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STEPS TOWARD THE HUBBLE CONSTANT. III. THE DISTANCE AND STELLAR CONTENT OF THE M101 GROUP OF GALAXIES

ALLAN SANDAGE AND G. A. TAMMANN
Hale Observatories, Carnegie Institution of Washington, California Institute of Technology
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ABSTRACT

The distance to M101 and its five late-type companions (NGC 5204, 5474, 5477, 5585, and Ho IV) is obtained by six methods from new data on the stellar content, after the reality of the group is tested using criteria of adjacency, resolvability, redshifts, and dynamical stability.

The brightest stars in M101 are isolated and measured relative to a new photometric sequence that covers the range $12.6 < B < 21.7$. Analysis of the color-magnitude diagram shows the brightest resolved blue star in M101 to have $B = 18.97$. Correction of older data suggests $B(3) = 20.6$ for NGC 5474, and $B(3) = 20.9$ in NGC 5585. Despite a serious study, no red supergiant variables with $B - V > 2.0$ were found in M101 brighter than a limit of $V = 21$. Further, after a thorough search, no Cepheids were found brighter than a limit of $B = 22.5$. Eight irregular blue variables were isolated from the total plate material that extends from 1909 to the present.

From these data, and from the largest H II regions in the six group members, the distance is calculated to be $D = 7.2 \pm 1$ Mpc, or $(m - M)_0 = 29.3 \pm 0.3$ which is more than 10 times that adopted by Hubble in 1936. This result forms the basis for extending the calibrations of H II regions and of stars in Papers I and II of this series to the Sc I galaxies so that the distance scale can be carried outward into the general field (Papers IV and VI).

The velocity-distance ratio for the M101 group alone, obtained from the adopted distance and from $\langle v_0 \rangle = 402 \pm 4.2$ km s^{-1} (and allowing 30 km s^{-1} mean random motion for the group [Paper V] in the error calculation), is

$$v/r = 55.5 \pm 8.7 \text{ km s}^{-1} \text{ Mpc},$$

which agrees well with the global value of the Hubble constant itself (Paper VI), showing the lack of measurable perturbation of the Hubble expansion flow at M101 (cf. Paper V).

Subject headings: Cepheids and W Virginis stars — galaxies, clusters of — galaxies, individual — luminous stars

I. INTRODUCTION

M101 (NGC 5457: $\alpha_{1950} = 14^{\rm h}01^{\rm m}.4$, $\delta_{1950} = 54°35'$) is a large, regular, late type (Sc I) supergiant galaxy in the Ursa Major Cloud with well developed and highly resolved spiral arms. Partial resolution into stars and H II regions occurred on early Crossley reflector plates at Lick, and on Mount Wilson plates taken with the 1.5-m and 2.5-m reflectors; and, as expected, the galaxy and its five companions yielded to substantial resolution with the Hale 5-m reflector.

A major effort on the stellar content was begun with that telescope in 1950 as part of the extended program of revising Hubble's 1936 distance scale. Segments of the completed results include studies of galaxies in the Local Group (M31 by Baade and Swope 1963; NGC 6822 by Kayser 1967; IC 1613 by Baade reported by Sandage 1971), galaxies in the M81–NGC 2403 group (NGC 2403 by Tammann and Sandage 1968), new data on the brightest resolved stars in nearby galaxies (Sandage and Tammann 1974*b*, Paper II), and the calibration of the *P–L*–third-parameter relation for Cepheid variables (cf. Kraft 1961*a*, *b*; Fernie 1966, 1967; Sandage and Tammann 1968, 1969, 1971). While most of the work beyond the Local Group was concentrated on galaxies in the M81–NGC 2403 group, enough plates were obtained of M101 to permit a new discussion of its distance. The problem is central for the present series on the Hubble constant because M101, as the nearest unobscured supergiant Sc I, provides the prime calibration of stars and H II regions for this luminosity class.

We have obtained the distance by six methods: three give lower limits, and three give direct determinations. The membership of the M101 group is discussed in § II; new data on the brightest resolved stars, variables, novae, supernovae, and H II regions are given in § III; the distance from this material is obtained in § IV; and a comparison with older determinations and a discussion of the significance of the results appears in § V.

II. GROUP MEMBERSHIP

In an early study, Holmberg (1950) isolated several systems near M101 which, on the basis of adjacency, redshift, and resolvability, he considered to be at the same distance. The group consisted of M101 itself, M51 and its companion (NGC 5194/5), three resolved dwarfs (NGC 5204, NGC 5474, and NGC 5585), and four additional possible members (Ho IV ≡ DDO 185 [van den Bergh 1959]; NGC 5301, NGC 5678, and NGC 5866) whose redshifts were unknown in 1950.

Ten years later, van den Bergh (1960*a*) included Holmberg's M101 group into his much larger Canes Venatici cluster that contained 22 spiral and irregular galaxies, and 12 dwarfs; but he showed that the cluster was dynamically unstable unless 20 times more mass was present than in the supposed members. The proposal was not accepted by Sérsic (1960), de Vaucouleurs (1965), or Karatchentsev (1970), and these authors returned to the original definition of the group (Holmberg 1950).

In a reanalysis, Holmberg (1964) concluded that NGC 5194/5 is considerably more distant than M101; that part of the original group including NGC 5204, NGC 5474, and NGC 5585 is at an intermediate distance; and that M101 is an isolated single *foreground* galaxy.

In the present work it was of great importance to know if any systems near the giant galaxy are true companions because distance determinations from the stellar contents are facilitated if a common distance exists for several galaxies. We, therefore, inquire again into the existence of the group using new redshifts and direct plates taken with the Hale 5-meter reflector. Our conclusion is that Holmberg's original group, slightly modified, does exist as a dynamical unit at a common distance. Again the arguments rest on adjacency, redshifts, and resolvability, with additional points based on dynamical stability, tidal distortion, and radio H I contour maps.

a) *Survey of the Region*

Following Holmberg's original work, we have resurveyed the region in a literature study, and by the inspection of direct plates in the Mount Wilson files. All galaxies in the Shapley-Ames (1932) catalog in the region of the UMa–CVn cloud that lie between galactic latitude and longitude limits of $b^{\mathrm{II}} > 45°$, $80° < l^{\mathrm{II}} < 210°$, were reconsidered. Additional fainter galaxies in this region listed in the *Reference Catalogue* (de Vaucouleurs and de Vaucouleurs 1964, hereafter called RCBG), and in the David Dunlap catalog of dwarf systems (van den Bergh 1959) were also considered. The plot of nearly 400 galaxies in the stated region clearly shows (cf. fig. 6 of RCBG) that most of the galaxies are associated with the supergalactic plane, with the exception of a concentration centered on M101 at $L_{\mathrm{SG}} = 64°$, $B_{\mathrm{SG}} = +23°$, well separated from the plane. A number of galaxies in this latter grouping are within 6° radius of M101, and, hence, are candidates for M101 group membership on the basis of adjacency.

b) *The Redshifts and Resolution into Stars and* H II *Regions*

The galaxies in the survey region were inspected for redshift and resolvability on direct plates. Of the 392 listed galaxies, 199 have redshifts either in the literature or from unpublished data in the current redshift program (Sandage 1974); 131 of these have velocities (corrected for galactic rotation) greater than $v_0 = 1000$ km s^{-1} and cannot possibly be connected with M101. The remaining 68 galaxies are listed in table 1 with literature references to all sources of redshifts known to us at the time of writing.

A circle of radius 6°.1 centered on M101 contains six galaxies with known redshifts (M101, NGC 5204, 5474, 5477, 5585, and Ho IV), four Shapley-Ames galaxies whose redshifts have not yet been measured (NGC 5376, 5422, 5430, and 5660), and 10 fainter galaxies from the RCBG (NGC 5368, 5379, 5389, 5443, 5475, 5484, 5673, 5707, IC 1029, and Ho V [A 1339]). The velocities of the first group, listed in column (8) of table 2 described later, are small and are closely the same as M101 itself with a mean of $\langle v_0 \rangle = 391$ km s^{-1}.

The case for group membership is further strengthened by the circumstance that *only these six galaxies* are well resolved on direct plates from both the Hale 5-m reflector and the Palomar Schmidt *Sky Survey*. The remaining four Shapley-Ames galaxies within 6°.1 radius are background objects. They are not well resolved on plates taken with the Mount Wilson 1.5- and 2.5-m reflectors, and their types clearly indicate remote, high-luminosity systems (NGC 5376, Sa; NGC 5422, S0; NGC 5430, SBb; and NGC 5660, Sc II).

To complete the survey, we inspected direct Schmidt plates to test a number of galaxies in the neighborhood of M101 for resolution, with the result that the next best resolved galaxy, besides the six listed in table 2, is NGC 5486. A spectrogram, taken to test for group membership, gave $v_0 = 1469 \pm 21$ km s^{-1} (corrected for galactic rotation), disproving any connection of NGC 5486 with M101, and by implication disproving membership for the other *less-resolved* neighboring galaxies listed in table 1.

Lying 10° from M101 are three faint Shapley-Ames galaxies (NGC 5866, S0; NGC 5879, Sc II; and NGC 5907, Sc on edge) that are close together in the sky and have similar velocities ($\langle v_0 \rangle = 933 \pm 67$ km s^{-1}). The three may form a group, but there is no question that they are more distant than M101; NGC 5879 is of high luminosity (Sc II) and has a much fainter apparent magnitude ($m_{\mathrm{H}} = 12.1$) than M101.

We next consider the very low-velocity galaxies in table 1 ($v_0 \leq 475$ km s^{-1}) other than the six tentative group members. Nine such galaxies exist, of which seven (NGC 4136, 4150, 4214, 4244, 4395, 4449, and 4736) are more than 20° from M101. We have put them in a separate group (CVn I Cloud, see the forthcoming Paper V) which is at about the same distance [$(m - M) = 29.3$] but is dynamically unrelated.

Of the remaining two, NGC 4236 is 20° from M101 and is a member of the much nearer M81–NGC 2403 group, based on the H II region sizes and the brightest stars (cf. Paper II). Support of this assignment also comes from the luminosity class as Ir IV (van den Bergh 1960*b*) whose mean absolute magnitude is $\langle M_{\mathrm{pg}}{}^0 \rangle = -17.81$ (Sandage and Tammann 1974, Paper IV) which, with $m_{\mathrm{pg}} \equiv m_{\mathrm{pg}}{}^0 = 10.05$ (Holmberg 1958) gives $(m - M)_0 = 27.86 \pm \sim 0.3$ for NGC 4236, which is nearly the same as for NGC 2403 itself (Tammann and Sandage 1968).

The distance of the remaining low-velocity galaxy NGC 4605 is less clear. Judged by the partial resolution into stars and by its low velocity of $v_0 = 279$ km s^{-1}, this peculiar, nearby edge-on Sc galaxy is a

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TABLE 1

REDSHIFTS FOR 68 GALAXIES IN THE UMa – CVn REGION ($80^{\circ} < \ell^{II} < 210^{\circ}$, $\beta^{II} > 45^{\circ}$) WITH $v_0 < 1000$ KM S^{-1}

Object	v km s^{-1}	ε(v) km s^{-1}	Source	Δv km s^{-1}	v_0 km s^{-1}	Object	v km s^{-1}	ε(v) km s^{-1}	Source	Δv km s^{-1}	v_0 km s^{-1}
NGC 3184	583	13	13, 14, 15	+ 5	588	NGC 4244	242	10	23	+ 29	271
3198	676	10	3, 14, 19	+26	702	4245	890	65	13	– 9	881
3319	754	21	11, 14, 19	+11	765	4251	1014	75	13	– 15	999
3432	646	9	23	–11	635	4258	470	8	23	+ 72	542
3486	724	100	2, 13	–47	677	4274	719	16	13, 15	– 8	711
3510	719	66	14	–46	673	4278	632	38	13, 17	– 9	623
3556	713	7	5, 11, 13, 14, 18, 21	+88	801	4310	901	100	6	– 8	893
3675	696	37	13, 16	+34	730	4314	883	85	13	– 5	878
3726	882	80	13, 19	+53	935	4395	294	50	13	+ 14	308
3769	737	50	17	+59	796	4414	715	100	13	+ 3	718
3769A	707	50	17	+59	766	4448	693	65	13	– 7	686
3877	828	11	22	+60	888	4449	201	4	23	+ 62	263
3913	831	50	24	+97	928	4485	786	50	17	+ 53	839
3938	792	41	10, 14, 19	+47	839	4490	565	3	23	+ 52	617
3941	957	41	13, 14	+13	970	4559	794	13	3, 11, 14	– 6	788
3949	681	160	13	+64	745	4605	140	70	14	+139	279
3990	720	45	14	+100	820	4618	554	21	14, 26	+ 56	610
4026	878	75	13	+80	958	4631	606	5	23	+ 18	624
4051	672	13	23	+53	725	4656/7	634	10	23	+ 18	652
4062	748	100	6	– 5	743	4736	246	12	23	+ 61	307
4088	733	62	14, 16	+81	814	4800	746	50	13	+ 85	831
4096	493	30	2, 4	+67	560	5033	901	14	10, 13, 14, 16	+ 54	955
4102	897	40	13, 14	+91	988	5055	513	9	23	+ 78	591
4111	794	14	13, 14, 25	+48	842	5194	464	5	23	+106	568
4136	445	50	13	–12	433	5195	554	15	23	+106	660
4143	784	100	13	+47	831	5204	208	13	3, 11, (14), 19	+146	354
4144	535	15	11	+64	599	5457	249	5	7, 9, 12, 14, 16, 20, 21, 27	+148	397
4150	244	50	13	– 9	235	5474	270	10	11, 29, 14, 22	+146	416
4151	966	5	4, 8, 13, 14, 15, 25	+33	999	5477	293	3	1, 9a, 22	+149	442
4157	782	20	4	+83	865	5585	303	12	3, 11, 14, 18	+163	466
4214	289	5	23	+ 21	310	5866	788	28	13, 14, 25	+183	971
4236	5	20	(14), 18, 21, 28	+161	166	5907	615	27	11, 13, 14, 18	+188	803
4242	661	112	16	+ 64	725	IC 750	683	30	22	+ 43	726
						Ho IV	130	26	9a, 14, 22	+ 142	272

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TABLE 2

OBSERVED PARAMETERS OF M101 GROUP MEMBERS

NGC Object (1)	Other Name (2)	Type (3)	L_C (4)	m_{pg} (5)	$a(0)$ (6)	i (7)	v_0 (km s^{-1}) (8)
5457.........	M101	Sc (Scd)	I	8.20	28′	72°	397
5204.........	...	Sc/Ir (Sm)	IV	11.62	7.2	35	354
5474.........	...	Scd pec	[IV]	11.22	7.2	80	416
5477.........	DDO 186	Sd:	IV–V	14.5	2.4	45	442
5585.........	...	Sd	IV	11.25	8.2	40	466
Ho IV.......	DDO 185 = A1353	IBm	IV–V	12.95	6	(20)	272

possible member of the M101 group. It lies 13° from M101 which, with $D = 7.2$ Mpc derived later for M101, is a projected distance of only 1.6 Mpc—only about three times the size of the Local Group. Pending more data, we consider NGC 4605 to be a possible member of the M101 group, but exclude it in the following discussion because our results depend only on the certainty of group membership, not the completeness.

