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Ultraviolet Spectroscopy of the Brightest Supergiants in M31 and M33

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IUE and Groundbased Observations of the Hubble-Sandage Variables in M31 and M33

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Abstract

Ultraviolet spectroscopy from the IUE, in combination with groundbased visual and infrared photometry, allows us to determine the energy distributions of the luminous blue variables, the Hubble-Sandage variables, in M31 and M33. The observed energy distributions, especially in the ultraviolet, show that these stars are suffering interstellar reddening. When corrected for interstellar extinction, the integrated energy distributions yield the total luminosities and black body temperatures of the stars. The resulting bolometric magnitudes and temperatures confirm that these peculiar stars are indeed very luminous, hot stars. They occupy the same regions of the M_{bol} vs. log T_e diagram as do η Car, P Cyg and S Dor in our galaxy and the LMC.

Many of the Hubble-Sandage variables have excess infrared radiation which is attributed to free-free emission from their extended atmospheres. Rough mass loss estimates from the infrared excess yield rates of 10^{-5} $M_{\odot}$/yr. The ultraviolet spectra of the H-S variables are also compared with similar spectra of η Car, P Cyg and S Dor.

Subject headings: galaxies: individual - stars: supergiants - stars: luminosities - stars: variables.

I. INTRODUCTION

The Hubble-Sandage (H-S) variables are among the most luminous stars known. These blue variables are spectroscopically and photometrically similar to the highly luminous, peculiar stars η Car and P Cyg in our galaxy and S Dor in the Large Magellanic Cloud. They are included in the class of stars termed "S Doradus variables" by Kukarkin et al. (1974). Five blue variables in M31 and M33 were the original H-S variables (Hubble and Sandage 1953): AF And (Var 19) in M31 and variables A, B, C and 2 in M33. Other luminous, blue stars which resemble the original group are also included as H-S variables; Hubble Var 15 and Var A-1 (Rosino and Bianchini 1973) and AE And (Sandage and Tammann 1974) in M31 and Var 83 in M33 (van den Bergh, Herbst and Kowal 1975).

These variable stars share common spectroscopic and photometric characteristics. They display irregular variability consisting of extended maximum and minimum phases, frequently lasting several years, and separated by relatively short transition phases. Their light curves may be found in Hubble and Sandage (1953) and Rosino and Bianchini (1973). The spectral characteristics of the H-S variables are discussed by Humphreys (1975, 1978). These variables display a strong, hot continuum extending into the ultraviolet, no apparent Balmer discontinuity and strong emission lines of H, He I and Fe II and [Fe II]. They show ultraviolet excess radiation and some have infrared excesses (Humphreys and Warner 1978). In AF And, Var A-1, Var 83, and Var 2, the infrared excess may be due to free-free emission from extended atmospheres, while in Var A it is very likely caused by circumstellar dust.

Current models suggest that the H-S variables are hot, massive supergiants surrounded by circumstellar envelopes (Humphreys 1978, Gallagher, Kenyon and Hege 1981, Wolf, Appenzeller and Cassatella 1980). Their photometric behavior combined with their low surface gravities, suggest that their atmospheres may be unstable in a manner similar to η Car (Davidson 1971). A better understanding of their evolutionary status and their role in massive star evolution requires information on their total luminosities and temperatures.

For this reason ultraviolet spectra were obtained with the International Ultraviolet Explorer (IUE) of the brightest H-S variables. The ultraviolet fluxes in combination with visual and infrared photometry, allow us to determine their energy distributions, luminosities and temperatures. The ultraviolet spectra can also be compared with possibly related objects like η Car, S Dor, and P Cyg. The observations and the resulting energy distributions are described in sections 2 and 3. The ultraviolet spectra are presented in section 4. In section 5 the importance of the Hubble-Sandage variables in massive star evolution is discussed.

II. OBSERVATIONS

Although the H-S variables are blue and have ultraviolet excesses, they are typically 16 to 17 magnitude in the visual, and only the very brightest can be observed with the IUE. Only five of the H-S variables were bright enough and then only marginally. These stars were all brighter than V = 17 mag and most were near V $\approx$ 16 mag at the time of observation. Long (LWR = 1800-3255 Å and short (SWP = 1135-2085 Å) wavelength low dispersion spectra were obtained of AF And in M31 and Var 83 and Var 2 in M33, but only long wavelength spectra were observed for Var B in M33 and Var A-1 in M31. Because of their faintness these stars could not be seen with the acquisition telescope and had to be acquired by blind offset from nearby stars which were typically V $\approx$ 12 to 14 mag. Table 1 is a journal of the ultraviolet observations, and includes the 1950 coordinates for these objects. The positions were measured from plates of M31 and M33 at Kitt Peak and ESO, and are based on coordinates of SAO stars. The accuracy of these coordinates is 1 arc sec from both the internal accuracy of the measurements and a comparison of the two independent determinations.

All of the 1981 IUE spectra were obtained at NASA's Goddard Space Flight Center, and were reduced according to standard procedures. Known reseau marks and hot pixels were removed from the spectra and patched over before any integrated fluxes were measured. The 1982 IUE spectra of Var 83 and AF And were recorded at the Villafranco Satellite Tracking Station of the European Space Agency. The geometrically and photometrically two-dimensional corrected images were converted to the format of the ESO two-dimensional data reduction system (IHAP) and analyzed in Garching.

Broadband fluxes were measured from the calibrated ultraviolet spectra for three passbands - a short wavelength (SW), a long wavelength (LW), and one (MW) centered on the 2200Å feature. The central wavelength and width of each passband are given below

	λ (μ)	Δλ (μ)
SW	0.160	0.1225-0.1975
MW	0.220	0.2050-0.2350
LW	0.270	0.2350-0.3050

and the corresponding fluxes for the five variables are in Table 2. Narrower passbands were not used because of the stars' faintness.

All of the available visual and infrared photometry is summarized in Table 3. The 1976 and 1977 observations are from Humphreys (1978) and Humphreys and Warner (1978). Additional UBVR photometry was measured in 1980, 1981 and Aug. 1982 with the Mark I 'computer photometer' on the KPNO 2.1-meter telescope and in Oct. 1982 with the pulse-counting photometer on the UM-UCSD 1.5-meter on Mt. Lemmon. Both visual photometers are aperture chopping instruments with simultaneous sky measurements. The JHK observations were made with the indium-antimonide system on the Mt. Palomar 5-meter in Oct. 1980.

III. THE SPECTRAL ENERGY DISTRIBUTIONS

Fluxes ranging from the ultraviolet to 2.2μ are now available for five of the H-S variables, and it is possible to discuss their energy distributions and a determination of their bolometric luminosities and temperatures. However, the observations must first be corrected for interstellar extinction, both foreground and internal reddening. These stars are in young stellar associations in the spiral arms of M31 and M33, and it is very likely that they suffer some reddening due to dust inside their galaxies. Indeed their observed energy distributions show that these stars are suffering some reddening.

Because of their peculiar emission line spectra, we cannot use the observed multicolor photometry to estimate their reddening. An alternative method is available from the neutral hydrogen maps which provide a means of estimating the visual extinction along the line of sight. Knapp, Kerr and Rose (1973) and Savage and Jenkins (1972) have shown that the column density of neutral hydrogen in our galaxy is proportional to E_{B-V}($n_{HI} = 5.6 \times 10^{21}\ E_{B-V}$). The n_{HI} is then determined along the line of sight to each star from the HI maps published by Roberts (1966) for M31 and by Wright, Warner and Baldwin (1972) for M33. The corresponding visual extinction, A_v, is found from the above relationship assuming that the ratio of total to selective extinction is 3. We do not know the exact location of the stars with respect to the neutral hydrogen along the line of sight and it is rather unlikely that all of the extinction estimated from the HI column density should be applied; consequently, we have assumed that on the average the stars experience only half the extinction from the neutral hydrogen. We also know that the minimum A_v due to foreground reddening is 0.4 mag in front of M31 (van den Bergh 1968) and 0.3 mag in front of M33 (van den Bergh 1968, Humphreys 1980). The adopted A_v is then defined as the foreground A_v and half that from the neutral hydrogen column density. This information is included in Table 4, together with the visual magnitude closest to the time of the ultraviolet observations and the resulting absolute visual luminosity from the adopted true distance moduli of 24.1 mag (van den Bergh 1976) and 23.9 mag (Humphreys 1980) for M31 and M33, respectively.

