1982ApJ...258..439S

THE ASTROPHYSICAL JOURNAL, 258:439–456, 1982 July 15
© 1982. The American Astronomical Society. All rights reserved. Printed in U.S.A.

DISTANCE AND ABSOLUTE MAGNITUDES OF THE BRIGHTEST STARS IN THE DWARF GALAXY SEXTANS A

ALLAN SANDAGE AND GEORGE CARLSON[1]
Mount Wilson and Las Campanas Observatories of the Carnegie Institution of Washington
Received 1981 November 6; accepted 1982 January 18

ABSTRACT

The color-magnitude diagram, apparent magnitudes of the brightest red and blue stars, and photometry for Cepheid variables are given for the nearby Im V dwarf galaxy, Sextans A. Based on a magnitude sequence measured to $V \approx 22$, $B \approx 23$, the mean magnitudes of the three brightest blue stars are $\langle V(3) \rangle = 17.98$ and $\langle B(3) \rangle = 17.88$. The three brightest red supergiants have $\langle V(3) \rangle = 18.09$ and $\langle B(3) \rangle = 20.14$.

Periods and magnitudes measured for five Cepheids give an apparent blue distance modulus of $(m-M)_{\rm AB} = 25.67 \pm 0.2$ via the *P-L* relation. With $A_B = 0.07$ for the foreground galactic absorption, the mean absolute magnitudes for the red supergiants of $M_V(3) = -7.56$ and $M_B(3) = -5.53$ provide an additional calibration of the brightest red stars as distance indicators.

If Sextans A were placed at the distance of the Virgo cluster at $(m-M)_0 = 31.7$, it would appear to have $B = 17.9$, $V = 17.4$, a diameter of 15″, and a lumpy structure due to its three OB associations. The surface brightness of $\mu_B = 23.5$ mag per square arcsec and the large angular diameter would make such a galaxy easily discoverable in the Virgo cluster itself using ground-based surveys. Resolution into stars of such dwarfs with Space Telescope may eventually permit the distance to the Virgo cluster to be determined directly.

Subject headings: galaxies: individual — galaxies: photometry — stars: Cepheids — stars: luminosities

I. INTRODUCTION

Distances to galaxies can be obtained if either the absolute luminosity or some fixed linear dimension of a specific stellar component can be identified and measured. Examples are Cepheid variables, brightest stars, novae, sizes and luminosities of H II regions, supernovae, and first-ranked cluster galaxies. To be useful, these or other proposed distance indicators must evidently satisfy two conditions. (1) They should have only a small intrinsic dispersion in the measured property, proved, for example, by forming distance ratios to show that the indicator is reliable, and (2) they must be calibrated in an immediately direct way using a primary source of great weight such as Cepheids. Much of the present debate over the distance scale is due to use of indicators of quite unknown value due to a failure to properly certify them, and the inability to calibrate even the nearest example.

If we require that the calibration must ultimately rest with Cepheids, the only available fundamental galaxies are those in the Local Group (Hubble 1925, 1926, 1929 for NGC 6822, M33, and M31; Baade and Swope 1963, 1965 for M31; Baade 1971 for IC 1613; Kayser 1967 for NGC 6822; and numerous authors for LMC and SMC), the M81/NGC 2403 Group (Tammann and Sandage 1968), and the South Polar Group (Graham 1982 for NGC 300). The sample can eventually be increased using (*a*) other members of the last two groups, and (*b*) the highly resolved dwarf field galaxies of type Sm and Im whose distance moduli are smaller than $m - M \approx 28$ such as WLM, Sextans A, Sextans B, NGC 3109, IC 5152, Leo A, and the Pegasus system. Cepheids have now been found in each of these galaxies.

The brightest resolved stars are a potentially powerful distance indicator, as they reach $M_B \approx -10$ in large spirals. Hubble (1936) used such stars as the foundation of his distance scale.[2] However, Holmberg's (1950) discovery that the absolute magnitudes of the brightest blue supergiants depend on the luminosity of the

[1]Normally at Department of Physical Sciences, Citrus College, Azusa, California, U.S.A.

[2]Hubble found a calibration of $M_{\rm pg}(\text{star}) = -6.1$, and, believing he had resolved such stars in galaxies as distant as the Virgo cluster, obtained a modulus for that cluster of $m - M = 26.8$ which is 5 mag, or a factor of 10 in distance, closer than the current value. It is now known that the knots he saw in his more distant galaxies are either H II regions or OB associations. The individual stars, similar to those he used for the calibration in M31, M33, NGC 6822, IC 1613, LMC, and SMC are, in fact, much fainter, below his plate limit at $B \approx 22$; further, his calibration of $M(\text{star}) = -6.1$ is, for technical reasons that are related to scale errors in magnitudes and to the *P-L* relation, too faint by ~ 3 mag for the average spiral in his sample.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S

parent galaxy weakens *their* use because the correlation of M(star) and M(galaxy) is nearly one-to-one for M_B(galaxy) brighter than ~ -17. Hence, the brightest resolved stars in an intrinsically faint, nearby galaxy have nearly the same apparent magnitude as those in an intrinsically bright, more distant galaxy over that part of the [M_B(star), M_B(galaxy)]-parameter space where the correlation exists.

Although the *blue* stars suffer from this partial degeneracy, the brightest *red* stars do not. With current calibration, their $\langle M_V(3) \rangle$ mean magnitude appears to be independent of the luminosity of the parent galaxy (Sandage and Tammann [ST] 1974*b*). Recent work by Humphreys (1979, with earlier references therein) suggests the same, indicating that red supergiants in M_V may, indeed, be good distance indicators.

The high luminosity at $\langle M_V(3) \rangle \approx -7.7$ (Sandage and Tammann 1974*b*, 1982) and the small dispersion of $\sigma \approx 0.2$ mag about this mean make such stars useful to much larger distances than Cepheids, which rarely reach brighter luminosities than $M_V \approx -6$. Furthermore, a theoretical understanding of why such a sharp upper bound to the luminosity exists may be available in terms of very high mass loss rates for the brightest main-sequence progenitors such that only at some critical lower mass loss rate can red supergiants exist at these bright luminosities.

In this paper we report data on the brightest red and blue stars and on the Cepheids in Sextans A ($\alpha_{1950} = 10^h08^m33^s$, $\delta_{1950} = -4°28'$; $l = 256°$, $b = +40°$) in an attempt to improve the present bright-star calibration. Similar data for M33 (photometry of the Cepheids), WLM, and NGC 3109 should follow shortly.

Photometric data for the brightest red and blue stars and the resulting color-magnitude (C-M) diagram are given in § II; data for the Cepheids and other variables are in § III; discussion of the distance using the Cepheid P-L relation, and the resulting calibration of M_B and M_V of the brightest stars is in § IV.

II. C-M DIAGRAM FOR THE BRIGHTEST STARS

a) *Photoelectric Calibration*

The brightest blue stars in Sextans A begin to resolve at $B \approx 18$, the brightest red stars at $B \approx 20$, and the brightest Cepheids at $B \approx 20$ with a range beyond the plate limit at $B \approx 23$. Magnitude scales, required to very faint limits, were determined photoelectrically and extended with secondary photographic images.

Photoelectric magnitudes in B and V were measured for 16 bright stars in the interval $11.6 < V < 16.3$, $12.2 < B < 16.8$, with the Mount Wilson Hooker reflector in 1975 and 1976, as listed in Table 1. The typical error is $\sim \pm 0.02$ mag. The identification of these bright standards (denoted by S) is given in Figure 1 reproduced from a du Pont 2.5-m reflector blue plate taken at Las Campanas. Also shown in Figure 1 are the identifications of six proper-motion stars found during the blink survey for the variables.

TABLE 1

PHOTOELECTRIC STANDARDS IN THE FIELD OF SEXTANS A

Name	V	B	$B-V$	$U-B$	n
S1	11.64	12.25	0.61	0.12	2
S2	13.04	13.75	0.71	0.34	2
S3	14.43	15.00	0.57	...	2
S4	15.66	16.36	0.70	...	1
S5	13.97	15.30	1.33	...	1
S6	13.72	14.36	0.64	0.14	1
S7	13.33	14.21	0.88	(0.46)	3
S8	11.76	12.22	0.46	0.05	1
S10	14.07	15.02	0.95	...	1
S15	12.89	13.55	0.66	0.16	1
S18	13.20	13.53	0.33	−0.04	1
S21	13.96	14.39	0.43	−0.01	1
S23	15.33	16.09	0.76	...	1
S24	16.31	16.82	0.51	...	1
S50	15.03	15.97	0.94	...	1
S51	13.28	14.00	0.72	...	1

The magnitude sequence was extended to $V = 21.3$, $B = 21.8$, using a 5.00 mag Pickering-Racine wedge with plates taken with the Palomar 5 m Hale reflector. The calibration curves for these plates are nearly identical in shape and slope with those for the other dwarf galaxies WLM, Leo A, Pegasus A, and Sextans B, also under study, where the standard star photoelectric calibration reaches $V = 17$, $B = 18$. This permits an extension of the sequence in Sextans A to the plate limit near $V = 22$, $B = 23$ by continuation, using the similar calibration curves.

b) *Photometry of the Brightest Resolved Stars*

Sixty-eight of the brightest stars in Sextans A are identified in Figure 2, reproduced from a yellow (103aD + GG495) plate taken with the 5 m Hale reflector in good seeing ($\lesssim 1''$). The secondary-wedge images, 5 mag fainter, are visible on the reproduction, 17'' south and slightly east of each bright star.

Yellow and blue plates were blinked to identify the brightest red stars so as to make certain that our sample is complete. The five brightest such red stars are numbers 21, 39, 50, 56, and 70, with many more fainter also marked.

