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Spectroscopic Observations of Several Stars Toward the Bok Globule B361

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Low dispersion spectroscopic observations have been made of six of the stars toward the Bok globule B361 in order to improve the reliability of the distance to this dark cloud. Five of the six stars have been selected from Schmidt (1975) to confirm and supplement his photometric data. The results of our MK classification of these stars reduce the uncertainty of the luminosity of the stars as well as they agree well with those by Schmidt in spectral type. Supplemented by our luminosity class estimation, Schmidt's data are used to re-evaluate the distances to the stars. The resultant distance-extinction diagram indicates a more reliable distance to B361 of 400 pc.

Keywords: MK classification, Bok globule.

§1. Introduction

B361 is a typical large dark globule (Bok and Cordwell 1973) with a round appearance on a Palomar Sky Survey (PSS) print. Because of the interesting appearance and isolation from the surrounding dark nebulosities, this globule has attracted much attention of many astronomers.

At the earliest stages of the study of B361, the gas distribution and the mass were investigated by star counts (Schmidt 1975; Tomita et al. 1979). It was found that the thermal pressure can not support the cloud against the self-gravitation.

These were followed by many works based on the molecular line observations (Milman 1977; Fischer et al. 1979; Clark and Johnson 1982; Arquilla and Goldsmith 1985, 1986; Hirano et al. 1985). These radio observations have provided us with the data which clearly suggest a velocity gradient in B361. However, the interpretation of this velocity gradient is still controversial.

In addition to these observations, measurements of the interstellar polarization of the stars toward B361 have been carried out (Williams et al. 1985; Seki and Hasegawa 1985). Informations on the dust temperature is also available from far-infrared observations (Keene 1981).

While much attention is thus paid on this object, no re-evaluation of the distance to B361 has been made after Schmidt (1975). Though the reliability of the distance estimation of this globule by him is rather higher than those of the other globules, we should point out that c_1 and/or β values are lacked in his uvbyβ measurements for several stars. Since the c_1 index is very important in the estimation of the luminosity for F-type stars, the lack of c_1 index will bring a large uncertainty in the distance estimation. It is desired to re-estimate the distances of the stars and thus re-determine the distance to B361.

The results (especially the values of visual extinction A_V) by Schmidt (1975) are also referred in the polarization works to relate the interstellar polarization to the magnetic field strength. It is also desirable to confirm the A_V values by him, because A_V plays an important role in the evaluation of the magnetic field strength from the interstellar polarization (Seki, Hasegawa 1986).

We intended to confirm and supplement the Schmidt's work by independent observations of some of the stars listed in his paper. Spectroscopic observations with a low dispersion seemed to be appropriate for our purposes.

§2. Observations

The spectroscopic observations were carried out in August 1984 and August 1985 at the Okayama Astrophysical Observatory with the Cassegrain Image-Intensifier-Spectrograph on the 188-cm reflector. With a grating of 600 lines mm^{-1} blazed at 5000 A, this spectrograph provides a dispersion of about 113 A mm^{-1} on the S-20 image intensifier and the same dispersion on a Kodak IIa-O (48 hours baked) plate behind the intensifier. The central wave-length of spectra was 4500 A in the 1984 session and 4300 A in the 1985 session. The slit width and length were set to be 0.2 mm and 6.0 mm, respectively, throughout the sessions. This slit width corresponds to 1."2 of arc.

Spectra were obtained for stars 1, 5, 6, 10, and 16 in Schmidt (1975), and for a star BD+47°3347. BD+47°3347 was selected because polarization measurements had been made by Seki and Hasegawa (1985) but no spectroscopic data was available in literature.

No filter was used in the observations of the above program stars. The spectra were widened to a half or two thirds of the slit length by trailing during the exposures. The exposure times are summarized in Table 1 with the plate numbers, the dates, and some comments. Two or three spectra were obtained for each star in most cases.