The broadband energy distributions from the ultraviolet to 2.2μ are shown in Figures 1 through 6 for the five H-S variables with IUE observations. The visual and infrared photometry closest to the time of the ultraviolet data are used for the energy distributions. This presents a small problem for some of the stars which were varying, because it was not always possible to have nearly simultaneous observations, but the colors of most of the stars show only small fluctuations even though the visual magnitude may be varying somewhat. Only one complete set of infrared photometry (JHK) is presently available for most of the stars, and these same infrared colors were assumed to be applicable to visual photometry obtained later. The original observations and the data corrected for the visual extinction defined above with the galactic ultraviolet extinction curve from Nandy et al. (1975) are both shown in the plots of the energy distributions. A blackbody is then fit through the dereddened observations using the galactic extinction curve. With these adopted blackbody curves the energy distributions were integrated from 0.09μ to 2.2μ to determine the total flux of the star and consequently its total luminosity. The blackbody temperatures and the luminosities (M_{Bol}) determined in this way are also included in Table 4.

We have investigated the effects of varying the adopted extinction on the blackbody temperatures and luminosities. It is obvious from the observations that all of the stars require some correction for interstellar extinction. The minimum extinction is that due to foreground reddening. A blackbody curve fit to these stars' observations when corrected for minimum extinction can usually be matched reasonably well with the ultraviolet photometry but gives a poor fit to the red and infrared observations, often with a very large infrared excess. (Evidence for free-free emission from some of the H-S variables is discussed below.) Figures 3 and 8 for Var A-1 and Var 15, respectively, show the effects of varying the extinction between the adopted value defined above and the maximum value from the neutral hydrogen column density. For Var A-1 higher extinction is probably appropriate and results in a better blackbody fit to the observations. However, for most of the H-S variables the maximum extinction gives a much poorer blackbody fit to the observations, often resulting in a very large depression of the visual, red and infrared photometry below the blackbody curve. Thus it seems that our adopted extinction based on the foreground reddening and the average extinction from the neutral hydrogen column density is justified for most of the stars.

Figure 1 for AF And illustrates the effects of varying the ultraviolet extinction curve. It is clear that the galactic extinction curve over corrects the flux in the 2200Å feature. This is the case for all of the H-S variables in both M31 and M33 and the excess may even be a little higher for stars in M33. On the average the 2200Å feature from hot stars in the LMC is somewhat lower, and when the ultraviolet extinction curve for the LMC (Nandy et al. 1980) is used the "excess" at 2200Å is largely eliminated for most of the stars, although it is still slightly above the blackbody curve for stars in M33. Use of the LMC extinction curve also results in higher temperature blackbody fits to the observations and consequently higher luminosities. It is perhaps premature to draw conclusions about the ultraviolet interstellar extinction in M31 and M33 on the basis of these data because the 2200Å region has low sensitivity with the IUE detector and the calibration at these low flux levels is uncertain. This is certainly a problem for future work when higher quality data are available for stars in more distant galaxies.

When the best-fit blackbody curve is placed through the ultraviolet and visual observations for some of the H-S variables, it is readily apparent that their infrared fluxes lie somewhat above the blackbody curves. It is very likely that these stars have some excess infrared radiation due to free-free emission from their extended atmospheres. The low resolution IUE spectra are inadequate to comment on evidence for mass loss from the line profiles. However, a rough mass loss ($\dot{M}$) estimate can be determined from the J-K color excess due to free-free emission from Hyland's (1979) empirical calibration of E_{ff}(J-K) versus $\dot{M}/V_\infty$ where V_∞ is the terminal velocity. The adopted intrinsic J-K colors are from Johnson (196(using the best-fit blackbody temperature from the energy distributions to approximate the true stellar temperature. Because we cannot measure V_∞ directly for these stars we adopted the value for P Cyg of 300 km/sec from Barlow and Cohen (1977). This assumption is reasonable because the H-S variables are spectroscopically and photometrically similar to P Cyg (see section V). R81 in the LMC, another member of this class of variables, has a V_∞ of 250 km/sec (Wolf et al. 1981). The resulting mass loss rates are given in Table 4 and for all the stars are around 10^{-5} $M_\odot$/yr which is comparable to the mass loss rates for the other luminous variables P Cyg, R81, R71 and S Dor. Although these rates are quite reasonable, they must be considered preliminary until higher resolution ultraviolet spectra become available.

The energy distributions for the individual stars are discussed below.

M31 - AF And - An LWR spectrum was obtained with IUE in November 1981, and in Oct./Nov. 1982 both SWP and LWR observations were successfully made. The latter observations are used for the energy distribution in Figure 2. It is fortunate that there is nearly simultaneous visual photometry from Aug. and Oct. 1982, although it is necessary to use the infrared colors from the 1980 observations. A 20,000 K blackbody gives a good fit to the ultraviolet and visual data; however, the infrared flux is significantly above any blackbody fit to the short wavelength observations. The same is true with the 1980 and 1981 observations. This infrared excess radiation, attributed to free-free emission in the star's extended atmosphere corresponds to a mass loss rate of 4.1 x 10^{-5} $M_\odot$/yr.

Var A-1 - Only 'long wavelength' (LWR) observations from IUE are available for Var A-1 and its energy distribution is shown in Figures 3a and 3b. The visual photometry from Dec. 1981 was obtained only one month after the ultraviolet spectrum. As with AF And it is difficult to fit the infrared observations with the visual and ultraviolet data. Figure 3a shows a 15,600 K blackbody fit to the data corrected for the adopted extinction. However Gallagher, Kenyon and Hege (1981) suggest that Var A-1 may be in a region of high extinction. For this reason, the observations are also shown in Figure 3b corrected for extinction based on the maximum value from the neutral hydrogen column density. A 27,300 K blackbody then gives a tighter fit to the observations at all wavelengths with a small excess in the infrared. A mass loss rate of 1.2×10^{-5} $M_{\odot}$/yr is derived from this free-free emission in the infrared.

M33 - Var 83 - This star seems to be the hottest in the group at this time. It is also now the visually brightest; consequently, it has the largest number of IUE observations. It is worth noting that Var 83 has been slowly getting brighter over the past six years and it is now the brightest it has ever been observed (V = 15.4 mag). Both LWR and SWP observations of Var 83 were obtained in June and November 1981 and in Oct./Nov. 1982. During this time the star brightened in the visual by nearly a magnitude. This makes it possible to compare the star's temperature and total luminosity as it brightens.

The energy distributions are shown in Figures 4a and 4b for the Nov. 1981 and Nov. 1982 observations, respectively. The 1981 visual photometry was obtained only one month later, but the infrared data are from the previous year. The best blackbody fit to the 1981 observations gives a temperature of 29100 K with an infrared excess, most likely the result of free-free emission. The corresponding mass loss rate is 3×10^{-5} $M_{\odot}$/yr. The 1982 observations show a significant change in the fluxes for both ultraviolet passbands. The short wavelength (.16μ) flux decreased while the star brightened at the longer wavelength (.27μ). The energy distribution clearly shows a shift in the peak flux to longer wavelengths, and a 20,000 K blackbody gives a good fit to the 1982 data. As the star brightened in the visual, its temperature decreased significantly by nearly 50%, however the total luminosity of Var 83 remained essentially the same; the bolometric magnitudes are -11.3 mag and -11.1 mag in 1981 and 1982, respectively.

Var 2 - Both LWR and SWP spectra were obtained with IUE in June 1981, but Var 2 decreased in brightness by nearly one magnitude between Nov. 1980 and Dec. 1981. Figure 5 shows the energy distribution with both sets of visual photometry. The ultraviolet data, taken in June 1981, fit quite well with the 1980 visual and infrared data with a blackbody temperature of 22,800°K. The Dec. 1981 photometry appears too low to fit the ultraviolet data. Therefore it is suspected that most of the decline in brightness occurred between June and Dec. 1981. Indeed, if Var 2 had been as dim in June as the December observations indicate, it could not have been observed with IUE.

The infrared excess yields a mass loss rate of about 3.5×10^{-5} $M_{\odot}$/yr.

Var B - Only the LWR spectrum is available from IUE, and no infrared observations were made of Var B in 1980. With this limited wavelength coverage only a rough temperature estimate can be obtained; however, the available photometry definitely indicates a hot blackbody. A 21,900°K blackbody gives a good fit to the data in Figure 6.

The remaining four H-S variables were too faint at the time for observation with IUE. However for the purpose of completeness it is possible to make some estimate of the temperature and luminosity of AE And and Var 15 in M31 from the visual and infrared photometry. Var C in M33 has been omitted from the discussion in this paper because of its limited wavelength coverage; only visual photometry is available. Var A is the most unique and potentially, the most interesting of the H-S variables. It is the only one which apparently has a circumstellar dust shell. Its peculiar energy distribution is discussed here, but because of its very high reddening it is not possible to determine the temperature and luminosity without further long wavelength observations.

M31 - AE And - This blue variable has photometric data from the visual through the infrared. The 1980, 1981 and 1982 visual observations are all shown in Figure 7 with the 1980 infrared photometry. The observed energy distribution is fit reasonably well by a 15,000 K blackbody. It is possible that a higher temperature blackbody could be drawn through the visible points, with the infrared partially attributed to free-free emission. Obviously, ultraviolet data is needed for a more accurate determination of the temperature of AE And.

