of absorption which need confirmation, and no information is available on their colors.

Shapley and Nail (1951) give values listed in table 14, showing that HV 11423 and HV 11546 may not be red enough to satisfy our color criterion. We are then left with HV 1475 which, under an *assumption* that $(B - V) = 2.0$, has V(max) = 11.1 and M_v(max) = −8.2, if $(m - M)_{AV} = 19.33$ is adopted.

Clearly more definitive work on the red stars in LMC and SMC is possible.

d) *The Calibration*

The available data from § II and from this section are set out in table 15 and plotted in figure 12. The sample is small and can be increased by work in M33,

TABLE 14

THREE BRIGHT RED IRREGULAR VARIABLES IN THE SMALL MAGELLANIC CLOUD

Star	m_{pg}(max)	Color
HV 1475........	13.1	Very red
HV 11423.......	12.8	Red
HV 11546.......	11.3	Red

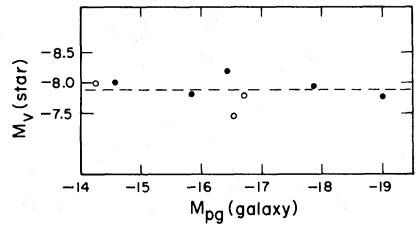

FIG. 12.—Calibration of the absolute luminosity of the brightest red supergiant from table 14. The mean line of $M_v{}^0$(max) = −7.9 is shown.

Ho I, NGC 4236, and NGC 2366, and by improved data in IC 2574 and Ho II which, for reasons explained in § II, have low weight. The weighted mean (IC 2574 and Ho II half-weight) gives $M_v{}^0$(max) = -7.9 ± 0.1 mag with no indication of a correlation with luminosity of the parent galaxy.

The lack of correlation is exceedingly interesting. In view of its presence for the bright *blue* stars, it is obvious that some mechanism is working that limits the effective luminosity of red supergiants to $M_v \simeq -8$, even though the main-sequence and blue supergiant progenitors (actually themselves in an earlier evolutionary stage) are much brighter. Either the effect is a funneling downward of the evolutionary tracks, or it is due to stars that are brighter than $M_v = -8$ going through their red supergiant phase so rapidly that they are not caught in that phase, while stars fainter than $M_v = -8$ move through that cool region of the H-R diagram much more slowly. The change in rate is apparently abrupt at the critical −8 mag level.

These problems have been extensively discussed by Stothers and others (Stothers 1969, 1972*a*; Stothers and Chin 1969; Humphreys 1970*c*; Schild 1970) in terms of a guillotine, provided by an efficient neutrino

TABLE 15

THE BRIGHTEST VERY RED VARIABLE STARS AT MAXIMUM IN DIFFERENT GALAXIES

Galaxy	$M_B{}^0$(galaxy)	Variable	m(max)	m_v(max)	$(B - V)_0$	Source*	$(m - M)_{AV}$	$M_v{}^0$(max) (mag)
Galaxy.........	...	...	...	...	...	text	...	−8.0
LMC..........	−17.86	HV 2450	12.88 pg	10.88	"Very red"	(1)	18.83	−7.95
SMC..........	−16.42	HV 1475	13.1 pg	11.1	"Very red"	(2)	19.33	−8.2
NGC 6822.....	−15.82	V 18	...	16.76	2.14	(3)	24.56	−7.80
IC 1613........	−14.55	V 42	18.5 *B*	16.5	~2.0	(4)	24.52	−8.0
NGC 2403.....	−19.00	V 41	...	19.98	2.36	(5)	27.75	−7.77
IC 2574........	−16.69	R1	...	19.8:	~2.0	(6)	27.59	−7.8:
Ho II..........	−16.53	R1	...	20.21	2.2	(6)	27.65	−7.44:

* SOURCE.—(1) Payne-Gaposchkin 1971. (2) Shapley and Nail 1951. (3) Kayser 1967. (4) Sandage 1971. (5) Tammann and Sandage 1968. (6) This paper.

TABLE 16

EXAMPLES OF IRREGULAR LUMINOUS BLUE VARIABLES

Galaxy	Variable	m(max) (date)	Source*	$(m - M)_{AB}$	Source*	M(max)	Remarks†
Galaxy	η Car	−1 vis (1843)	1	14.0	2	−14.4 *B*	A
	P Cyg	3 vis (1600)	3	13.4	4	−10.0 *B*	B
LMC	S Dor	9.2 pg	5	18.91	6	− 9.7 pg	C
M33	B	14.7 pg (1963)	7, 12	24.68	6	−10.0 pg	
	C	15.3 pg (1947)	8	24.68	6	− 9.4 pg	
	No. 2 (=Y Tri)	15.6 pg (1924)	8, 9	24.68	6	− 9.1 pg	
	A	15.7 pg (1950)	8	24.68	6	− 9.0 pg	
M31	No. 19 (=AF And)	15.4 *B* (1971)	11	24.76	6	− 9.4 *B*	
	A-1	14.9 *B* (1910)	11	24.76	6	− 9.9 *B*	
	(AE And)	16.2 *B* (1969)	11	24.76	6	− 8.6 *B*	
NGC 2403	V12	16.46 *B*	10	27.80	6	−11.3 *B*	
	V38	18.2 *B*	10	27.80	6	− 9.6 *B*	
	V37	19.0 *B*	10	27.80	6	− 8.8 *B*	
Ho II	V1	19.8 *B*		27.67	6	− 7.9 *B*	D