We also reject from group membership M51 (NGC 5194/95), which is the most conspicuous galaxy just outside the 6°.1 circle. Originally included by Holmberg, we believe it to be a background galaxy; its velocity, averaged with its probable associate NGC 5055 is $\langle v_0 \rangle = 606 \pm 48$ km s^{-1} compared with $\langle v_0 \rangle = 391$ km s^{-1} for the M101 group. Inclusion would lead to an unbound group unless much invisible matter is postulated (cf. the Appendix). But, more directly, inspection of Hale 5-m reflector plates shows that M51 is considerably less resolved than is M101 and its companions, clearly indicating a larger distance. We note in passing that if we had included M51 into the M101 group, the finally derived distance to M101 would have been even larger than $(m - M)_0 = 29.3 \pm 0.3$ (§ IV), which is already by far the largest distance yet proposed for the system.

Finally, a deep IIIa-J Schmidt plate (6°.5 × 6°.5) centered on M101 was searched for dwarf companions such as those listed in the DDO catalog (van den Bergh 1959). Besides DDO 191, which is a possible member from a consideration of the luminosity distance ($m - M \simeq 29.1 \pm 1$ using $M_{pg}^0 \simeq -14.5 \pm 1$ for luminosity class Ir V [cf. Paper IV] with $m_{pg} \simeq 15.4$ from Zwicky and Herzog [1968]), we isolated six dE galaxies and 10 S/Ir systems, but do not consider them further here because of lack of additional data.

c) *Additional Data for Group Membership*

Several further points support group membership for M101, NGC 5204, 5474, 5477, 5585, and Ho IV.

1. H I *distribution.* Beale and Davies (1969) have shown that the H I contours of M101 encompass NGC 5477; the result is confirmed by Roberts (1972). Although Rogstad's (1971) contours determined by interferometry do not extend to NGC 5477, smooth large-scale structure is resolved out by Fourier methods; the pencil-beam results of Beale, Davies, and Roberts seem conclusive. Similarity of the redshifts of M101 and NGC 5477 suggest that the confluence of the radio halos is real.

2. Tidal distortion. The asymmetrical appearance of NGC 5474 was interpreted as tidal distortion by van den Bergh (1960*b*). The displaced nucleus from the symmetry center of the disk is typical of a galaxy in a tidal field (Toomre 1969), and it is clear that such a field can be exerted only by the nearest large neighbor, which is M101.

The neutral hydrogen distribution in M101 is itself asymmetrical, as first noted by Dieter (1962) and later confirmed by Beale and Davies (1969), and by Guélin and Weliachew (1970). The possibility that this might be artificial, caused by beam smearing of a hydrogen companion (Roberts 1972) seems excluded by interferometry (Rogstad 1971; Allen, Goss, and van Woerden 1973). Tidal distortion by a companion, or companions (NGC 5474, 5477) seems possible.

3. Dynamical stability. A calculation showing that the total energy of the six proposed group members is negative is given in the Appendix. Hence, if the candidates are assumed to be at the same distance, the aggregate is bound. This is perhaps the strongest argument for the reality of the group and, conversely, that NGC 5194/5 plus NGC 5055 are not members.

d) *The Group Defined*

Table 2 lists observed properties of the adopted group members. The galaxy types in column (3) are from the Hubble Atlas (Sandage 1961), or from the RCBG. The luminosity classes in column (4) are from van den Bergh (1960*b*, 1966), or by us (for NGC 5474). The apparent magnitudes in column (5) are from Holmberg (1958), except for NGC 5477 which is from Zwicky and Herzog (1968), a value to be checked because *Schraffierkassette* magnitudes for low-surface-brightness dwarfs may be unreliable. The galactic absorption at this latitude is taken to be zero (cf. Sandage 1973); hence these magnitudes are identical with m_{pg}^0. The correction to face-on orientation, following Holmberg (1958), is $A_i = 0.28(\csc i - 1)$ which, for M101 is 0.01 mag, giving $m_{pg}^{0,i} = 8.19$. Following the convention of Papers I and II, we apply no orientation correction for luminosity class IV or later. The diameter of the major axis in column (6) is from data of Holmberg (1958), corrected to face-on by $\log a(0) = \log a - 0.15 \log a/b$ following Heidmann, Heidmann, and de Vaucouleurs (1971*a*). The face-on diameter of NGC 5477 is from the RCBG, reduced to Holmberg's system by adding 0.19 to $\log a(0)$ (Heidmann *et al.* 1971*a*). We are aware of the problem of diameter corrections (Tully 1972), but here they affect only the distance estimate from diameters as given later.

The inclination in column (7) is a compromise from three sources: (*a*) RCBG, (*b*) Roberts (1969), and (*c*) Holmberg (1958), as reduced by Heidmann *et al.* (1971*a*). For M101, Volders (1959) determined an optical value of $i = 63°$, contrary to Holmberg's (1958) $i = 90°$. RCBG lists $72° \pm 7°$, while Heidmann *et al.* (1971*a*) give an uncertain $i = 79°$ and Rogstad and Shostak (1972) $i = 68°$. We adopt here $i = 72°$, with an error of at least $\pm 10°$. Note, then, that the mass of M101 obtained from the observed rotation curve is almost indeterminate (cf. Appendix).

The inclination of NGC 5477 is clearly a guess made by application of Hubble's (1926) equation $\cos^2 i = (1 - q^2)/(1 - q_0^2)$ where $q = a/b$ and $q_0 = 0.12$ (for Sd) (Heidmann *et al.* 1971*a*). Similarly, i for Ho IV follows from Holmberg's (1958) observed value of q, adopting $q_0 = 0.24$ for Im galaxies. Note that i here is 90° for *face-on* systems following Holmberg, contrary to the convention of the RCBG, Roberts (1969), and Heidmann *et al.* (1971*a*).

TABLE 3

COMPARISON OF OPTICAL AND 21-CENTIMETER RADIAL VELOCITIES FOR M101 GROUP MEMBERS

Galaxy	v (optical) (km s^{-1})	Source*	v (21 cm) (km s^{-1})	Source*	v (adopted) (km s^{-1})
M101..........	229 ± 27	14, 16	249 ± 5	7, 9, 12, 20, 21, 27	249
NGC 5204.....	(272)	14	207 ± 13	3, 11, 19	208
NGC 5474.....	234 ± 4	14, 22	275 ± 4	11, 29	270
NGC 5477.....	292 ± 3	22	300 ± 8	1, 9a	293
NGC 5585.....	304 ± 70	14	303 ± 12	3, 11, 18	303
Ho IV.........	111 ± 26	14, 22	141 ± 20	9a	130

* The source numbers are the same as in table 1.

Finally, in column (8) of table 2 we list the adopted velocity, corrected for galactic rotation of 300 sin $l^{\text{II}} \cos b^{\text{II}}$ taken from table 1, where all the redshift sources have been averaged.

To assess the reliability of the observed velocities, we list the optical and 21-cm radio data in table 3; the velocities are heliocentric, i.e., not corrected for galactic rotation. The agreement of the optical and radio radial velocities is generally satisfactory. The optical value for NGC 5204 may contain a rotational component (Mayall in Humason, Mayall, and Sandage 1956). The same may apply to NGC 5474 because the optical value of 234 km s^{-1} lies considerably below the mean 21-cm velocity but still within the wing of the 21-cm profile as determined by Hutchmeier (1974). We have given higher weight to the 21-cm determination.

The conclusion is that the group is well defined as a single dynamical unit and that its members are nearly at the same distance. The galaxies listed in table 2 are within 6°.1 radius from M101 itself, giving a back-to-front ratio for a spherical aggregate of only $\Delta r/r \leq 0.11$ or $\Delta(m - M) \leqslant 0.2$ mag, which we shall neglect because it is smaller than our final errors in the group distance (§ IV).

The five companions to M101 are illustrated in figure 1 (plate 2) which shows their extreme resolvability into stars and H II regions. All plates, except for Ho IV, were taken with the Hale 5-m reflector; Ho IV is from a Palomar Schmidt plate.

III. THE STELLAR CONTENT OF M101 AND ITS COMPANIONS

The brightest stars, the variables, one normal nova, three supernovae, and the largest H II regions in M101 and its companions have been isolated and measured. These data are discussed in this section.

a) The Photometric Sequence

A photoelectric sequence of 21 stars between $12.6 < B < 21.7$ was set up in an interarm region of M101 with the Mount Wilson 1.5-m and the Hale 5-m reflectors in 1962 and 1963. Because the region is not free from background contamination, the photoelectric measurements fainter than $B \simeq 20$ required mapping of the background gradients near each star. This could be done only approximately; therefore, photographic transfers were made with the Hale reflector to Baum's (unpublished) sequence in SA 57. The method of eye estimates relative to an appropriate step-scale largely eliminated the first-order effects of variable contamination.

The two yellow transfers showed no measurable difference in zero point with the 16 brightest photoelectric stars; only a slight systematic difference was present for the one available B transfer, and we suspect the photographic work here rather than the photoelectric. We are therefore confident that the systematic accuracy of the sequence is considerably better than $\sim \pm 0.2$ mag over the entire range, although, naturally, the errors for any individual star fainter than $B \simeq 20$ can be substantial, depending on the background.

The primary and secondary sequences are listed in table 4 for stars that are identified in figure 2 (plate 3). The adopted values in the last two columns are the result of smoothing the photoelectric values using seven B plates and three V plates taken with the Hale reflector. From the internal consistency of the measurements, the accuracy of these values is $\sim \pm 0.06$ mag (rms) in B (7 plates) and ± 0.09 mag (rms) in V (3 plates). Further comparison shows that the smoothed adopted values and the raw photoelectric values differ by $\sigma = 0.11$ mag ($n = 6$) for V; the zero points agree within ~ 0.03 mag in the mean. The results appear to be satisfactory considering the nature of the difficult photometric problem in this field.

From the internal tests we believe that the adopted magnitudes lie closely on the BV system, and that the systematic errors are smaller than 0.2 mag at $B = 21.5$, $V = 20.5$. Fainter than this, the sequence depends on the (few) available photographic transfers, and the sequence for $B \geq 22$, $V \geqslant 21$ should be considered as preliminary.

The 12 photoelectric stars with known U values permit a partial determination of the reddening in the M101 field ($b^{\text{II}} = 60°$). The ($U - B$, $B - V$)-diagram, after eliminating stars I, J, and R which do not contribute to the problem, and A, B, and F which suffer small UV excesses probably due to decreased blanketing, shows that $E(B - V) = 0.00 \pm 0.02$ mag. The result is consistent with zero reddening (statistically) for $b^{\text{II}} \geqslant 50°$, which we have adopted in previous papers. (We note in passing that star J has the colors of a white dwarf.)

b) *The Brightest Resolved* (*Nonvariable*) *Stars in M101*

It was shown in Paper II that the brightest resolved red and blue stars are good distance indicators in late-type galaxies if they can be isolated from the foreground of our own Galaxy, and separated from groups, associations, open and globular clusters, and compact H II regions of the parent galaxy. The observational problem proved to be extraordinarily difficult in M101 because of the large number of potentially confusing H II regions in the spiral arms. Further, crowding in parts of the spiral arms makes the isolation of true stars more difficult.

The first attempts showed that, as in NGC 2403, casual inspection of the face of the galaxy for the brightest stars would be unsuccessful. Contamination by foreground stars at the required level ($B \gtrsim 18.5$) is severe, and many of the objects are diffuse. The only method that proved feasible was to mark every candidate, measure its magnitude and color, and study the resulting color-magnitude diagram relative to similar diagrams for suitable comparison fields. As in Paper II, foreground contamination could be eliminated by considering only those stars in the sample bluer than $B - V \simeq 0.4$.

An area of 0.079 square degrees (radius 9′.5) centered on M101 was studied. For counting, the region was divided into two parts, an inner circle of radius 5′, and a concentric outer annulus. The main disk of M101 is contained in the inner circle; the annulus is dominated by parts of the outer two principal spiral arms (cf. fig. 2).

The brightest 559 objects with near stellar appearance between $17.5 \leq B \lesssim 21.8$ were marked. Completeness was attempted to $B = 20.8$, but certainly not achieved in the regions of high background and severe crowding.

Photometry by step-scale methods was done on five B and three V Hale 5-m reflector plates. During the process, all objects were eliminated whose stellar appearance became doubtful on two or more plates, leaving 199 candidate stars in the circle and 227 in the annulus. But because all clumps, small associations, and compact H II regions could not be removed completely, the derived luminosity of the remaining brightest objects is clearly an *upper* limit for the real stars.

The C-M diagram for the 426 candidates brighter than $B = 20.75$ and $V = 20.5$ is shown in figure 3 (*middle*), where no distinction is made between stars in the inner circle and in the annulus as there is no systematic difference in the separate diagrams. The line imposed by the limit of the photometry at $V = 20.5$ is shown.