Var 15 - This star appears to be the coolest of the H-S variables. The energy distribution in Figure 8a is best fit by a blackbody of 8300 K. Even with the maximum visual extinction from the HI data (Figure 8b) applied, a relatively low temperature is still indicated, 12,400 K. Since a low temperature is unusual for this group of stars, the 1973 and 1977 observations were also examined and they also suggest a temperature near 8000 K.

M33 - Var A - This peculiar star is the most interesting member of the H-S group. It may very well be an extragalactic η Car. Its light curve (Hubble and Sandage 1953, Rosino and Bianchini 1973) is quite similar to η Car. In late 1950, Var A reached maximum brightness ($M_{pg} \approx 15.7$ mag) with a color index of +0.33 mag. After a very rapid decline followed by a secondary peak, the color index had reddened to +1.5 and the star had dimmed to $M_{pg} \approx 19$ mag. It has remained faint ever since (see Table 3). Humphreys and Warner (1978) found that Var A has a large infrared excess with a V-K of 4.8 mag. Var A's photometric behavior plus its infrared radiation suggests the ejection of one or more shells in 1950-53, followed by the formation of circumstellar dust.

Figure 9 shows its energy distribution. Clearly the infrared flux is increasing with wavelength and is highly suggestive of circumstellar dust. The observations corrected for interstellar extinction determined as for the other variables are shown, and it is obvious that Var A may have additional reddening perhaps due to circumstellar dust. To test this idea a value for circumstellar extinction is estimated. Assuming dust formed after Var A reached maximum, much of the presently observed red color may be attributed to circumstellar dust. The color index at maximum, transformed to B-V, is assumed to be due to the star plus some interstellar reddening, and the extinction from circumstellar dust is defined as:

$$(E_{B-V})_{CS} = (B-V)_{now} - (B-V)_{max} .$$

A B-V of 1.01 mag is adopted from the observations in Table 3 and the excess attributed to circumstellar dust is .57 mag. Assuming the same ratio of total to selective extinction (R) as for interstellar dust yields $A_{V_{CS}}$ of 1.71 mag. The value of R may be larger than 3 for the circumstellar dust, but it is at present unknown. This then gives a total reddening of 2.73 mag ($A_{V_{IS}} + A_{V_{CS}}$). The energy distribution corrected for this total reddening i also shown in Figure 9. These results are of course all very preliminary, but it is very interesting that with a correction for circumstellar reddening Var A is still brightening at K(2.2μ). Certainly longer wavelength observations especially at 10μ are needed.

IV. THE ULTRAVIOLET SPECTRA OF THE HUBBLE-SANDAGE VARIABLES

Several of the brightest members of the 'S Doradus' class of variables have been observed previously with IUE. Wolf et al. (1980, 1981a, b) have discussed the ultraviolet spectra of S Dor, R71, and R81 in the LMC.. Cassatella et al. (1979) Luud and Sapar (1980), and Lamers et al. (1983) have described the ultraviolet spectrum of P Cyg, and Cassatella, Giangrande and Viotti (1979) and Viotti et al. (1981) have briefly commented on the spectrum of η Car.

All of these stars are in the Galaxy or the LMC, and are therefore sufficiently bright to be observed with the IUE high dispersion camera. Most of the previous work, mentioned above, is primarily concerned with an analysis of the line profiles and a determination of the mass loss rates. There has been no previous attempt to compare the energy distributions and the main spectral features in the ultraviolet region as derived from the low dispersion data. Therefore, we have also obtained low dispersion spectra of η Car, P Cyg, and S Dor for a comparative discussion with our ultraviolet spectra of the H-S variables for which only a few features can be recognized due to the low signal to noise. The combined IUE short and long wavelength spectra of η Car, P Cyg, and S Dor are shown in Figure 10a with the principal line identifications from the above references. The ultraviolet spectra of AF And in M31 and Var83 in M33 from two different times are shown in Figure 10b.

The observed energy distributions of P Cyg and η Car are strongly affected by interstellar reddening and both stars showed a marked 2200 Å depression. Both the short and long wavelength spectra of η Car show strong features, many in absorption, which are blends of metallic lines and are difficult to disentangle at low dispersion. The spectrum of η Car shows a strong MgII doublet at 2793 Å and 2803 Å, a very broad absorption centered at 2600 Å due mainly to FeII multiplet 1, and a sharp drop below 2415 Å, attributed to a combination of absorption by FeII multiplet 2 and extinction by the 2200 Å feature. In the short wavelength spectrum, CIV is not as prominent as three strong absorption features, centered at 1565 Å, 1620 Å, and 1700 Å to which the main contributors are probably low ionization ions of Fe, Mg, Ni and Al.

In P Cyg, the absorption lines in the 2000-3000 Å region are not as prominent as in η Car, only the MgII doublet and the FeII multiplet 1 are readily apparent. The same is true for S Dor where only MgII is strong, and the fainter lines have been identified with FeII by Wolf et al. (1980). The same authors show that in the short wavelength range CIV at 1500 Å is the strongest feature.

The change in the slope of the continuum of Var83 between June 1981 and November 1982, discussed in the previous section, is easily recognized in the ultraviolet spectra shown in Figure 10b. However, only a few spectral features can be definitely identified. At short wavelengths, SiII + SII at 1260 Å, Si II + OI at 1303 Å and CII at 1335 Å are probably present and are mainly interstellar in origin. SiIV 1394-1403 Å and CIV 1550 Å are not clearly identified. At long wavelengths three absorption features are seen centered at approximately 2400 Å (FeII,2), 2600 Å (FeII,1) and 2800 Å (MgII). In this respect, the spectrum of Var 83 is more like that of η Car than S Dor. In AF And we cannot clearly identify any features.

V. DISCUSSION - THE HUBBLE-SANDAGE VARIABLES AND MASSIVE STAR EVOLUTION

The IUE data presented in this paper confirm the high luminosities and high temperatures suspected from the earlier visual spectra and photometry of the H-S variables. Their bolometric luminosities and absolute visual luminosities corresponding to the time of the ultraviolet observations are summarized in Table 4 together with the blackbody temperatures from their energy distributions. M_V ranges from -7.0 to -9.6 mag and M_{Bol} from -8 to ≈ -11.5 mag. The brightest magnitudes recorded in the literature (see Humphreys 1978 for references and the data) are used to derive the visual luminosities at 'maximum light' which range from -9.0 mag to perhaps as bright as -11 mag. Of course some of these stars may not have been observed at their maximum brightness and it is unfortunate that we do not know their corresponding bolometric luminosities.

The positions of the H-S variables on the M_{Bol} vs. temperature H-R diagram are shown in Figure 11 using the bolometric luminosities and blackbody temperatures in Table 4. This H-R diagram from Humphreys (1983) is a composite for the brightest stars in six Local Group galaxies. Only stars brighter than M_{Bol} = -9.0 mag are shown and the evolutionary tracks for massive stars are from Maeder (1980). It is clear from their positions on the H-R diagram that the H-S variables are among the most luminous stars known. Var 83 and Var A-1 lie on or near the empirically determined upper luminosity boundary for normal supergiants. They are both in the same general region of the diagram where η Car is also found, while AF And, Var 2 and Var B have luminosities and temperatures similar to P Cyg. Only AE And and Var 15 have relatively low luminosities compared to the other H-S variables. Both are presently very faint, perhaps near minimum light, and neither has ultraviolet observations. When ultraviolet data are available higher temperatures might be indicated. Actually these two stars are rather similar to S Dor and R71 in the LMC (Appenzeller and Wolf 1981) which have luminosities between -8.5 and -9.5 mag and temperatures of 9000 to 14000 K.

The H-S variables are obviously very massive stars, presumably evolved past the core hydrogen burning stage based on their positions on the H-R diagram. Because of their irregular variability and probable high mass loss rates, we may surmise that they have reached the point in their evolution when the expected pulsational instabilities in the core (Schwarzschild and Harm 1959, Appenzeller 1970) and high radiation pressure at the surface are responsible for rapid mass loss. In the case of η Car, and presumably Var A, the mass loss is very likely sporadic and very rapid (Humphreys and Davidson 1979) and has resulted in the formation of an extensive dust shell. None of the H-S variables has quite the high luminosity of η Car ($M_{Bol} \simeq -12$ mag), but of course most of them have only been observed for about 60 years and the information on maximum brightness is necessarily incomplete. Nevertheless, P Cyg, S Dor, R71, and the H-S variables appear to be less extreme examples of the η Car phenomenon. It is possible that all stars above some initial mass, say >60–80 $M_\odot$, pass through an η Car/P Cyg stage during which they shed a large amount of matter.