Figure 3 (see fold-out page 447) is a subtraction photograph which illustrates the ease with which such red stars can be found, but which also shows the contamination problem: many faint red field stars exist over the outlying areas. Some of these foreground dwarfs must contaminate the face of Sextans A itself. This is also shown by Figure 1 by noting the central position of the proper-motion stars 1, 2, and 4. These stars are red, seen by detailed comparison of Figures 1 and 3.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S

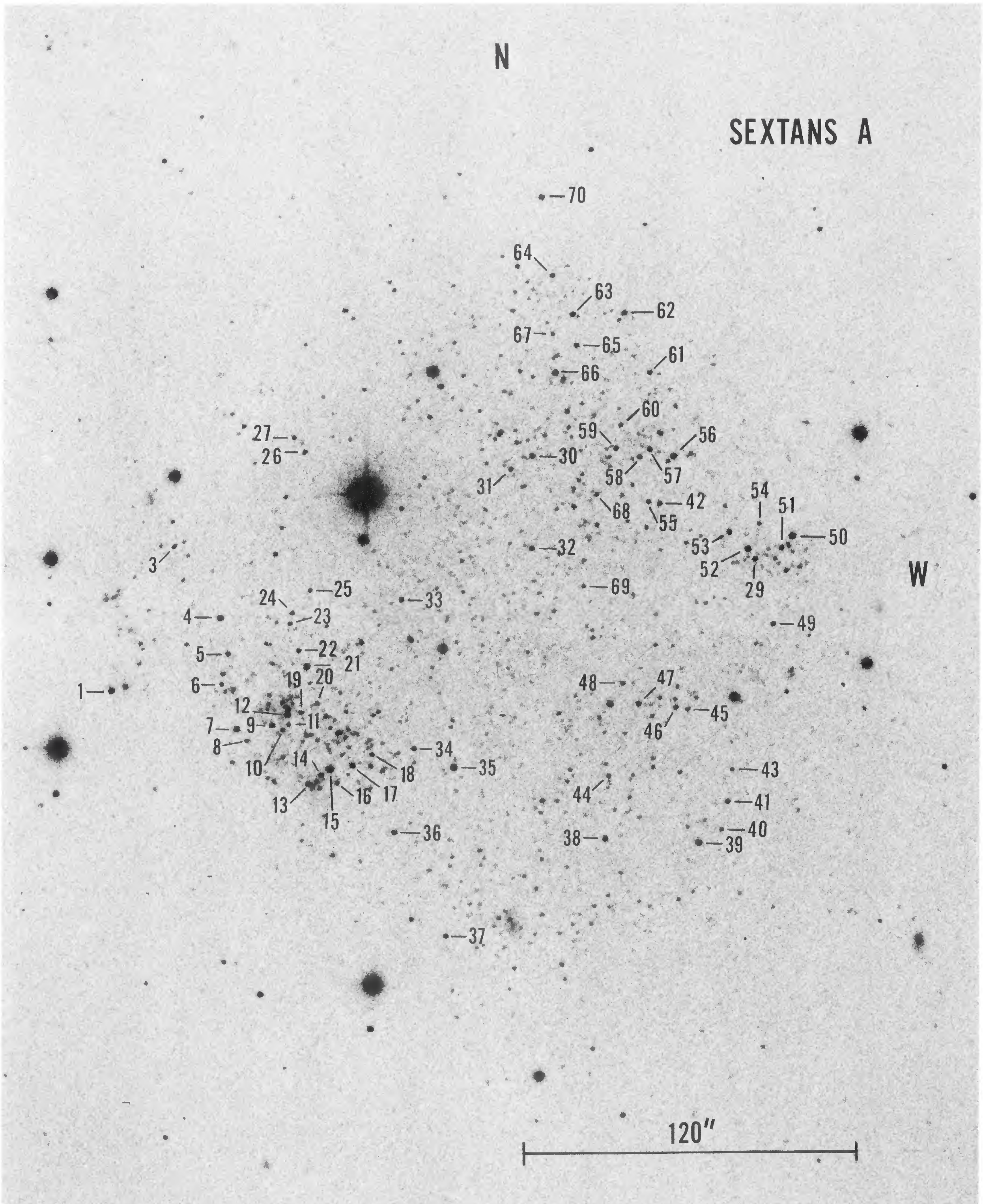


FIG. 2.—Identification chart of the program stars listed in Table 2. Reproduction is from a yellow (103aD+GG495) plate taken with the Palomar 5-m Hale reflector (PH 7117S). Secondary images, 17″ south (and slightly east) of the bright stars, are 5.00 mag fainter than their primaries.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

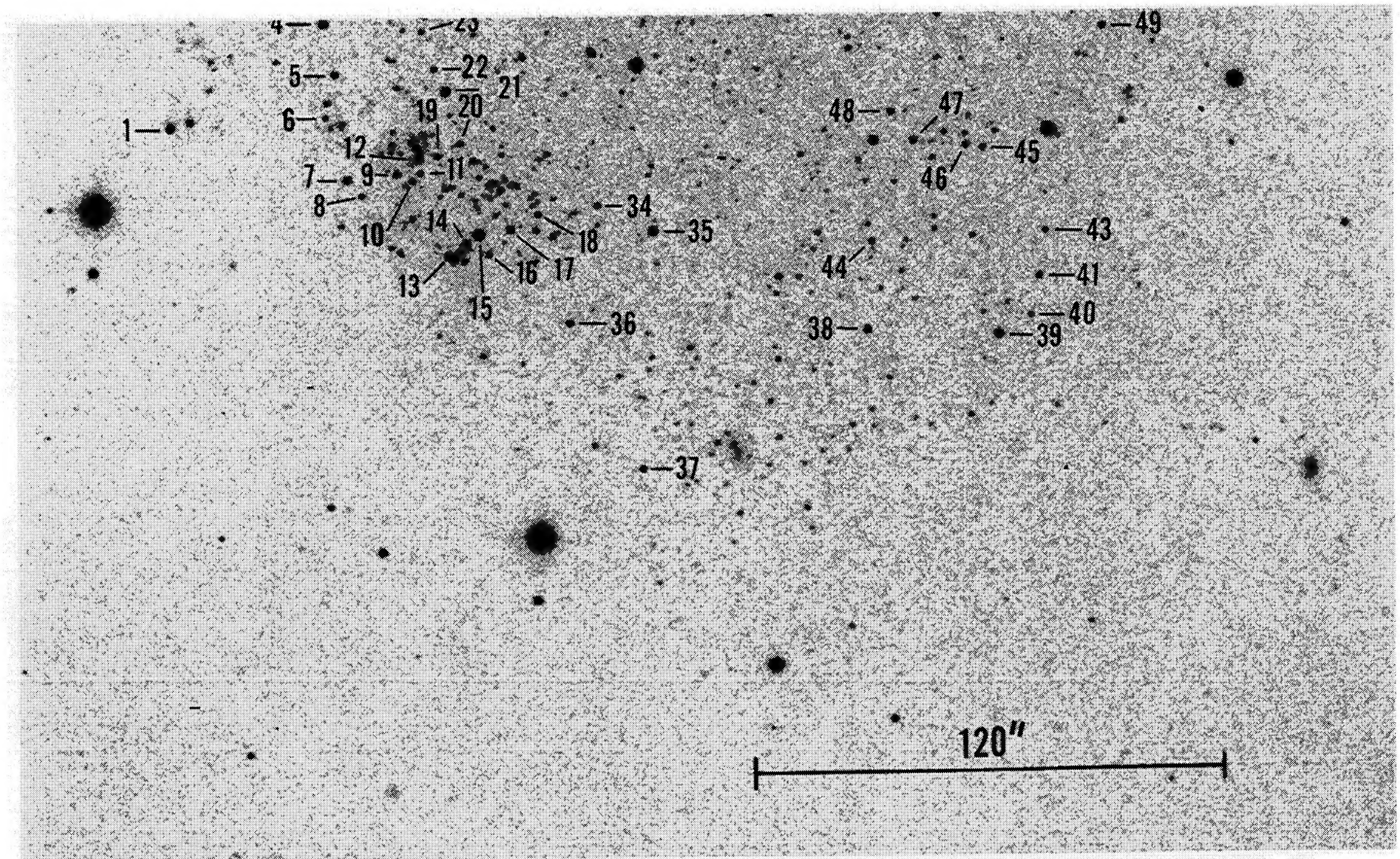


FIG. 2.—Identification chart of the program stars listed in Table 2. Reproduction is from a yellow (103aD+GG495) plate taken with the Palomar 5-m Hale reflector (PH 7117S). Secondary images, 17″ south (and slightly east) of the bright stars, are 5.00 mag fainter than their primaries.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

