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THE ASTRONOMICAL JOURNAL VOLUME 74, NUMBER 8 OCTOBER 1969

Observational Studies Relating to Star Formation. II

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(Received 22 April 1969; revised 1 July 1969)

Observational evidence is presented in support of the view that star formation may occur in small, primary condensations having masses $\lesssim 100\ M_\odot$. The small aggregate containing the T Tauri-like star BM And is discussed in some detail, and other examples are cited of similar groups of early-type stars.

I. INTRODUCTION

THEORETICAL studies by Hunter (1966, 1969) indicate that star formation may occur in relatively low-mass clouds of about $50M_\odot$. In Paper I of this series, Aveni and Hunter (1967) cited several examples of early-type stars that may have formed above the Galactic plane. Moreover, it does not appear that these objects can be associated genetically with known associations or early-type clusters. [However, the best example of this phenomenon (ρ Leo) may be anomalous. Stothers (private communication) has suggested that this object may be an evolved helium-rich star having an age substantially greater than that adopted by the authors.] The case for isolated star formation has received some further support in the work of Reddish (1967), who has noted the presence of Wolf–Rayet stars in the field. Reddish has concluded that these objects are massive young stars undergoing the final stage of pre-main-sequence contraction.

High-dispersion radio studies by Heiles (1967, 1968) have revealed cloudlets in the interstellar medium, some of which have masses comparable with those of upper main-sequence stars. One possible interpretation of these cloudlets is that they are protostars and protoclusters undergoing the initial phases of collapse resulting from a thermal instability (Hunter 1966, 1969; Heiles 1967).

An investigation complimentary to that undertaken in Paper I would be to examine in detail the properties of small young groups of stars and gas that are clearly isolated from other young Population I objects. In Sec. II of the present paper, we examine the properties of one such group which includes the T Tauri-like star BM And, and in Sec. III we estimate the properties of other small groups.

II. THE BM ANDROMEDAE COMPLEX

The T Tauri-like star BM And [$\alpha = 23^h35^m\!.0$, $\delta = +48°10'$ (1950)] is imbedded in the southern end of a teardrop-shaped nebulosity having dimensions $2° \times 0.25°$, which was first recognized by Whitney (1949). Some regions of the surrounding cloud, which is illuminated by a pair of late B stars, show considerable obscuration. An examination of the catalogue of Alter *et al.* (1958) reveals that no recognized early-type cluster or association lies within about 10° or 75 pc at the distance of the cloud. Accordingly, it seems meaningful to regard the nebulosity as an isolated structure.

Plates II(a) and II(b) are enlargements of the POSS prints of the area. The basic astronomical data for the numbered stars on Plate II(a) have been obtained and are given in Table I. In the last column, + denotes certain membership, − denotes certain nonmembership,