In addition to the program stars, we observed 26 MK standard stars covering F0-K2 during the same sessions. These MK standards were selected from Yamashita et al. (1977) and Buscombe (1981). The neutral density filter

Table 1. Exposure times of program stars

Star No. or name	Plate No.	Exposure time (minute)	Observing date	Comments on sky and/or exposure condition
1	IS1472	67	August 18-19, 1985	Hazy, Under
5	IS1288	40	August 26-27, 1984	Cloudy, Under
	IS1460	66	August 16-17, 1985	
6	IS1284	18	August 24-25, 1984	Under
	IS1461	37	August 16-17, 1985	
	IS1461	50	ibid	
10	IS1471	70	August 18-19, 1985	
16	IS1289	18	August 26-27, 1984	
	IS1465	30	August 17-18, 1985	
BD+47°3347	IS1465	4	August 17-18, 1985	
	IS1465	12	ibid	

(ND filter) with density 1 or 2 was inserted in the observation of the bright standard stars. The exposure times were 10-300 sec.

§3. Spectral Type and Luminosity Class

The spectral type and the luminosity class of each program star were determined by comparing visually the prints of the spectra with those of the standards which we had obtained and with those in the published atlases for the MK classification. The atlases which we based on were

(1) Abt, Meinel, Morgan, and Tapscott (1968) with a grating dispersion of 128 A mm^{-1},

(2) Morgan, Abt, and Tapscott (1978) with a dispersion of 125 A mm^{-1},

(3) Keenan and McNeil (1976) with a grating dispersion of about 80 A mm^{-1}, and

(4) Yamashita, Nariai, and Norimoto (1977) with a prismatic dispersion of 73 A mm^{-1}.

In some cases microphotometer measurements of the spectra were made for both the programmed and standard stars to compare and determine the spectral types precisely.

Unfortunately the transparencies of the ND filters used in the observations of the standard stars have a significant wavelength-dependency: the transparency falls off rapidly with decreasing wavelength in the spectral region of $\lambda < 4000A$. The usage of the ND filters has resulted in significantly different appearances of continuum features and in steep continuum gradient at a CaII HK region compared with the spectra without the ND filter. The steep gradient at the CaII HK region causes the decrease in the reliability of the line ratios of CaII K to Balmer lines in the standard spectra. Also, we would not take into account the continuum intensity distributions in the determination of the spectral type.

We give here a comment on the influence of city lights. The spectra taken at the Okayama Observatory have been appreciably contaminated by city lithts; the FeI 4046 line and the FeI,II 4352-53 lines are heavily contaminated by the Hg emissions at 4047-48A and 4358A in the city lights. We did not use the spectral features near the Hg emissions in determining the spectral type.

We now present in Fig.1 the spectra of the program stars in order of spectral type with several spectra of the standards. Our estimations of the spectral types and the luminosity classes are summarized in Table 2 with the distances revised by us (see below). We also give the estimations by Schmidt (1975) in the same table for comparison. The followings are the descriptions of the spectra of the program stars.

Table 2. Estimated spectral types and luminosity classes

	This work			Schmidt(1975)	
Star No. or name	Spectral type	Luminosity class	Distance (pc)	Spectral type	Distance (pc)
BD+47°3347	B5	V-IV	1000	----	----
1	late B	----	1490	A or B	1490 or 2500
6	F1-2	V-IV	300-500	F4V	300
5	F6-8	V-IV	360-650	F7V	140
10	F9-G0	V	440	F6V	420
16	K0-2	V	105	later than G0	----

3.1. BD+47°3347

The spectrum of this star is characterized by the strong Balmer lines and by the definitely recognizable HeI 4471 and HeI 4026 lines. The CaII K 3934 line is very weak in strength. Instead, the HeI 3927 and 4388 lines appear. Hence the spectral type is earlier than A0. With little traces of MgII 4481 and of HeII 4200,4542,4686, the existence of the strong HeI 4471 restricts the spectral type of this star to B0-B8. Finally, we estimate the spectral type to be B5 based on the following evidence: (i) the Balmer lines are significantly strong; (ii) the HeI 3820 line can not be found on the print;