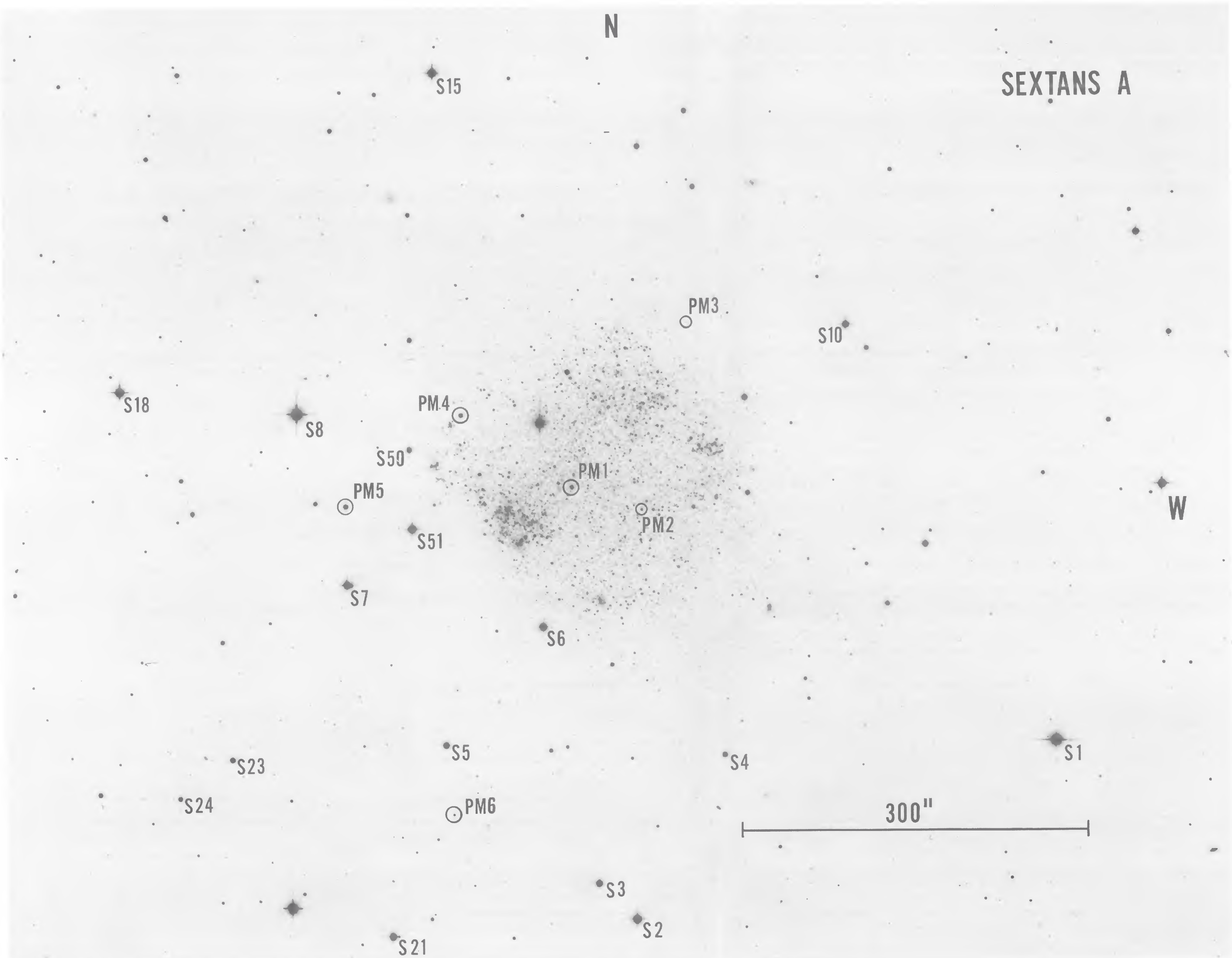
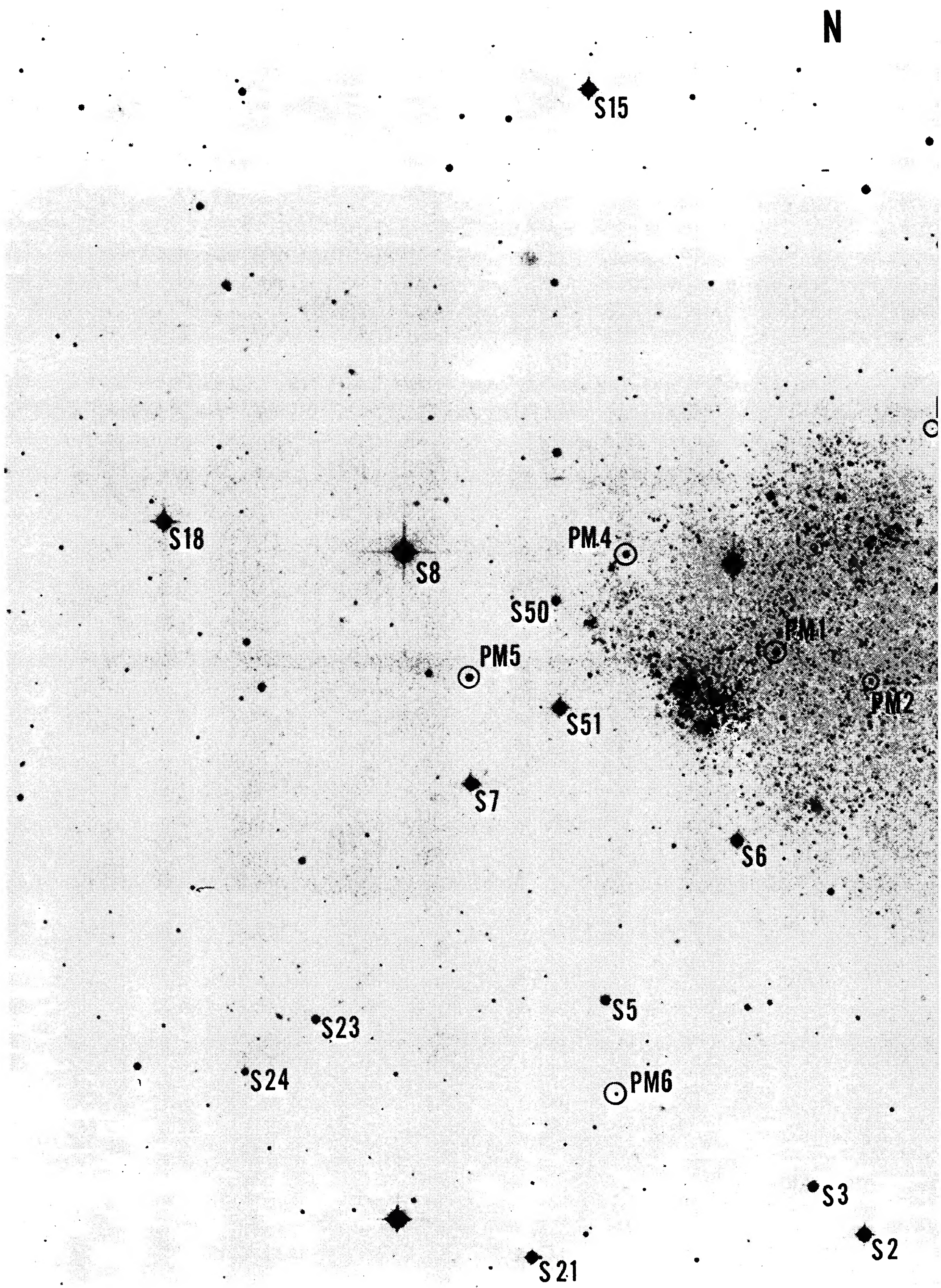


FIG. 1. — Identification chart of the photoelectric standards, listed in Table 1, reproduced from a blue (103aO + GG385) plate taken with the du Pont 2.5 m reflector at Las Campanas. Six proper-motion stars, found by blinking Hale 5 m plates with a 26 year interval, are also marked.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S



© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S

TABLE 2

COLORS AND MAGNITUDES OF BRIGHT STARS IN SEXTANS A

Name (1)	V (2)	$B-V$ (3)	Note (4)	Name (1)	V (2)	$B-V$ (3)	Note (4)
1	18.37	0.73		37	19.25	1.49	
3	19.56	0.22		38	18.83	−0.04	
4	18.38	−0.36		39	18.22	1.24	
5	19.15	0.09		40	20.10	1.69	
6	19.92	−0.43		41	19.46	1.91	
7	18.74	0.00		42	19.40	−0.06	
8	19.66	0.02		43	20.00	1.52	
9	19.21	2.09	Var	44	19.73	−0.29	
10	19.66	0.02		45	19.87	1.84	
11	20.03	0.18		46	19.35	1.87	
12	18.71	0.34		47	19.31	0.06	
13	19.21	0.73		48	19.25	−0.06	
14	19.33	−0.08		49	19.27	0.54	
15	17.25	0.22		50	18.05	2.06	Var
16	20.08	1.88		51	19.25	−0.09	
17	19.01	0.11		52	18.32	−0.16	
18	19.62	2.21		53	18.74	−0.04	
19	19.63	−0.21		54	19.57	−0.26	
20	19.88	−0.15		55	19.71	−0.24	
21	18.11	1.94	Var	56	18.10	2.15	Var
22	19.91	1.31		57	19.04	1.94	
23	20.20	−0.23		58	19.20	2.07	
24	19.60	0.09		59	19.48	−0.10	
25	19.82	−0.21		60	19.83	−0.21	
26	19.84	−0.57		61	19.33	−0.10	
27	19.95	1.95		63	19.03	−0.02	
29	18.88	0.48		64	19.65	0.13	
30	19.39	0.04		65	19.53	1.77	
31	19.42	−0.20		66	18.50	0.60	
32	19.16	0.03		67	20.11	−0.23	
33	19.34	−0.09		68	19.74	1.41	
34	19.54	−0.04		69	19.94	0.04	
35	18.00	0.70		70	18.58	1.86	
36	19.45	−0.27					

However, many of the brightest red candidates (numbers 9, 16, 18, and 21) are in the large association in the SE corner of Sextans A and are likely members for that reason. Furthermore, stars 9 and 21 are variable, as are numbers 50 and 56 in the small association on the west side. Hence, contamination is not a problem here because the brightest red stars in Sextans A, freed from the foreground field, can be identified by these methods.

Magnitudes for the stars in Figure 2 are listed in Table 2 as measured with a step-scale that was calibrated for each plate using the secondary Pickering-Racine wedge images of the photoelectric sequence. The calibration curves show scatter of $\sigma \approx 0.07$ mag, and are well defined. The magnitudes in Table 2 are the mean of measurement of two plates in each color. They have errors smaller than $\sim \pm 0.2$ mag in B and in V.

The Argelander step-scale method of photometry is adequate for the present problem. It is accurate to the stated level and is effective in obtaining *C-M* diagrams, luminosity functions, and magnitudes of the brightest stars and of the variables. It need hardly be said that conventional photographic iris photometry is out of the question in fields of this type because of crowding and variable background. On the other hand, modern methods of microphotometry or direct digital CCD detection with image reconstruction and background subtraction might give comparable results, but, of course, with much greater effort.

One note of caution, however, is required. We have not studied the color equation between the photographic plates and the photoelectric B, V system for stars redder than $B-V \approx 1.2$. Hence, although the values in Table 2 are listed as if they were on the $(B-V)_{pe}$ system, there may be uncertainties in the photographic color system at the ± 0.2 mag level for these red stars.

c) The C-M Diagram

The *C-M* diagram from data in Table 2 is shown in Figure 4. It is similar in form to that of IC 1613 (Sandage and Katem 1976), M33 (Humphreys and Sandage 1980), and the solar neighborhood of the Galaxy (ST 1974*b*; Humphreys 1978). The main sequence is

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S

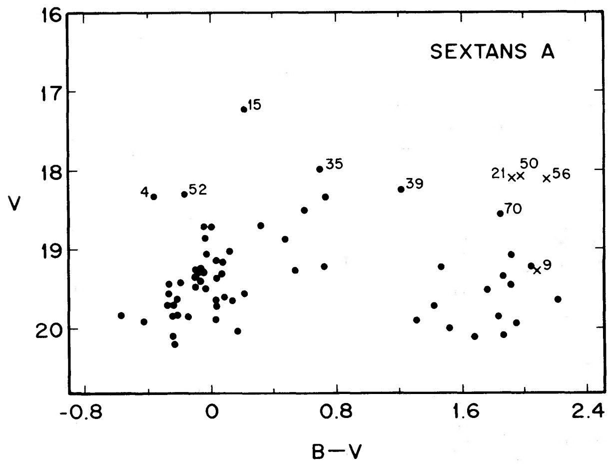


FIG. 4.—Color-magnitude diagram for the stars listed in Table 2. Known red variables are marked as crosses.

evident near $B-V=0.0$, starting at about $V\approx18$. The red supergiants clump near $B-V\approx2.0$, also beginning near $V=18$.

