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THE YOUNG OPEN CLUSTER NGC 346 IN THE SMALL MAGELLANIC CLOUD

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ABSTRACT

We present CCD photometry and spectrographic observations for stars in the open cluster NGC 346, which excites the largest H II region in the Small Magellanic Cloud. These observations show that NGC 346 is an extremely young cluster, containing more than 20 hot O-type stars. A radial-velocity study of the brightest stars, and also of the nearby supergiant Of star Sk 80, discloses atmospheric expansion due to strong stellar winds, but no large-amplitude radial-velocity variations due to short-period binary motion. However, two stars are probably longer period binaries.

Key words: open cluster–CCD photometry–radial velocities–O-type stars

I. Introduction

NGC 346 is the compact star cluster exciting the largest and brightest H II region, N66 (Henize 1956), in the Small Magellanic Cloud (SMC). To our knowledge, this cluster has never been the subject of a photometric study, probably due to its compactness and because the brightness of the H II region where it is immersed greatly hinders both photographic and photoelectric measurements. With the coming into operation of the new CCD detectors, it has become possible to subtract the background efficiently. We have therefore obtained wide-band CCD photometry of the NGC 346 cluster region, which enables us to construct a color-magnitude diagram for this cluster. As expected, this diagram corresponds to a very young cluster.

Spectra of the two visually most luminous stars of NGC 346 were obtained by Walborn (1978), who found one of them to have the earliest O-type spectrum in the SMC, and the other to be a later O-type giant. Walborn (1978) also noted the discrepancy between the high integrated radio continuum flux from N66 (McGee, Newton, and Butler 1976) and the known available ionizing radiation assuming that the bright early O-type member of NGC 346 is the major source of radiative excitation.

We have obtained spectra of the six brightest stars in NGC 346, and also of the nearby Of star Sk 80 (Sanduleak 1968). These spectra show that there are other very early O-type stars within the cluster, one of them classified as early as O3 III(f), which contribute preponderately to the ionization, thus bringing the optical data to a better agreement with the observed radio flux. Furthermore, a new radio continuum map (Mills *et al.* 1982) obtained with higher angular resolution also shows N66 to be a complex of several individual radio sources.

When the present work was essentially completed, we received a preprint (Walborn and Blades 1986) reporting the discovery of two additional O-type stars in NGC 346. Their spectral classification is in agreement with our results.

From a radial-velocity study of the brightest stars in NGC 346, they have been found to exhibit negative Balmer absorption velocities indicating atmospheric expansion as a consequence of their powerful stellar winds. Large radial-velocity variations due to short-period binary motion were not found, but two of the stars could be longer period binaries.

The purpose of this paper is to present these new photometric and spectrographic data and discuss the properties of NGC 346 revealed by them.

II. Observations and Reductions

A. *CCD Photometry*

Using the 1-m Yale telescope at CTIO equipped with the CCD direct camera we secured several frames of NGC 346 and also of the sequence II (Vigneau and Azzopardi 1982) in an area of the SMC very close to the zone under study. The frames were obtained in the *VRI* colors of the Kron-Cousins system. The CCD used was a 388 × 576 GEC chip cooled to −143° C. Each pixel subtended 0.43 arc second on the sky. The seeing was about 1.5 arc seconds during most of our observing run. Flat-field frames were obtained by means of the white spot painted inside the telescope dome. Bias frames were obtained too, but we have found them to be well reproduced by the overscan part of each frame.

The reductions were performed at the La Plata Observatory using software written by one of us (H.G.M.) and

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adapting Stetson's (1979*a,b*) technique of interactive image processing. In order to save disk space we used 191 × 288 "super-pixels" similar to the procedure used by Walker (1984). In this configuration our pixels are 0.86 arc second square indicating that the stars were somewhat undersampled.

A 3 × 3 boxcar filter was convolved with the final stellar images in order to suppress the high-frequency noise and to facilitate the convergence of Stetson's two-dimensional Gaussian fitting. The central 200 × 300 pixel area, containing the cluster core, was reduced at full resolution and without filtering. These differences in the reduction procedures are reflected in the symbols used to represent the stars in the diagrams but no systematic differences resulted between them.