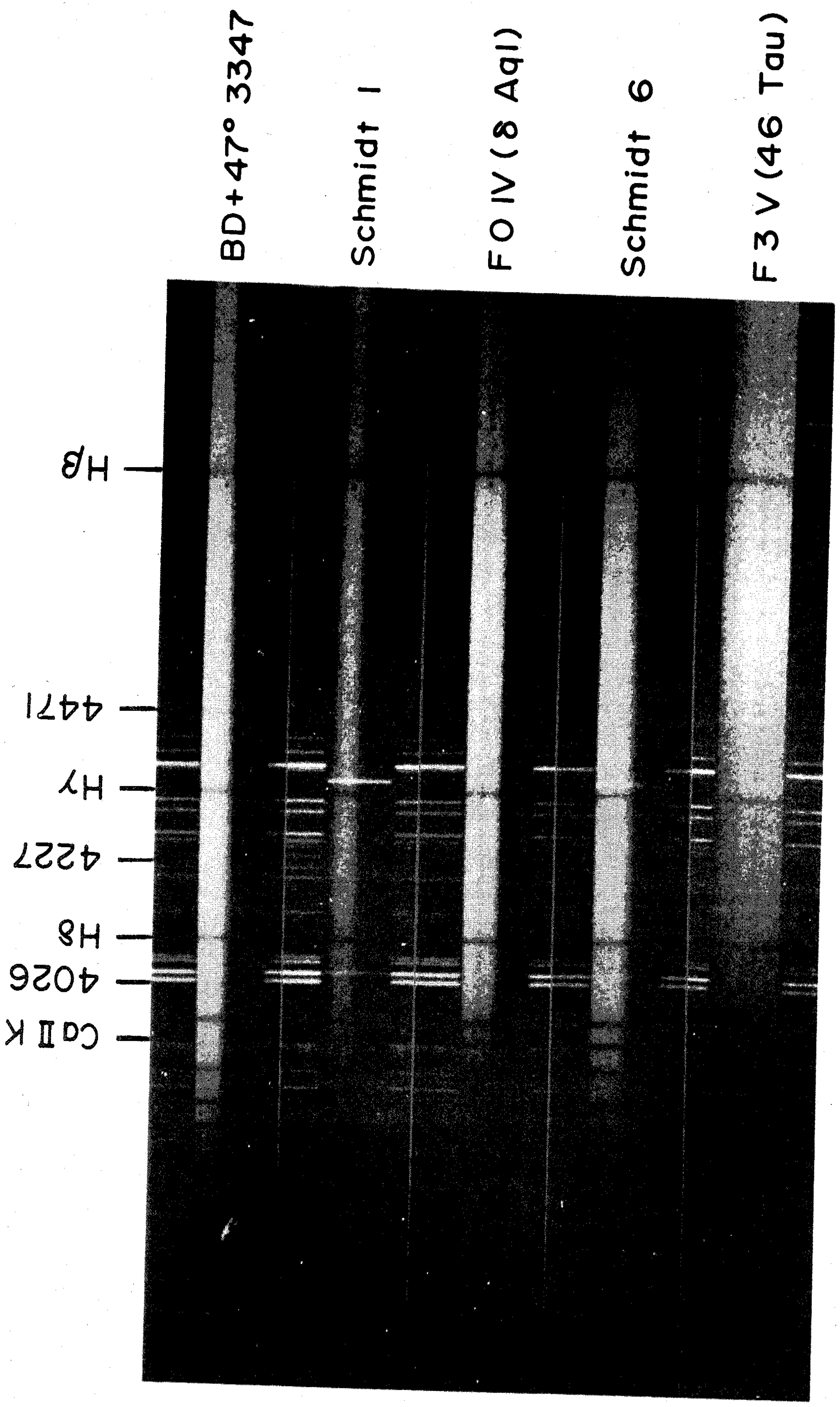
BD+47° 3347
Schmidt 1
F 0 IV (8 Aql)
Schmidt 6
F 3 V (46 Tau)
Hβ
4471
Hγ
4227
Hδ
4026
Ca II K