The three brightest blue stars may be numbers 4, 15, and 52. Number 15 is in the association in the SE corner, and, from its position, can be assumed to be an A or F supergiant member such as A43 in IC 1613 (Humphreys 1980) or 5A in M33 (Humphreys and Sandage 1980), but spectra will be required for a proof. If number 15 is included, the mean apparent magnitudes of the three brightest blue stars are $\langle V(3)\rangle=17.98$ and $\langle B(3)\rangle=17.88$.

The three brightest red supergiants are numbers 21, 50, and 56, plotted as crosses in Figure 4. They are variable; hence there is no question of *their* membership. The plotted values are the mean colors and magnitudes from two plates in each color. The data refer to widely different times, hence represent some sort of average over the light curves. The mean magnitudes for the red stars are $\langle V(3)\rangle=18.09$ and $\langle B(3)\rangle=20.14$.

d) *Field Star Contamination*: *Proper Motion Stars*

As mentioned above, some slight contamination due to field stars must occur in Figure 4. The area of Sextans A covered by the marked stars in Figure 2 is 0.003 square degrees. Counts in SA 45 (Sandage and Katem 1982 as plotted in Fig. 20 of Humphreys and Sandage 1980), which is at galactic latitude $-31°$ rather than $+40°$ as for Sextans A, give 40 stars between $V=17$ and 18 mag, 40 stars between 18 and 19 mag, and 50 stars between 19 and 20 mag at all colors, in 0.056 square degrees. These numbers average to ~7 in 0.003 square degrees between $V=17$ and 20, but are less than 1 per unit magnitude interval between $B-V=0.4$ and $B-V=1.0$ in the $V=17$ to $V=20$ interval. Hence, Figure 4 should be virtually free of field stars, even more so because the four such stars within the main body of Sextans A, known from their proper motions to be field stars, are not plotted. To be sure, however, it is not possible without spectra to tell if stars 35 and 39, for example, are in the field or are, in fact, F, G, or K Ia supergiants such as are known in M33, LMC, and the Galactic solar neighborhood at these bright absolute luminosities.

TABLE 3

PROPER MOTIONS FOR SIX FIELD STARS

Name	μ (arcsec yr^{-1})	θ (deg)
PM1......	0.036 ± 0.004	289 ± 5
PM2......	0.084 ± 0.003	289 ± 5
PM3......	0.029 ± 0.002	207 ± 9
PM4......	0.126 ± 0.003	291 ± 1
PM5......	0.048 ± 0.004	293 ± 4
PM6......	0.036 ± 0.003	280 ± 3

The proper motions of the six stars identified in Figure 1 are listed in Table 3, as measured on a pair of Hale 5 m plates (PH 90MH and PH 7128S) with a time interval of 25.9 years. The quoted errors are internal, based on 20 independent measurements of each star. The proper motions should be absolute, as the reference frame is formed from the very distant blue stars of Sextans A itself. The azimuth angle, as usual, is measured from north through east.

III. VARIABLES

a) *Discovery*

A total of 56 plates are available, taken between 1950 and 1980 with the Palomar 5 m Hale reflector and the Las Campanas du Pont 2.5 m reflector. Because the focal length of the du Pont and the Hale telescopes are the same, plates in equal seeing from both telescopes have the same limiting magnitude ($B\approx23$).

Fifty of the 56 available plates are blue (103aO+GG385); the other six are yellow (103aD+GG495). Nineteen plate pairs, separated in epoch from 2 days to ~2 years, were blinked to search for variables. Ninety-nine candidates were marked, 27 of which were suspected to be variables at least twice.

Inspection of all candidates on all plates showed that most of the suspects are probably constant. They are so near the plate limit as to give illusory results for reasons described in the discussion on faint variables in NGC 2403 (Tammann and Sandage 1968).

Five of the candidates (V1, V3, V24, V25, and V28 identified in Fig. 5) proved to be Cepheids. Three others (V5, V6, and V20) are definitely variable, but the data are insufficient to determine periods. Undoubtedly some of the other candidates are also variable, but they appear above the plate limit on only a few of the best seeing plates, and are not considered here further.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S

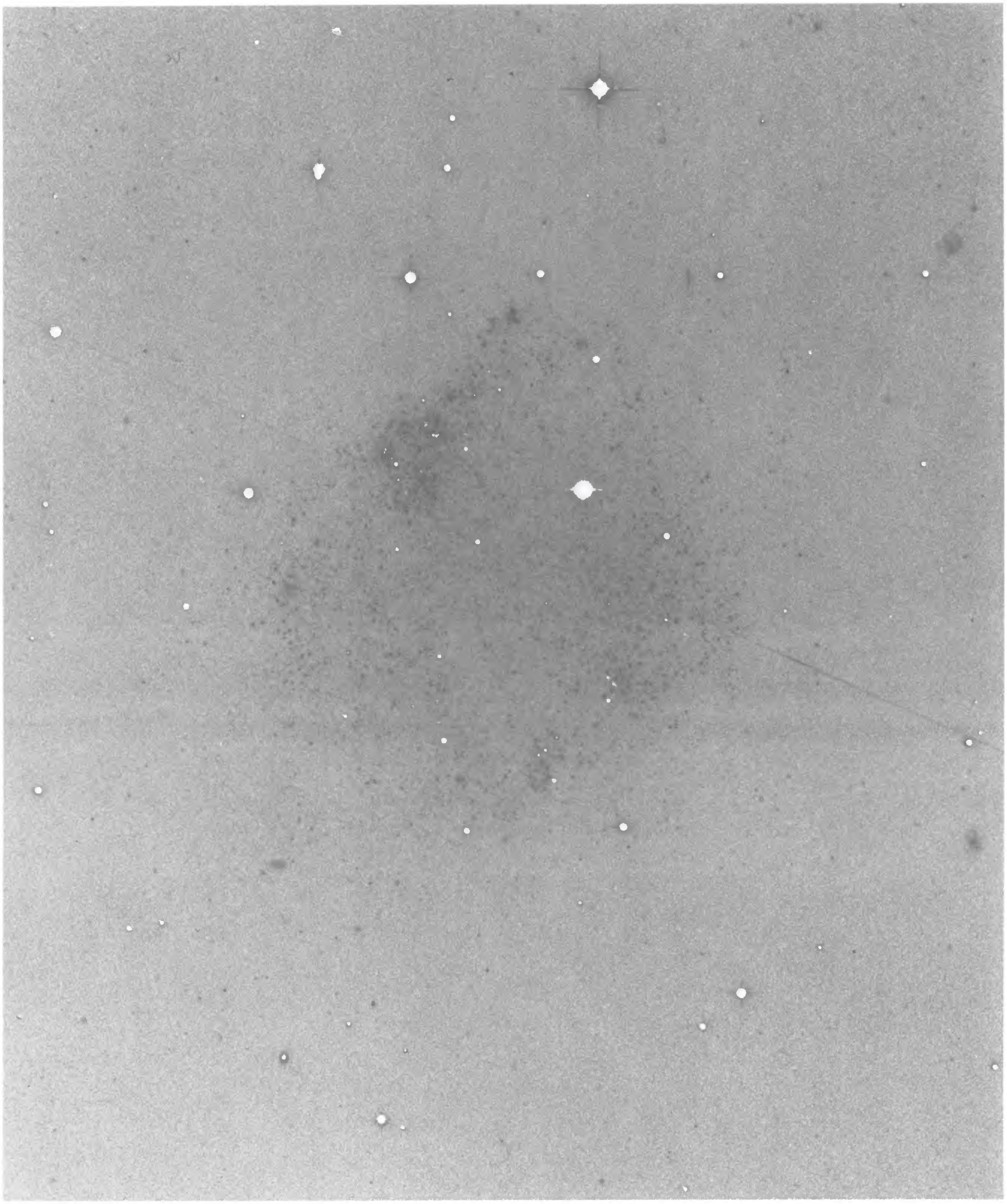
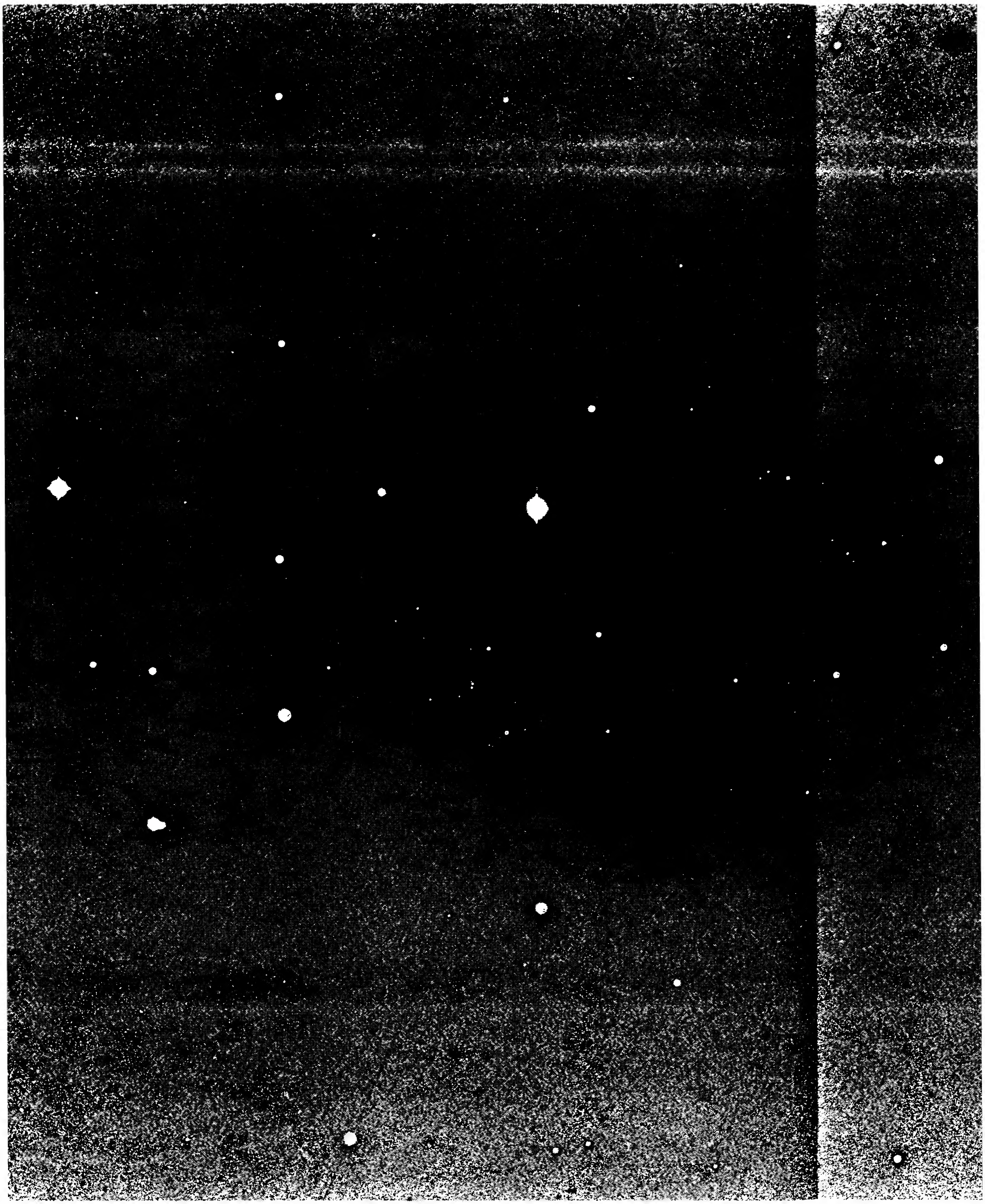