To assess the contamination, two comparison fields, again each of area 0.079 square degrees, were selected sufficiently far from M101 to be free from its stars. After exclusion of nonstellar objects, all stars were measured on two blue and two yellow Palomar Schmidt plates, with the results shown in figure 3. The photometry could not be carried beyond $V = 19.25$, and this limit is shown.

Interpretation of the results is not straightforward. The simplest statement is that an appreciable number of M101 stars begin fainter than $B = 19.0$, showing straightaway that the galaxy is considerably more distant than NGC 2403. (Not only is $B = 19.0$ fainter than the corresponding value of $B = 18.2$ in NGC 2403 [Tammann and Sandage 1968, fig. 15], but the absolute magnitude of the brightest stars in M101 is expected to be brighter than in NGC 2403 by the arguments of Paper II.)

Inspection of the color distribution in figure 3 shows four stars at $B \simeq 19.0$ in M101 that are bluer than $B - V = -0.2$; there are no similar stars in the comparison fields. However, an interpretation as an upper limit at $B = 19.0$ would be dangerous because our colors are not accurate enough to make such a detailed selection. We must rely more heavily on statistics with the present data.

Histograms of the distributions in M101 and the comparison fields are shown in figure 4 (*lower*), where again it is clear that the M101 distribution begins near $B \simeq 19.0$. Unfortunately, the comparison-field data end at $B = 19.75$—near the crucial value. To extend them we have called on Becker's (1967, 1970) faint *BV* photometry in SA 51 ($b^{\mathrm{II}} = 21°$) and SA 57 ($b^{\mathrm{II}} = 85°$), and have reduced the number of stars per 0.25 mag interval per 0.079 square degrees to $b^{\mathrm{II}} = 60°$, following the high-latitude galactic model of Vashakidse (1937) and of Bok and MacRae (1941), using

$$A_{b_2}(m_{b_2}) = \sin^3 b_1 \sin^{-3} b_2 A_{b_1}(m_{b_1}) ,$$

where A is the number of stars at m per magnitude interval per unit area, and b is the galactic latitude, and where the magnitudes are related by

$$m_{b_2} = m_{b_1} + 5 \log (\sin b_1 \sin^{-1} b_2) - \Delta\alpha_1 + \Delta\alpha_2 ,$$

where $\Delta\alpha$ is the galactic absorption.

The separate reductions of the two Selected Areas to $b^{\mathrm{II}} = 60°$ for M101 do not agree well (differ by a factor of ~ 3), but their mean values shown in figure 4 (*lower*) fit well with the comparison areas, and we adopt this extension to $B = 21.2$.

A different representation of the statistics is shown in figure 4 (*upper*), which gives running means of the histograms. The impression is repeated that the excess of M101 stars begins at $B \simeq 18.75$. But as the number of excess stars is very small until $B \simeq 19.5$, we have looked in detail at the 25 individual stars in the M101 area between $B = 18.75$ and 19.50.

Surprisingly, it was possible to decide with little doubt that 16 of these stars are in the foreground because of their isolated position. Of the remaining nine stars, the four brightest have $B = 18.97$, $B - V = -0.19$; $B = 18.98$, $B - V = 0.66$; $B = 19.00$, $B - V = -0.34$; and $B = 19.06$, $B - V = 0.10$. Hence, after restriction to $B - V < 0.4$ by the precepts of Paper II, we adopt $B = 18.97$ for the brightest, and $\langle B \rangle = 19.0$ for the three brightest in M101. We

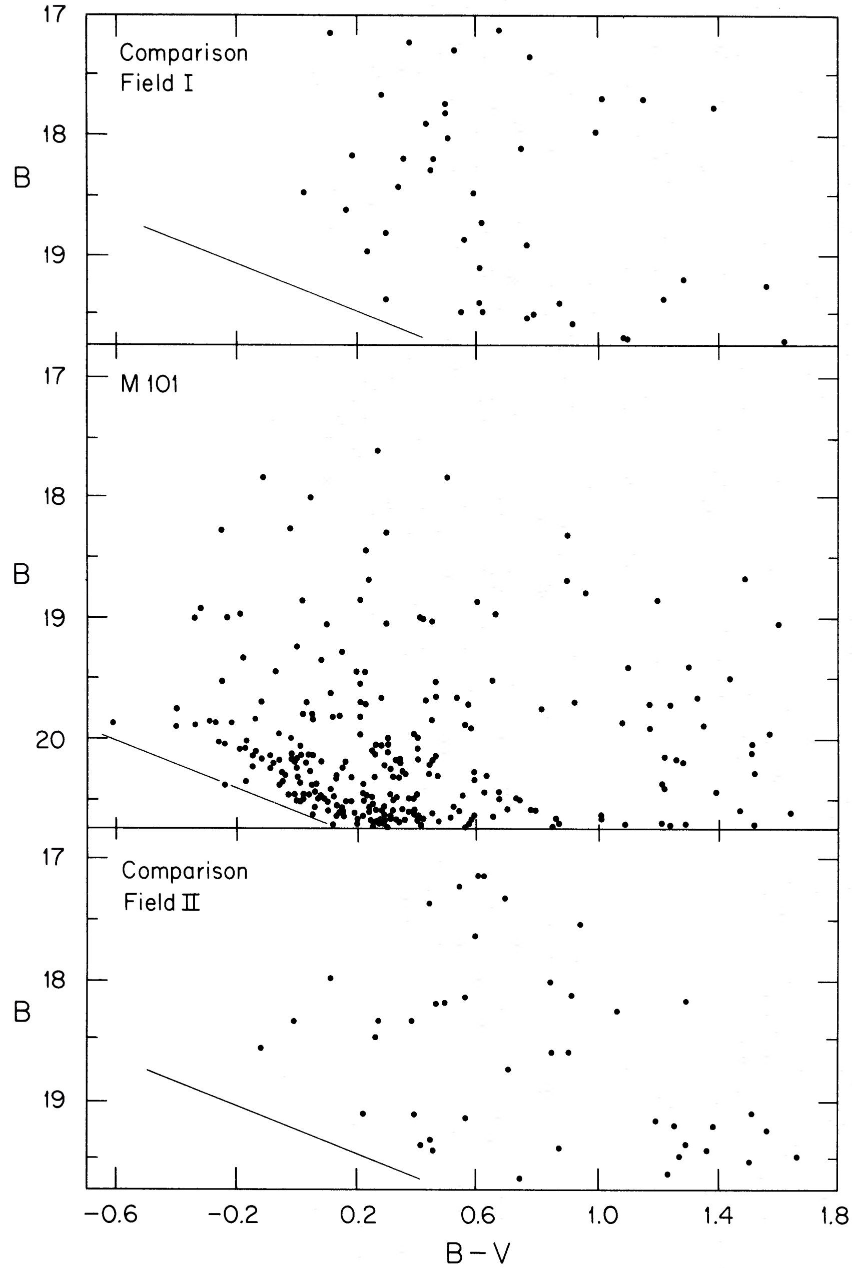

FIG. 3.—Color-magnitude diagram for the brightest stars in an area of 0.079 square degrees centered on M101 (middle) compared with the distribution in two control fields that have the same area near, but uncontaminated by, M101 itself.

believe that Baade's value of $m_{pg} = 17.9$ (quoted by Holmberg 1950), and Hubble's (1936*a*) value of $m_{pg} = 17.5$ may represent confusions with brighter diffuse regions, which are numerous, but red.

c) *Brightest Stars in NGC 5474 and NGC 5585*

In lieu of new data, Hubble's (1936*a*) values of $m_{pg} = 19.5$ and $m_{pg} = 19.8$ for the mean of the three brightest stars in NGC 5474 and NGC 5585, respectively, have been corrected for the well-known scale errors that affect all pre–1950 photometry fainter than $m_{pg} \simeq 16$. Fortunately, the correction can be made here with fair ease. Variable V1 in M101 was estimated by Hubble to be $m_{pg} = 19.7$ on plate Ri 118 relative to his adopted (unpublished) sequence; we find $B = 20.8$ for this star on the same plate relative to the new

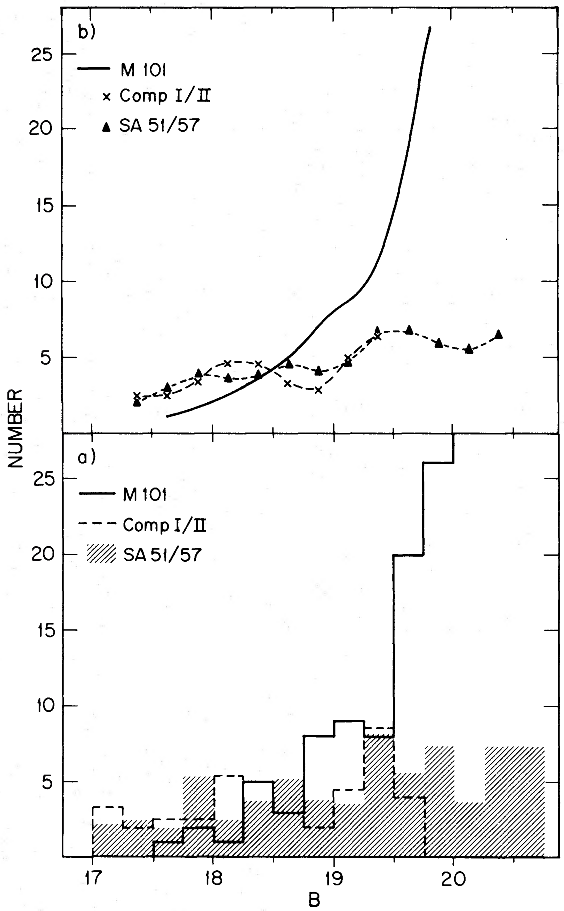

FIG. 4.—(*a*) Histograms of the number of candidate stars in the M101 area, together with the two comparison regions, and the mean of Becker's SA51 and SA57 $A(m)$ distributions reduced to $b^{\mathrm{II}} = 60°$. (*b*) Running means

$$1/2[0.5N(m - 0.25) + N(m) + 0.5N(m + 0.25)]$$

of the three histograms.

photoelectric sequence of table 4. Hence, $m_{\mathrm{pg}}(3) \simeq 20.6$ in NGC 5474 and $m_{\mathrm{pg}}(3) \simeq 20.9$ in NGC 5585 for Hubble's brightest candidate stars on a true Pogson scale. These values seem reasonable on other grounds; the two galaxies are not well resolved into individual stars on Palomar Schmidt plates, hence values brighter than ~ 20.5 mag are impossible.

The result is important regardless of the precise value because there is no doubt from the plates that $m_{\mathrm{pg}}(3)$ is fainter in the two companion galaxies than in M101. Hence, the previous conclusions from other data that the absolute magnitude of resolved blue stars depends on the luminosity of the parent galaxy (Paper II) is strengthened.

d) *Bright Red Supergiants in M101*

The bright, red, variable supergiants, found in all late-type galaxies of the Local Group and the M81–NGC 2403 group, and discussed as a distance indicator in Paper II (Sandage and Tammann 1974*b*, § VII) *cannot* be found in M101 to the limit of our plates. We made a special search by blinking all good *B* plates ($n = 7$) against three good and one poor *V* plates, using the same techniques with which such red stars were easily found in NGC 2403 (Tammann and Sandage 1968, § VIII). After this initial failure, we selected the 106 reddest stellar objects in M101 with *B* fainter than 20 mag and estimated the initial *B* and *V* magnitudes from two *B* and two *V* plates. No stars were found to be redder than $B - V = 1.9$, and hence *none* are candidates for red supergiants. The statement is positive to $V = 21.0$ and $B = 22.9$. Using $\langle M_V \rangle = -7.9 \pm 0.1$ from the calibration of Paper II, we conclude from these data (§ V) that the modulus of M101 must be greater than $(m - M)_{AV} = 28.9$.

e) *The M101 Variable Stars*

As was his custom in M31, M33, NGC 6822, M81, and NGC 2403, Hubble maintained a log and a marked chart of suspected variables in M101. The chart was kept current until 1953 as plates from the Hale 5-m telescope began to accumulate, and it formed the early basis for our present study of the variables. The photographic material now available consists of 15 blue Mount Wilson 1.5-m plates, nine blue Mount Wilson 2.5-m plates, and 27 blue and five yellow Palomar 5-m Hale reflector plates.

Max Wolf (1909*a*) found the first variable in M101, later known as the supernova SS UMa. Ritchey (1917) found two variables (Ri 1 and Ri 2) on Mount Wilson 5-m plates which can be identified from information given by Hubble (1929), named here V1 and V4. At various times Hubble marked 18 additional candidate variables, but the list was reduced in his final summary (circa 1952) to eight (or nine including SS UMa). We have scrutinized Hubble's final list by a restudy of the plate material, and have confirmed six of the eight candidates.

Six pairs of nine *B* plates and one *V* pair were then blinked in a new study to find additional variables. At the faint level of the plates we encountered the same problem as in NGC 2403 (Tammann and Sandage 1968, § V); constant stars on luminous background appear to vary according to plate conditions such as grain clumpiness, background gradients, and quality. The effect is pronounced if the background is severely nebulous. Even bright stars seem to vary in a seemingly persuasive manner. The problem is the main reason why it was extraordinarily difficult to form a definite opinion on the variability of some stars.

In addition to blinking, we investigated many small fields in M101 by memorizing the stellar configurations and then inspecting the available plates, region by region. We believe that this method is more sensitive and more reliable than normal blinking, but is less systematic and is extraordinarily time consuming.