Fig. 1

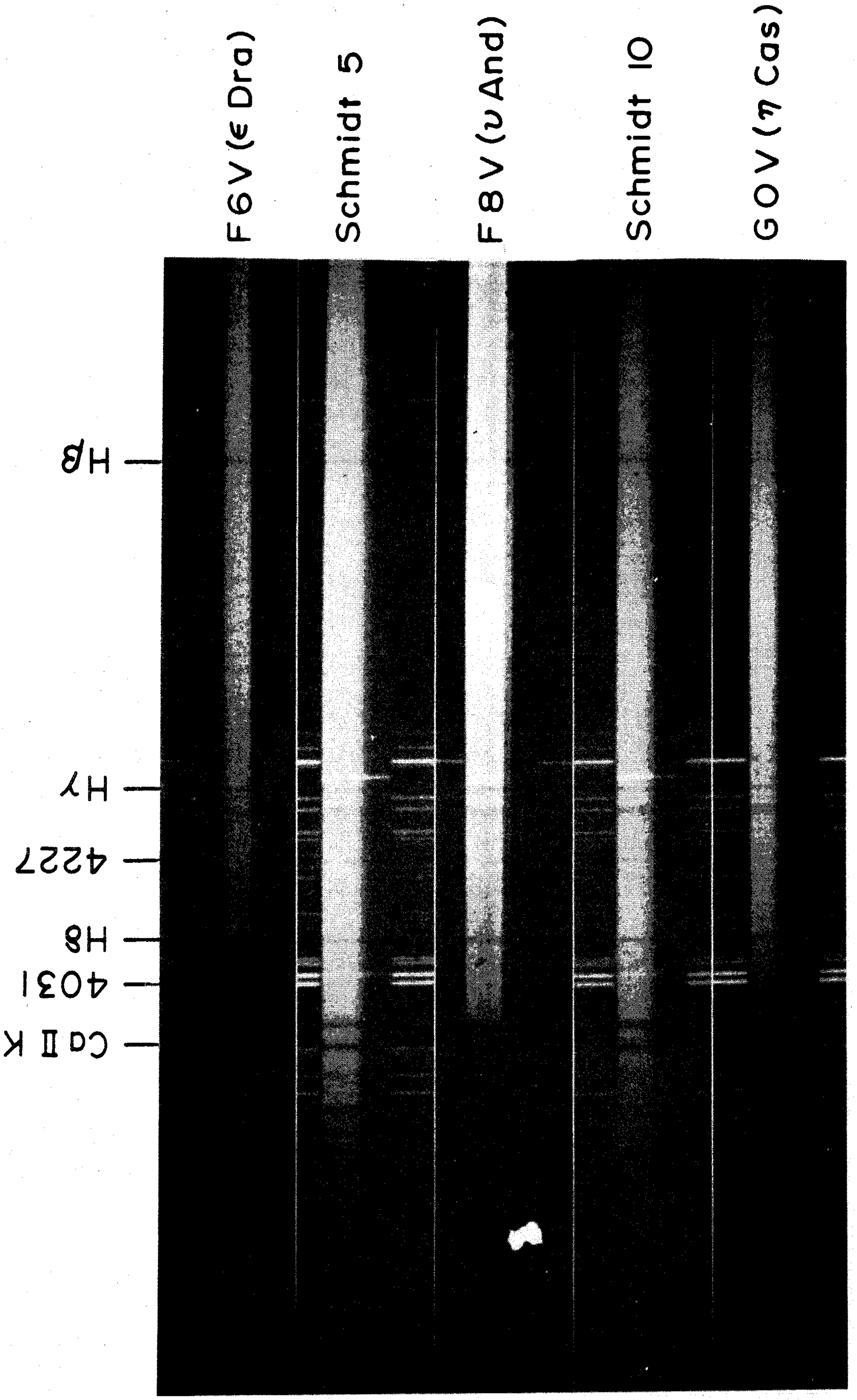

Fig. 1 (continued)