Since our exposures were 5, 4, and 3 minutes long for the *V*, *R*, and *I* bands, respectively, we estimate that our internal errors are below 0.01 mag for stars brighter than $V = 16.1$. Figures 1 and 2 present the finder charts for the NGC 346 cluster region, where the observed stars are identified.

B. *Spectroscopy*

Forty-eight photographic spectra of the brightest stars in NGC 346 were obtained by one of us (V.S.N.) at the Cerro Tololo Inter-American Observatory, Chile. The spectrograms were secured with the Cassegrain spectrograph, equipped with an image tube, attached to the 1-m Yale telescope. A sky suppressor was used in order to avoid as much nebular contamination as possible. However, because the central part of the N66 nebula is extremely bright, and the stars are faint, nebular lines appear on top of Balmer lines for most of the stars.

The spectra have a reciprocal dispersion of 45 Å mm^{-1}, are 1 mm wide, and were recorded on Kodak IIIa-J emulsion baked in forming gas. A He-Ar lamp was used as a comparison source. The plates were developed in D-19 together with intensity calibration plates exposed with a spot sensitometer.

The spectrograms were measured for the determination of radial velocities with the Grant oscilloscope-display engine at IAFE, Buenos Aires. All lines visible in the spectra were measured. The determination of the radial velocities of the stellar absorption lines was in many cases complicated by the presence of superimposed nebular emission lines. The wavelengths used in the determination of radial velocities were taken from Moore's (1945) table.

We have also obtained digitized intensity tracings of the spectrograms, from which we calculated the equivalent widths for the He I and He II lines used in the spectral