FIG. 3.—Photographic subtraction of a Las Campanas blue negative from a yellow positive film copy. Red stars appear white, blue stars black. Either a satellite or a meteor trail is visible. The subtraction was done by John Bedke in the Observatories' photo lab.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S



© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S

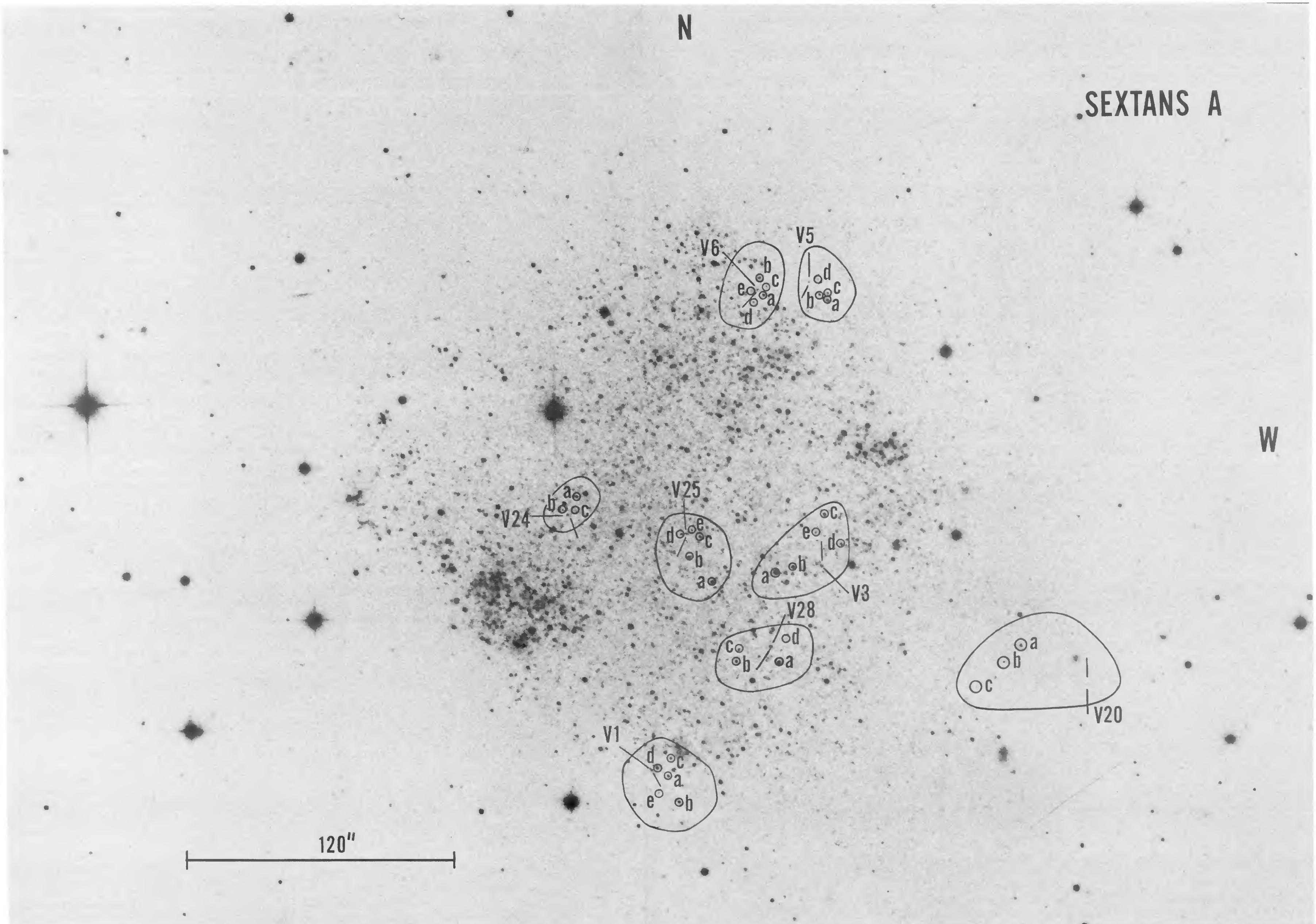
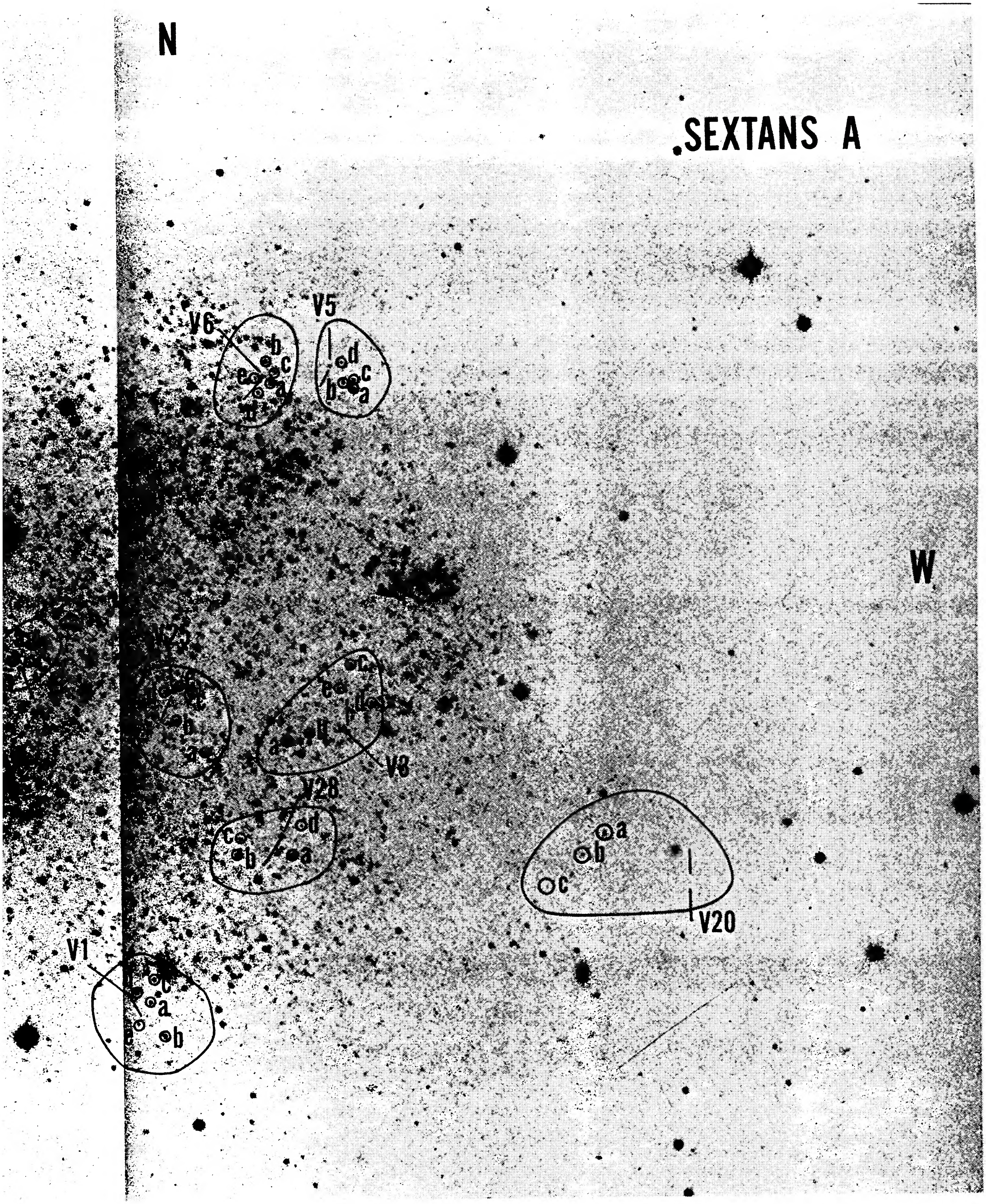


FIG. 5.—Identification of eight variable stars and the sequence stars listed in Table 4. Reproduction is from the same Las Campanas blue plate as for Fig. 1.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S



ɔquence stars listed in Table 4. Reproduction is from the same Las Campanas blue plate as for Fig. 1.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S

TABLE 4

COMPARISON STARS FOR THE VARIABLES

Name (1)	Star (2)	B (3)	V (4)	$B-V$ (5)	Name (1)	Star (2)	B (3)	V (4)	$B-V$ (5)
V1	a	20.91	21.20	−0.3	V20	a	21.26	...	...
	b	20.98	21.02	0.0		b	21.97	...	...
	c	21.68	21.78	−0.1		c	22.81	...	...
	d	22.23	22.1	+0.1	V24	a	21.03	21.60	−0.6
	e	22.34	>22.3	~0		b	22.03	22.08	−0.1
V3	a	19.42	19.31	+0.1		c	22.30	...	...
	b	20.35	20.35	0.0	V25	a	20.65	20.41	+0.2
	c	20.79	21.20	−0.4		b	21.15	21.20	−0.1
	d	21.47	21.85	−0.4		c	21.57	21.40	+0.2
	e	21.74	21.85	−0.1		d	21.77	...	...
V5	a	20.63	20.50	+0.1		e	22.16	...	...
	b	21.63	22.10	−0.5	V28	a	20.43	20.70	−0.3
	c	21.97	21.25	+0.7		b	21.04	20.80	+0.2
	d	22.38	...	...		c	21.81	22.18	−0.4
V6	a	21.21	21.30	−0.1		d	22.55	>22.6	...
	b	21.52	21.54	0.0					
	c	22.05	21.80	+0.3					
	d	22.12	21.80	+0.3					
	e	22.44	21.60	+0.8					

The original numbers assigned during the blinking have been retained as the final numbers.

b) *Photometry*

Comparison stars that bracket the brightness range were chosen for each of the eight variables. These stars, identified in Figure 5, are listed in Table 4 with magnitudes determined via step-scale, calibrated, as before, using the primary photoelectric sequence extended with the Pickering-Racine wedge.