* SOURCE.—(1) Innes 1903; Gratton 1963. (2) $(m - M)_0 = 12.15$ for Tr 16/Cr 228 (Walborn 1973); the mean reddening for these clusters is $E(B - V) = 0.45$, and therefore $(m - M)_{AB} = 14.0$. Assuming that $(B - V)_{obs} \simeq 0.6$ (Feinstein 1967) holds also for the maximum in 1843 gives $B(\max) = -0.4$ and $M_B(\max) = -14.4$. (3) Zinner 1952. (4) Probably a member of Cyg OB1 (van Schewich 1968). The distance modulus is then ~ 11.0 (Walker and Hodge 1968). With $E(B - V) = 0.61$ (Woolf *et al.* 1970) and $A_B = 2.44$ mag, then $(m - M)_{AB} = 13.4$. If $(B - V)_{obs} = 0.40$ (Viotti 1971) also holds for maximum, then from $V(\max) = 3$, it follows that $B(\max) = 3.4$. (5) Gaposchkin's (1942) maximum of 8.6 should be corrected by +0.7 mag (Lourens 1964). The brightest value reported is then $S_{pg} = 9.22$ (Wesselink 1956). (6) Paper I of this series. (7) Rosino and Bianchini 1973. (8) Hubble and Sandage 1953. (9) The very bright maximum of 14.6 vis (Wolf 1923) is not considered here since the photometric zero point may be uncertain. (10) Tammann and Sandage 1968. (11) Sharov 1973. (12) A single observation with $m_{pg} = 14.3$ (Sharov 1973) is excluded.

† See text.

loss process that apparently must turn on at $M_v \simeq -8$ for red supergiants.

Whatever the cause, the red supergiants are clearly of prime importance as easily recognized distance indicators for distances as large as $(m - M)_{AV} \simeq 28$ [provided that blue plates can be obtained to $B \simeq 22$ so as to test for the color criterion of $(B - V) \gtrsim 2.0$].

VIII. IRREGULAR LUMINOUS BLUE VARIABLES

The class of blue, very bright irregular variables first isolated in M31 and M33 (Hubble and Sandage 1953), and later found in other galaxies, is apparently heterogeneous enough that no well-defined absolute magnitude exists. For example, η Car, a star apparently of this type, was 6 mag absolutely brighter than AE And in M31. Because of the large spread in absolute magnitude, stars of this type are clearly not as useful as distance indicators as once believed; but they do become as bright, and often much brighter (such as NGC 2403–V12) than the brightest nonvariable stars. We treat them here as a separate class because inclusion with the constant blue stars discussed in § IV would make the correlations of figures 9 and 10 much poorer. Because these stars can be readily recognized and eliminated from the sample if enough material is available, the separation into a special class has an advantage because the stars need not then be considered for the distance scale problem.

A summary of possible members of the class is given in table 16. The list is not complete. Besides the stars in this table, others exist such as the very bright P Cygni variables AG Cas and HR Car (Viotti 1971), AG Per, and others—all of which are, however, probably fainter than P Cyg itself. Fainter examples exist in M31 (Hubble 1929; Meinunger 1971), in M33 (No. 1 of Hubble 1926, and an outlying star found by Baade as reported by Hubble and Sandage 1953), and in NGC 2403 (Tammann and Sandage 1968).

Use of stars of this kind can give only the roughest indication of distance. If we eliminate the two brightest in table 16 (η Car and NGC 2403–V12) and the faint variable V1 in Ho II (Remarks D), the mean luminosity is $\langle M_B \rangle \simeq -9.4 \pm 0.4$(a.d.), but the elimination of the three stars from the sample is rather arbitrary.

The remarks to table 16 are:

A) If the reddening of η Car is $E(B - V) \simeq 1.1$ (Pagel 1969; Viotti 1969; Ade and Pagel 1970), the star may have considerable circumstellar absorption because the mean reddening of the cluster is only $E(B - V) = 0.45$. If, then, A_B(circumstellar) $\simeq 2.6$, it follows that $M_B{}^0(\max) = -17$. We have used the lower luminosity here because the extragalactic variables cannot easily be corrected for circumstellar absorption.[2]

B) With $E(B - V) = 0.61$ (Woolf, Stein, and Strittmatter 1970), P Cyg does not seem to have individual absorption. The lowest extinction of Humphreys's Cyg OB1 supergiant members is $E(B - V) = 0.64$ (HD 193183), whereas the mean for the association is $E(B - V) = 1.1$; hence no excess reddening of P Cyg itself is indicated.

C) S Dor fits well into the class of blue irregular

[2] Recently Feinstein, Marraco, and Muzio (1973) have suggested an even higher true distance modulus of $(m - M)_0 = 12.65 \pm 0.20$ for η Car; in that case the present absolute magnitude values would be even brighter by 0.5 mag.

variables as regards light curve (Gaposchkin 1942; Lourens 1964), absolute magnitude, colors of $B - V \simeq 0.0$ and $U - B \simeq -1.0$ (Alexander and Thackeray 1971; Mendoza 1970), and spectrum (Martini 1969). Its radial velocity proves it to be a member of LMC (Wesselink 1956).

D) Because only a few plates are available, the observed maximum·luminosity is undoubtedly too faint.