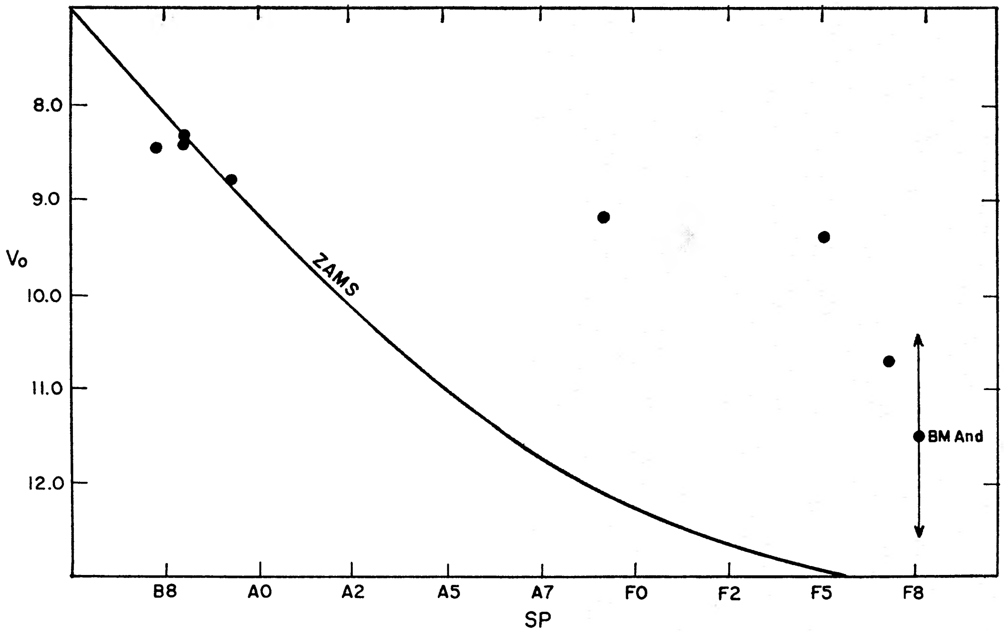

FIG. 1. Spectrum–magnitude diagram of the member stars in the BM And group.

and uncertain members are indicated by 0. Two Case 4° objective-prism plates were examined and a list of possible members was drawn from those plates. Spectra of these stars were than obtained at classification dispersion with the Yale 40-inch telescope. Spectra of two additional stars were obtained at Victoria. Photometric data has been acquired from both Steward and Yale Observatories. The internal consistency of the photometry is about $\pm 0^{m}.03$ in V. A distance of 440 pc has been adopted for the group, derived from the mean spectroscopic parallax of the two exciting stars (No's. 25 and 26). We have included as possible members stars having distances of 440±100 pc as determined by the method of spectroscopic parallax. The clustering tendency of members is apparent from an examination of Plate II(a) where the member star numbers have been underlined. A few outlying stars have distances in agreement with that of the group but there seems to be no clear way of deciding whether they are true members. A spectrum–magnitude diagram of the member stars is given in Fig. 1, where the visual magnitude (V_0) has been corrected for interstellar absorption. The zero-age main-sequence (ZAMS) is also included in this figure.

TABLE I. Basic data for stars in BM And field.

No.	BD	V	$B-V$	$3E_{B-V}$	Sp.	V_0-M_v	Memb.
00	+48°4119	9.23			G5 V	$\leqslant$4.13	−
01	+48°4117	10.49	0.49	0.00	F8 V	6.49	−
02	+48°4234	9.05	0.35	0.45	A7 V	6.60	−
03	+47°4224	9.63	0.47	0.00	F5 V	6.43	−
04	+47°4228	11.09	0.39	0.57	A7:	$\geq$8.52	0
05	+47°4227	10.82	0.36	0.81	A3:	$\geq$8.51	0
06	+47°4217	9.47	0.46	0.03	F5 IV	7.54	+
07	+47°4213	9.38	0.41	0.09	F2 IV–V	6.5	0
08	+47°4211	8.65	−0.06	0.09	B8 Vp	8.76	+
09	+47°4219	10.79	0.47	0.00	F7 IV–V	7.9	+
10	+47°4221	9.73			G5 V	$\leqslant$4.63	−
11	BM And	12.4–14.6	1.22	2.07	F8e		+
12	+47°4210	10.48	0.48	0.30	F2	$\geq$7.38	0
16	+47°4225	10.42	0.80		F–G		0
18	+47°4215	13.21	0.86	1.44	F2	$\geq$8.97	−
19	+47°4206	9.30	0.37	0.12	A9 III	8.58	+
20	+47°4209	8.94	0.12	0.54	B9 V:	8.10	+
22	+48°4112	7.11	0.65	0.36	F8:	$\geq$2.75	−[1]
23	+48°4114	9.06	0.09	0.45	B9	$\geq$8.31	0
24	+48°4115	9.29	0.10	0.12	A2	$\geq$7.97	0
25	+47°4214	8.55	0.00	0.18	B9 V	8.07	+
26	+47°4220	9.50	0.17	0.60	B9.5 V	8.37	+
27	+47°4216	9.01			G8 V	$\leqslant$3.5	−
28	+47°4218	10.91	0.35	0.45	A7 V[2]	8.46	0

[1] Eliminated on the basis of proper motion.
[2] Probably a metallic line star. Class given based upon Ca K-to-H ratio.