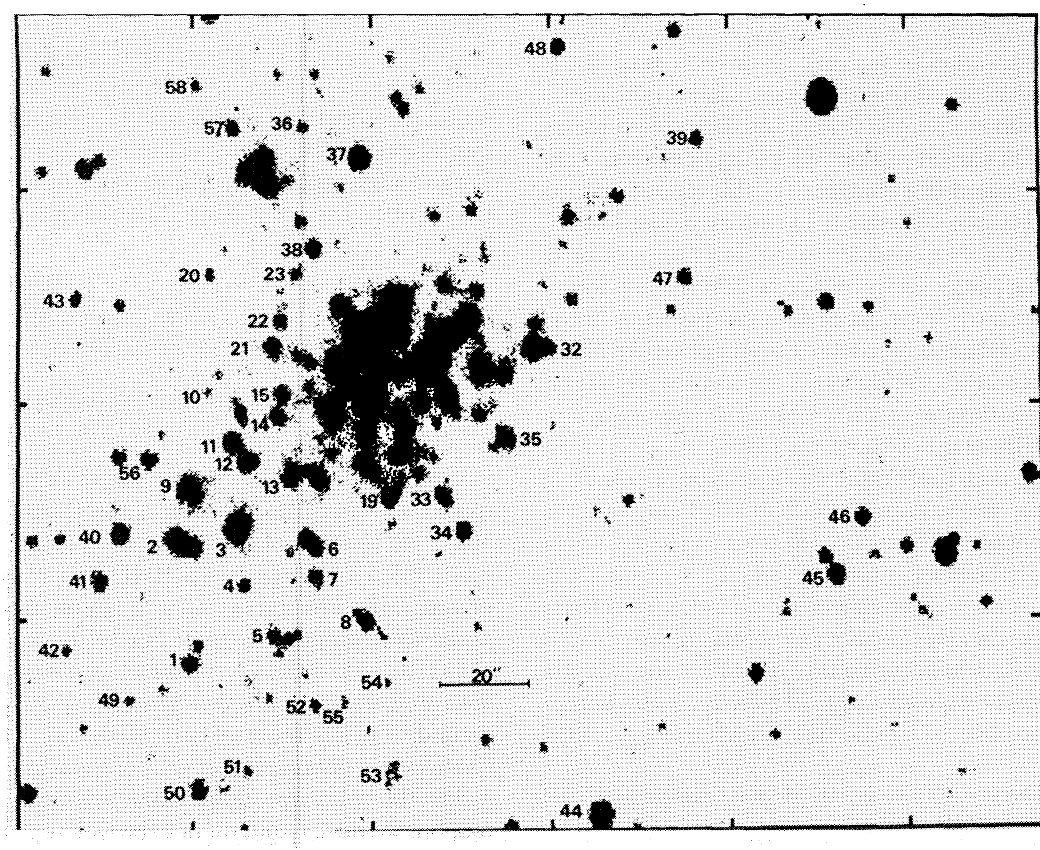

FIG. 1–Identification chart for the stars in the NGC 346 area. Due to the printer characteristics this representation is slightly anisotropic, the scale being elongated in the N-S direction with a 6/5 relation. The scale indicated is therefore an average of both directions. North is to the top and east to the left.

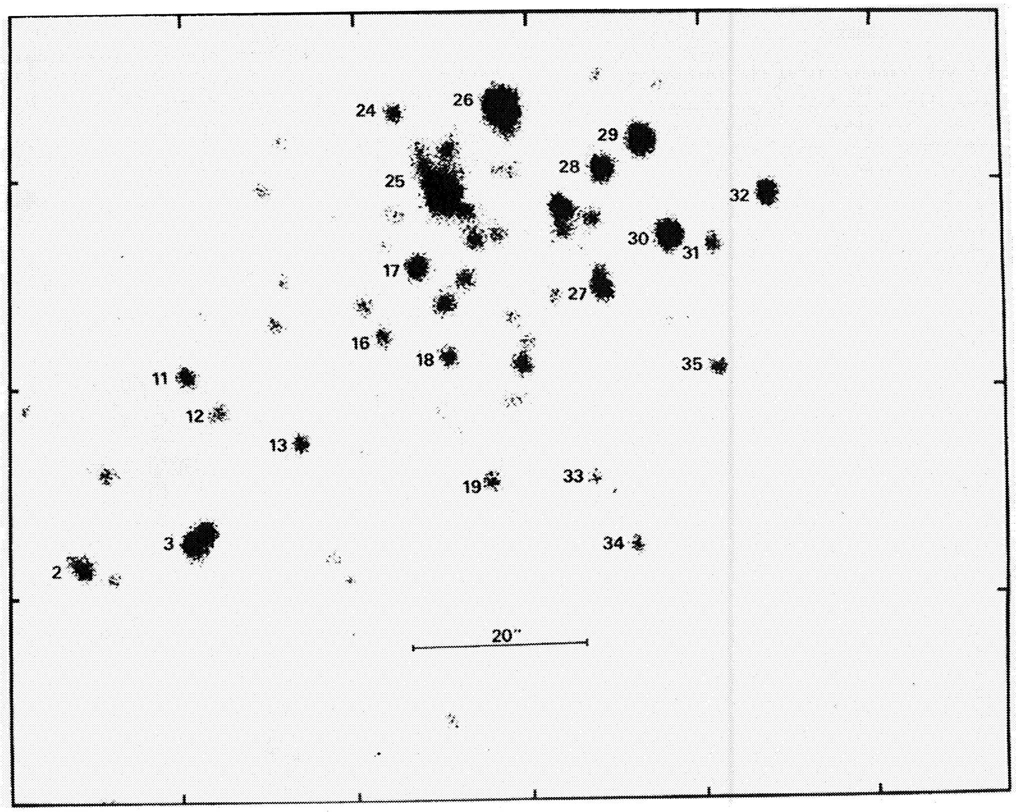

FIG. 2–Identification chart for the inner zone of NGC 346. This is the 200 × 300 pixel area which was reduced at full resolution and contains (although some stars are not labeled) all stars with numbers between 1 and 35. The representation is anisotropic as in Figure 2.

classification of the stars in NGC 346.

III. Results and Their Discussion

The magnitudes and colors derived from the CCD photometry for the stars in NGC 346 are presented in Table I, with the stars identified according to the numbering system of Figures 1 and 2. The two bright unnumbered stars to the west of the cluster (one near star 39 and the other near star 46) were not included in our study because they were found to be close doubles of widely different colors.