IX. CONCLUSIONS

1. The brightest blue stars in galaxies increase in luminosity as the luminosity of the parent galaxy is greater. The neglect of this effect when determining distances from the brightest stars yields too small distances for field Sc I and Sc II galaxies, because the galaxies accessible for the calibration are all of luminosity classes II–III or fainter.

2. The very red supergiants at maximum light reach $\langle M_v^0 \rangle = -7.9 \pm 0.1$, irrespective of the luminosity of the parent galaxy. This can be understood by postulating a guillotine that makes brighter stars of this kind either very short lived or nonexistent.

3. The data for brightest blue stars, in combination with the H II regions from Paper I, show that an important assumption of this series—that the (Cepheid) distance to NGC 2403 applies to all members of the NGC 2403 group (including the outrider NGC 4236)—is satisfactory.

We wish to thank the night assistants on the Palomar Hale telescope for their cheerful help during the long course of collecting data for this project. Roberta Humphreys was very kind in providing a convenient listing of her supergiant catalog, and we are grateful for it. John Bedke and Felice Woodworth prepared the illustrations for press with their usual great skill and patience. It is always a pleasure to thank Raquel Ferrer for her dedication in preparing the manuscript.

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APPENDIX A

GALACTIC STARS NEAR THE BORDERS OF THE CEPHEID INSTABILITY STRIP IN FIGURE 7

It has been suggested that there are stable stars within the Cepheid instability strip (Fernie and Hube 1971; Schmidt 1972; Breger 1972). If real, this might be understood if the abundance of helium were low ($Y \lesssim 0.25$) in these stars (Cox, King, and Tabor 1973). The present sample of supergiants is too restricted to make a meaningful investigation of this question, but four stars in the present list do indeed fall into or near the instability strip. The four stars follow:

1) BD+58°2249 = HD 203338–9 = BS 8164, a member of Cep OB2. The star is classified as M1ep Ib + B (Bidelman 1954). The position of the composite system in the C-M diagram is therefore a rèsult of the B companion.

2) Very near the upper edge of the instability strip lies R Pup, a G0 Ia star (Bidelman 1951). The adopted distance of its parent cluster, NGC 2439, is $(m - M)_0 = 11.0$ mag (Becker and Fenkart 1970). The star was found visually to be variable by Gould, and in 1901 an amplitude of 0.6 was suggested (Pickering 1901). More recent observers have failed to detect a variability (cf. Bidelman 1951), and it is listed as constant in the third edition of the Variable Star Catalog. This catalog already comments on its nearness to the instability strip. It is not impossible that R Pup is another example of a Cepheid which has ceased to pulsate.

3) Just outside the instability strip, but close to its lower boundary is HD 25056, a G0 Ib star (Bidelman 1957), member of Cam OB1. No variability is known for this star.

4) AX Sgr falls, as a probable member of Sgr OB4 (Humphreys 1970*a*), into the upper extrapolation of the instability strip. It is classified as G8 Ia (Morgan and Roman 1950), less likely as M2 (Neckel 1958). The third addition of the Variable Star Catalog gives a photographic magnitude range of 9.2–10.0, where it is listed as a semiregular giant or supergiant with an uncertain cycle of 350^d. If, in fact, the star proves to be a Cepheid, it would be of the greatest interest. Not only should it have a period well over 100^d, which would make it the galactic Cepheid with the longest period, but also it would play a very important role—if its membership in Sgr OB4 is real—for testing our understanding of the *P-L-C* relation.

It must be cautioned, however, that to place any given field star unambiguously within the very narrow $[\Delta(B - V) \simeq 0.3$ mag$]$ Cepheid strip is difficult, because of the problems of determining precise $E(B - V)$ values. Often errors of 0.05 mag in $B - V$ determine whether a star is in or out of the strip. Hence, the four stars we have mentioned, although interesting, do not constitute a case.

APPENDIX B

DATA FOR THE BRIGHTEST RED STARS IN THE GALAXY

I. ALPHA ORIONIS

Its position near the outer edge of the Ori OB1 association and the luminous bridge connecting α Ori with the Orion complex (Morgan, Strömgren, and Johnson 1955) makes the star a likely member of the association. However, the luminosity class M2 Iab (Morgan and Roman 1950) or M1–M2 Ia–Ib (Morgan and Keenan 1973) would indicate that it is in the foreground. Additional indications of this are given by Lesh (1968) and Stothers (1969). However, if α Ori is a member, its luminosity is as follows:

The true distance modulus of Ori OB1 is $(m - M)_0 = 8.2$, which is the mean from Sharpless (1952), Morgan and Loden (1966), and Becker and Fenkart (1971). The mean $E(B - V)$ for the four early-type supergiants in the association is 0.06 (Humphreys 1970*a*); hence $(m - M)_{AV} = 8.38$. With $V = 0.40$, $B - V = 1.89$ (Lee 1970), which seems to correspond closely to maximum light (Kukarkin 1931), one obtains $M_v{}^0(\max) = -7.98$ and $(B - V)_0 = 1.83$ mag. This magnitude becomes ~ 0.3 fainter if α Ori is attributed to the nearer subgroup Ori OB1a (Blaauw 1964; Lesh 1968). The amplitude in visual light is ~ 0.9 mag; a cycle of 2070 days has been proposed (Kukarkin 1931).