Stars later than A0 apparently have not yet contracted onto the main sequence. Accordingly, an approximate age for the group is $\sim 4\times 10^{6}$ yr. The stellar mass content is 30 $M_{\odot}$, including the uncertain members, and $\sim 20\ M_{\odot}$ if only member stars are counted. A survey of several plates of the area has turned up three red variable stars which may be members. The inclusion of these in the group does not increase our mass estimates significantly.

In order to estimate the mass of nonstellar material associated with the complex, we make the following assumptions:

(a) The opacity and gas-to-dust ratio in the cloud are the same as that of the interstellar matter in the vicinity of the sun, avoiding interstellar clouds.
(b) The cloud may be represented by a sphere of radius R pc.

We denote the mean hydrogen number density in the interstellar medium by N_{IS} and the visual absorption per kpc by A_{IS}. Then the mass of the gas is given by

$$M_G = 1.43\times10^2 \frac{A_c}{A_{IS}} N_{IS} R^2$$

solar masses, where A_c is the mean visual absorption in the cloud derived from member stars. A mean molecular weight of 1.38 for the interstellar material has been assumed. We adopt $N_{IS}=0.1$ atoms/cm^3 (Carruthers 1967; Morton 1967) and $A_{IS}=0^m.3$/kpc (Allen 1963). As a test of the method we have applied this technique to determine the mass of the Coalsack. Using the dimensions and absorption given by Rodgers (1960), the resulting mass is 3700 $M_\odot$. Assuming a dust-to-gas ratio of 1% by mass this implies 37$M_\odot$ of dust in the Coalsack, a result in satisfactory agreement with Rodgers' determination of 18 $M_\odot$ by a different method.

For the member stars of the BM And group, we adopt an average absorption of $0^m.7$, a result confirmed by star counts taken on the POSS plates. A reasonable estimate of the radius of the cloud is 1 pc. This results in a gas mass of approximately 30 $M_\odot$. Therefore, we conclude that the total mass of the BM And complex is $\lesssim 60\ M_\odot$.

III. OTHER EARLY-TYPE AGGREGATES OF LOW MASS

IC 348: Blaauw (1962) has called attention to the young cluster in the emission nebula IC 348 in the vicinity of *o* Per. He estimates a total stellar mass of only 40 $M_\odot$ for this group. However, due to the proximity of other material connected with the II Per association, it is not possible to determine whether this cluster is a primary condensation or merely a fragment of a larger cloud.

NGC 7129: Dorschner and Gurtler (1964) and van den Bergh (1966) have noted the presence of this reflection nebulosity on the POSS prints, and Racine (1968) has obtained spectra and photometry of a few member stars. Included among the members are a pair of early B stars, one $L_{H\alpha}$ star and T Tauri-like nebulosities. A further study of this region is currently in progress. We have estimated the total mass of the cluster to be about 200 $M_\odot$.

NGC 7023: The cluster of stars associated with this nebulosity consists of a single B3 IVe star surrounded by a halo of faint red irregular variables. We estimate that the total mass of the complex does not exceed 150 $M_\odot$.

IV. CONCLUDING REMARKS

On the basis of the material presented in the preceding sections, it appears that primary condensations of about 100 $M_\odot$ or less have formed recently out of the interstellar matter in our Galaxy. The BM And complex in particular has all the earmarks of a young, isolated condensation that is still intact. The exciting stars are of late enough spectral type so that they have not expelled the nonstellar material from the group. Since BM And lies about 75 pc from the edge of the I Lac association, it could be argued that the cluster is related physically to that aggregate. However, if this is the case, in view of the compact nature of the BM And group, it must have been expelled from I Lac as a separate gas cloud prior to the epoch of star formation. Since the masses of the primary condensations quoted in this paper are more than an order of magnitude smaller than one would expect using Jeans' criterion for gravitational instability, it is probable that the initial phases of such collapses were initiated by a nongravitational mechanism such as thermal instability. We do not imply that all star formation occurs in small groups. However, more attention should be paid to the properties of such groups, since they are inherently simpler structures than larger aggregates such as I Ori.