A color-color diagram is presented in Figure 3, and Figure 4 is a color-magnitude diagram for stars listed in Table I, except as noted in the remarks. From the intrinsic colors of the O-type stars and also from the clump of stars near observed color indices $(V-I) = -0.04$ and $(V-R) = 0.03$ in the two-color diagram (Fig. 3) we adopted a color excess of $E(B-V) = 0.16$ in constructing the color-magnitude diagram of Figure 4. The large and small circles in both figures denote stars in the inner and outer parts of the cluster, respectively. The absolute magnitudes of the stars in Figure 4 were defined adopting the distance modulus of 19.0 mag for the Small Magellanic Cloud (Gascoigne 1974).

The absorption lines in the spectra of the six stars observed in NGC 346 are very broad, and furthermore, nebular emission lines appear superimposed on the stellar absorptions, which make the resulting spectra therefore difficult to classify. We made intensity tracings of the spectra, which were then summed. Figure 5 shows the mean spectra of the five brightest stars in the NGC 346 cluster, and also the one corresponding to the nearby Of star Sk 80. The spectrum of this latter star has been classified by Walborn (1977) as O7 *Ia*f. Equivalent widths were measured of λ4471 He I and λ4541 He II absorptions in the spectrum of each star in order to classify our spectra following the spectral classification criteria of Conti and Alschuler (1971). The spectral classifications, as well as the absolute magnitudes for the six brightest stars of NGC 346, are listed in Table II. We note that the M_v values for the stars 28, 29, and 32 are consistent with those found for their galactic counterparts (cf. compilation of Humphreys and McElroy 1984). Stars 26 and 30 have brighter M_v, and are probably binaries (see below). The absolute magnitude that we derive for star 25 would correspond to a supergiant. In fact, the spectrum of this star probably refers to a visual multiple system as noted by Walborn (1978).

Table III lists the radial velocities of the stars in NGC 346, and also those of the nebular emission lines, whose mean radial velocity value of $+163 \pm 4$ km s^{-1} is in excellent agreement with previous determinations: +162 km s^{-1} for H109α (McGee *et al.* 1976), $+159 \pm 7$, $+165 \pm 6$, $+152 \pm 8$ for Hα (Bok *et al.* 1964), and +163 km s^{-1}

TABLE I

NGC 346 - VRI (Kron-Cousins) CCD Photometry

Star	V	V-R	V-I	Remarks
1	15.39	-0.16	-0.25	
2	14.26	0.07	-0.02	
3	13.56	0.04	-0.07	1
4	16.48	0.06	0.08	
5	16.18	-0.12	-0.26	
6	14.89	0.19	0.34	1
7	15.93	0.01	-0.04	
8	15.54	0.38	0.64	3
9	14.84	0.42	0.07	
10	17.14	0.07	0.51	
11	14.82	-0.07	-0.17	
12	15.27	0.01	-0.10	
13	15.19	0.04	-0.04	
14	15.56	0.03	-0.08	
15	15.69	-0.00	-0.18	
16	15.25	0.01	-0.19	
17	14.55	0.06	-0.10	
18	15.02	-0.00	-0.10	
19	15.40	0.07	0.02	
20	16.81	0.81	1.52	4
21	15.43	-0.02	-0.14	
22	16.24	-0.02	-0.03	
23	16.84	-0.01	-0.16	
24	14.99	-0.07	-0.28	
25	12.89	0.07	-0.05	2
26	12.39	-0.01	-0.08	2
27	14.15	-0.06	-0.19	5
28	14.14	0.02	-0.07	
29	13.43	0.01	-0.13	
30	13.55	0.02	-0.09	
31	15.08	0.03	-0.07	
32	13.98	0.01	-0.09	
33	15.64	0.17	0.28	
34	15.44	0.03	-0.08	
35	15.03	-0.03	-0.13	
36	16.71	0.46	-0.05	
37	14.19	0.11	0.11	
38	15.51	0.03	-0.11	
39	15.82	0.01	-0.11	
40	14.81	-0.01	-0.17	
41	15.63	0.39	0.29	
42	16.75	0.46	0.26	6
43	16.07	0.06	0.08	6
44	13.36	0.68	1.46	4
45	14.82	0.14	0.20	6
46	15.46	0.14	0.17	6
47	15.58	0.14	0.17	
48	15.50	0.01	-0.18	
49	16.74	0.04	-0.05	
50	14.83	-0.02	-0.15	
51	16.89	0.07	0.08	
52	16.46	0.04	0.10	
53	15.77	0.51	0.82	1
54	17.41	0.47	0.50	
55	17.23	0.12	-0.07	
56	15.71	0.03	0.03	
57	16.04	0.10	-0.09	
58	16.70	0.07	-0.02	

Remarks to Table I:

1: integrated magnitude of a double star, not in Figures 3 and 4.