II. RW CEPHEI

This star (BD 55°2737) is considered a bona fide member of Cep OB1 (Humphreys 1970*a*). Assuming with Stothers (1972*b*) a true distance modulus of $(m - M)_0 = 12.4$ for the association, and using $\langle E(B - V)\rangle = 0.65$ from 14 earlier supergiants in Cep OB1 (Humphreys 1970*a*), gives $(m - M)_{AV} = 14.85$. With $V = 6.65$ and $(B - V) = 2.22$ (Lee 1970), one obtains $M_v{}^0 = -7.70$ and $(B - V)_0 = 1.57$. However, the value must be corrected to maximum light, which is $m_{pg}(\max) = 8.4$ (Florja 1949). Assuming an unchanged color of $(B - V) = 2.22$ gives $m_v(\max) = 6.2$, and hence $M_v{}^1(\max) = -8.15$.

The absolute magnitude depends on the adopted color excess. The luminosity would be still higher if $E(B - V) = 1.16$, corresponding to spectral type G8 Ia (Morgan and Roman 1950), or $E(B - V) = 1.11$ for spectral type K0 0–Ia (Morgan and Keenan 1973), although the intrinsic colors of such luminous stars are uncertain.

That RW Cep may indeed be the most luminous red supergiant known in the Galaxy is independently indicated by the fact that it and R Pup are the only stars of type K0 or later classified as luminosity class 0–Ia by Keenan in the most recent list defining the MK system (Morgan and Keenan 1973).

III. PZ CASSIOPEIAE

This late-type (M3 Ia, Humphreys 1970*b*) very luminous star (BD 60°2613) is a member of Cas OB5 (Humphreys 1970*b*). The true distance modulus of the association is 12.53 ± 0.37 according to Reddish (1967), which agrees with the distance to NGC 7790 (which may be part of the association; Reddish 1961) of 12.53 adopted by Sandage and Tammann (1969). The mean reddening of 15 early-type supergiants in the association is $E(B - V) = 0.74$ (Humphreys 1970*a*), giving $(m - M)_{AV} = 14.75$. With $V = 8.60$, $(B - V) = 2.69$, also from Humphreys, it follows that $M_v{}^0 = -6.15$ and $(B - V)_0 = 1.95$. The maximum luminosity is, however, considerably brighter. With $m_{pg}(\max) = 9.8$ (Götz and Wenzel 1956), and assuming $B - V = 2.69$ unchanged through the cycle, it follows that $V(\max) = 7.1$, and $M_v(\max) = -7.65$.

Although this star is apparently somewhat fainter than RW Cep and possibly α Ori (if the latter is a member of Ori OB1), it is, with $(B - V)_0 = 2.0 \pm \sim 0.2$, the reddest galactic supergiant considered here. The amplitude of PZ Cas is $\Delta m_{pg} \simeq 2$ mag; a cycle of 900 days has been proposed (Götz and Wenzel 1956).

IV. VV CEPHEI

A very high luminosity of $M_v \simeq -7.3$ has been suggested by Stothers and Leung (1971) for this M2p star. If, however, the variable is a member of Cep OB1, it is considerably fainter.

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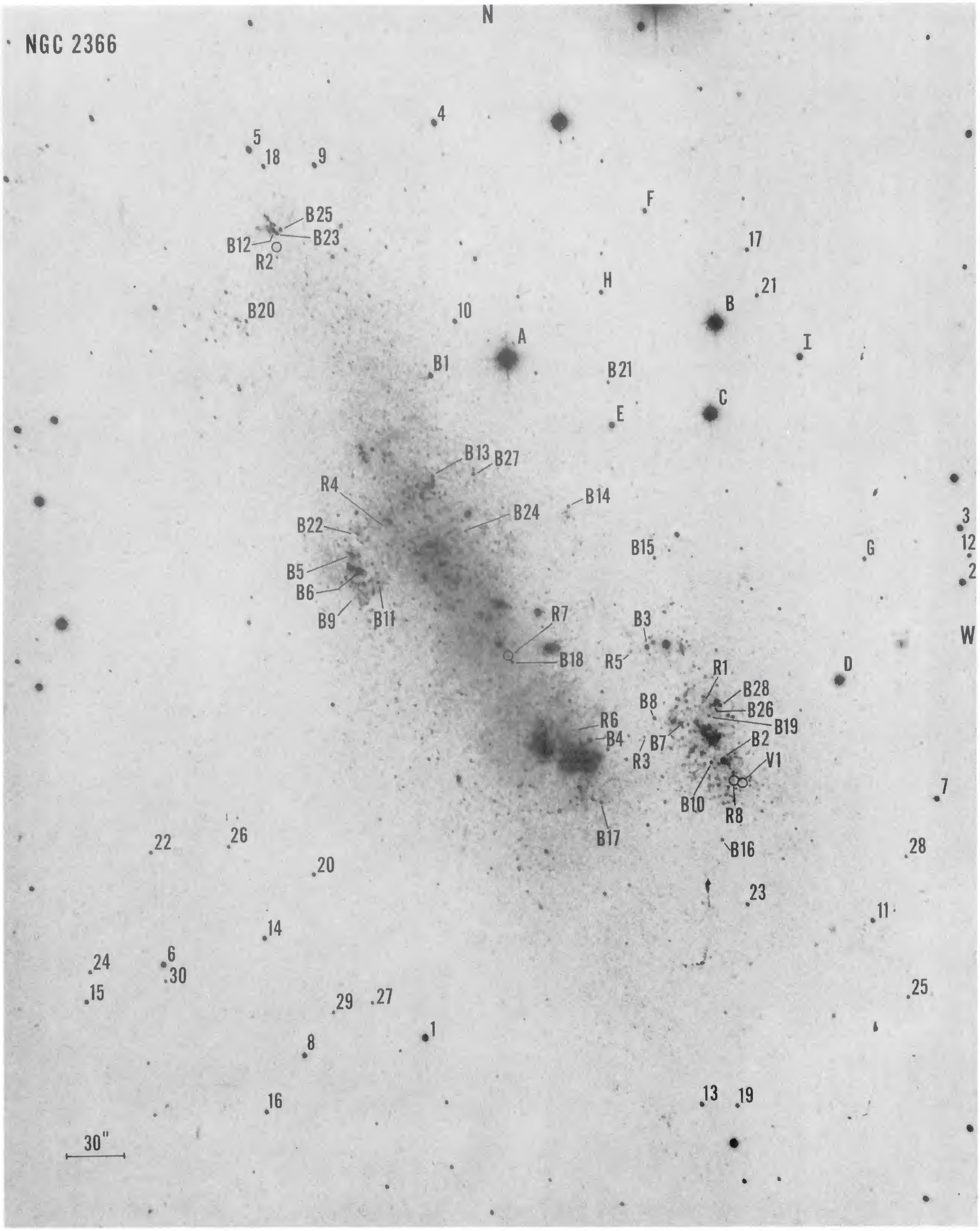