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Table 1

Journal of Observations with IUE

Star	(1950) α	δ	Image No.	Date	Exposure Time (min.)
M31 AF And	0^h40 48.6	+40 55 45.0	LWR 11850	November 1981	420
			SWP 18689	November 1982	391
			LWR 14756	November 1982	316
M31 Var A-1	0^h42 05.6	+41 14 13.8	LWR 11853	November 1981	430
M33 Var 83	1^h31 21.7	+30 19 16.7	LWR 10956	June 1981	210
			LWR 10971	June 1981	390
			SWP 14342	June 1981	165
			LWR 11881	November 1981	340
			SWP 15359	November 1981	395
			SWP 8247	October 1982	380
			LWP 1718	November 1982	365
M33 Var 2	1^h31 29.0	+30 23 16.5	LWR 10966	June 1981	240
			SWP 14355	June 1981	180
M33 Var B	1^h31 00.0	+30 22 48.1	LWR 11861	November 1981	360

Table 2

Fluxes from the IUE Observations

Star	Date	Flux (10^{-19} Watts/cm^2) SW(.16)	MW(.22μ)	LW(.27)
M31 AF And	November 1981	-	0.80	2.35
	November 1982	2.40	0.60	2.03
M31 Var A-1	November 1981	-	0.34	1.14
M33 Var 83	June 1981	5.10	1.41	3.50
	November 1981	4.84	1.24	3.51
	November 1982	2.93	1.29	3.99
M33 Var 2	June 1981	3.74	1.09	2.22
M33 Var B	November 1981	-	1.46	3.31

Table 3

Summary of Visual and Infrared Photometry[1]

Star	Date	V (mag)	U-B (mag)	B-V (mag)	V-R (mag)	V-I (mag)	V-J (mag)	V-H (mag)	V-K (mag)
M31 AE And	Sept. 1976	17.00	-0.81	+0.10	+0.34	+0.62	...	...	...
	Oct. 1977	17.33	-0.78	+0.06	+0.24	...	...	...	...
	Nov. 1980	17.94	...	+0.08	+0.41	...	...	+0.91	+0.82
	Dec. 1981	17.79	-0.85	0.00	+0.47	...	...	...	...
	Aug. 1982	17.57	-0.95	+0.08	+0.41				
	Oct. 1982	17.39	-0.96	+0.05	...				
M31 Var 15	Sept. 1976	17.47	-0.49	+0.44	+0.66	+0.84	...	...	...
	Oct. 1977	17.69	-0.57	+0.36	+0.63	...	...	...	...
	Nov. 1980	17.32	...	...	+0.74	...	+1.41	+1.59	+1.96
	Dec. 1981	17.27	-0.49	+0.43	+0.80	...	...	...	...
	Aug. 1982	17.01	-0.35	+0.48	+0.71				
	Oct. 1982	17.35	-0.27	+0.33	+0.95				
M31 AF And	Sept. 1976	16.05	-0.85	+0.11	+0.43	+0.74	...	...	...
	Oct. 1977	16.11	-0.82	+0.18	+0.35	...	...	...	+1.3
	Nov. 1980	16.42	...	-0.01	+0.26	...	+0.74	+1.07	+1.33
	Dec. 1981	16.52	-0.92	+0.13	+0.37	...	...	...	...
	Aug. 1982	16.40	-0.90	+0.18	+0.41				
	Oct. 1982	16.35	-0.91	+0.20	+0.49				
M31 Var A-1	Sept. 1976	16.26	-0.54	+0.41	+0.54	+0.71	...	...	...
	Oct. 1977	16.25	-0.49	+0.40	+0.58	...	...	...	+1.8
	Nov. 1980	16.59	...	+0.39	+0.50	...	+1.13	+1.36	+1.47
	Dec. 1981	16.75	-0.65	+0.42	+0.50	...	...	...	...
	Aug. 1982	16.39	-0.71	+0.40	+0.51				
	Oct. 1982	16.60	-1.12:	+0.35	+0.95:				
M33 Var B	Sept. 1976	17.11	-0.82	+0.01	+0.93	...	...	...	...
	Oct. 1977	17.31	-1.02	-0.11	+0.05	...	...	...	...
	Dec. 1981	16.14	-0.75	+0.22	+0.37	...	...	...	...
	Aug. 1982	16.30	-0.39	+0.14	+0.34				
	Oct. 1982	15.63	-0.51	+0.31	+0.53				
M33 Var 2	Sept. 1976	18.17	-1.00	-0.17	+0.46	...	...	...	...
	Oct. 1977	18.10	-1.03	-0.19	+0.42	...	...	...	...
	Nov. 1980	16.36	...	+0.22	+0.41	...	+0.59	+0.89	+1.05
	Dec. 1981	17.29	-0.93	+0.05	+0.43	...	...	...	...
	Aug. 1982	17.43	-0.85	+0.15	+0.45				
	Oct. 1982	17.63	-1.00:	+0.01:	+0.51:				
M33 Var 83	Sept. 1976	16.72	-0.93	+0.05	+0.22	...	...	...	...
	Oct. 1977	16.63	-0.87	0.00	+0.30	...	...	...	+2.5
	Nov. 1980	16.51	...	+0.10	+0.34	...	+0.27	+0.45	+0.68
	Dec. 1981	16.16	-0.90	+0.05	+0.37	...	...	...	...
	Aug. 1982	15.67	-0.90	+0.18	+0.35				
	Oct. 1982	15.43	-0.83	+0.20	+0.24				

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Table 3 (continued)

Star	Date	V (mag)	U-B (mag)	B-V (mag)	V-R (mag)	V-I (mag)	V-J (mag)	V-H (mag)	V-K (mag)
M33 Var A	Oct. 1977	18.55	+0.05	+0.84	+1.25	...	...	...	+4.8
	Nov. 1980	18.45	...	+1.05	+1.10	...	+2.31	+3.26	+4.43
	Dec. 1981	18.43	...	+1.24:	+1.14				
	Aug. 1982	18.09	+0.11	+0.88	+1.03				
M33 Var C	Sept. 1976	17.17	-0.79	-0.05	...	...	...	...	...
	Oct. 1977	16.98	-0.76	0.00	+0.10	...	...	...	...
	Nov. 1980	17.21	...	-0.01	+0.08	...	...	...	...
	Dec. 1981	17.23	-0.77	+0.10	...	...	...	...	...
	Aug. 1982	17.15	-0.43	+0.09	+0.29				
	Oct. 1982	16.48	-0.59	+0.09	+0.52				

[1]The errors in the visual photometry for most of these stars is .02 to .05 mag and for the infrared photometry it is typically 0.10 mag.

Table 4

Summary of Luminosities and Temperatures for

the Hubble-Sandage Variables

Star	V (mag)	Date	A_V (mag)	V_o (mag)	M_V (mag)	M_{Bol} (mag)	T_{BB} (°K)	$M_{V_{max}}$ (mag)	$\dot{M}$ (10^{-5} $M_\odot$/yr^{-1})
M31 AF And	16.35	Oct. 82	1.05	15.30	-8.8	-10.6	20000	-9.9	4.1
Var A-1	16.59	Nov. 80	1.05	15.54	-8.6	-9.7	15600	-10.6	1.4
			1.70	14.89	-9.2	-11.5	27300	-11.3	1.2
AE And	17.79	Dec. 81	0.70	17.09	-7.0	-8.3	15000	-10.2	-
Var 15	17.27	Dec. 81	1.05	16.22	-7.9	-8.4	8300	-8.9	-
			1.70	15.57	-8.5	-9.5	12400	-9.6	-
M33 Var 83	16.16	Dec. 81	1.10	15.06	-8.8	-11.3	29100		3.0
	15.43	Oct. 82	1.10	14.33	-9.6	-11.1	20000	-9.6	3.0
Var 2	16.36	Nov. 80	.97	15.39	-8.5	-10.7	22800	-9.1	3.5
Var B	16.14	Dec. 81	.75	15.39	-8.5	-10.3	21900	-9.9	-
Var A	18.45	Nov. 80	2.73[1]	15.72	-8.2	-	-	-	-
			1.02[2]	-	-	-	-	-9.6	-
Var C	-17.2	80/81	0.90	16.3	-7.6	-	-	-9.0	-

[1]Var A - A_v includes circumstellar component.

[2]Var A - A_v interstellar only.

Figure Captions

Figure 1 The effects of varying the extinction curve for the ultraviolet are illustrated for AF And. The energy distribution, log λF_λ (watts/cm^2) vs. log λ (microns) is shown for AF And with the 1982 observations (•) corrected for ultraviolet extinction using the galactic curve (O) and the curve for the LMC (◘). The extinction curves for the two galaxies only gave different results for wavelength shorter than about 2500Å. The 2200Å feature can be better fit with a blackbody when the LMC extinction curve is used.

Figure 2 The energy distribution, log λF_λ (watts/cm^2) vs. log λ (microns), for AF And with the 1982 observations (•). When corrected for the adopted extinction (O) using the galactic curve, a 20000 K blackbody gives a good fit to the data with a small excess in the infrared.