Some suspected variables were also marked during the step-scale photometry on the many plates used for the C-M diagram and during the search for very red stars. In total, we marked about 30 possible or suspected new variables. After careful examination and after

TABLE 4

PHOTOELECTRIC STANDARDS: THE ADOPTED PRIMARY AND SECONDARY SEQUENCES

STAR	PHOTOELECTRIC			n	n	ADOPTED	
	B	V	U	60″	200″	B	V
A.........	12.66	12.01	12.72	2	3	...	...
B.........	14.12	13.50	14.16	2	3	...	...
C.........	14.67	13.99	14.90	4	1	...	...
D.........	16.09	15.50	16.19:	4	...	...	...
E.........	16.20	14.92	...	1	...	...	...
F.........	16.27	15.62	16.36	1	2	...	...
G.........	16.83	16.22	17.08	2	...	...	...
H.........	17.36	16.25	18.37	...	1	...	...
I.........	17.99	16.54	19.27	1	1	...	...
J.........	17.95	17.92	17.20	...	1	...	...
K.........	18.15	16.60	19.42	...	2	...	...
L.........	18.92	17.94	19.67	...	1	...	...
M.........	19.44 ± 0.01	18.30 ± 0.01	...	...	2	19.44	...
N.........	19.49 ± 0.02	18.76 ± 0.02	19.85	...	2	19.59	18.87
O.........	19.83 ± 0.01	19.29 ± 0.06	...	...	1	19.60	19.10
P.........	20.26 ± 0.03	18.80 ± 0.03	...	...	1	20.24	18.83
Q.........	20.65 ± 0.04	20.50 ± 0.13	...	...	1	20.93	20.52
R.........	20.81 ± 0.10	20.49 ± 0.12	...	...	1	20.85	20.48
S.........	21.06 ± 0.04	19.92 ± 0.07	...	...	1	20.80	19.78
T.........	21.15 ± 0.06	...	...	...	1	21.51	21.23
U.........	22.11 ± 0.15	...	...	...	1	21.68	20.00

SECONDARY SEQUENCE

Star	B	V	Star	B	V
1........	19.94	19.31	7........	21.51	20.71
2........	20.39	20.33	8........	21.81	20.21
3........	20.48	20.44	9........	22.15	21.04
4........	20.59	18.93	10........	22.72	21.00
5........	20.96	20.73	11........	22.90	21.07
6........	21.11	20.49			

excluding objects whose variability was suspected on only one plate, or on plates of poor quality, we rejected all but three of the new variables, named here V7, V8, and V9. These, together with the six confirmed original variables of Hubble, Wolf's supernova of 1909, two additional supernovae (SN 1951 discovered by Humason [Bowen 1951], and SN 1970 discovered by Lovas [1970]), and a normal nova (Bowen 1952), complete the known variables in M101. The most straightforward conclusion from the present material is that the discovery of variables in M101 is much more difficult than in NGC 2403 (Tammann and Sandage 1968) and, hence, that M101 is more distant (cf. § V).

Of the nine non-novalike variables, the data show that eight belong to the class of bright, blue irregular variables (Hubble and Sandage 1953; Paper II). The remaining variable, V7, is our only Cepheid candidate, but even the evidence for this classification is poor.

The nine variables are identified in figure 2 as V1–V9.

i) *The Bright Blue Variables*

The data for the eight stars of this class are listed in table 5. The colors are mean values from the few possible determinations, and are of low weight. The epochs of maximum and minimum brightness are listed, but the sparse plate material leaves many gaps over the 60-year observing interval. The absolute magnitudes are based on $(m - M)_{AB} = 29.3$ derived in § V.

We have reluctantly included "variables" V5 and V6. Hubble had noted that V5 "seems to be irregular," or at another time, as a "possible Cepheid"; but this possibility is now excluded using the total material. The evidence is only marginal that V5 and V6, in fact, vary; they are bright only on two early plates in 1910 taken with the Mount Wilson 1.5-m reflector.

Variable V9 lies at the edge of the large H II region NGC 5447, and its image is affected by background; but there is almost no doubt that the star does vary.

The best representatives of the class are V1, V4, and V8. The most luminous was V1 (≡Ri 1) which gradually brightened from 1910 to 1934, reaching $B = 19.2$ from 1934 to ~1938; it had faded to $B = 21.6$ by 1950 and has not been observed to be brighter since. The star is located in the distant northeast spiral arm, and is not within the area of most Hale reflector plates.

ii) *Cepheids*

Hubble marked three stars as possible Cepheids, two of which we could not confirm; the third (V5) was discussed in the last subsection.

There are no other Cepheid candidates to $B_{\max} =$ 22.5 mag. The only star we now consider to be a possible candidate is the new (certain) variable V7. On

TABLE 5

PHOTOMETRY OF BRIGHT BLUE VARIABLES IN M101

Star	B (max)	B (min)	$B - V$	M_B (max)	Remarks
V1......	19.2(1934/38)	21.6(1960)	0.5	−10.1	Ri 1: good case
V2......	19.5(1938)	20.5(1952)	0.25	− 9.8	Very likely
V3......	19.8(1925)	20.8(1950)	0.4	− 9.5	Very likely
V4......	19.4(1927)	21.8(1957)	0.5	− 9.9	Ri 2: good case
V5......	20.0(1910)	21.5(1956)	0.5	− 9.3	Bright on 2 plates
V6......	20.8(1910)	21.7(1950)	0.3	− 8.5	Bright on 2 plates
V8......	20.5(1935/46)	22.0(1960)	0.35	− 8.8	Good case
V9......	19.9(1927/47)	20.7(1950)	0.4:	− 9.4	Heavy background

several 5-m plates it appears to be as bright as $B =$ 22.5 mag, but on other equally good plates it is almost invisible. There are no background problems. A period of 2 months or longer is possible, but the sparse data are not, in fact, sufficient to establish periodicity.

iii) *Novae*

An apparently normal nova appears on only one 5-m Hale reflector plate taken 1952 April 22 by Humason. It is invisible on similar plates taken 1952 March 30 and June 15. The image looks genuine, and we accept it as real. Its magnitude on the discovery plate is $B = 20.70$, which corresponds to $M_B = -8.6$ (using $[m - M]_{AB} = 29.3$). As still brighter novae exist at $M_B \simeq -9.5$ in our Galaxy (Schmidt-Kaler 1957) and in M31 (Arp 1956), the derived absolute magnitude is not anomalous.

iv) *Supernovae*

1. *SN 1909*. This variable (SS UMa) was found by Max Wolf (1909*a*) on a plate taken with the Walz reflector of the Heidelberg Observatory on 1909 February 21. Ritchey had overlooked the star on his excellent Mount Wilson 1.5-m plate taken 1910 March, but Hubble (1929) apparently independently rediscovered it much later. The supernova is far from the center of M101, and perhaps for this reason is not listed in the early master lists of novae in spirals (Ritchey 1917; Shapley 1917; Lundmark 1920). Only since Baade's (1938) study has the variable been generally accepted as a probable supernova.

Its position is marked in figure 7, which is a long-exposure IIIaJ plate from the Palomar 1.2-m Schmidt taken to trace the outermost extent of M101. Although SN 1909 is indeed far from the center, the plate shows that it is clearly associated with the galaxy; it lies near the still considerable background of the outer spiral arms.

Wolf (1909*a*) estimated the magnitude at discovery to be $m_{pg} \simeq 10$, but this value as well as his later estimates (compiled by Müller and Hartwig 1918) were much too bright. Revised magnitudes were estimated by K. Reinmuth (cited by Baade 1938) and by Himpel (1942). Through the kindness of Professor H. Elsässer, it was possible to remeasure the original plates relative to our sequence (table 4) during a visit by one of us (G. A. T.) to Heidelberg. It is a pleasure to thank Professor A. Bohrmann for helping to locate this archive material.

The resulting magnitudes, now on the B system, are listed in table 6, where the mean errors were determined from the scatter in the iris-photometer calibration curves. Also listed are magnitudes from two Mount Wilson plates by Ritchey and from four Crossley plates from Lick, two before Wolf's discovery plate and two after, which were very kindly loaned from Lick by Professor G. H. Herbig. The light curve from these data is plotted in figure 5. Magnitude estimates by Hoffleit (1939) from plates taken with a 3-cm and a

TABLE 6

B-MAGNITUDES OF SUPERNOVA 1909 IN M101

Date	JD (2,400,000+)	Telescope	m_B
1899 June 7.........	14,813.7	Crossley	>19.7
1908 July 28........	18,151.7	Crossley	>19.7
1909 Jan. 26........	18,333.49	Tessar	>14.3
1909 Feb. 21........	18,359.48	Walz	13.56 ± 0.10
1909 Mar. 14.......	18,380.47	Walz	13.47 ± 0.08
1909 Apr. 8	18,405.35	Walz	13.58 ± 0.08
1909 May 9.........	18,436.42	Walz	14.32 ± 0.10
1909 Aug. 7.........	18,526.41	Walz	15.12 ± 0.20
1910 Mar. 8........	18,739.40	Walz	17.7 ± 0.3
1910 Mar. 10/11.....	18,742.3	60-inch	17.78 ± 0.15
1914 Mar. 20.......	20,212.88	Crossley	>19.6
1915 May 14/16.....	20,634.3	60-inch	>20.8
1916 Mar. 28.......	20,951.93	Crossley	>20.2

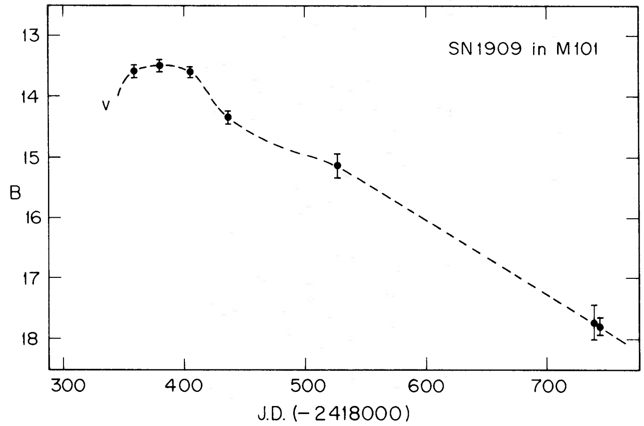

FIG. 5.—Light curve for Wolf's supernova SN 1909 whose position is identified in fig. 7. The star was not detected to a limit of $B = 14.3$ on a very small-scale plate taken at Heidelberg 1909 January 26, 26 days before the discovery plate.

4-cm aperture telescope show considerable scatter, and are not plotted.

Table 6 contains a controversial value. Wolf, after his discovery, inspected earlier plates for information concerning the maximum phase. The supernova was invisible on a plate of 1907 April 5, but Wolf (1909*b*) reported the object to be present, and as bright as on the discovery plate, on a plate taken on 1909 January 26 with a 31-mm focal length Tessar camera. Reinmuth (cited by Baade 1938) and Himpel (1942) apparently confirmed the information. The result led several authors (Baade 1938; Hoffleit 1939; Minkowski 1964) to comment on the unusually flat maximum with a duration of ≥ 70 days. However, we attempted to find the variable on the plate in question, aided by a modern large-scale print of M101, and were unsuccessful. The plate scale is, of course, minute, but there is very little doubt for us that the object is below the plate limit at $m_{pg} \sim 14.3$ on 1909 January 26. If, however, this result is not correct, we are quite certain that it would be impossible to determine a magnitude for the supernova with an accuracy of better than 1 mag. Because of this result, SN 1909 loses some of its strangeness because the maximum lasted now for "only" ~ 46 days.

There are additional implications of this faint limit from the 1909 January 26 plate. Hoffleit (1939) has proposed that the observed maximum of SN 1909 may correspond to the standstill in brightness observed in many supernovae some time after maximum. If we assume that the supernova was of Type II, it may then be compared with SN 1970g, which also appeared in M101. The light curve by Barbon, Ciatti, and Rosino (1973*b*) has a standstill commencing $\sim$25–30 days after maximum when the star had faded by ~ 1 mag. If these values also apply to SN 1909, the maximum brightness of ~ 12.5 mag would have been reached about 1909 January 21–26, but this would now be incompatible with the January 26 Tessar plate. And this interpretation is further unsatisfactory because the similarity of the two light curves would still be very poor.

An alternative would be to compare SN 1909 with Type I light curves, which Barbon, Ciatti, and Rosino (1973*a*) show to be similar from object to object. Type I supernovae reach an inflection point at ~ 35 days postmaximum, after which they decline almost linearly in magnitude. The observed decline of SN 1909 of ~ 0.012 mag per day corresponds well with the fast subtype of Type I proposed by Barbon *et al.* (1973*a*), but the interpretation again is in direct conflict with the lack of the supernova image on the January 26 plate. We are convinced that the plate definitely does not show the supernova at the required maximum of $m_{pg} \sim 10.5$.

The only possibility that we cannot exclude is that the supernova reached maximum after January 26, then came to the inflection point after an unusually fast decline within ≤ 25 days, and was caught just at that moment; but the interpretation is artificial.

Hence, in the absence of additional information, we consider the most natural interpretation to be that SN 1909 was discovered at maximum or even slightly before and that the light curve is unusual because it shows an exceptionally slow decline during the first ~ 100 days. Furthermore, the absolute magnitude at maximum of $M_B(\max) = -15.8$ (with $m - M = 29.3$) is faint. Within a unit volume corresponding approximately to the Local Supercluster, $\langle M_B(\max)\rangle = -17.6 \pm 0.9$ (σ) for Type II supernovae, using $H_0 = 55$ km s^{-1} Mpc^{-1} (Yilmaz and Tammann 1974). If, then, SN 1909 is Type II (albeit its unusual light curve), it would be too faint by $2\,\sigma$. The discrepancy would be worse if it were compared with Type I supernovae, which are intrinsically brighter.