FIG. 1.—The identifications of the photoelectric sequence (A–I), the secondary sequence (1–30), and the brightest blue stars (B1–B28) in NGC 2366. This, and the plates in figures 2–6 were taken with the Hale 5-m reflector.

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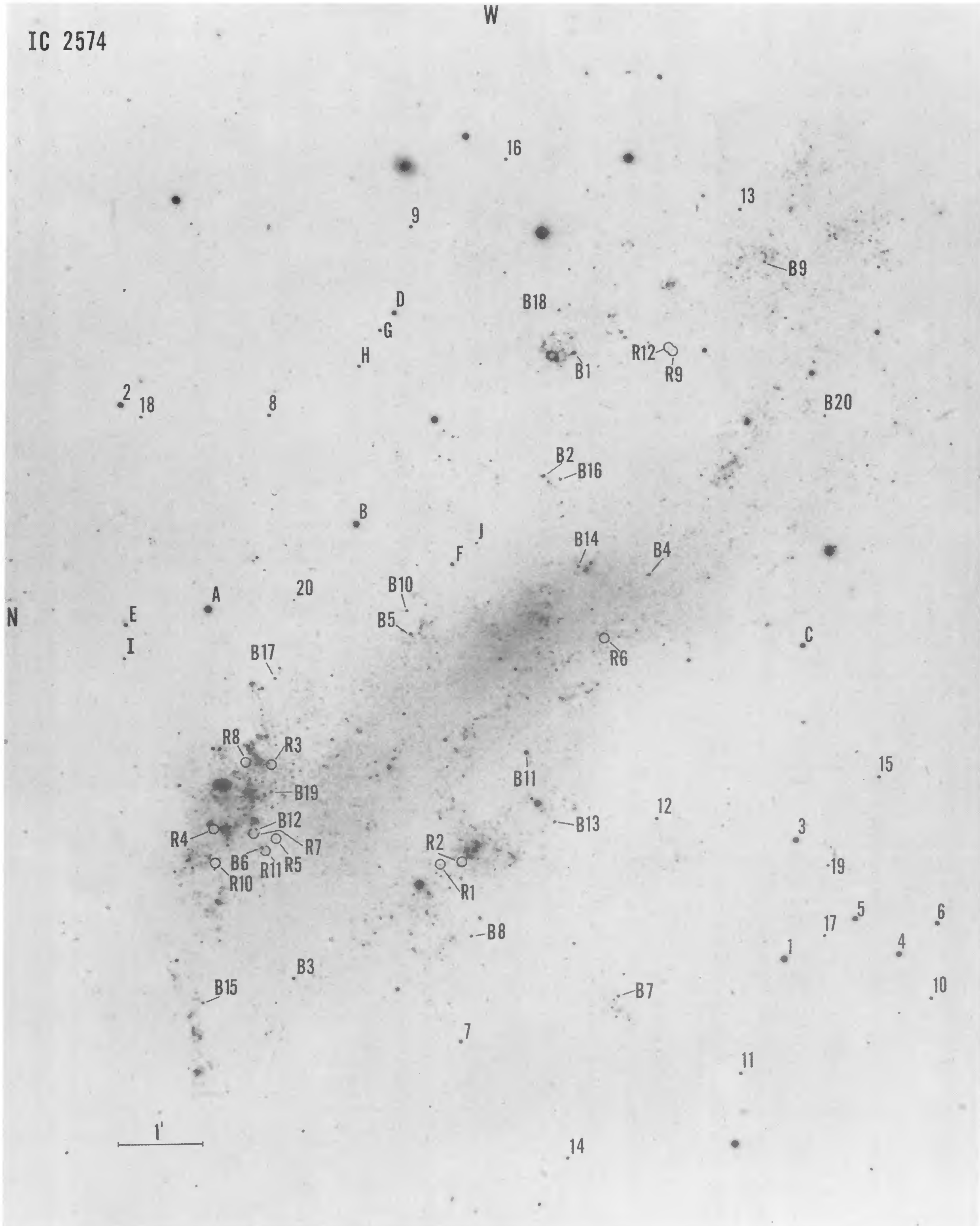

FIG. 2.—Identification of the photoelectric sequence (A–J), the secondary sequence (1–20), the brightest blue stars (B1–B20), and the brightest very red supergiant candidates (R1–R12) in IC 2574.