Figure 3a The energy distribution, log λF_λ (watts/cm^2) vs. log λ (microns), for Var A-1 with the 1980 (•) and 1981 (▲) observations. A 15600 K blackbody is fit to the data corrected for the adopted extinction, open symbols.

Figure 3b Same as Fig. 3a for Var A-1 with the maximum extinction applied to the observations. A 27300 K blackbody is shown fit to the data with a small excess in the infrared.

Figure 4a The energy distribution, log λF_λ (watts/cm^2) vs. log λ (microns), for Var 83 with the Nov. 1981 observations. When corrected for the adopted extinction a 29100 K blackbody is fit to the data.

Figure 4b Same as Fig. 4a for Var 83 with the Nov. 1982 observations. Comparison with Fig. 4a illustrates the shift in the peak flux for longer wavelengths as Var 83 brightened.

Figure 5 The energy distribution, log λF_λ (watts/cm^2) vs. log λ (microns) with the 1980 (●) and 1981 (▲) observations. When corrected for the adopted extinction (open symbols) a 22800 K blackbody gives a good fit to the 1980 photometry and the ultraviolet data.

Figure 6 The energy distribution, log λF_λ (watts/cm^2) vs. log λ (micrions), for the 1981 observations of Var B. A 21900 K blackbody is shown fit to the limited visual and ultraviolet photometry corrected for the adopted extinction.

Figure 7 The energy distribution, log λF_λ (watts/cm^2) vs. log λ (microns), for AE And. The 1980 (●), 1981(▲) and 1982 (■) visual photometry is all shown. There are no ultraviolet observations. When corrected for the adopted extinction (open symbols) the data is fit reasonably well with 15000 K blackbody.

Figure 8a The energy distribution, log λF_λ (watts/cm^2) vs. log λ (microns), for Var 15 showing the 1980 (●) and 1981 (▲) observations. A 8300 K blackbody is fit through the observations corrected for the adopted extinction (open symbols).

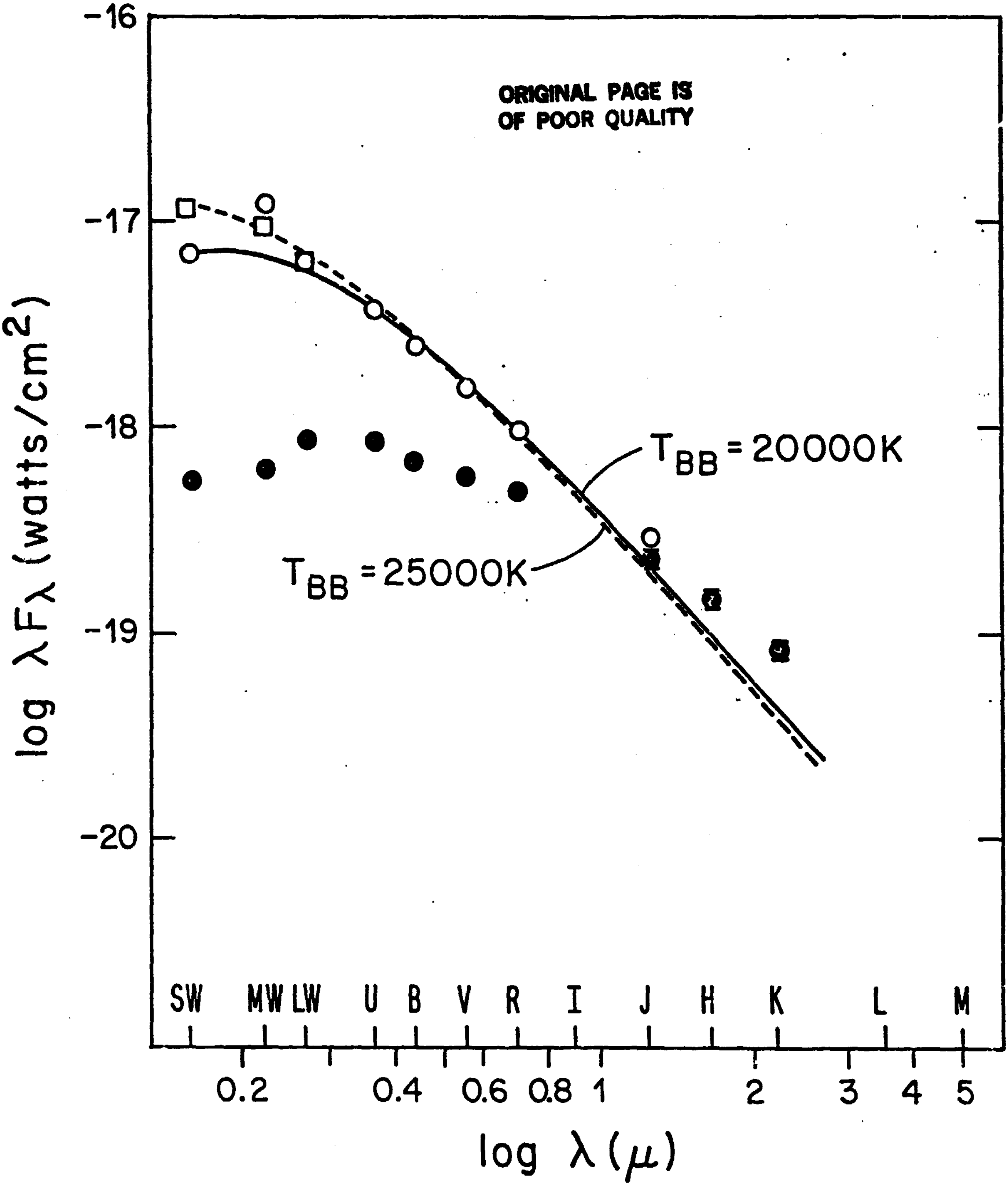
Figure 8b Same as Fig. 8a for Var 15 with the maximum extinction.

Figure 9 The energy distribution, log λF_λ (watts/cm^2) vs. log λ, for Var A with the 1980 observations. The data is shown when corrected for interstellar extinction and for possible circumstellar extinction (see text).

Figure 10a The combined short and long wavelength ultraviolet spectra (1200-3000 Å) of P Cyg and η Car in the Galaxy and of S Dor in the Large Magellanic Cloud (LWR only). The flux scale is indicated on the left for P Cyg and on the right for η Car and S Dor.

Figure 10b The observed ultraviolet spectra of Var 83 in M33 obtained at two different dates and of AF And in M31. The 1982 spectrum of Var 83 has been shifted upward by one unit and that of AF And by two units. These spectra have a poor signal to noise in the 1950 to 2350 Å interval due to the low sensitivity in the IUE camera in that wavelength range.

Figure 11 The HR diagram, M_{Bol} vs. log T_e, for the most luminous stars ($M_{Bol} \leq -9.0$ mag) in six Local Group galaxies. The positions of the H-S variables are marked with X's and by name.