2: data correspond only to the brightest member of the group.

3: V observation affected by a cosmic ray, not in Figures 3 and 4.

4: red star, not in Figure 4.

5: integrated magnitude of a double star.

6: probably nonmember, far from cluster center, not in Figure 4.

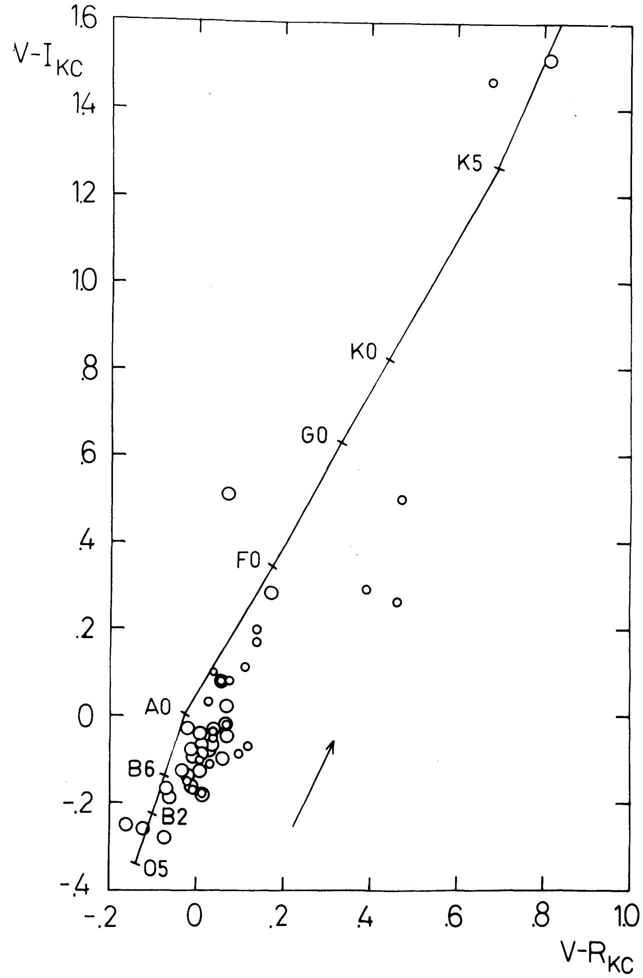

FIG. 3–Two-color diagram for NGC 346. Large circles stand for stars in the inner zone, reduced at full resolution, and closer to the cluster core. The intrinsic colors of the main-sequence stars are indicated as a full line and labeled at selected spectral types. The arrow indicates the direction and the amount of adopted reddening.

(Feast 1970). These values also confirm our radial velocities in Tables III and IV, showing that they are not affected with large systematic errors.

All the observed stars have negative mean velocities of the Balmer absorptions with respect to the velocities of the nebular emissions. This fact indicates mass outflow due to stellar winds at the atmospheres of the observed stars. The mean velocities of the He lines generally agree better with those of the nebular lines.

Large-amplitude, short-period radial-velocity variations are not apparent from our data. However, we note that the last three velocities of the He II absorptions in the spectrum of the star 26 in Table III are more negative by about 40 km s^{-1} than the previous values. This may indicate that the aforementioned star has variable radial velocity, and could be a binary with a period longer than about 15 days. Furthermore, the fact that the mean velocity of the He II absorptions for the first two observing runs