Photometry of each variable relative to its comparison sequence was done by eye-estimate twice, separated in time so that all memory of the first estimates was lost. Also the plates were measured at random so that no prejudice within a systematic time-sequence exists. Comparison of the two independent measurement sets gives an average difference of $\langle \Delta B \rangle = 0.14$ mag, showing that the accuracy of the listed (mean) magnitude is ~0.1 mag.

Data for the five Cepheids of known period are given in Table 5, which lists the Julian Day, the year, the plate number with telescope (PH = Palomar Hale; CD = Chile du Pont), the observer's initial (B = Baade; MH = Humason; S = Sandage), the phase (periods from Table 6), and the B magnitude. The phases have been shifted to be zero at maximum light.

c) *Elements of the Cepheid Light Curves*

Except for V24, the time distribution of the plates was inadequate to suggest even approximate periods of the variables by the usual method of fitting together light-curve segments. Therefore, we used a computer search program due to Marraco and Muzzio (1980), following Lafler and Kinman (1965), and Jurkevich (1971).

Satisfactory light curves could be obtained for V1, V3, V24, V25, and V28 shown in Figure 6. The elements are listed in Table 6, where the rows give the Julian Day of maximum phase calculated to be near the mean epoch (1965 March) of the observations, the period, and the internal uncertainty of the period, assuming that the cycle count over ~30 years is correct and that a phase shift of 0.05 would be detected. Row 3 gives the dispersion measure in magnitudes about the mean curve, calculated by the computer code. The photometric parameters are in rows (6)–(9).

One should be cautious in using the B(min), and hence the B(med) and amplitude A_B values, because such photometry is close to the plate limit. V1 and V24 probably fall below the plate limit at minimum suggested by their flat minima. For this reason, we have put higher weight on the distance determination using maximum rather than mean light (§ IV). Further observations are needed to confirm the listed periods, especially for V28 which shows a somewhat scattered light curve.

d) *Other Variables*

Variables V5, V6, and V20 definitely vary, but insufficient data are available to determine their types reliably. Partial light curves for V5 and V6 are shown in Figure 7 from data obtained during the long 1978 observing run at Las Campanas, Chile.

Evidently, V5 is an eclipser. It is near maximum at $B \approx 21.0$ most of the time, but twice (1956 March 14/15 on plate PH 1383B, and 1978 February 4/5 on CD

© American Astronomical Society • Provided by the NASA Astrophysics Data System

TABLE 5

BLUE MAGNITUDES FOR FIVE CEPHEIDS IN SEXTANS A

JD 2,430,000+ (1)	YEAR (2)	PLATE (3)	V1 Phase (4)	V1 B (4)	V3 Phase (5)	V3 B (5)	V24 Phase (6)	V24 B (6)	V25 Phase (7)	V25 B (7)	V28 Phase (8)	V28 B (8)
3355.76	1950	PH 90MH	.95	21.57	.31	21.38	.63	22.03	.84	21.75	.57	21.66
3356.76		PH 95MH	.01	21.06	.36	21.50	.73	22.03	.89	21.81	.61	21.88
3357.76		PH 106MH	.07	20.98	.41	21.52	.82	22.03	.94	21.23	.65	21.81
3358.76		PH 112MH	...	.....	...	.....	.92	21.83	.00	21.10	...	.....
3389.697		PH 21B	.06	21.31	.86	20.26	.86	21.83	.61	21.85	.87	21.81
3391.699		PH 33B	.19	21.57	.96	20.16	.06	21.23	.72	21.67	.95	20.55
5542.756	1956	PH 1363B	.51	22.24	.37	21.11	.38	21.83	.62	21.85	.51	21.43
5543.778		PH 1375B	...	.....	.42	21.51	.48	22.03	.68	21.81	.55	21.43
5547.780		PH 1383B	.83	21.97	.61	21.69	.87	21.33	.89	21.89	.71	21.81
5548.737		PH 1391B	.89	22.24	.65	21.63	.97	21.23	.94	21.15	.75	21.50
5809.029		PH 1601B	.63	21.88	.92	20.35	.54	22.03	.97	21.05	.98	20.55
5810.015		PH 1610B	.69	22.23	.97	20.16	.64	22.08	.02	21.05	.02	20.55
5811.020		PH 1619B	.75	22.10	.02	20.16	.74	21.93	.08	21.15	.06	20.67
5838.009		PH 1635B	.49	22.25	.29	21.11	.39	21.83	.53	21.97	.12	21.04
5870.907	1957	PH 1340S	...	.....	.84	21.58	.62	22.03	.30	21.53	.41	21.50
5931.675		PH 1639B	...	.....	.70	21.58	.59	22.03	...	.....	...	.....
5932.718		PH 1649B	...	.....	.75	21.45	.69	22.03	.63	21.85	.84	21.73
6163.994		PH 1785B	...	.....	...	.....	...	.....	.10	21.10	.94	20.74
6193.954		PH 1795B	.38	22.24	.07	20.39	.36	22.03	.71	21.85	.11	20.92
6248.867	1958	PH 1808B	...	.....	.66	21.55	.75	22.03	...	.....	.27	21.12
6251.839		PH 1820B	.10	21.44	.80	21.52	.04	21.13	.83	21.75	.39	21.43
6309.689		PH 1831B	...	.....	...	.....	.72	22.03	.95	21.05	.66	21.35
6310.672		PH 1834B	.88	22.23	.57	21.65	.82	21.93	.00	21.05	.70	21.27
6311.689		PH 1848B	.95	21.68	.62	21.50	.92	21.03	.05	21.10	.74	21.88
6312.684		PH 1861B	.01	21.31	.67	21.52	.02	21.23	.11	21.19	.78	21.88
6313.683		PH 1873B	.08	21.04	.71	21.65	.12	21.03	.16	21.23	.82	21.88
6338.691		PH 1894B	...	.....	.89	21.31	...	.....	...	.....	...	.....
12782.956	1976	PH 7099S	...	.....	...	.....	.66	22.03	...	.....	.15	21.19
12787.053		PH 7118S	...	.....	.90	20.70	.06	21.53	.96	21.00	.31	21.43
12809.895		PH 7128S	...	.....	.97	20.16	.31	21.63	.19	21.32	.20	21.27
13540.727	1978	CD 138S	.77	22.23	.43	21.38	...	.....	...	.....	...	.....
13541.767		CD 143S	.84	22.10	.48	21.50	.21	21.43	.63	21.77	.98	20.98
13543.758		CD 156S	.97	21.44	.57	21.52	.40	21.83	.73	21.85	.05	20.55
13545.768		CD 168S	.10	21.31	.67	21.31	.60	21.93	.84	21.44	.13	20.98
13546.811		CD 182S	.16	21.04	.71	21.58	.70	21.93	.90	21.77	.17	20.86
13547.774		CD 189S	.22	22.10	.76	21.50	.80	21.83	.95	20.95	.21	21.19
13548.780		CD 197S	.29	22.23	.81	21.58	.90	21.23	.00	20.90	.25	21.12
13549.825		CD 206S	.36	22.25	.86	21.58	.00	21.23	.06	21.05	.29	21.19
13550.790		CD 212S	.42	22.23	.90	21.04	.09	21.43	.11	21.10	.33	21.27
13552.757		CD 224S	.54	22.23	.99	20.16	.29	21.53	.22	21.28	.41	21.73
13553.805		CD 234S	.61	22.23	.04	20.16	.39	21.83	.28	21.53	.45	21.96
13554.784		CD 243S	.68	22.24	.09	20.26	.49	22.03	.33	21.67	.49	21.73
14309.619	1980	CD 1294S	.21	22.10	.68	21.52	.64	22.08	.00	21.00	.16	21.19
14311.669		CD 1317S	.34	22.23	.77	21.47	.84	21.63	.11	21.19	.24	21.19
14313.664		CD 1338S	.47	22.10	.87	21.11	.04	21.23	.22	21.32	.32	21.35
14315.626		CD 1360S	.60	22.29	.96	20.16	.23	21.13	.32	21.73	.40	21.43
14317.625		CD 1372S	...	.....	.05	20.26	...	.....	...	.....	...	.....