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log λFλ (watts/cm²)
T_BB = 20000K
T_BB = 25000K
SW
MW
LW
U
B
V
R
I
J
H
K
L
M
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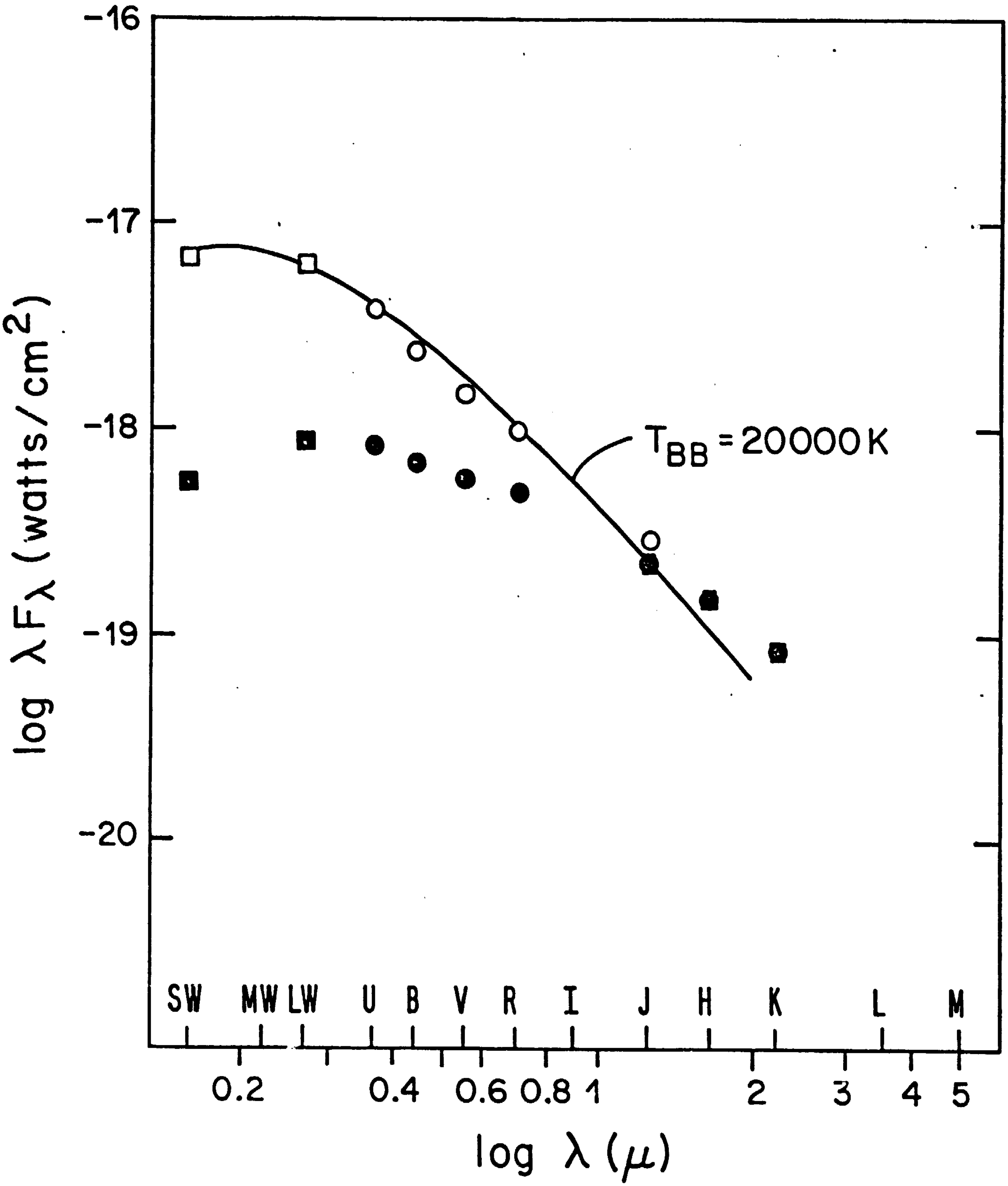
0.6
0.8
1
2
3
4
5
log λ (μ)

Fig. 1 AF And



-16
-17
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-20
log λF_λ (watts/cm²)
T_BB = 20000 K
SW
MW
LW
U
B
V
R
I
J
H
K
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M
0.2
0.4
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4
5
log λ (μ)

Fig. 2 AF And

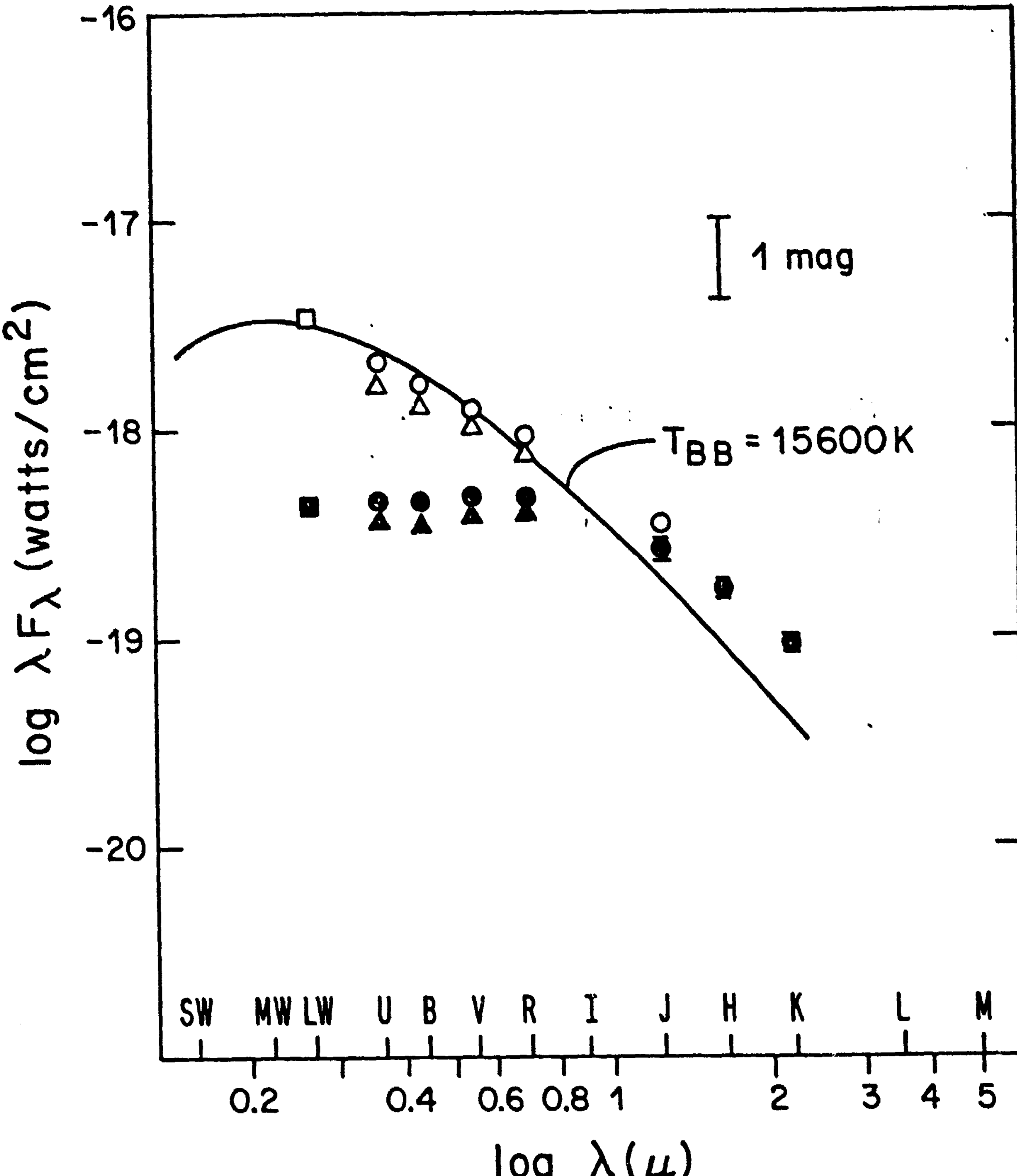
-16
-17
-18
-19
-20
log λF_λ (watts/cm²)
1 mag
T_{BB} = 15600K
SW MW LW U B V R I J H K L M
0.2 0.4 0.6 0.8 1 2 3 4 5
log λ(μ)

Fig. 3a

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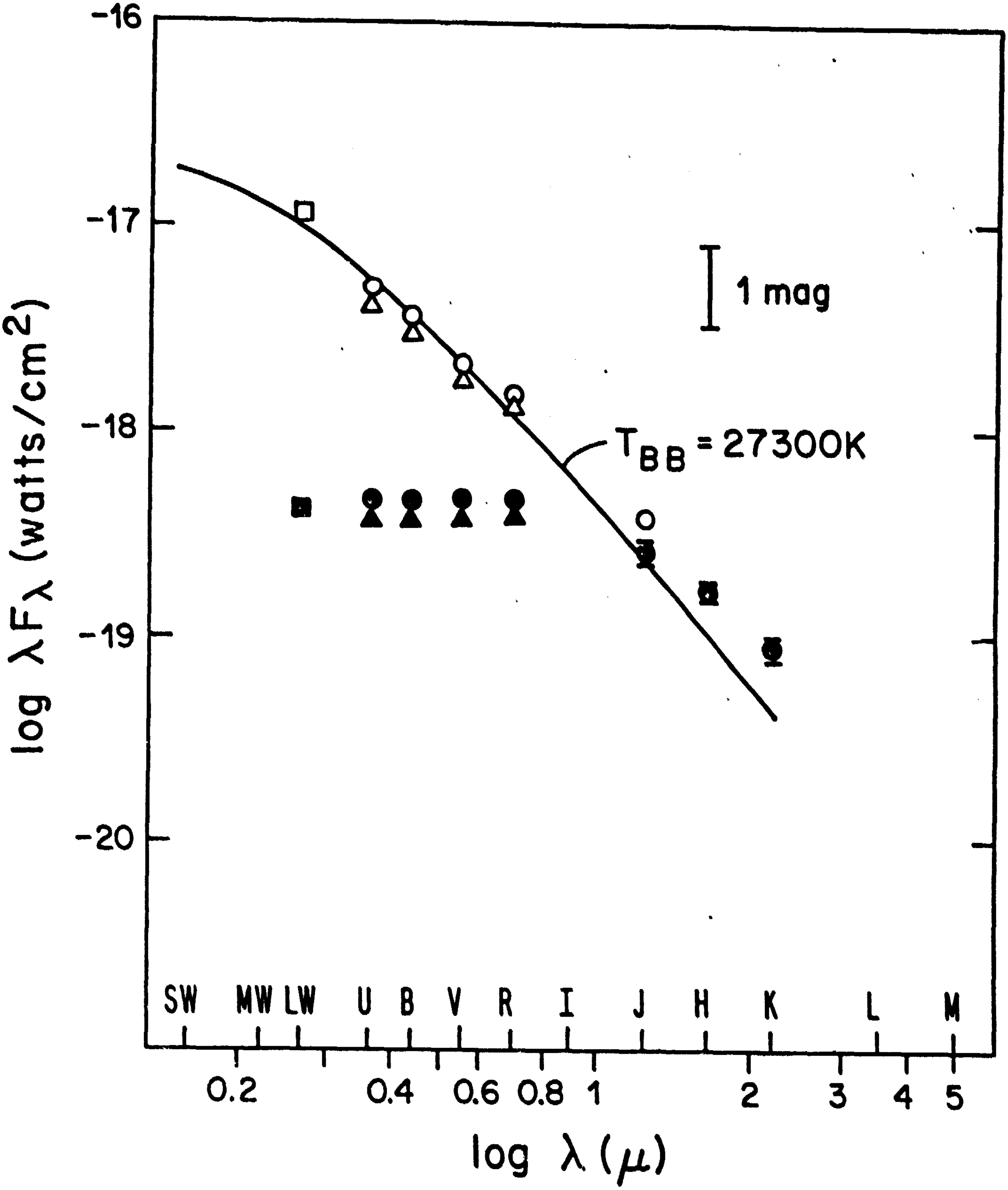