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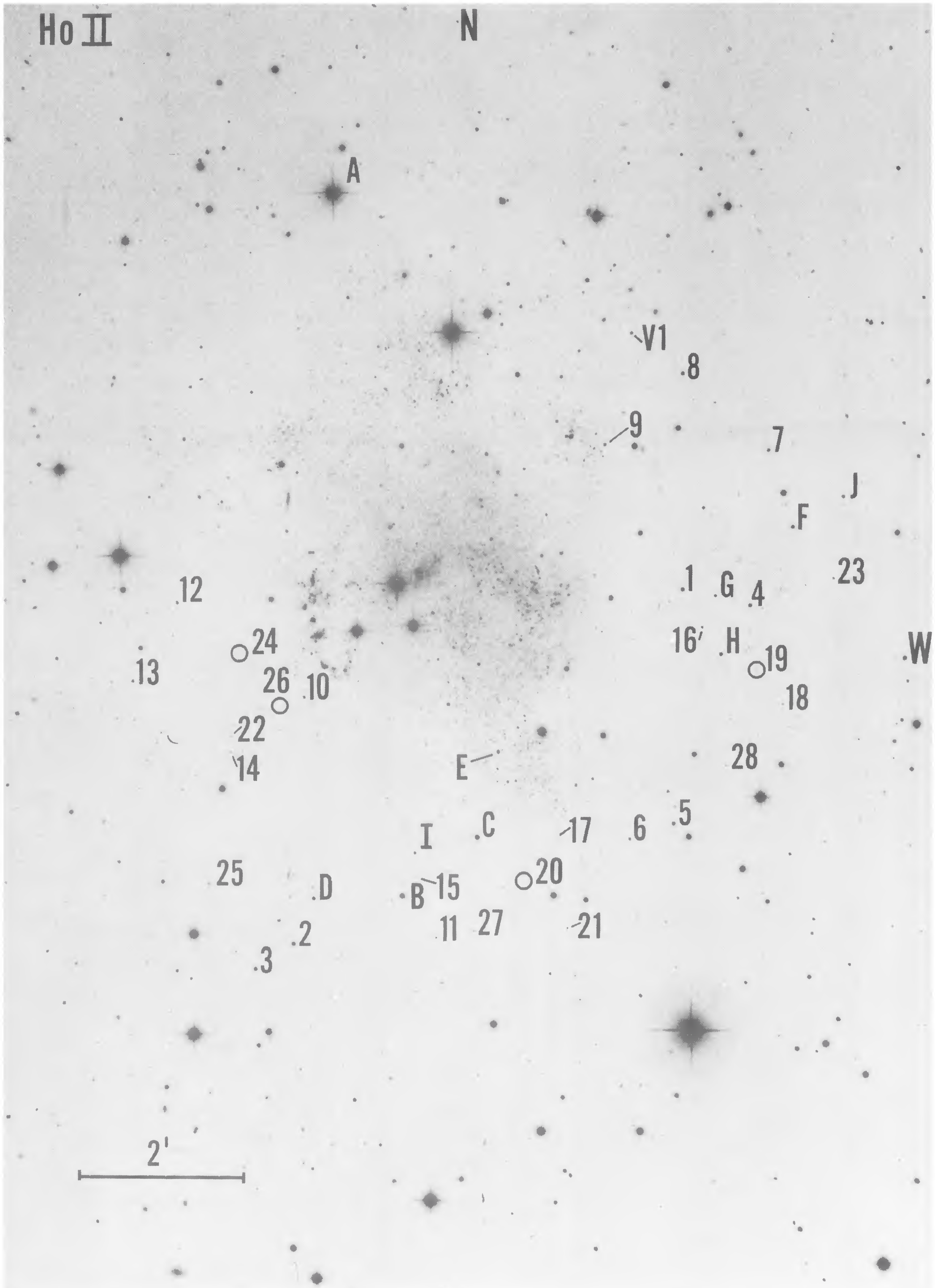

FIG. 3.—Identification of the photoelectric sequence (A–J), the secondary sequence (1–28), and the variable V1 in Ho II.