One further point needs clarification. Wolf's (1909*a*) suggestion that the star is visible on an illustration of M101 in a pre–1909 German edition of Newcomb's *Astronomie für Jedermann* cast considerable doubt in the past on the true nature of the star. We have been unable to locate a copy of this edition, but there can be no doubt that the problem is a result of poor reproduction for the following reason. According to Kobold (1909), Schorr identified the original plate from which

TABLE 7

MAGNITUDES OF SUPERNOVA 1951 IN M101 ESTIMATED FROM HALE REFLECTOR PLATES

Date	JD (2,400,000+)	Filter	Plate Quality	m_B
1950 July 16......	33,479.7	...	fair/good	>22.2
1951 Feb. 3.......	33,682.0	...	poor	17.46 ± 0.05
1951 Feb. 7......	33,685.0	...	poor	17.72 ± 0.08
1951 Apr. 27......	33,765.0	...	fair	17.91 ± 0.05
1951 May 4.......	33,802.8	...	fair/poor	18.19 ± 0.06
1951 May 30......	33,828.7	...	fair/poor	18.22 ± 0.08
1951 July 2.......	33,830.7	GG1	very good	18.34 ± 0.02
1951 July 3.......	33,831.7	GG1	good	18.46 ± 0.05
1951 Aug. 4......	33,863.7	GG1	fair	18.39 ± 0.12
1951 Nov. 29.....	33,981.1	WG2	fair/good	19.55 ± 0.06
1952 Jan. 3.......	34,016.1	WG2	fair/good	20.47 ± 0.04
1952 Jan. 30......	34,043.0	WG2	fair/good	20.36 ± 0.06
1952 Mar. 25.....	34,097.9	...	poor	20.98 ± 0.15
1952 Mar. 30.....	34,103.0	WG2	poor	20.89 ± 0.15
1952 Apr. 22......	34,126.0	...	fair/good	21.22 ± 0.09
1952 June 13......	34,177.7	...	poor	21.8 ± 0.2
1952 June 15......	34,179.7	...	poor	>21.8
1953 Feb. 7.......	34,417.0	WG2	very poor	...
1953 Mar. 17.....	34,455.0	WG2	good	>22.2
1951 Aug. 4......	33,863.7	GG11	fair/good	17.19 ± 0.06*
1952 May 14......	34,147.8	GG14	fair/good	21.04 ± 0.20*

* Values for *V*.

the book illustration is taken as the Crossley plate of 1899 June 7, which is one of the Lick plates sent by Herbig that we inspected for table 6. The supernova is definitely not on this plate.

Also, Kobold's (1909) suggestion that the star may be visible on an illustration by Roberts (1894) is not correct; the proposed image is a flaw (Roberts 1911). In view of these results, Hoffleit's (1939) suspicion that the star is at the plate limit ($m_{pg} \sim 13.5$) on material in 1908 and 1937 is questionable. This new evidence is also consistent with the result that from 1890 to 1906 the star is always below the plate limit (Gaposchkin cited by Hoffleit 1939). Furthermore, Beyer (1951) observed the region of M101 on 101 nights between 1929 and 1946 and found no evidence for the star brighter than his limit at ~ 14 mag. Finally, except for 1910/11, the star is invisible on all available Mount Wilson and Palomar plates.

In summary, there is little doubt that the variable was a supernova with a somewhat peculiar light curve and a faint absolute magnitude at maximum.

2. *SN 1951.* Found by Humason on a 5-m Hale reflector plate taken 1951 February 3, this variable was announced as a supernova (Bowen 1951), and has since become a standard illustration in astronomical textbooks. Although the classification as a supernova was later questioned (Bowen 1952) on the basis of faintness, we believe that the evidence now to be discussed shows the star to be a genuine member of the class.

The variable lies near the edge of the giant H II region NGC 5462 at the position marked in figure 7. The object has not yet been detected as a continuum radio source at 21 cm (Allen *et al.* 1973).

The magnitudes, estimated with a step-scale relative to the sequence in table 4, are listed in table 7 and plotted in figure 6. The mean errors of measurement, determined from five independent estimates for each plate, vary as functions of apparent brightness and also, naturally, of plate quality.

The light curve can be represented by two straight lines of slopes 0.005 mag day^{-1} for the first 200 days, and 0.011 mag day^{-1} for the next 300. The slow decline and the bright absolute magnitude (M_B at least as bright as -11.8) excludes straightaway the possibility that the star was a normal nova. Also shown in figure 6 is a segment of the light curve of SN 1970g, again in M101, normalized in time so that the portions with similar decay rates overlap. The data are from Barbon *et al.* (1973*b*), and from Bahcall, Kowal, and Tammann (1974).

If one makes a strict analogy with SN 1970g, then SN 1951 was discovered roughly 120–130 days after maximum, and the outburst would have occurred in October 1950 when the star would have been $B = 11$ to 12 mag. We know of no plate material at this epoch. Martha Hazen Liller kindly inspected the Harvard plate collection. On four plates taken in 1950 mid-December and one plate in 1951 mid-January with a wide-angle patrol camera (scale: 1200″ mm^{-1}), the star is not visible; the plate limit is somewhere near $m_{pg} \simeq 12$, and the data are not in contradiction with the interpretation of a maximum in October 1950.

The Sonneberg plate collection has about 20 plates of M101 for the period from 1950 July to 1951 February. Professor J. Wempe kindly inspected these and reported that the variable lies close to the plate edge where the images are poor. However, it appears certain that no star brighter than $m_{pg} \simeq 10$ was present, and this limit is again compatible with our assumed maximum of $m_{pg} \simeq 11$–12 in the autumn of 1950.

If figure 6 is compared with the average light curve of *Type I* supernovae (Barbon *et al.* 1973*a*), the best

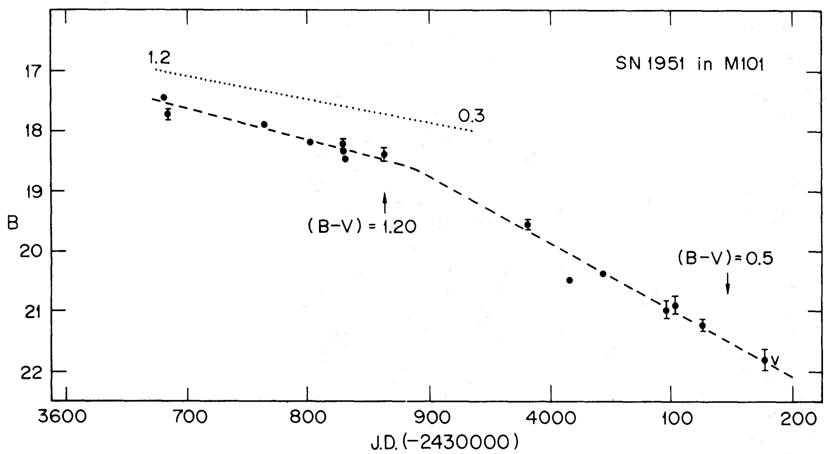

FIG. 6.—Light curve for Humason's supernova SN 1951 in M101 identified in fig. 7. Approximate colors are indicated at two epochs. Faint end of the light curve SN 1970g in M101 shown as a dotted line starting 120–130 days after maximum. The two numbers at the end points are rough interpolated $B - V$ colors. Data for SN 1970g from Bahcall *et al.* (1975).

possible fit is somewhat less satisfactory, as the reader can judge independently.

Hence, because the qualitative agreement of this variable with the Type II supernova 1970g is impressive as regards light curve, apparent brightness, rate of decline, and the color change from red to blue, we believe that the variable was a supernova in which the maximum was missed by several months.

3. *SN 1970g.* This supernova, discovered by Lovas (1970), is at the edge of the giant H II region NGC 5455 as shown in figure 7 (plate 4). Kirshner *et al.* (1973) and Barbon *et al.* (1973*b*) have classified the star as Type II. From their light curve, Barbon *et al.* suggest that the maximum occurred 1970 July 25 ± 3, with B(max) = 11.5 mag, corresponding to M_B(max) = −17.8, which matches closely the mean value of Type II supernovae mentioned earlier (Yilmaz and Tammann 1974). Additional photometric data are available (Bahcall *et al.* 1974) which have been used in the discussion of the faint end of the light curve in earlier paragraphs. This supernova is particularly noteworthy since it is the first active supernova to be detected at radio wavelengths (Gottesmann *et al.* 1972; Goss *et al.* 1973).

In summary: the fact that three supernovae have occurred in M101 during only 60 survey years is consistent with the high expectation rate for nearly face-on supergiant Sc galaxies (Tammann 1974).

f) The H II *Regions*

The isolation of the largest H II regions presents problems of definition. For example, the nature of NGC 5471 (Seyfert 1940) is still questioned. At various times it has been considered to be a super H II region far from the center but related to M101 in a normal way, a giant cluster, and a separate companion galaxy.

Although Seyfert (1940) assumed NGC 5471 to be part of M101, his high velocity of 500 km s^{-1} cast doubt on the assumption. Furthermore, the enormous angular size (∼30″), the resolved structure of five or six separate condensations, and the sharp boundary which is not similar to NGC 604 in M33 and 30 Dor in the Large Magellanic Cloud, add to the uncertainty.

However, we believe that NGC 5471 is a giant H II region in M101 for four reasons: (1) Searle (1971) discovered that the spectrum is that of a high-excitation H II region typical of those in the *outer* arms of other galaxies; (2) direct Hα plates taken with the Hale reflector (one interference photograph and four RG 2 plates as described in Paper I) show high surface brightness in Hα over the entire face of the object; (3) new radial velocities show that Seyfert's high velocity of 500 km s^{-1} is incorrect (discussed below); and (4) photographic evidence from the insert in figure 2 shows the fundamental difference between NGC 5471 and the true companion galaxy NGC 5477 (cf. figs. 1 and 7). (The condensations shown there in NGC 5471 are also found at 21 cm [Allen, Goss, and van Woerden 1974].)

Another unusual object, NGC 5455, is identified in figure 2. Short-exposure Hα photographs show it to be a definite H II region. The third large Hα complex is NGC 5462. Hα plates show that the region has an extensive network of Hα filaments throughout the superassociation which, by the precepts of Paper I, are taken to define an H II region. The three largest H II regions in M101 are, then, NGC 5471, NGC 5462, and NGC 5455, in that order. The fourth largest, NGC 5461, is also identified in figure 2.

The angular diameters, reduced to standard conditions by the methods of Paper I, are listed in table 8 which, for M101, are the mean of four plates. If the fourth region, NGC 5461, had been substituted for one of the first three, the $\langle \theta_H, \theta_C \rangle_3$ value of the final column would have been virtually unchanged. Similar data for the three largest regions in the five companion galaxies, obtained from image-tube Hα interference plates of 7- and 25-min exposure times, similar to those described in Paper I, are also listed in table 8.

TABLE 8

ANGULAR SIZES OF H II REGIONS REDUCED TO STANDARD CONDITIONS

	I		II		III					
GALAXY	θ (maj)	θ (min)	θ (maj)	θ (min)	θ (maj)	θ (min)	$\langle\theta\rangle_1$	$\langle\theta_H, \theta_C\rangle_1$	$\langle\theta\rangle_3$	$\langle\theta_H, \theta_C\rangle_3$
M101:										
Halo......	27″3	24″1	38″4	21″8	29″7	13″9	25″70	17″88	25″87	16″51
Core......	11.8	8.3	4.35	2.95	8.45	7.05	10.05		7.15	
NGC 5204										
Halo......	10.0	6.6	11.6	6.2	5.8	5.0	8.30	4.95	7.53	4.40
Core......	1.9	1.3	0.8	0.5	2.1	1.0	1.60		1.27	
NGC 5474:										
Halo......	16.4	8.7	14.8	9.6	9.7	7.0	12.55	6.73	11.03	6.17
Core......	0.9	0.9	0	0	3.15	2.85	0.90		1.30	
NGC 5477:										
Halo......	7.0	6.0	8.6	4.8	5.8	3.9	6.50	4.09	6.02	3.47
Core......	1.85	1.5	1.1	1.1	0	0	1.68		0.93	
NGC 5585:										
Halo......	11.55	6.6	7.45	5.0	5.8	4.6	9.08	5.79	6.83	4.28
Core......	3.1	1.9	2.1	1.0	1.3	1.0	2.50		1.73	
Ho IV:										
Halo......	9.45	4.5	7.9	6.1	4.1	2.4	6.98	4.34	5.75	3.31
Core......	1.7	1.7	1.1	0.8	0	0	1.70		0.88	

As a check on the membership of the adopted M101 regions, we have measured the radial velocities of NGC 5471 and NGC 5462 from new plates obtained by Searle, and by us. The results, summarized in table 9, are consistent with Rogstad's (1971) radio rotation curve of M101 shown in figure 8. This appears to remove any remaining doubt of the membership of NGC 5471 on dynamical grounds. We also note in passing that the velocity of the companion galaxy NGC 5477 from table 2, after projection onto the M101 major axis, is consistent with Keplerian motion about M101 itself.

In a final effort to clarify the nature of NGC 5471, we have measured its color and magnitude together with those of NGC 5462 and NGC 5455 during the course of other photometry with the Hale reflector, with the results listed in table 10. The colors are typical of H II regions with their underlying exciting stars, as modified by the emission lines from the gas. Note particularly the colors of NGC 5462, which is dominated by the stars themselves. Note also the large linear halo diameters of all the regions. These dimensions rival the size of small galaxies (cf. Sargent and Searle 1970).

To an objection against the extreme size and luminosity of the M101 regions, one must consider that decreasing the distance to M101 decreases also the distance to the companion galaxies. Because the H II regions in these companions are now at the correct size relative to those in the calibrating galaxies of the Local and M81–NGC 2403 groups (Paper I, fig. 9), they would be dwarfed by reducing the M101 distance to make its own regions smaller. We find this consequence much harder to accept than the result that the largest H II regions in Sc I galaxies are larger than those in lower luminosity spirals—a result consistent with data in Papers I and II.

IV. THE DISTANCE OF M101 AND ITS COMPANIONS

The data provide three lower limits and three direct determinations of the distance.

a) *Lower Limits to the Distance*

i) *Resolvability*

The best Hale reflector plates of galaxies in the M81–NGC 2403 group and the M101 group show that the resolution into stars is more difficult in the dwarfs of the latter aggregate than in dwarfs of the first group by

TABLE 9

RADIAL VELOCITIES OF LARGEST H II REGIONS IN M101
(km s^{-1}, uncorrected for solar motion)

NGC	v (here)	v (de Vaucouleurs)*	v (21 cm)†	v (adopted)
5471.......	280.6 ± 2.7‡	306 ± 6	282 ± 5	284 ± 2
5462.......	293.5 ± 2§	219 ± 12	288 ± 6	293 ± 2
5455.......	...	219 ± 7	184 ± 4	193 ± (10)

* de Vaucouleurs and de Vaucouleurs 1971.

† Allen *et al.* 1974.

‡ Measured from 3 plates loaned by L. Searle.

§ Measured on two plates, one loaned by L. Searle.