ACKNOWLEDGMENTS

We thank Dr. S. Morris of the Dominion Astrophysical Observatory for obtaining two spectra and Dr. C. B. Stephenson of the Warner and Swasey Observatory for the objective-prism plates. Special thanks are due to Julian Schreur of the Steward Observatory for gathering some of the *UBV* photometry. One of us (A.F.A.) was supported in part by the National Science Foundation (grant No. GP-8977). The initial phase of this work was undertaken while J.H.H. was a guest investigator in the Space Sciences Division of the Naval Research Laboratory. Additional support for J.H.H. was provided by the National Science Foundation (grant No. GP-7482).

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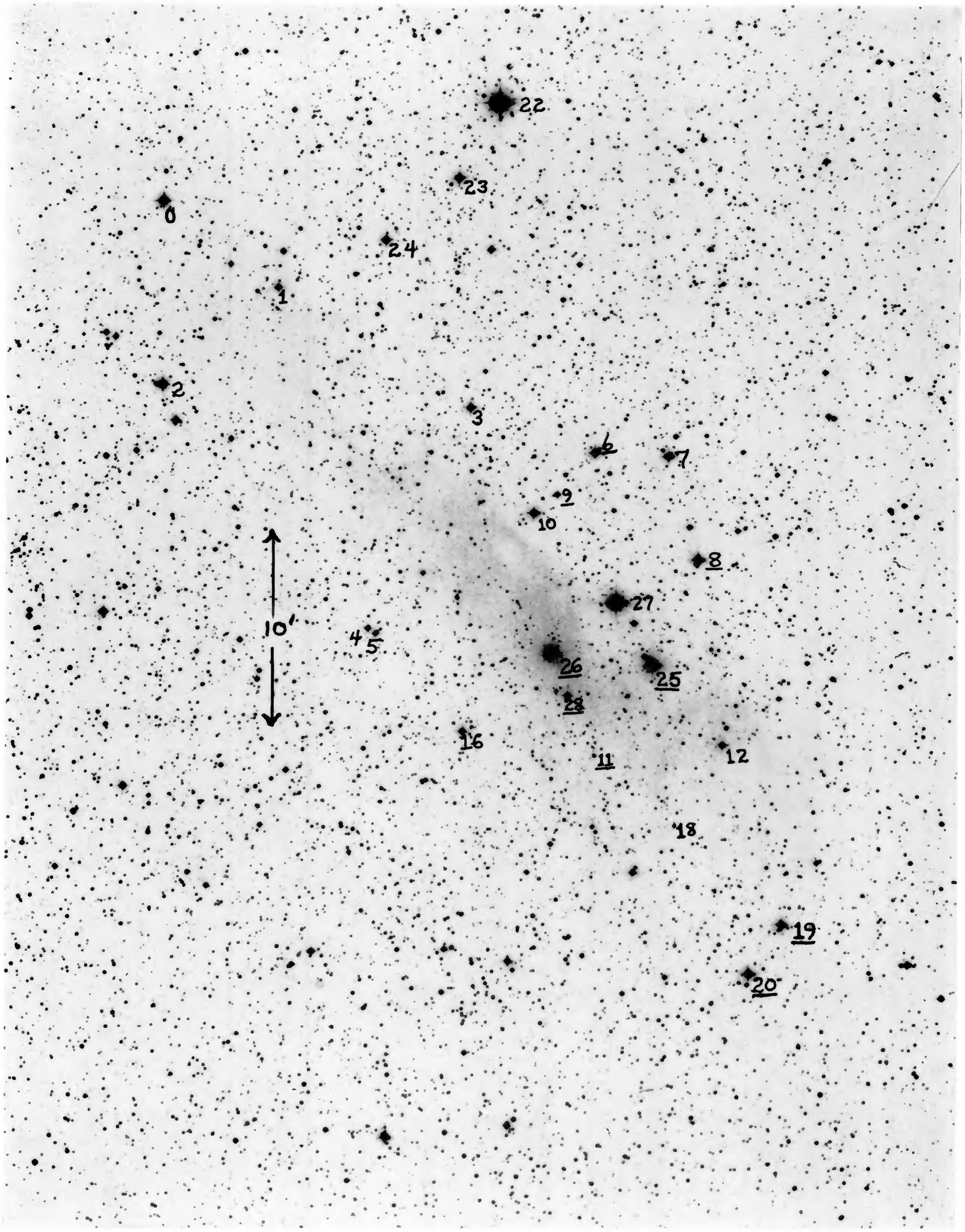

PLATE II(a) (No. 1, Aveni and Hunter). Palomar Observatory Sky Survey E plate of the BM And region.