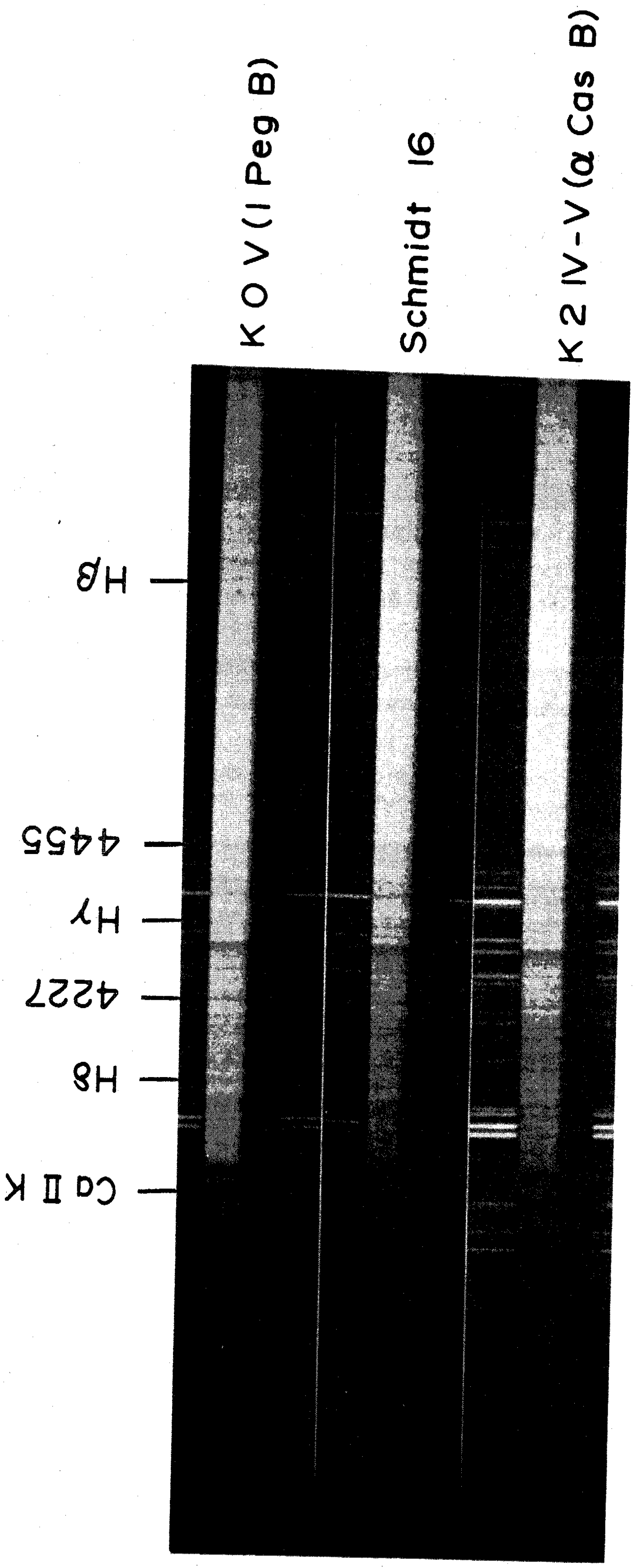

Fig. 1 (continued)

(iii) the HeI 4026 and 4471 lines are easy to be recognized but the HeI 4388 and 4144 lines are not.

The luminosity class of this star seems to be V. However, we have no definite reason for rejecting the class IV.

According to the Bonner Atlas (Schmidt 1968), the visual magnitude by the naked eye observation of BD+47°3347 is 9.4 mag. This suggests a distance of 1.3 kpc or 0.8 kpc for no reddening or an A_V of 1.0 mag, respectively, with a visual absolute magnitude M_V of -1.1 mag for a B5V star (Keenan 1963). If we assume a spectral type of B8V and an A_V of 1.0 mag, the distance is derived to be 0.5 kpc.

3.2. Star 1

Very strong Balmer lines appear in the spectrum of this star. Any lines including the CaII K line other than the Balmer lines can not be found at all, suggesting that this star is a late B star. The broad Balmer lines suggest a luminosity class of V. No further spectral detail of star 1 can be discussed from our under-exposed spectrum.

The photometric data for this star (Schmidt 1975) could be interpreted as either A or B star, and Schmidt tentatively regarded this star as an A star. However, our spectrum indicates that star 1 is a B star. Hence we should adopt the values for the B-star case in Schmidt (1975): the distance should be 1490 pc and the visual extinction should be 2.93 mag.

It should be noted that we do not exclude a possibility that this star is a rapid rotator: the Balmer lines are broad and B-stars are often rapid rotators. However, according to Crawford (1978), if we interpret uvbyβ data of a rapidly rotating B star assuming it to be a slow rotator, the result will not be in serious error.

3.3. Star 6

The Balmer lines and the CaII K line are strong. The CaI 4227 line can be identified easily, while the G-band is very weak. Thus star 6 is a late A star or an early F star. We can hardly recognize metallic lines other than CaI 4227 in the spectrum of this star. This indicates the luminosity class to be III-V, because many metallic lines appear with comparable strengths to CaI 4227 in the class I spectra in the MK spectral atlases.

We have standard spectra of F0IV(δAql), F2III-IV(β Cas), F3V(46 Tau), F6V(ε Dra), and F5III(HD160365) to be compared with the spectrum of star 6. In the F5III and F2III-IV spectra, many metallic lines appear, indicating that the luminosity class of star is IV-V. It is difficult to distinguish the spectrum of star 6 from the either of F0IV or F3V on Fig.1. However, the microphotometric measurements of these spectra show that (i) the Hγ wing is more developed in the F0IV spectrum than in the F3V spectrum, (ii) the G-band is deeper in the F3V spectrum than in the F0IV spectrum, and (iii) the appearance of the spectrum of star 6 at the Hγ-G-band region is that between F3V and F0IV. Thus the spectral type and the luminosity class of star 6 are F1-2 and IV-V, respectively.