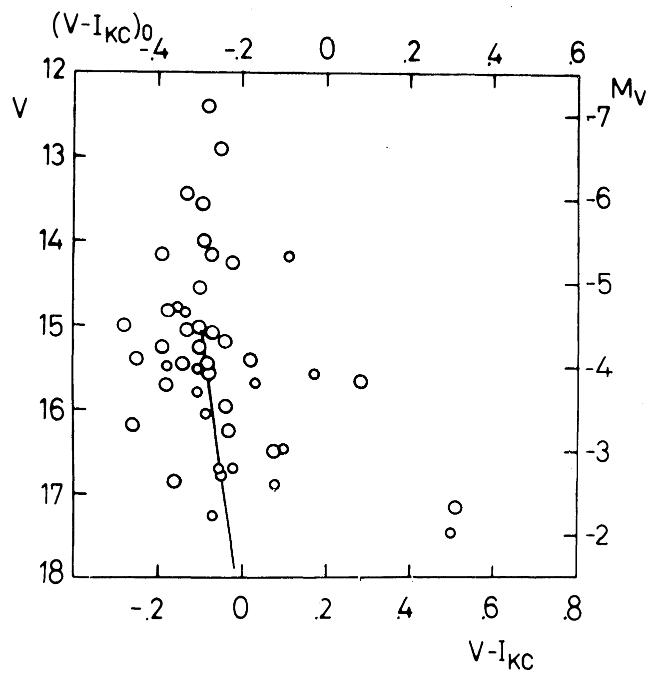

FIG. 4–Color-magnitude diagram for NGC 346. Large circles have the same meaning as in Figure 4. The upper and right margins are labeled with intrinsic color index and absolute magnitudes according to the color excess and distance modulus mentioned in the text. Also the ZAMS is shown as a continuous line.

is more positive than the nebular velocity, and the brighter value of the absolute magnitude of this star as compared to the other stars with similar spectral types, likewise suggest a binary nature.

Also the star 30 has an absolute magnitude brighter than the stars 28 and 32, which have similar spectral types. Although only three radial-velocity values are available for the star 30, they all are more negative than the nebular emissions and could well arise from velocity variations due to binary motion. We therefore consider this star as a probable binary too.

There exist two discrepant radial-velocity values for Sk 80 in the literature, namely $+180 \pm 3$ km s^{-1} (Ardeberg and Maurice 1977), and $+131 \pm 11$ km s^{-1} (Thackeray 1978). This star was therefore placed in our observing program to determine if it might be a binary system. The results of our radial-velocity measures for Sk 80 are presented in Table IV, which clearly shows that no evidence for binary motion with a velocity variation larger than 20 km s^{-1} is found from our data. Different lines in the spectrum of Sk 80 have different radial velocities, similar to the velocity gradients observed in the spectra of Galactic Of stars (e.g., Conti, Garmany, and Hutchings 1977). Note that only the N III emissions in Table IV have velocities comparable to those of the nebular lines (cf. Table III), and that all the absorptions, even those of the He II lines, have negative velocities with respect to the nebular value. This implies that the absorption lines are formed in

TABLE II

Spectral Classification and Absolute Magnitudes of the Brightest Stars in NGC 346

Star	Spectral Type	Source	M_V	Remarks
25	08.5 III	a,c	-6.6	No. 2 in a
26	04 III(f)	a	-7.1	No. 1 in a
28	05-6: V:	c	-5.4	Only 1 weak spectrum
29	03 III(f)	b,c	-6.1	No. 3 in b
30	05-6 V	b,c	-5.9	No. 4 in b
32	04-5 V	c	-5.5	

a: Walborn (1978).
b: Walborn and Blades (1986).
c: This study.

a part of the atmosphere moving outward, as is the case for Galactic stars with strong stellar winds.

NGC 346 is clearly an extremely young cluster, in fact the youngest one found in the SMC, as inferred from the very early spectral types of the brightest stars and the *C-M* diagram which indicates the presence of over 20 stars earlier than about spectral type O9. Also the H II region N66 in the heart of which these young and massive stars sit, is the largest and brightest, and has the highest thermal radio flux (cf. McGee *et al.* 1976) in the SMC.