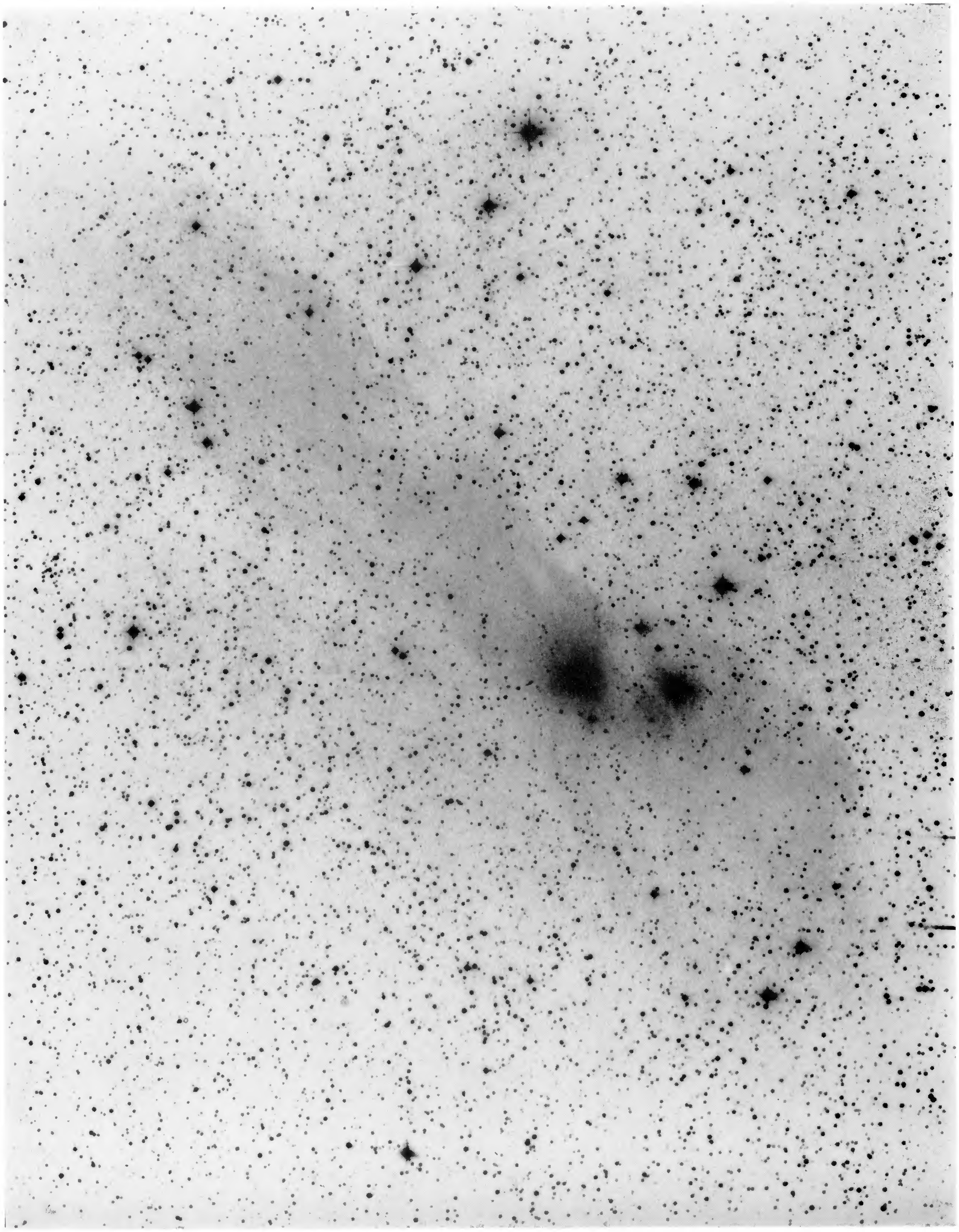

PLATE II(b) (No. 2, Aveni and Hunter). Palomar Observatory Sky Survey O plate of the BM And region.