Fig. 3b Van A-1

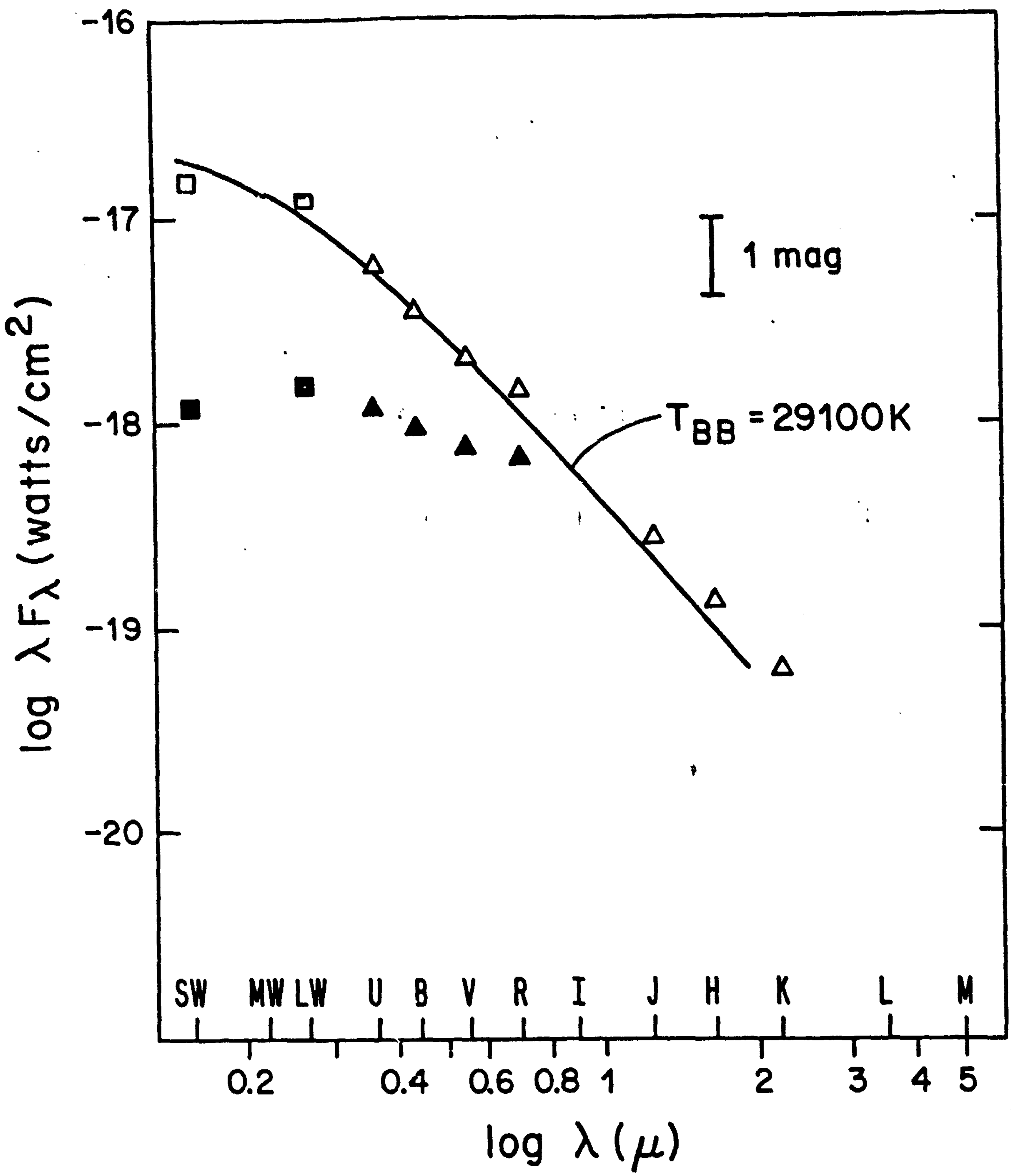
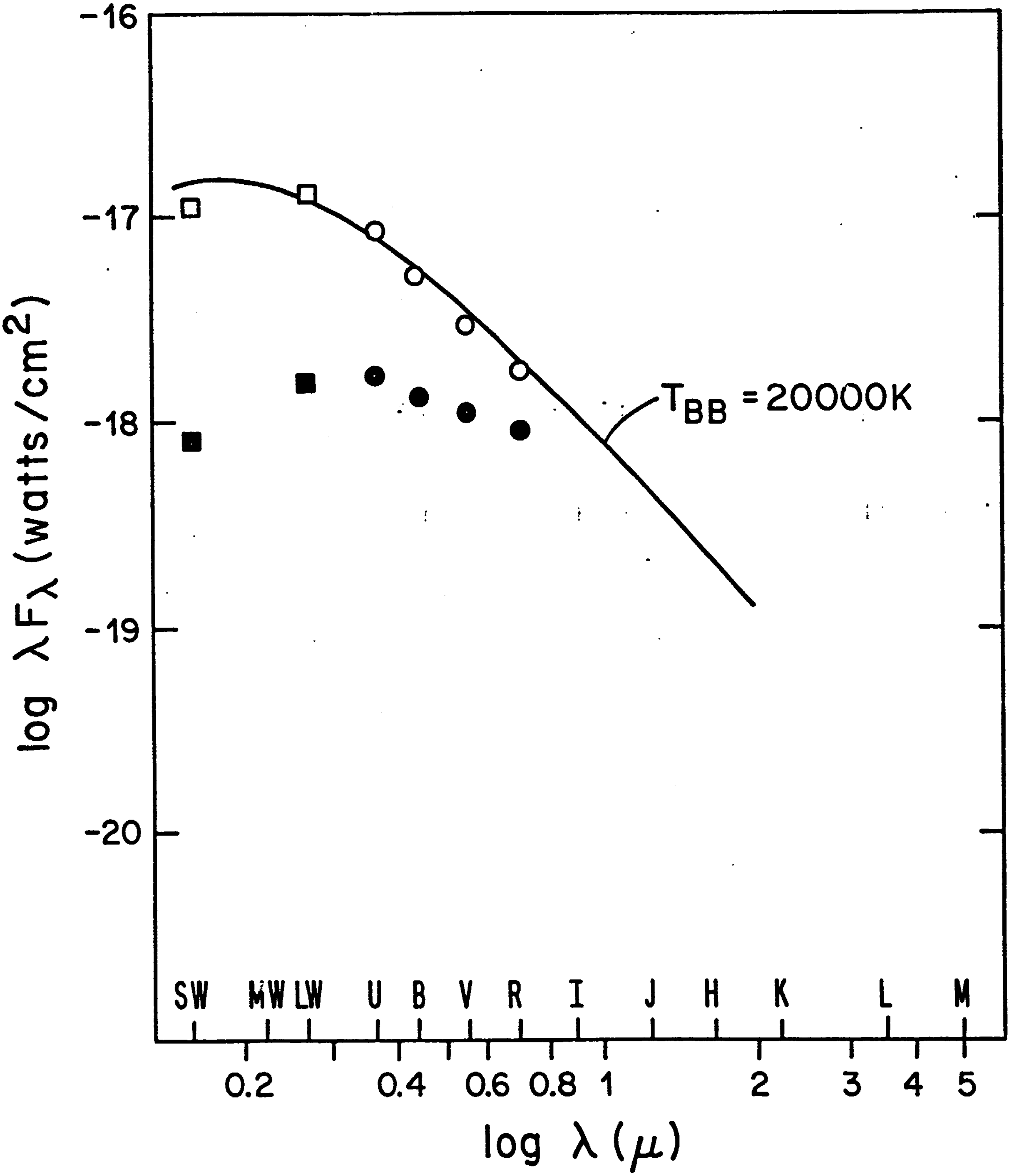