Walborn (1978) has noted that the integrated radio continuum flux, implying an excitation parameter $u = 332$ pc cm^{-2} (McGee *et al.* 1976) from N66, is too high if the star 26 of the open cluster is the main excitation source for the nebular emission. However, the very early spectral types of the other stars in the cluster, as well, clearly indicate that star 26 alone is not responsible for the high thermal radio flux, but that the other members of the open cluster provide the foremost contribution. From our spectral types, considering the stars 26 and 30 to be spectroscopic binaries with similar components, and the excitation parameters tabulated by Panagia (1973), assuming $T_e = 1.4\ 10^4$ K for the H II region (Dickel 1965), we obtain a combined excitation parameter for the cluster stars with observed spectra of about 290 pc cm^{-2}. Taking into account the large uncertainties existing in the calibration of ionizing photons as a function of spectral type, this value is in acceptable agreement with that determined from the radio continuum flux of McGee *et al.* (1976). Moreover, the new higher angular resolution radio observations of N66 (Mills *et al.* 1982) with a beam of 43 arc seconds, show that the radio source is multiple, consisting of at least three separate sources, the most intense one being centered at the cluster NGC 346. Thus, our optical observations, combined with those of Mills *et al.* (1982) at radio wavelengths, explain the discrepancy noted by Walborn (1978).

We also note the remarkable similarity of the radio continuum map of Mills *et al.* (1982) with the direct photograph of the NGC 346 region obtained by V. M. Blanco, as illustrated in Walborn's paper.