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1974ApJ...191..603S

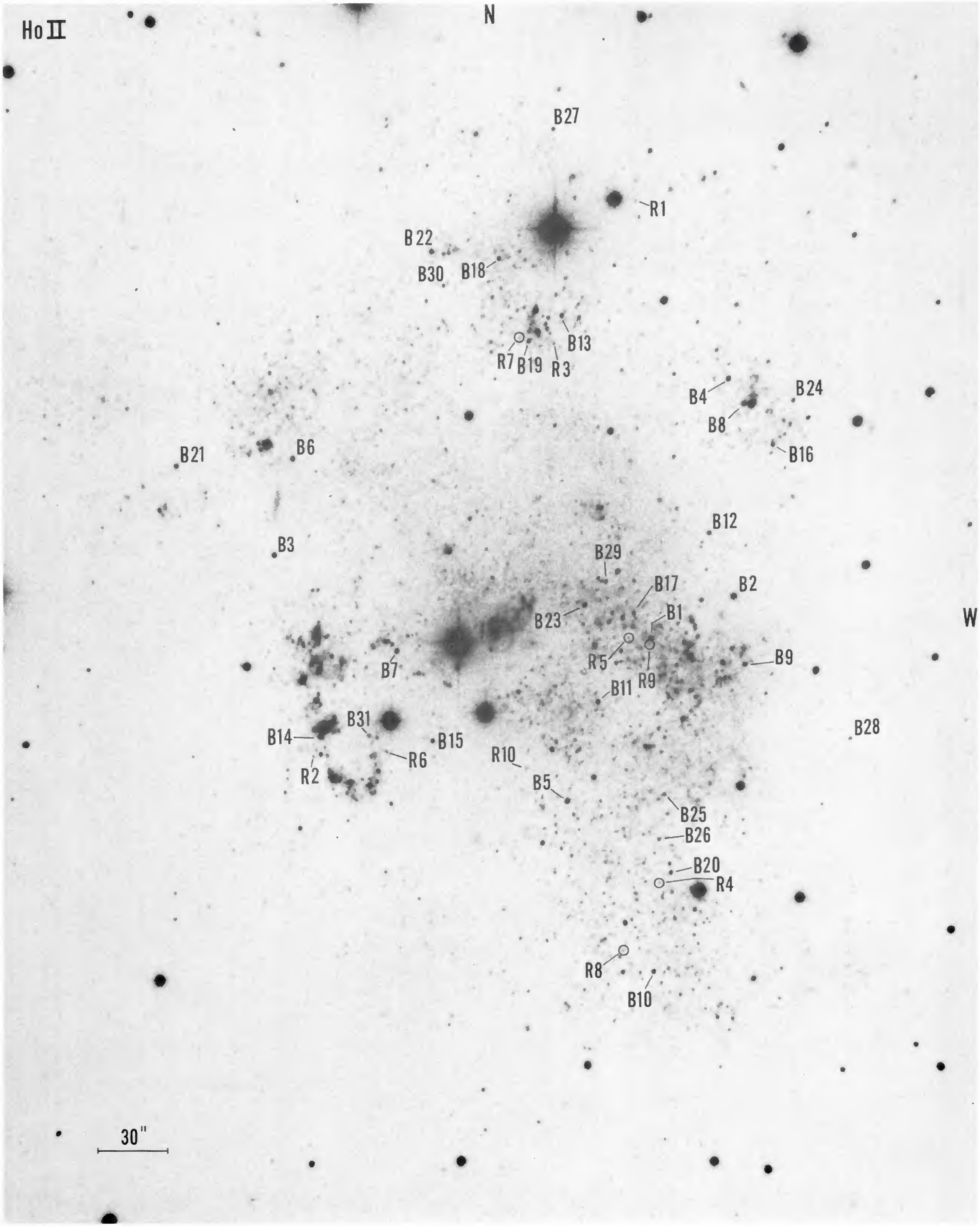

FIG. 4.—Identification of the brightest blue stars (B1–B31) and the very red supergiants (R1–R10) in Ho II.

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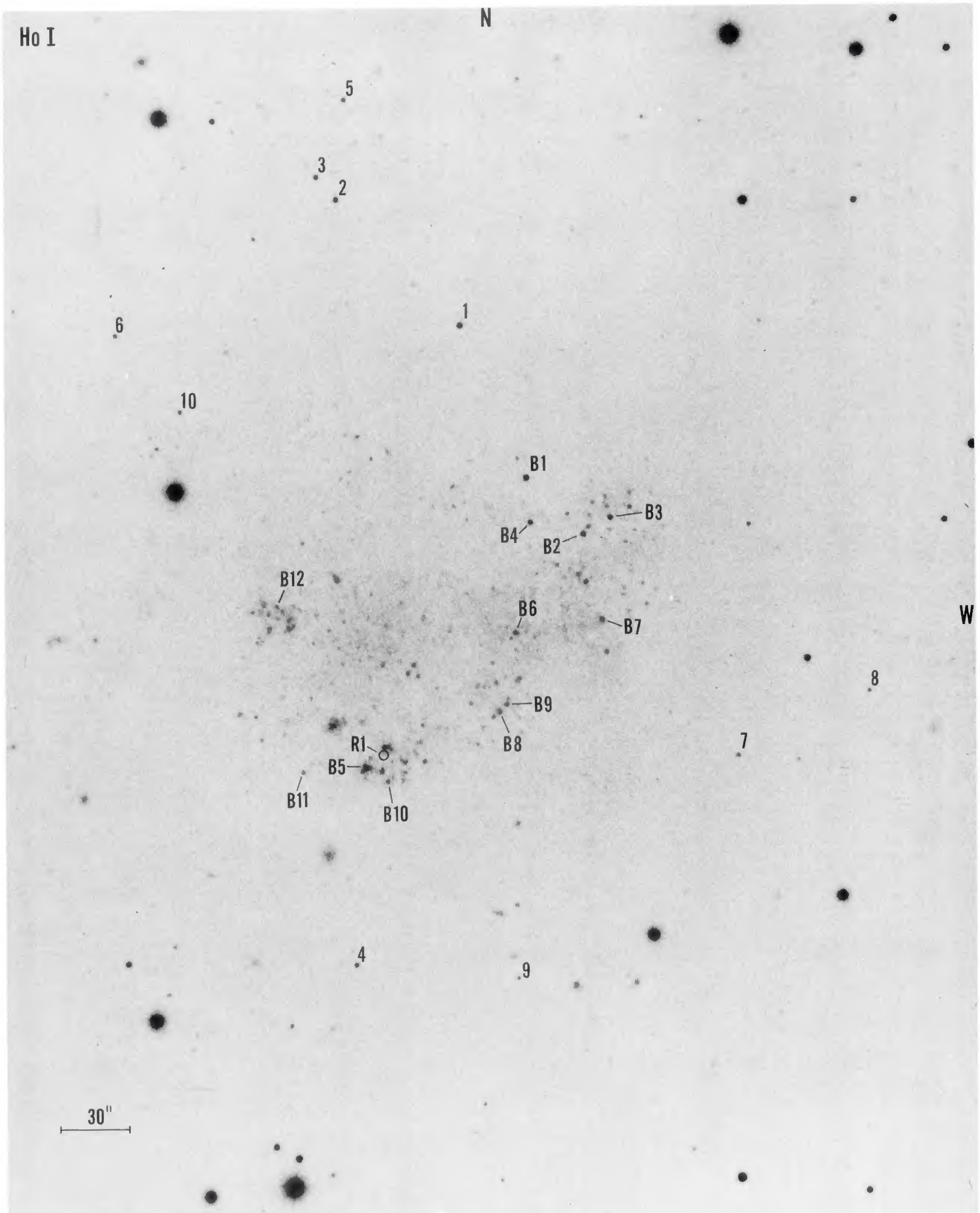