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S

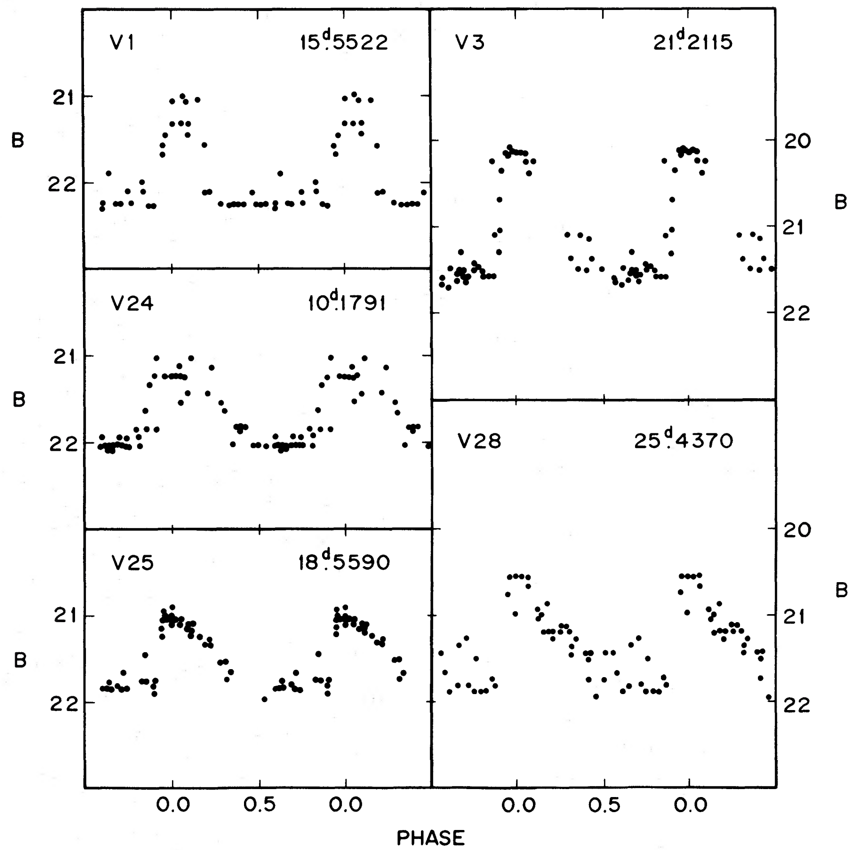


FIG. 6.—Light curves in B for the five Cepheids listed in Table 4

TABLE 6
ELEMENTS OF THE CEPHEIDS IN SEXTANS A

Parameter (1)	V1 (2)	V3 (3)	V24 (4)	V25 (5)	V28 (6)
JD 2,438,800+ ...	47.522	43.921	36.905	53.280	36.517
P(days)	15.5522	21.2115	10.1791	18.5590	25.4370
Period Unct.	$\pm 0^d.001$	$0^d.002$	$0^d.0005$	$0^d.002$	$0^d.003$
σ(mag)	0.11	0.22	0.11	0.08	0.17
Log P	1.192	1.327	1.008	1.269	1.405
B(max)............	21.00	20.16	21.10	21.00	20.43
B(min)	22.23	21.60	22.03	21.85	21.80
B(med)............	21.62	20.88	21.57	21.43	21.12
A_B.................	1.23	1.44	0.93	0.85	1.37

156S) it was observed at minimum near $B = 22.2$. In both instances the minima were narrow, less than ~ 3 days. The variation is real because PH 1383B and CD 156S are among the best plates of the collection. Two other minima were observed (1957 April 2/3 on PH 1639B and 1958 April 15/16 on PH 1831B) and, although these plates are among those of the poorest seeing, these minima are also real. The star is blue, near $B - V \approx 0$, which tends to support the classification as a main-sequence eclipsing binary.

V6 may be a Cepheid whose minima are at or below plate limit, and with a maximum near $B = 21.2$. Almost all our data show the star to be fainter than $B = 21.6$. Only during the long 1978 run at Las Campanas do the data show a trend, plotted in Figure 7. The star is relatively red, supporting the tentative classification of V6 as a Cepheid.

V20 is below the plate limit except for two short intervals in our data. On the four successive nights of 1958 April 16–19, V20 rose from $B = 21.9$ to $V = 21.7$.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S

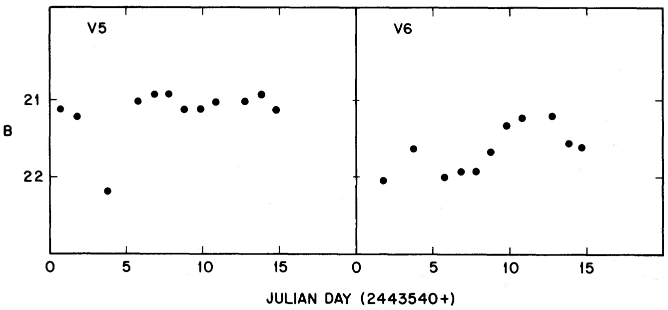


FIG. 7.—Variation of V5 and V6 during the long 1978 observing run at Las Campanas

Also, on the first night of the 1980 March 11/12 run, $B=21.4$ but fell to $B=21.7$ by 1980 March 19/20. The star is invisible on all other plates in the collection.

IV. DISTANCE AND CALIBRATION OF THE BRIGHTEST STARS

a) The Cepheid P-L Relation

Because of the finite width of the instability strip and the sloping lines of constant period in the $(M_B, \log T_E)$-diagram, the Cepheid period-luminosity relation has intrinsic scatter, amounting to $\Delta M_B \sim \pm 0.6$ mag from the ridge-line read at constant period (Sandage 1958; Arp 1960; Sandage and Tammann 1968, 1969). The scatter can be almost entirely removed by accounting for the position within the strip by using a color term in the *P-L* relation. Amplitude can also be used as such a measure (Sandage and Tammann 1971). However, in the absence of reliable data on colors or on amplitudes, one is forced to use the *P-L* relation without a third parameter by minimizing the dispersion within the ± 0.6 mag spread.

Color data do not exist in Sextans A, and our amplitudes are of low weight because some of the stars disappear below plate limit at minimum light. In what follows, the distance depends on the *P-L* relation alone.

We have chosen not to use directly the *P-L* calibration given in ST (1968, 1969) where the shape and intrinsic dispersion of the two-parameter relation rests with older data. Rather, we have proceeded by using the large body of new photoelectric photometry for 78 Cepheids in LMC discussed by Martin, Warren, and Feast (1979) to test again the intrinsic dispersion and the slope of the ridge-line *P-L* relation. The zero points of these ridge and envelope lines are then set using some adopted apparent blue modulus of LMC.

This procedure, applied to Sextans A, is given in Figure 8. The top panel shows the individual Cepheids in LMC taken from Table 3 of Martin *et al.* using $\langle B \rangle$ values found by adding their columns (2) and (3). The shape of the envelope-lines and their separation, from ST (1968), are superposed. The ordinate is intrinsic absolute blue magnitude found by subtracting 19.11 from the $\langle B \rangle$ values for the 78 Cepheids. This follows by adopting a true modulus of LMC of $(m-M)_0 = 18.59$ (Sandage and Tammann 1971, Table 5), but increased by 0.2 mag using a Hyades modulus of 3.23 as in Table 2 of the RSA (Sandage and Tammann 1981). The apparent blue modulus is then $(m-M_{AB}) = 19.11$ obtained by assuming $E(B-V)=0.08$ and adding $4E(B-V)=A_B=0.32$ to $(m-M)_0=18.79$ for LMC.

This resulting calibration of Figure 8 is 0.12 mag *fainter* than Table A1 of ST (1968). If, on the other hand, we adopt $(m-M)_0=18.69$ for LMC given by Martin *et al.* from a number of considerations, then $(m-M)_{AB}=19.01$ and the ordinates in Figure 8 would be fainter by 0.1 mag than shown.

This new calibration is repeated in the lower panels of Figure 8 where the relation between the maximum and the mean *P-L* correlation is taken from Table A1 of ST (1968). Also shown as points are the five Cepheids in Sextans A using their maximum and their mean B magnitudes from Table 6. Here, the intensity-mean value $\langle B \rangle$ was found by adding 0.1 mag to B(med) (Sandage 1971, Table 6).

The resulting apparent blue moduli for Sextans A are $(m-M)_{AB}=25.84$ using B(max) and $(m-M)_{AB}=25.62$ from $\langle B \rangle$, as marked in Figure 8. If we had used $(m-M)_{AB}=19.01$ for LMC from Martin *et al.*, these values would be $(m-M)_{AB}=25.74$ and 25.52, respectively. Or, if we use $(m-M)_{AB}=18.91$ from ST (1974*a*, Table 2) based on $m-M=3.02$ for the Hyades, the Sextans A values become $(m-M)_{AB}=25.64$ from B(max) and 25.42 from $\langle B \rangle$.

We finally adopt the Martin, Warren, and Feast (1979) apparent modulus of $(m-M)_{AB}^{LMC}=19.01$, and give double weight to the B(max) value to obtain

$$(m-M)_{AB}^{\text{Sextans A}} = 25.67,$$

where ± 0.2 mag may be an appropriate estimate of the error. If we adopt $A_B=0.07$ for the foreground galactic absorption (Kraan-Korteweg and Tammann 1979), then