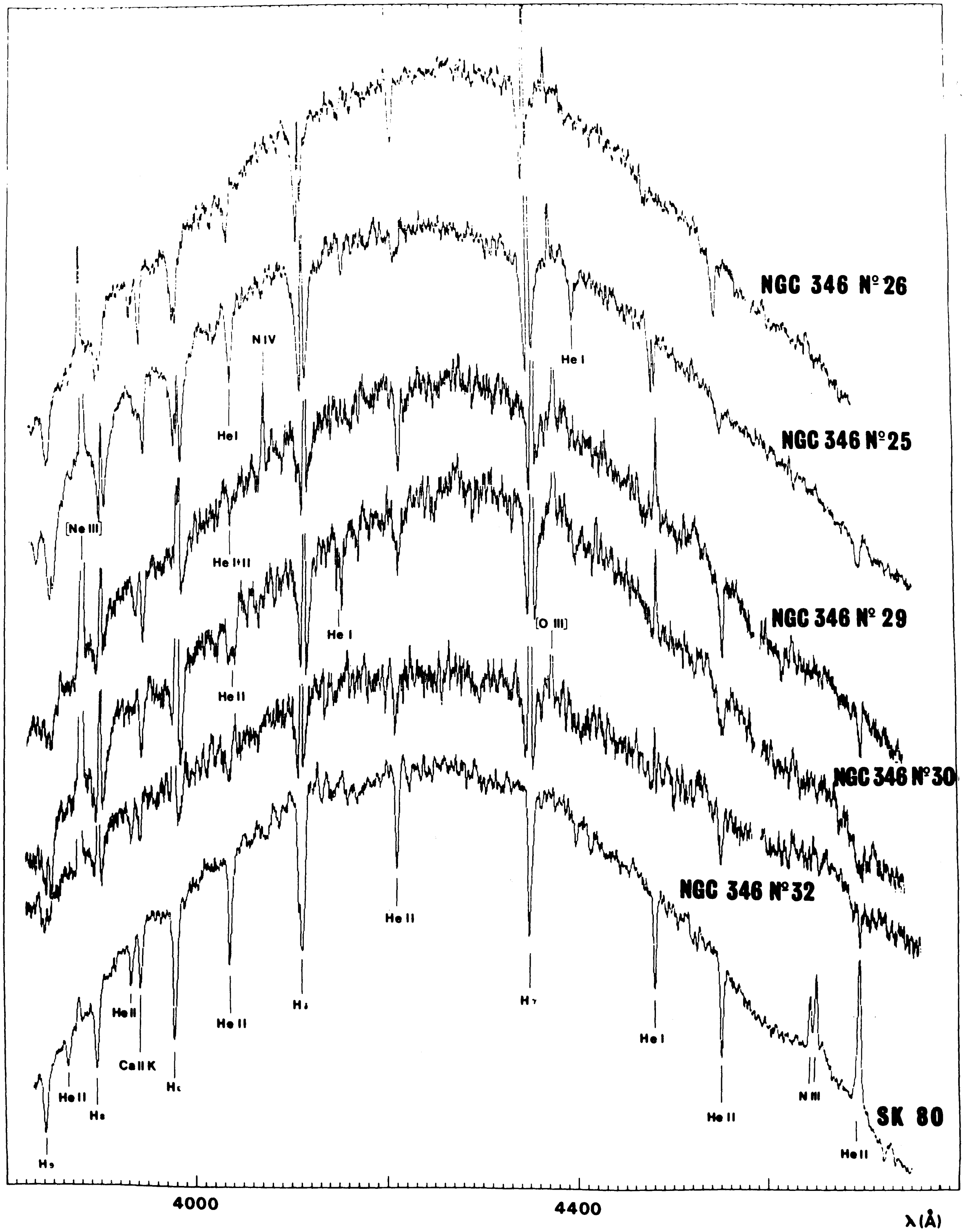

FIG. 5–Relative intensity tracings of the spectra of the five brightest stars in NGC 346, and of the nearby supergiant Of star Sk 80.

The present observations, obtained with a relatively small aperture telescope, have disclosed the presence of numerous hot O-type stars in the cluster NGC 346, which excites the largest emission nebula in the Small Magellanic Cloud. Obviously it would be quite important to obtain higher resolution photometry and spectroscopy with a larger aperture telescope in order to study the stellar content of NGC 346 in more detail.

TABLE III

Heliocentric Radial Velocities (in km s^{-1}) of Stars in NGC 346

Star	JD (2440000+)	Mean H	Absorption He	N IV 4058 emission	Nebular Emission
		a	b		c
26	4894.74	97	149		170
	4895.72	87	160		159
	4896.70	118	162		162
	4897.69	139	228		163
	4898.68	109	168		162
	5189.80	120	155		161
	5190.76	139	174		164
	5191.76	129	187		163
	5192.76	94	179		161
	5196.74	141	195		164
	5198.84	131	172		156
	5199.72	106	160		163
	5254.59		127		165
	5255.57	156	135		164
	5257.68	99	138		159
	Mean	119±21	166±26		162±3
		d	e		c
25	5189.83	139	157		161
	5190.80	147	146		165
	5191.80	127	168		160
	5196.80	113	147		159
	5197.85	115	138		159
	5198.71	130	168		151
	5199.82	153	163		160
	Mean	132±15	155±12		159±4
		d	f	N IV 4058 emission	c
29	5255.60	124	146	162	166
	5256.60	173	155	159	169
	5257.62	128	153	179	161
	5258.61	76	152	165	164
	Mean	125±40	152±4	166±9	165±3
		d	f		c
30	5255.64	133	115		163
	5256.66	141	129		161
	5260.67	109	140		155
	Mean	128±17	128±13		160±4
32	5260.60	120	176		168

Notes to Table:

a - Mean of Hβ, Hδ, Hα
b - Mean of λλ4541, 4199, 4025
c - Mean of Hδ, Hα, Hβ
d - Mean of Hδ, Hα
e - Mean of He I + He II (λλ4471, 4387, 4026, 4541, 4686)
f - Mean of λλ4199, 4541, 4686

TABLE IV

Heliocentric Radial Velocities (in km s^{-1}) of SK 80

JD (2440000+)	absorptions H a	absorptions He II b	absorptions He I 4471	emissions He II 4686	emissions N III 4634-40
4892.61	77	171	135	172	150
4893.78	88	145	125	171	158
4894.70	74	135	107	192	158
4895.75	75	138	127	196	148
4896.66	79	157	127	196	166
4897.65	71	149	137	190	157
4898.65	93	142	146	195	160
5123.92	68	164	157	171	163
5126.91	82	156	149	196	134
5184.76	97	149	119	196	151
5189.77	107	158	158	180	177
5190.83	84	135	130	188	163
5191.83	82	163	133	180	159
5192.80	86	142	120	189	160
5196.85	82	136	108	189	160
5197.81	76	138	133	192	174
5198.80	87	151	130	184	146
5199.75	99	172	155	178	166
Mean	84±10	150±12	133±15	186±9	158±10

Notes to Table:

a - Mean of Hβ, Hδ, Hα
b - Mean of λλ4541, 4199, 4025

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