According to new calibrations (Crawford 1975) of the uvbyβ system for F type stars, the photometric data (Schmidt 1975) for star 6 correspond to an F2-3 star, though Schmidt (1975) estimated this star to be an F4 star. Hence our estimation and the Schmidt's data for this star are consistent in spectral type. As for the luminosity class, it is not adequate to compare ours with Schmidt's. His photometric data lack the c_1 value, which is a very important index in the estimation of the luminosity class of the F type stars (Crawford 1975), so that his result is in fact highly uncertain. Our results have improved the situation restricting the luminosity class of star 6 to IV-V.

We tentatively supplement the Schmidt's data based on our result. According to Crawford (1975), the average values of δc_1 of F stars are 0.0 mag (ZAMS), 0.032 mag (luminosity class V), and 0.115 mag (class IV). If we assume these values in addition to the Schmidt's data, we obtain an A_V of 1.0 mag and distances of 300 pc (ZAMS), 344 pc (V), and 500 pc (IV). In deriving the above values, we have assumed the relation $A_V = 4.3\ E(b-y)$ and the equations for the intrinsic color $(b-y)_0$ and for the absolute visual magnitude M_V in Crawford (1975).

3.4. Star 5

The CaII HK lines are strong, and the G-band and the CaI 4227 line are evident with the moderate Balmer lines in intensity. A detailed inspection of the spectrum of this star reveals that the Balmer lines are stronger than the CaI 4227 line but weaker than the CaII K line, indicating that the spectral type of star 5 is earlier than G2 and later than F5 (see the atlases which we have referred). Comparing with the published MK atlases, we estimate the luminosity class of this star to be III-V, because the CaI 4227 line is clearly seen but other many metallic lines including FeII 4173-79 are weak. This estimation of the luminosity class is confirmed and improved by comparing the spectrum of star 5 with those of the F6III(HD160365) and F8III(υPeg) standards which we have obtained: the FeII 4173-79 feature and the SrII 4078 line are stronger in the F6III and F8III spectra than in the spectrum of star 5. Thus we conclude that the luminosity class of star 5 is IV or V.

After the more precise comparisons with the standards of F3V, F6V, F8V (υAnd), and G0V(ηCas), we find

(i) the relative strength of G-band to Hδ is lower in star 5 than in G0V, indicating that star 5 is earlier than G0,

(ii) the relative strengths of G-band and CaI 4227 to Hγ are higher in star 5 than in F3V, indicating that star 5 is later than F3V,

(iii) the spectrum of star 5 is similar to the both spectra of F6V and F8V.

We conclude star 5 to be a F6-8 and V-IV star.

We are consistent with Schmidt (1975) in the spectral-luminosity class estimation of star 5. However, his estimation of the absolute magnitude of this star is doubtful, because he has used an uncertain c_1 value: the c_1 value of 0.172 mag in Schmidt (1975) for star 5 seems to be abnormally low for an F star. If we adopt the calibrations by Crawford (1975), the above c_1 value implies a δc_1 of -0.185 mag, whereas δc_1 normally takes values from 0.0 mag to +0.1 mag for ZAMS-IV. Since the estimation of the absolute magnitude depends on δc_1, an adoption of an inaccurate δc_1 value leads to an inaccurate distance estimation. We tentatively assume that the c_1 measurement on star 5 by Schmidt is invalid and that $\delta c_1 = 0.0$ mag(ZAMS), 0.032 mag(V), or 0.115 mag(IV) based on our spectral-luminosity estimation and on Crawford (1975). Then, from the photometric data except for c_1, we find for star 5

$$A_V = 0.537 \text{ mag},$$

$$M_V = 4.17 \text{ mag(ZAMS)},\ 3.82 \text{ mag(V)},\ \text{or } 0.29 \text{ mag(IV)},$$

and

$$\text{distance} = 360 \text{ pc(ZAMS)},\ 424 \text{ pc(V)},\ \text{or } 650 \text{ pc(IV)},$$

where we have used the empirical equations by Crawford (1975) in evaluating $(b-y)_0$ and M_V.