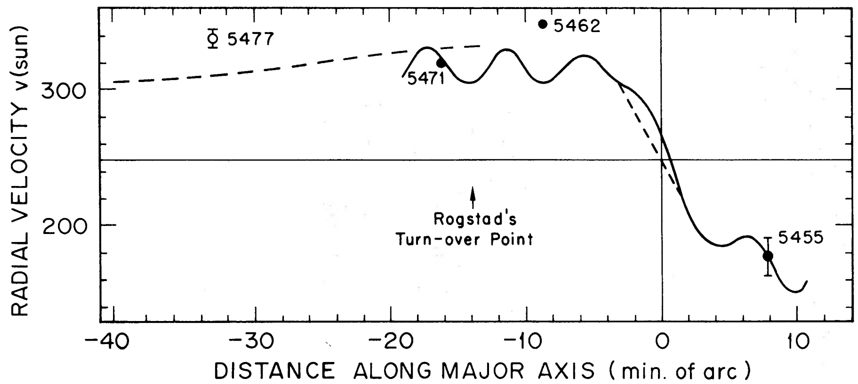

FIG. 8.—The 21-cm rotation curve of M101 according to Rogstad (1971), extrapolated by Kepler rotation assuming all mass is inside a 21′ radius, and the turnover radius as shown. The systemic velocity is assumed to be 249 km s^{-1} (heliocentric, not corrected for galactic rotation). The radial velocities of the three largest H II regions and of the nearby companion galaxy NGC 5477 are shown after projection onto the major axis of M101.

at least one magnitude. The modulus of the M81 group is $(m - M)_{AB} = 27.8$ (Tammann and Sandage 1968); hence $(m - M)_{AB} = (m - M)_0 \geq 28.8$ mag for M101.

ii) *Lack of Red Variable Supergiants*

As discussed in § III*d*, the nondetection of these stars requires $(m - M)_0 \geq 28.9$ mag for M101.

iii) *Cepheids*

There are no Cepheids with $B(\max) \leq 22.0$ mag within regions of M101 that are comparable with those regions of NGC 2403 where Cepheids were found with moderate ease. In NGC 2403 ($[m - M]_{AB} = 27.80$), the brightest Cepheid has $B(\max) = 21.24$ (Tammann and Sandage 1968); hence a *minimum* distance of M101 would be $(m - M)_0 = 28.56$. But the brightest possible Cepheid in M101 (V7) has $B(\max) \simeq 22.5$ mag, and therefore the minimum modulus is rather ≥ 29.0 mag. The brightest actual Cepheid may still be fainter, and in addition, because M101 is intrinsically larger than NGC 2403, it is expected that the apparently brightest Cepheid will have a longer period, hence an even brighter absolute magnitude there. Hence, the lower limit of $(m - M)_0 \geq 29.0$ appears to be quite stringent.

b) *Direct Distance Determinations*

i) H II *Regions*

Distances follow directly from the angular sizes of the three largest H II regions listed in table 8, combined with the linear sizes calibrated in Paper I (eq. [7]), with the results shown in table 11A. In forming the mean distance of the group, M101 itself is given zero weight because equation (7) of Paper I applies only to luminosity classes equal to or fainter than II–III; indeed it is the purpose of the present paper to test the extrapolation of equation (7) to $L_c = 1$. Giving each of the companions unit weight, the mean distance is 7.39 ± 0.45 Mpc, or $(m - M)_0 = 29.34 \pm 0.13$. If M101 had been included by adopting a linear extrapolation of equation (7) (Paper I), the distance would be 7.11 ± 0.45 Mpc, or $(m - M)_0 = 29.26 \pm 0.13$. The agreement shows a principal result of this paper: *equation* (7) *of Paper I is valid for Sc I galaxies.* The consequence of this for the calibration of the luminosity classes in Paper IV is discussed in § V.

TABLE 10

PARAMETERS OF LARGEST H II REGIONS IN M101

NGC	V	$B - V$	$U - B$	$M_B{}^0$*	$\mathfrak{M}_{\mathrm{H\,I}}$*†	Major Axis (kpc)* Core	Major Axis (kpc)* Halo
5471.......	13.72‡	0.32	−0.81	−15.26	0.1	0.15	1.35
5462.......	13.95§	0.06	−0.88	−15.29	...	0.41	0.96
5455.......	15.05‖	0.11	−0.95	−14.14	...	0.30	1.04

* Assuming $(m - M)_0 = 29.3$

† According to Allen *et al.* 1973, in $10^9\ \mathfrak{M}_{\odot}$.

‡ Within 30″.6 diaphragm, excludes some of the halo.

§ Within 48″.3 diaphragm.

‖ Within 12″.19 diaphragm, excludes most of the halo.

TABLE 11

DISTANCE TO M101 GROUP BY THREE METHODS

A. FROM H II REGIONS

Galaxy	L_C	$\langle\theta_H, \theta_C\rangle_3$	$\langle D_H, D_C\rangle_3$	r (Mpc)
M101..........	I	16".51	460.5	5.75
NGC 5204.....	IV	4.40	171	8.02
NGC 5474.....	[IV]	6.17	171	5.72
NGC 5477.....	IV–V	3.47	123	7.30
NGC 5585.....	IV	4.28	171	8.24
Ho IV.........	IV–V	3.31	123	7.65

B. FROM BRIGHTEST STARS

Galaxy	L_C	m_{pg}	M_{pg}^0	$(m - M)_0$	Weight
M101..........	I	18.97	−10.0	28.97	2
NGC 5474.....	[IV]	20.6	− 8.81	29.41	1
NGC 5585.....	IV	20.9	− 8.81	29.71	1

C. FROM LUMINOSITY CLASSES

Galaxy	L_C	m_{pg}	M_{pg}^0	$(m - M)_0$	Weight
M101..........	I	8.19	−21.25	29.44	0
NGC 5204.....	IV	11.62	−17.81	29.43	2
NGC 5474.....	[IV]	11.22	−17.81	29.03	1
NGC 5477.....	IV–V	14.5	−16.39	30.89	½
NGC 5585.....	IV	11.25	−17.81	29.06	2
Ho IV.........	IV–V	12.95	−16.39	29.34	1

ii) *Brightest Stars*

From the results of § III*b*, *c*, the magnitude of the first brightest star is $B = 18.97$ in M101, 20.6 in NGC 5474, and 20.9 in NGC 5585. The distances follow using the calibration of Paper II (eq. [3]) with the results listed in table 11B.

The photometry in M101 is more reliable than in the companions; on the other hand, the calibration of Paper II must be extrapolated to luminosity class I, which we did conservatively to adopt $M_B = -10$ there. From these considerations we weight the M101 value by 2 and the companions by 1, where the error of unit weight is estimated to be ~ 0.6 mag. The mean distance modulus from table 11B then becomes $(m - M)_0 = 29.27 \pm 0.30$.

As a second principal conclusion we note that if $(m - M)_0 = 29.3$ as finally adopted, then it follows that the calibration of the brightest star in Sc I galaxies is $M_B = -10.3 \pm 0.3$. This value is close to the extrapolation of equation (3) of Paper II and provides its justification.

iii) *Luminosity Classes*

In Paper IV we shall derive the absolute luminosities of the individual luminosity classes using H II distances as calibrated in Paper I. The results of applying the calibration to the M101 companions is shown in table 11C.

Because the M101 group enters the calibration of the fainter classes in Paper IV with very little weight, it is not circular reasoning to use the results of that calculation here for the M101 companions. The justification is that the companions were used in Paper I to determine only the *slope* of the $\langle D\rangle = f(L_C)$ relation; in Paper IV they are only several of a number of independent galaxies that enter the $M_{pg} = f(L_C)$ calibration (their omission leaves the results virtually unchanged).

However, M101 *itself* is crucial to the Paper IV calibration at the bright end because the distance we finally adopt here ($[m - M]_0 = 29.3$) provides the justification for the extrapolation of equation (7) of Paper I to Sc I galaxies. For this reason we give M101 zero weight in table 11C. The companions are assigned indicated weights on the basis of the reliability of the data: L_CIV–V has lower weight than IV, and the apparent magnitude of NGC 5477 is in question.

The weighted mean from table 11C is $(m - M)_0 = 29.35 \pm 0.25$, where the error is determined assuming that unit weight corresponds to ± 0.6 mag.

Combining the results of the last three methods gives $(m - M)_0 = 29.3 \pm 0.3$ (the formal error from the stated precepts is ± 0.15 mag, but this is clearly unrealistic), or $D = 7.24 \pm \sim 1.0$ Mpc, which we adopt.

c) Two Additional Hints to the Distance

i) *Bright Blue Irregular Variables*

Although the bright blue irregular variables are not accurate distance indicators, we may compare $B(\max) = 19.2$ for V1 with $\langle M_B(\max)\rangle = -9.4 \pm 0.4$ derived in Paper II, by arbitrarily eliminating brighter stars of the class. Adopting a modulus of 29.3 gives $M_B(\max) = -10.1$ for V1, which is virtually the same as for P Cyg and for variable B in M33 (Paper II, table 16), but is still considerably fainter than V12 in NGC 2403 and η Car. Hence, the data on the bright blue variables in M101 are compatible with the adopted distance. We consider, however, that they provide no direct determination because of the large dispersion in the absolute magnitude of these stars.

ii) *Diameters of Galaxies*

Heidmann (1969) has proposed that the intrinsic luminosity L of a galaxy does not generally increase with the square of the diameter, but rather as $L \propto D^q$, where $q \neq 2$, and that this fact can be used for distance determinations. The effect is a different representation of Holmberg's (1958) discovery that the mean surface brightness of spirals increases with increasing absolute luminosity.

Heidmann *et al.* (1971*b*) derive

$$(m - M)_0 = \frac{m_{\rm pg}{}^{0,i}}{1 - 0.5q} + \frac{2.5q}{1 - 0.5q} \log a(0) + K ,$$

where $m_{\rm pg}{}^{0,i}$ is the Holmberg magnitude corrected for galactic absorption and inclination, and $a(0)$ is the corrected major axis as given, for example, in table 2. For spirals, these authors find $q = 2.6 \pm 0.1$.

The constant K can be determined from the spirals in the Local Group and the M81–NGC 2403 group. Because the authors include spirals as late as Sm, there are seven available calibrators (M31, M33, LMC, M81, NGC 2403, NGC 4236, and IC 2574) from which we obtain $K = 86.06 \pm 0.77$. Applied to the five spirals in the M101 group (excluding the Ir Ho IV), the equation gives $\langle (m - M)_0 \rangle = 29.1 \pm 1.0$. The error is large because the method suffers from the nearness of q to the divergent value of *2* in the presence of a large cosmic dispersion. Nevertheless, the result shows that the evidence from diameters is in agreement with our adopted value of 29.3 to within the substantial error of the method.

A summary of the various distance determinations of this section is given in table 12.

TABLE 12

SUMMARY OF INDIVIDUAL MODULI FOR M101

Method	$(m - M)_0$
Resolvability....................	≥ 28.8
Lack of red supergiants...........	≥ 28.9
Lack of Cepheids................	≥ 29.0
H II regions.....................	29.26 ± 0.13
Brightest stars..................	29.27 ± 0.30
Luminosity classes...............	29.35 ± 0.25
Blue irregular variables...........	(28.6 ± 1)
Apparent diameters..............	(29.1 ± 1)
Adopted......................	29.3 ± 0.3

V. JUSTIFICATION AND DISCUSSION

a) *The Distance*

Between 1931 and about 1950 Hubble's distance to M101 was consistently greater in modulus by only ~1 mag from M31. For this reason, our very large change in the distance to $\Delta(m - M)_0 = 5.1$ mag from M31 was unexpected, and hence generally suspect.

However, the new result here, which is more than 10 times Hubble's (1936*b*) distance, does not depend on one distance indicator alone, but rather on a number of independent methods (table 12). In particular, it does not depend on the extrapolation to Sc I galaxies of equation (7) of Paper I for the H II region calibration, or of equation (3) of Paper II for the brightest stars.

Rather, we consider the principal result of the present paper to be the calibration of these H II regions and brightest star relations for Sc I systems themselves, using the new distance to M101 which has largely been determined from the companions, or by methods that are independent of the H II regions or the brightest stars in M101 itself (table 12). The result has been that if $(m - M)_0 = 29.3$, then the extrapolation of the calibration equations of Papers I and II to the Sc I point ($L_C = 1$) is, in fact, confirmed to within the cosmic dispersion discussed in Papers I, II, and IV (to follow), and hence that the basis of the method of Paper IV is justified.

The increase in the distance here is clearly drastic, as can be seen from table 13, which summarizes some of the older values from a variety of methods. However, from the modern data we can see no way to escape the conclusion that the modulus difference between M101 and M31 is, in fact $(m - M)_0 \simeq 5$ mag. Evidence, based on linear size, that this is not unreasonable, is given in figure 9 (plate 5), which is a comparison of very deep exposures of both M31 and M101 taken with the Palomar 1.2-m Schmidt on IIIaJ emulsions, scaled to equal linear dimensions using $(m - M)_0 = 24.18$ for M31, and $(m - M)_0 = 29.3$ derived here for M101. The image of M101 has been tilted in the photolab to imitate the apparent flattening of M31. There clearly is no gross difference in the major diameters of the two galaxies. The slightly larger intrinsic diameter of M101 is indeed expected because of the higher luminosity class. If any of the smaller distances of table 13 had been used, the image of M101 would have been smaller than M31, contrary to the evidence from the luminosity classification. We take this to be independent confirmation of the results of table 12.

b) *The Velocity Field*

Finally, using $(m - M)_0 = 29.3$, we now anticipate the results of Papers V and VI (to follow) on the isotropy and the quietness of the expansion field to determine the v/r ratio for the M101 group, and to show that this ratio agrees closely with the global value of the Hubble constant itself.