FIG. 5.—Identification of the photographic B sequence (1–10), the brightest blue stars (B1–B12), and the brightest red supergiant candidate (R1) in Ho I.

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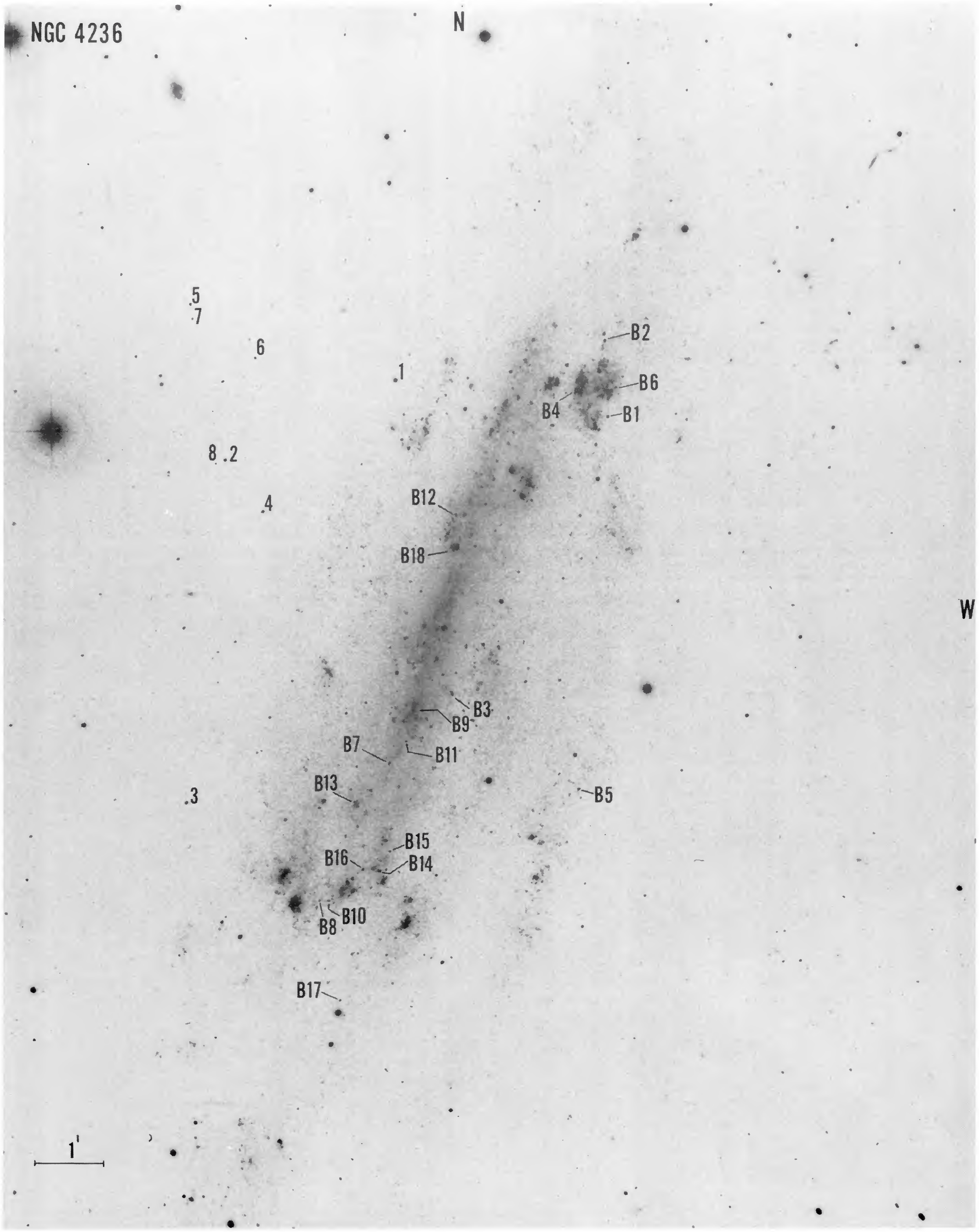

FIG. 6.—Identification of the photographic B sequence (1–8), and the brightest blue stars (B1–B18) in NGC 4236.

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