3.5. Star 10

The CaII HK lines and the G-band are strong in the spectrum. The Balmer lines also appear and are comparable to the G-band in strength. The CaI 4227 line is evidently recognized. These characteristics indicate a spectral type of late F or early G. According to Abt et al. (1968), the CaI 4227 line is stronger than the Balmer lines in the spectra of G0 or later, while the CaI 4227 line is weaker than the Balmer lines in the spectrum of star 10. Hence the spectral type of star 10 is earlier than G0.

We have obtained standard spectra for F8Ib(γCyg), F8III(υPeg), F8V, G0Ib(βAgl), G0III(HD6903), and G0V(ηCas). In the spectra of F8Ib, G0Ib, and G0III, we can easily recognize many metallic lines, which scarcely appear in the spectrum of star 10 and in the F8V spectrum. The both spectra of the F8V star and star 10 can also be distinguished from the F8III spectrum: the FeII-TiII 4173-79 feature is stronger in F8III, and the SrII 4078 line is also stronger in F8III than in F8V and star 10. These differences are more easily found by microphotometric measurements of the plates than on photographic prints.

The microphotometric measurements also enable us to determine the spectral type precisely. The relative strength of G-band to Hγ or Hδ in the star 10 spectrum is found to fall between those in the F8V and G0V spectra by the measurement. The relative intensities of MnI 4031-34, CaI 4227, FeI 4272, and FeI 4384 to Hγ are found to be close to those in the G0V spectrum. Based on these results, we conclude that star 10 is a F9V or G0V star. A comparison with the G1IV(ζHer) spectrum suggests that star 10 may not be a class IV star.

Schmidt (1975) estimated star 10 to be an F6V star, slightly earlier than our estimation. His photometric data for star 10 correspond to F7 according to Crawford (1975).

We now re-evaluate the distance of star 10 from the Schmidt's data, where c_1 index is again lacked. If $\delta c_1 = 0.032$ mag (the average value for class V (Crawford 1975)), then A_V will be 0.62 mag and the distance will be 440 pc.

3.6. Star 16

A number of absorption lines are seen in the spectrum. The CaII HK lines are very strong and the G-band is well developed. The CaI 4227 line, the blend of FeI 4271-Cr 4275, and the FeI 4326 line are as strong as the Balmer lines. These characteristics restrict the spectral type of this star to late G or early K.

In the above spectral-type range, the luminosity effect appears as the CN-band absorption in our standard spectra: the CN-band absorption increases to suppress the continuum shortward of 4216 A with the increase of the luminosity. The effect is appreciable even at the luminosity class IV, resulting in an emission-line-like appearance of the less affected part of the spectrum between 4216 A and CaI 4227 A (see the K2IV-V(αCas) spectrum in Fig. 1). The spectrum of star 16 can be compared with the K2IV-V spectrum to be classified to class V.

Finally, we compare the relative intensities of FeI 4271, 4326, 4384, 4405, and 4444, and of CaI 4227, 4442, 4435, and 4455 to Hγ in the spectrum of star 16 with those in the K0V(1 Peg B) and K2IV-V spectra, and conclude star 16 to be a K0-2V star.

Now the photometric data (Schmidt 1975) for this star can be used to estimate the distance of this star. Since the uvbyβ calibrations have not been carried out sufficiently for K stars because of this system being unsuitable for later than G0 stars, we adopt several (b-y) values for nearby (< 10 pc) K stars (photometric standard stars) from Crawford and Barnes (1970) as the intrinsic color $(b-y)_0$. The observed (b-y) of 0.51 mag for star 16 is compared with the intrinsic colors of 0.472 mag(K0V) and 0.492 mag(K1V) to deduce the color excesses of 0.04-0.02 mag or the visual extinctions of 0.18-0.09 mag. If M_V is 5.9 mag (Keenan 1963), the observed visual magnitude of 11.14 mag (Schmidt 1975) implies distances of 102-107 pc. Thus star 16 is very slightly reddened and is undoubtedly a foreground star of B361.

§4. Discussion

The spectral types estimated by us agree well with those by Schmidt (1975): for stars 5, 6, and 10, the disagreements are very slight or non, and for stars 1 and 16 the both estimations are consistent. This suggests that the derived values of A_V for the above stars from the photometric data are not in large error.