From the discussion in the Appendix, the M101 group is stable, and the radial velocity of the barycenter is $v_0 = 402 \pm 4.2$ km s^{-1} (corrected for galactic

TABLE 13

SOME OLDER ADOPTED DISTANCE MODULI TO M101

$(m - M)_0$	Method	Author
23.0...........	Variables	Hubble and Humason 1931
23.0...........	From Hubble and Humason	Whitford 1936
24.1...........	Brightest stars*	Hubble 1936*b*
23.7...........	From Hubble	Holmberg 1950
28.2...........	Assuming $H_0 = 100$	van den Bergh 1960*b*
28.1...........	H II regions	Sérsic 1960
27.7...........	H II regions	Sandage 1962
27.7...........	From Sandage†	Holmberg 1964
28.3...........	Various methods	de Vaucouleurs 1975
27.7...........	Same as Holmberg 1964	Holmberg 1969

* The value is not an independent determination because Hubble (1936*a*) used M101 for the calibration of the brightest stars themselves, taking $(m - M) = 23.5$ from "novae" and irregular variables in M101.

† For M101 itself, Holmberg (1964) adopted $(m - M)_0 = 27.7$, but for the other three group members (NGC 5204, 5474, and 5585) his surface brightness-color-luminosity relation gave $(m - M)_0 = 29.5$! This difference led him to reject the three galaxies as group members. We take here the opposite point of view that the method is suspect for Sc I galaxies.

rotation by $300 \sin l^{\mathrm{II}} \cos b^{\mathrm{II}}$). With $D = 7.24 \pm 1.0$ Mpc, and accepting (from Paper V) that the random motion of the group is less than 30 km s^{-1} (statistically), the local v/r ratio is

$$\langle v_0 \rangle / \langle r \rangle = (402 \pm 30)/(7.24 \pm 1.0) = 55.5 \pm 8.7 \text{ km s}^{-1} \text{ Mpc}^{-1},$$

which, remarkably, agrees with the global value of the actual Hubble constant (Papers V and VI). The significance of the agreement is the main result of Paper V, where it is shown that the result must be expected because there is no measurable perturbation on the ideally smooth Hubble expansion velocity field.

c) *Summary*

In summary, the main result of the present study is that the distance to M101 is $D = 7.24 \pm 1.0$ Mpc. The value forms the basis for the extension of the calibrations in Papers I and II to Sc I galaxies, and permits the calibration of the $\langle M_{\mathrm{pg}} \rangle = f(L_C)$ values in Paper IV, and of H_0 in Paper VI. The increase by a factor of ~ 10 in distance here from Hubble's (1936*b*) value is carried to larger distances in the later papers of this series, and is the principal reason for the decrease by a factor of ~ 10 in our final value of the Hubble constant compared with Hubble's 1936 value.

Many people have helped with this study. We wish to thank R. J. Allen, W. H. Goss, and H. van Woerden, S. R. Fisher and R. B. Tully (for their radio redshift of NGC 5477), W. K. Hutchmeier and W. L. W. Sargent for several radio and optical redshifts, W. A. Baum for use of his unpublished photoelectric sequence in SA 57, L. Searle for loan of his spectrograms of NGC 5471, 5474, and 5477 for redshift measurement, A. Toomre for discussions on the tidal distortion problem of M101/NGC 5474/5477, and H. Elsässer, A. Bohrmann, G. H. Herbig, M. H. Liller, and J. Wempe for their kindness in either locating archive photographic plates for remeasurement or for inspecting such plates themselves.

As always, it is a pleasure to thank Felice Woodworth for her preparation of the diagrams for publication. John Bedke prepared the photographs for publication with his customary skill, and we are grateful for his great effort. The artificial tilting of M101 in figure 9 presented special difficulties for which he developed new techniques. And again, as always, we are grateful to Raquel Ferrer and Helen Czaplicki for preparing the manuscript for press.

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APPENDIX

DYNAMICAL STABILITY OF THE M101 GROUP

Assuming that the galaxies move in randomly distributed circular orbits in a spherical volume (the precepts of Limber and Matthews 1960), the kinetic energy of the group is

$$T = \frac{3}{2} \sum m_i v_i^2 , \qquad \text{(A1)}$$

where v_i is the velocity of the galaxy i with mass m_i relative to the barycenter, and where projection factors are properly accounted for.

The gravitational potential energy, again following Limber and Matthews, is

$$-\Omega = \frac{2G}{\pi} \sum_{\text{pairs}} \frac{m_i m_j}{r_{ij}} , \qquad \text{(A2)}$$

TABLE A1

DERIVED PARAMETERS FOR M101 GROUP MEMBERS
(Distance = 7.2 Mpc)

NGC Object (1)	$M_{pg}{}^0$ (2)	L (in $10^9 L_\odot$) (3)	$\mathfrak{M}$ (in $10^{10} \mathfrak{M}_\odot$) (4)	$\mathfrak{M}/L$ (5)	$\mathfrak{M}/L$ adopted (6)	$\mathfrak{M}$ (in $10^{10} \mathfrak{M}_\odot$) adopted (7)	$\mathfrak{M}_H$ (in $10^9 \mathfrak{M}_\odot$) (8)	$\mathfrak{M}_H/\mathfrak{M}$ (9)
5457.......	−21.11	39.1	62.4	16.0	(6.45)	25.2	23.0	0.09
5204.......	−17.68	1.66	0.63	3.8	(3.8)	0.63	1.6	0.25
5474.......	−18.08	2.39	8.0	33.5	(15.1)	3.6	1.6	0.04
5477.......	−14.8	0.12	...	...	10	0.1	0.08	0.08
5585.......	−18.05	2.33	2.7	11.6	(11.6)	2.7	2.0	0.07
Ho IV.....	−16.35	0.49	...	...	10	0.5	...	...

where r_{ij} is the projected linear distance between galaxy i and j. Stability, of course, requires the total energy $T + \Omega$ to be negative.

Further, if the present situation represents a fair time average, the virial theorem requires $2T + \Omega = 0$, from which the total mass can be calculated approximately.

Knowledge of the individual masses is required to apply equations A1 and A2. We estimate them from the available data listed in table A1, assuming the distance to be 7.2 Mpc (§ IV). The luminosities $L_{pg}(\odot)$ in column (3) are calculated from the m_{pg} values of table 2 [$(m - M)_0 = 29.3$], assuming $m_{pg}(\text{Sun}) = 5.37$ (Stebbins and Kron 1957). The masses, listed in column (4), derived from various observations, are taken from Roberts (1969) as reduced to our adopted distance. The mass of M101 is based on Rogstad's (1971) radio rotation curve corrected to our distance and to our inclination of $i = 72°$ (the derived mass varies as $\cos^{-2} i$, and hence the mass derived in this way is uncertain by a factor of at least 2).

The mass-to-light ratios in column (5) are from columns (3) and (4). Because these values appear unreasonably erratic, undoubtedly because of the low weight of the mass determinations, we have smoothed the $\mathfrak{M}/L$ ratios on the basis of other knowledge (cf. Roberts 1969), and list them in parentheses in column (6). Further, it is *assumed* that $\mathfrak{M}/L = 10$ for NGC 5457 and Ho IV, reflecting mildly the possibility that $\mathfrak{M}/L$ increases with decreasing luminosity as suggested by Roberts's (1969) data. Column (7) lists the adopted masses from these precepts, using the conservative value for M101 from Roberts (1969, corrected to $D = 7.2$ Mpc), which is a lower limit. The mass of NGC 5474 is arbitrarily reduced to $3.6 \times 10^{10} \mathfrak{M}_\odot$, and the remaining are either from column (4) or from the adopted $\mathfrak{M}/L$ values in column (6), combined with column (3).

The hydrogen mass, reduced to $D = 7.2$ Mpc, is listed in column (8) from Allen *et al.* (1973) for NGC 5477, and from Roberts (1969) for the remainder. A test of how reasonable our adopted masses in column (7) may be, is given by the $\mathfrak{M}_H/\mathfrak{M}$ ratios in column (9). The ratios for all but NGC 5204 are reasonable (cf. Roberts 1969), suggesting that the masses in table A1 are consistent to within factors of ~ 2.

The masses listed in column (7) were used to calculate T and Ω from equations (A1) and (A2), and further to calculate the barycenter velocity of the group as $v_0 = 402.2 \pm 4.2$ km s^{-1}, corrected for the standard galactic rotation. The kinetic energy is $T = 6 \times 10^{57}$ ergs, with an error due to uncertainties in the observed velocities of only ~ 25 percent. This is true only because the velocities are exceptionally accurate, a point we shall return to later.

The potential energy is $-\Omega = 7 \times 10^{57}$ ergs, which is uncertain by a factor of 2 because of the uncertainty of the M101 mass, but this is a *lower* limit because we used the smallest mass among the various possibilities. Even so, $\Omega + T < 0$, and the group is clearly stable!

The result seems beyond question, despite the fact that many of the groups discussed by Rood, Rothman,

TABLE A2

KNOWN STABLE GROUPS OF GALAXIES

Group	de Vaucouleurs Name	N	Source
Stephan's Quartet.......	...	4	Limber and Mathews 1960
VV 116................	...	5	Burbidge and Burbidge 1961
NGC 3395............	G43	3 (+2)	Karatchentsev 1966
Local Group...........	G1	10	Herbst 1969
M96 (NGC 3368).......	G11	7	Rood *et al.* 1970
NGC 833..............	...	4	Burbidge and Sargent 1971
NGC 1023 (HMS)*......	G7	5 (+1)	Materne 1974
NGC 7331.............	...	4	Materne and Tammann 1974
M101..................	...	6	Here
Shakhbazian I..........	...	...	Robinson and Wampler 1973

* The NGC 1023 group seemed highly unstable formerly, but recent accurate velocities show the group to be stable (Materne 1974).

and Turnrose (1970) appear to be unstable. However, it is clear from the example of G1023 (Materne 1974) that at least some of these groups are in fact stable, with $\mathfrak{M}/L$ ratios of order 10, and are proved to be so when the radial velocities are known with high accuracy. As more accurate velocities become available (errors of order ± 10 km s^{-1}) it is foreseen that the number of stable groups will, in fact, increase substantially. The list of stable groups known at this time is summarized in table A2.

As a corollary of the stability condition $\Omega + T < 0$, is it clear that the mass of the group determined from the virial theorem, $\langle\Omega\rangle + 2\langle T\rangle = 0$ must be nearly the same as the sum of the individual masses from table A1. Direct calculation following Rood *et al.* (1970) gives $\mathfrak{M}_{VT} = 57 \times 10^{10}\, \mathfrak{M}_\odot$, which is the same to within the errors as the "visible" mass of 33 $\times$ $10^{10}\, \mathfrak{M}_\odot$ obtained by summing column (7) of table A1.

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ALLAN SANDAGE: Hale Observatories, 813 Santa Barbara Street, Pasadena, CA 91101

G. A. TAMMANN: Astronomisches Institut der Universität Basel, Binnigen, Switzerland

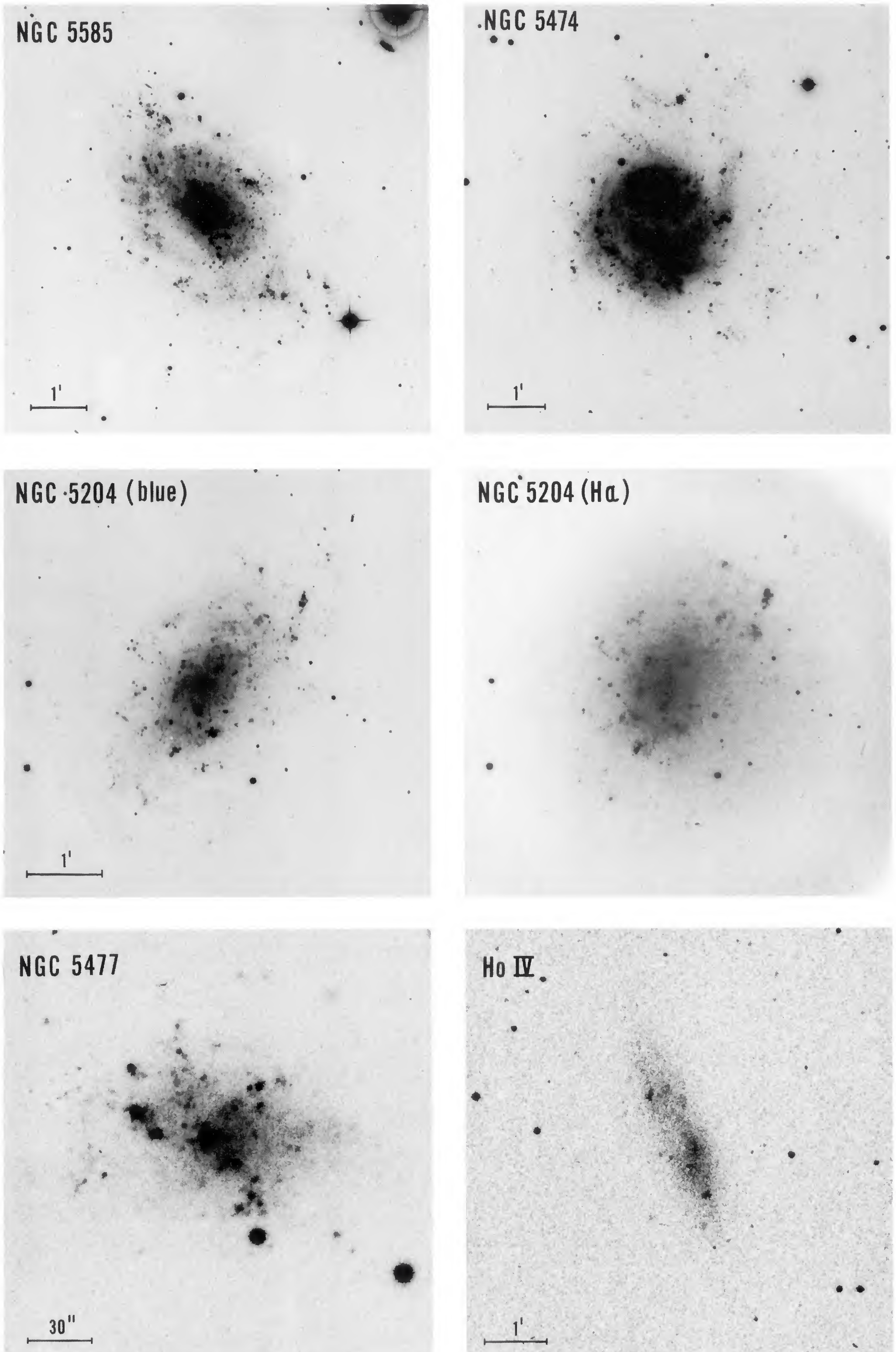

FIG. 1.—Reproduction of direct photographs for the five companions of M101 taken at the prime focus of the Hale 5-m telescope, except for Ho IV which is from a Palomar Schmidt plate (blue). The Hα exposure for NGC 5204 is from an image-tube exposure behind an 80 Å (total half-width) Hα interference filter. The other exposures are with Eastman 103aO behind a Schott GG13 filter.