$$(m-M)_0 = 25.60 \pm 0.2.$$

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S

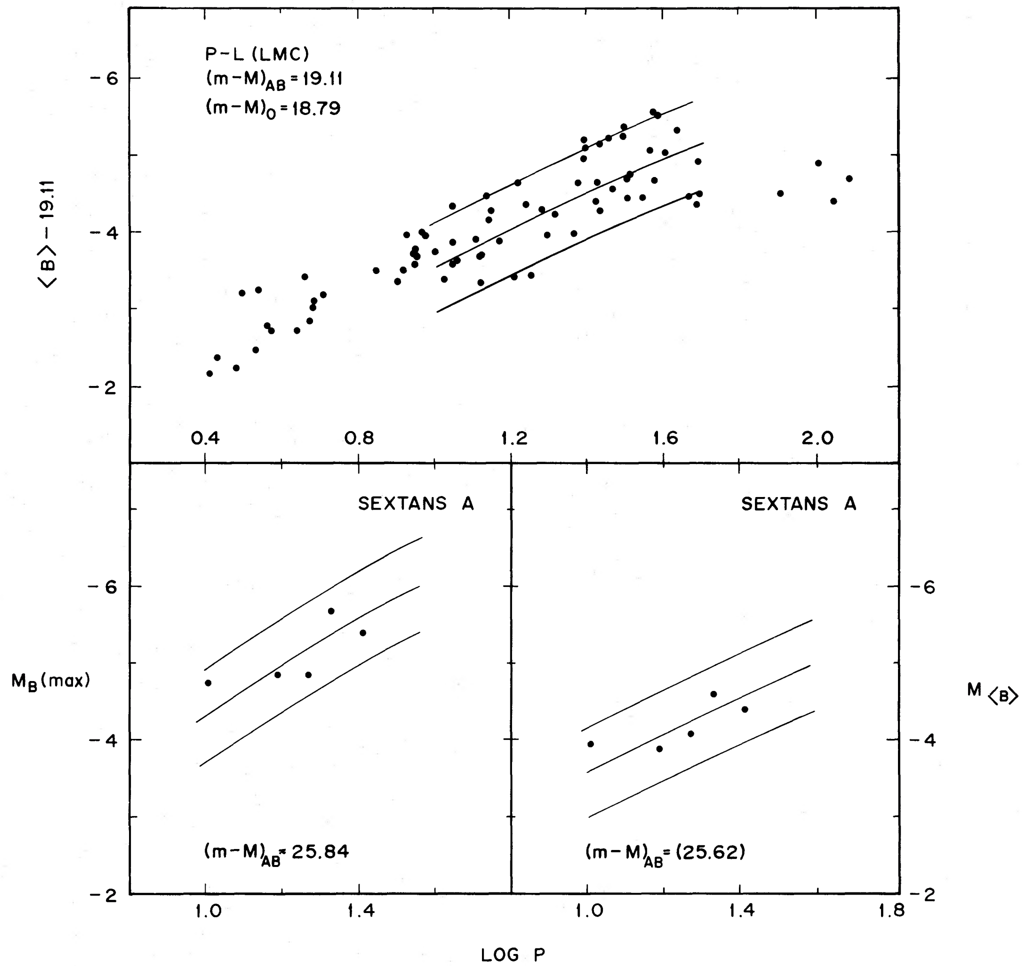


FIG. 8.—The period-luminosity relation for LMC Cepheids discussed by Martin, Warren, and Feast (1979) in the top panel. The zero point of the ordinate assumes $(m-M)_{AB}=19.11$ for LMC. The shape of the envelope and the ridge lines are from the calibration by Sandage and Tammann (1968). The five Cepheids in Sextans A are plotted in their respective M_B(med) and $M_{\langle B\rangle}$(max)*P-L* relations in the bottom panels. The adopted modulus in the text differs slightly from the values marked.

b) *Calibration of the Brightest Stars*

The values in § II*c* for the brightest stars are $\langle V(3)\rangle = 17.98$ and $\langle B(3)\rangle = 17.88$ for the mean of the three most luminous blue stars, and $\langle V(3)\rangle = 18.09$ and $\langle B(3)\rangle = 20.14$ for the three brightest red stars. If these stars suffer no *internal* absorption and if the same galactic absorption of $A_B = 0.07$ mag applies to them as well as to the Cepheids, then their intrinsic absolute magnitudes, using $(m-M)_{AV} = 25.65$ and $(m-M)_{AB} = 25.67$, are

$$M_V(3) = -7.67 \quad \text{and} \quad M_B(3) = -7.79$$

for the brightest blue stars, and

$$M_V(3) = -7.56 \quad \text{and} \quad M_B(3) = -5.53$$

for the brightest red supergiants.

These values have been used elsewhere (Sandage and Tammann 1982) in a rediscussion of the calibration of $M(3)$ for both the red and blue brightest stars by combining the presently available data from all primary calibrators. The new calibration given there is $\langle M_V(3)\rangle = -7.72 \pm 0.17\ \sigma$ for the three brightest red stars.[3] Sextans A at $M_B^0(\text{gal}) = -14.0$ and Ho IX at $M_B^0(\text{gal}) = -13.5$ are the two faintest galaxies in the sample. In Ho IX, ST (1982) give $\langle M_V(3)\rangle = -8.1$ for the red stars. Hence, because Sextans A and Ho IX

[3] This value is ~ 0.3 mag fainter than adopted by Humphreys (1980, with earlier references therein) due to our different precepts for the internal absorption correction. We have chosen not to make that correction, whereas Humphreys has made it to individual red supergiants when color photometry exists. Our ignoring of any internal absorption in the parent galaxy seems justified for two reasons: (1) the brightest stars in a given galaxy as seen from an outside observer are expected to be biased toward low internal absorption, and (2) although internal absorption may increase the magnitude scatter, it will not introduce a *systematic* error in distances, provided that the calibration of $\langle M_V(3)\rangle$ and its application is done consistently.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1982ApJ...258..439S

bracket the red supergiant mean of $\langle M_V(3)\rangle = -7.72$ that ST found using all 16 calibrating galaxies (which cover 6 magnitudes in absolute luminosity), there is no evidence from these data that $\langle M_V(3)\rangle$ for red supergiants becomes progressively fainter than this mean, even for galaxies as faint as $M_B \approx -13.5$. Therefore, the caution concerning the possibility of such a statistical effect (Humphreys 1980) seems not to apply here. Hence, the main-sequence blue star progenitors apparently are still sufficiently numerous, even for Sextans A, for their daughters to appear near the upper envelope of the red supergiant upper limit of about -7.7 (ST 1982, Fig. 1*a*).

V. INTRINSIC PROPERTIES OF SEXTANS A AND ITS APPEARANCE FROM THE VIRGO CLUSTER

Holmberg (1957) measured the total apparent magnitudes of Sextans A to be $m_{pg} = 11.55$, $m_{pv} = 11.32$. The value listed in the *Second Reference Catalog* (de Vaucouleurs, de Vaucouleurs, and Corwin 1976) is $B_T = 11.87$ obtained by an adopted transformation from Holmberg. And, because $m_{pv} \simeq V$, the color is $B - V \approx +0.5$.

The angular diameter of the main body of Sextans A is $\theta \approx 4'$, giving, as before, an area of ~ 0.003 square degrees. Hence, the average surface brightness in B is

$$\mu_B = 23.5 \text{ mag per square arcsec},$$

which is ~ 1.5 mag fainter than the night sky air glow in B.

Using the apparent distance moduli in the last section, the absolute magnitudes are

$$M_{B_T} = -13.8 \quad \text{and} \quad M_{V_T} = -14.3.$$

Hence, at the Virgo cluster with a distance modulus of $(m - M)_0 = 31.7$ (Sandage and Tammann 1976, 1982), a galaxy like Sextans A will have $B \approx 17.9$, $V \approx 17.4$, and an angular diameter of $\sim 15''$. The image will have a lumpy appearance due to the associations, shown best in Figure 1. Such galaxies should be visible on large-scale plates like those now available from the du Pont 2.5 m reflector's Las Campanas Survey of the Virgo cluster. The plate scale of $10''.9$ mm^{-1} gives images of ~ 1.5 mm diameter for such galaxies. The surface brightness, although ~ 1.5 mag fainter than the night sky, still is bright enough to give sufficient contrast with the airglow to be discovered in a careful search. A catalog of such objects is underway as part of the preparation for study with Space Telescope where measurement of the brightest resolved stars can be expected to give the distance to the Virgo cluster directly.

It is a pleasure to thank the night assistants and the mountain crew at Las Campanas (Chile), at Mount Wilson, and at Palomar Mountain for help at the telescopes during the long interval over which the plates and the photometry were accumulated. We also wish to thank Nancy Newton for the diagrams, Maria Anderson for preparing the manuscript, and John Bedke for making the reproductions in the Observatories' photo lab.

We are grateful to the Citrus College Computer Center for generously making available their facilities, used for the period determination.

Finally, it is also a pleasure to acknowledge the National Aeronautics and Space Administration for partial support through grant NAGW-118 concerned with astronomical ground-based preparations before the launch of Space Telescope.

REFERENCES

Arp, H. C. 1960, *A.J.*, **65**, 404.
Baade, W. 1971, in Sandage, A. *Ap. J.*, **166**, 13.
Baade, W., and Swope, H. H. 1963, *A.J.*, **68**, 435.
______. 1965, *A.J.*, **70**, 212.
de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G. 1976, *The Second Reference Catalog of Bright Galaxies* (Austin: University of Texas Press).
Graham, J. 1982, in preparation.
Holmberg, E. 1950, *Medd. Lund Obs.*, Ser. II, **No. 128**.
______. 1957, *Medd. Lund. Obs.*, Ser. II, **No. 136**.
Hubble, E. 1925, *Ap. J.*, **62**, 409.
______. 1926, *Ap. J.*, **63**, 236.
______. 1929, *Ap. J.*, **69**, 103.
______. 1936, *Ap. J.*, **84**, 158.
Humphreys, R. M. 1978, *Ap. J. Suppl.*, **38**, 309.
______. 1979, *Ap. J.*, **231**, 384.
______. 1980, *Ap. J.*, **238**, 65.
Humphreys, R. M., and Sandage, A. 1980, *Ap. J. Suppl.*, **44**, 319.
Jurkevich, I. 1971, *Ap. Space Sci.*, **13**, 154.
Kayser, S. E. 1967, *A.J.*, **72**, 134.
Kraan-Korteweg, R. C., and Tammann, G. A. 1979, *Astr. Nach.*, **300**, 181.
Lafler, J., and Kinman, T. D. 1965, *Ap. J. Suppl.*, **11**, 216.
Marraco, H. C., and Muzzio, J. C. 1980, *Pub. A.S.P.*, **92**, 700.
Martin, W. L., Warren, P. R., and Feast, M. W. 1979, *M.N.R.A.S.*, **188**, 139.
Sandage, A. 1958, *Ap. J.*, **127**, 513.
______. 1971, *Ap. J.*, **166**, 13.
Sandage, A., and Katem, B. 1976, *A.J.*, **81**, 743.
______. 1982, *A.J.*, "*Selected Area 45*," in preparation.
Sandage, A., and Tammann, G. A. 1968, *Ap. J.*, **151**, 531.
______. 1969, *Ap. J.*, **157**, 683.
______. 1971, *Ap. J.*, **167**, 293.
______. 1974*a*, *Ap. J.*, **190**, 525.
______. 1974*b*, *Ap. J.*, **191**, 603.
______. 1976, *Ap. J.*, **210**, 7.
______. 1981, *A Revised Shapley-Ames Catalog* (Carnegie Institution Publication 635) (RSA).
______. 1982, *Ap. J.*, submitted.
Tammann, G. A., and Sandage, A. 1968, *Ap. J.*, **151**, 825.

GEORGE CARLSON: Department of Physical Sciences, Citrus College, 18824 East Foothill Boulevard, Azusa, CA 91702

ALLAN SANDAGE: Mount Wilson and Las Campanas Observatories, 813 Santa Barbara Street, Pasadena, CA 91101-1292

© American Astronomical Society • Provided by the NASA Astrophysics Data System