As for the luminosity estimation, our measurements have reduced the uncertainties in Schmidt (1975), restricting the luminosity classes of stars 6 and 10 to IV-V. Our results also have improved the reliability of the estimated distances for stars 1 and 5.

However, some uncertainties still remain in our luminosity class estimations. Except for star 16, we could not detect differences between the classes IV and V by our spectral resolution and equipment. Thus, there are some uncertainties in the re-evaluated distances of the program stars.

Finally, we present a revised distance-A_V diagram based on the newly determined and re-evaluated distances and extinctions in the present work. This is shown in Fig. 2, where the values for stars 2, 3, 4, 7, 8, 9, 11, and 12 have been adopted from Schmidt (1975) without corrections.

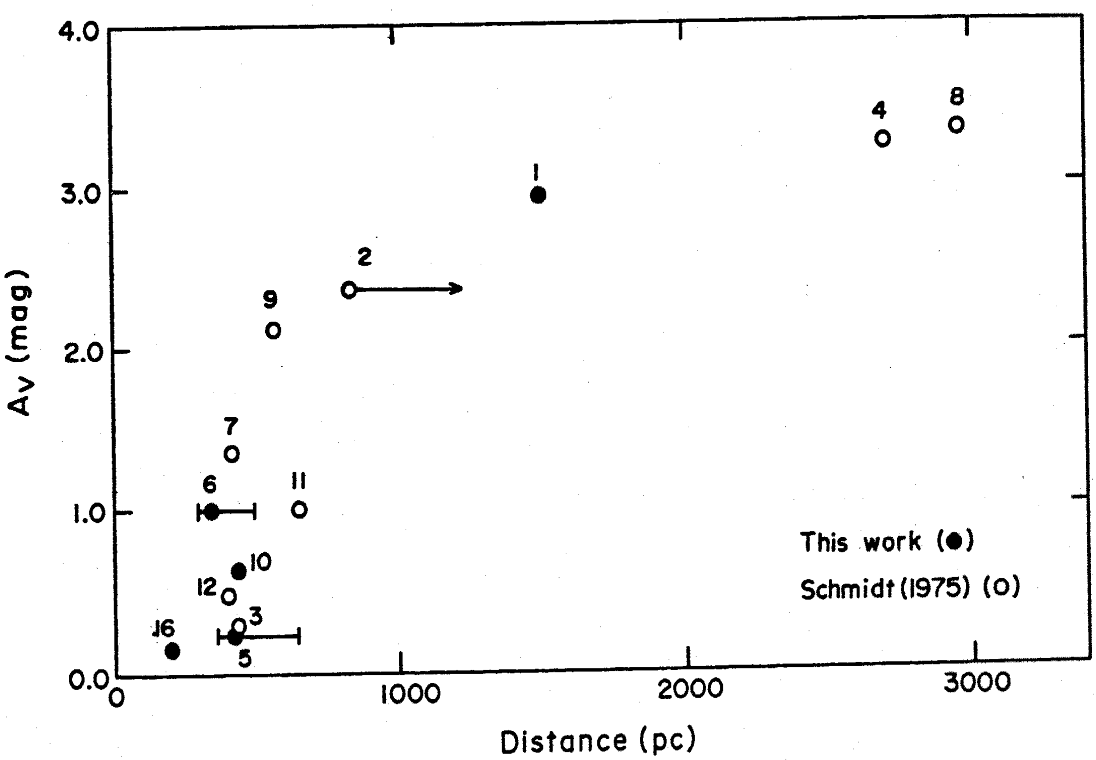

Fig. 2. The visual extinction against the distance. The values adopted from Schmidt (1975) are represented by open circles. Our estimations are represented by closed circles. The error bars for stars 5 and 6 correspond to ZAMS (left end) and class IV (right end), while the closed circles are for class V. See Schmidt (1975) for star 2.

This figure strongly suggests that A_V increases abruptly at around 400 pc and that B361 lies at this distance. Of the stars plotted in Fig. 2, stars 3, 10, and 12 are seen on the outer edge of B361 on the PSS print, so it is possible that these stars with slight extinctions are more distant than B361. Star 5 is, however, seen at the center of B361 with a slight extinction and can be regarded as a foreground star, since the total visual extinction of B361 is about 10 mag (Schmidt 1975). Then the distance to star 5 gives a lower limit of the distance to B361 or 360 pc. It is plausible that B361 lies between star 5 and 7 and therefore is 360-420 pc distant.

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