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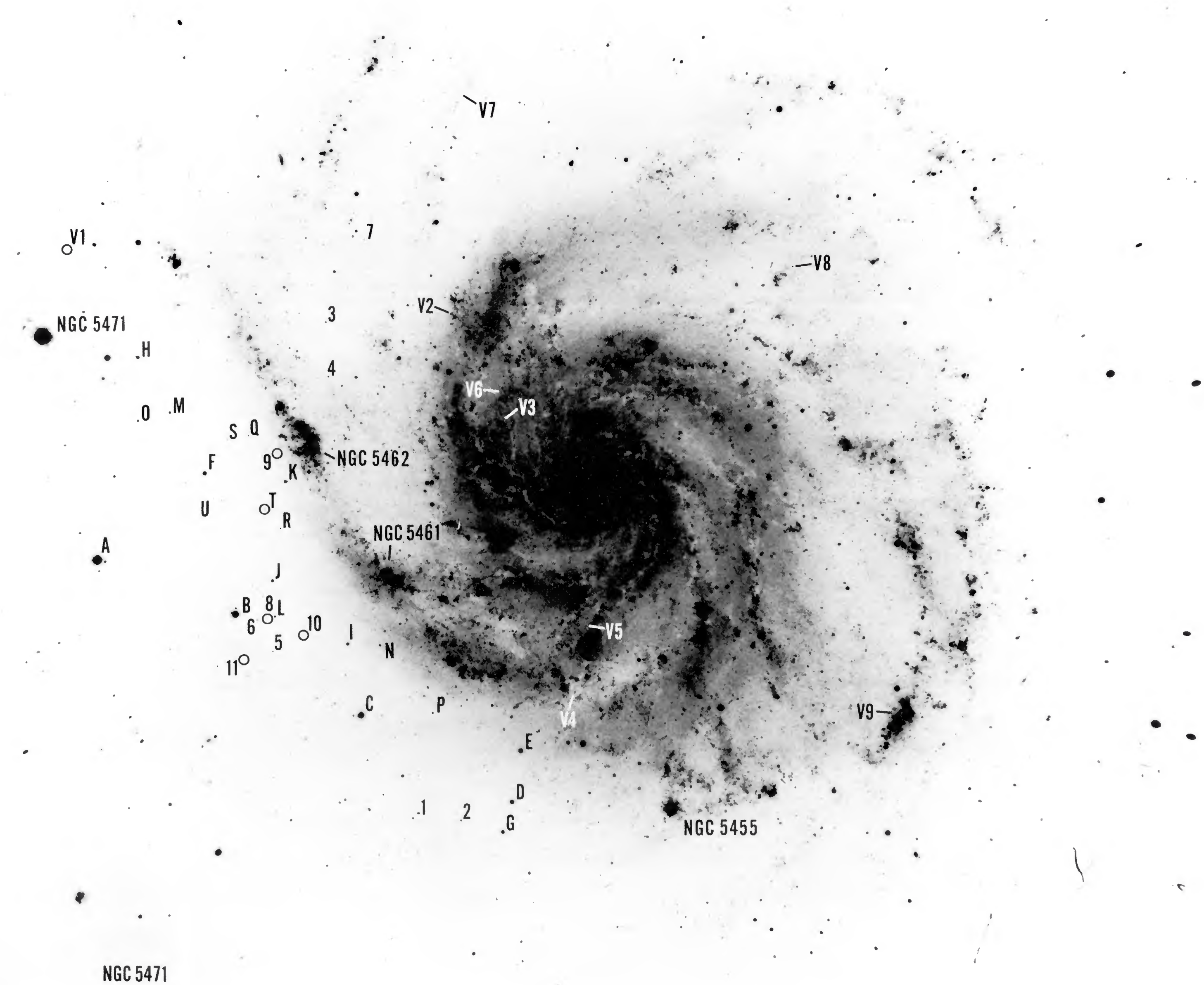

FIG. 2.—Identification chart for various components of the stellar content of M101 from a prime-focus blue plate taken with the Hale 5-m telescope. The photoelectric sequence (A–U) and the secondary photometric sequence (1–11) stars are marked. Variable stars V1–V9 are indicated by V numbers. The four largest H II regions are identified by their NGC numbers. The insert photograph is of the H II region NGC 5471 taken with the Mount Wilson 2.5-m reflector to show the internal structure.

SANDAGE AND TAMMANN (*see* page 227)

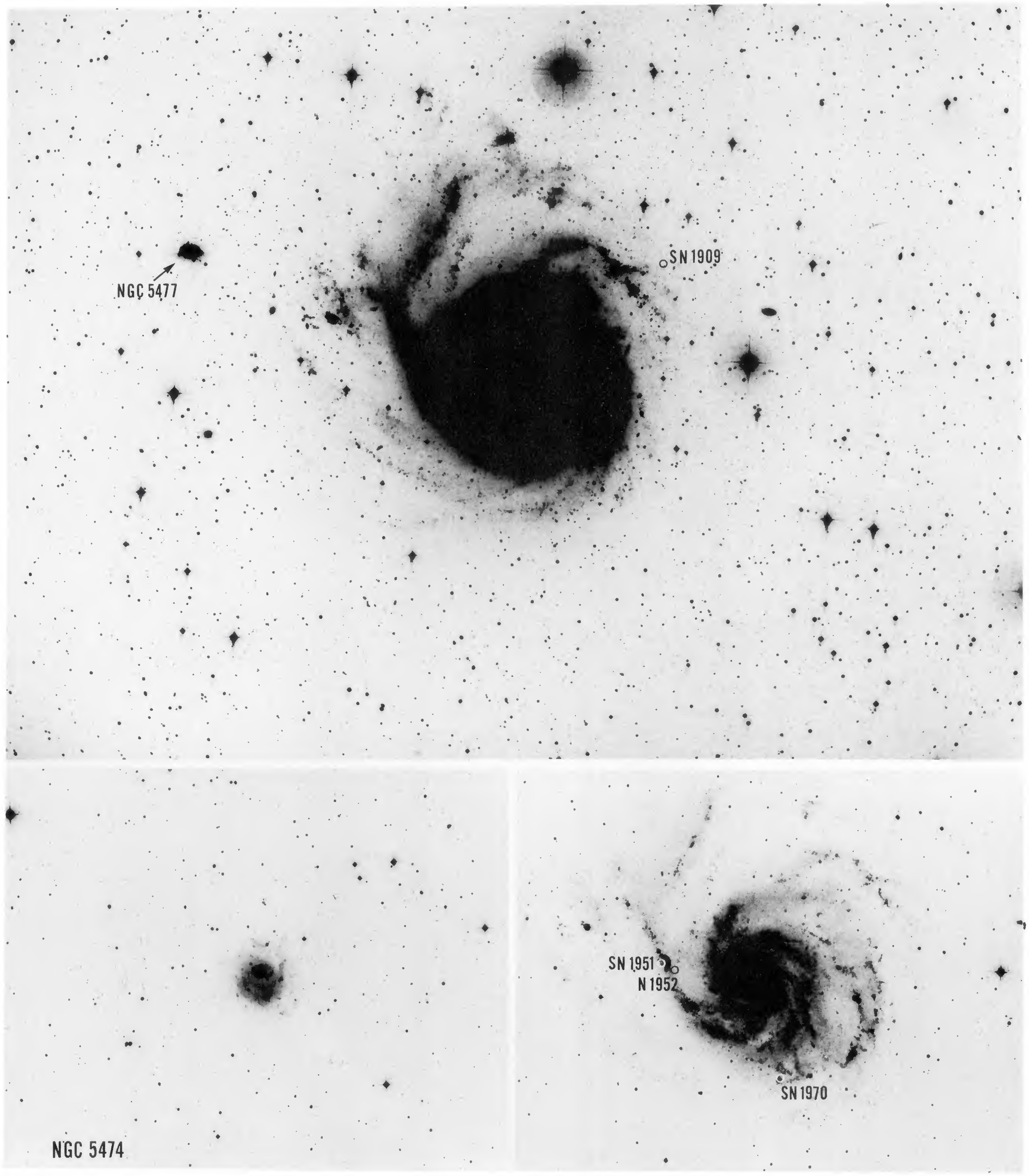

FIG. 7.—Composite from three long-exposure IIIaJ Palomar Schmidt plates. The 1909 supernova and the companion galaxy NGC 5477 are marked. Note that SN 1909 is not isolated from the outer arm structure. The inserts show the tidally distorted companion galaxy NGC 5474, and, at the right, the positions of the other two supernovae and of the normal nova of 1952.

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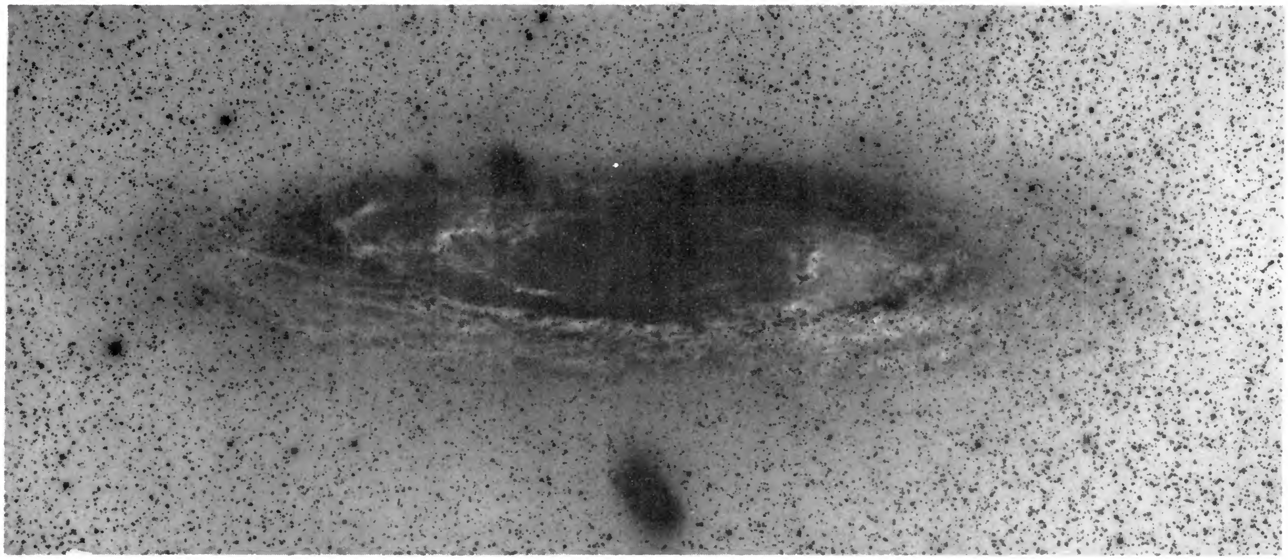

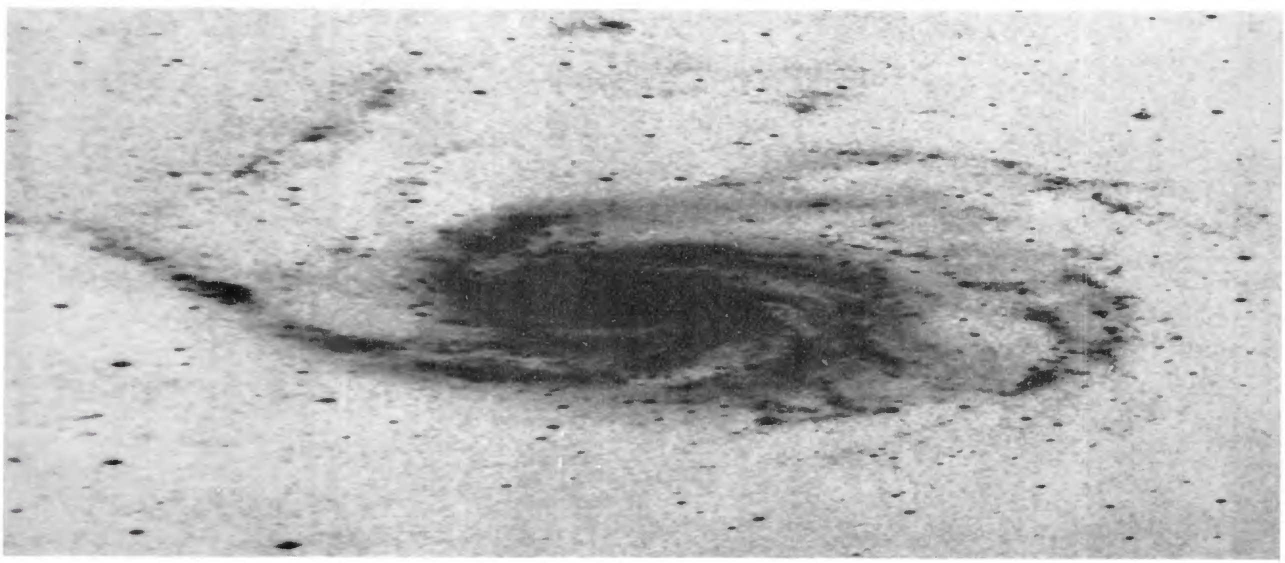

FIG. 9.—Comparison of the linear scales of M31 and M101 based on true moduli of $(m - M)_0 = 24.18$ for M31 and $(m - M)_0 = 29.3$ for M101. The image of M101 is photographically tilted to imitate approximately the inclination of M31. The outermost identifiable OB associations in M31 define nearly the same linear diameter of the major axis as in M101. Both reproductions are from original Palomar 1.2-m Schmidt plates taken with Eastman IIIaJ emulsion.

SANDAGE AND TAMMANN (*see* page 239)