-16
-17
-18
-19
-20
log λ F_λ (watts/cm^2)
1 mag
T_{BB} = 29100K
SW MW LW U B V R I J H K L M
0.2 0.4 0.6 0.8 1 2 3 4 5
log λ (μ)

Fig 4a Van 83



-16
-17
-18
-19
-20
log λF_λ (watts/cm²)
T_BB = 20000K
SW
MW
LW
U
B
V
R
I
J
H
K
L
M
0.2
0.4
0.6
0.8
1
2
3
4
5
log λ (μ)

Fig. 4b Var 83

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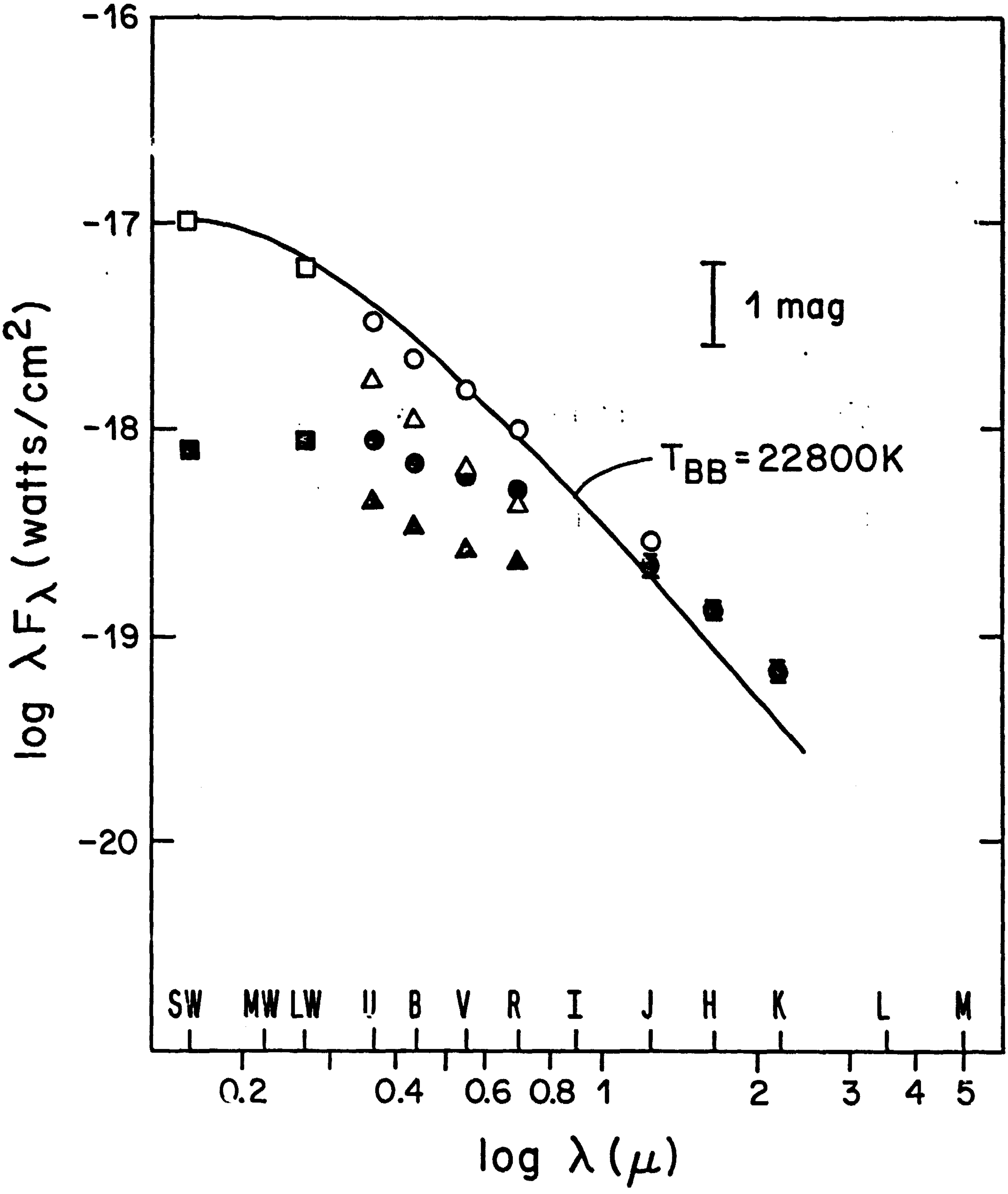


Fig 5 Var 2

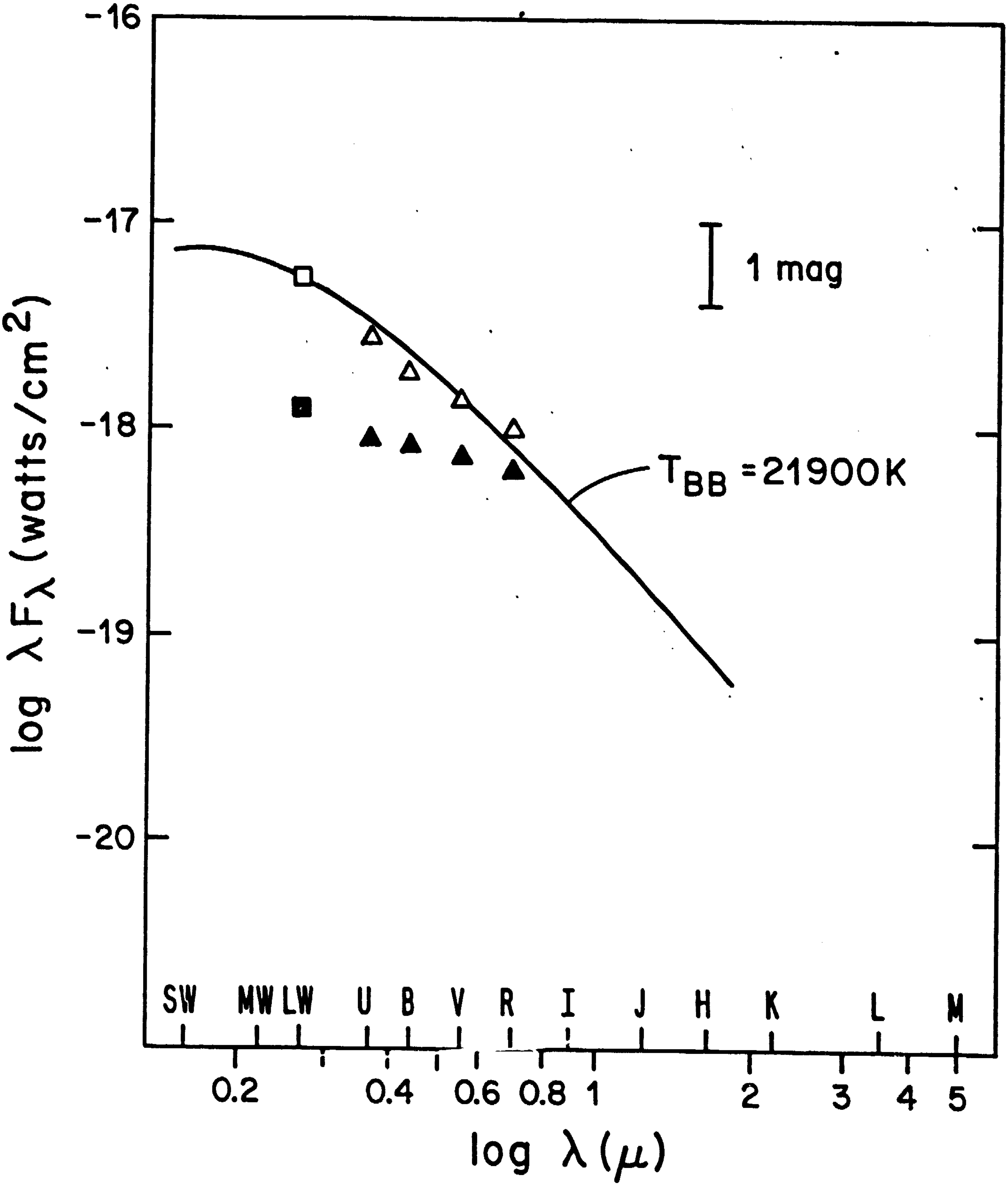
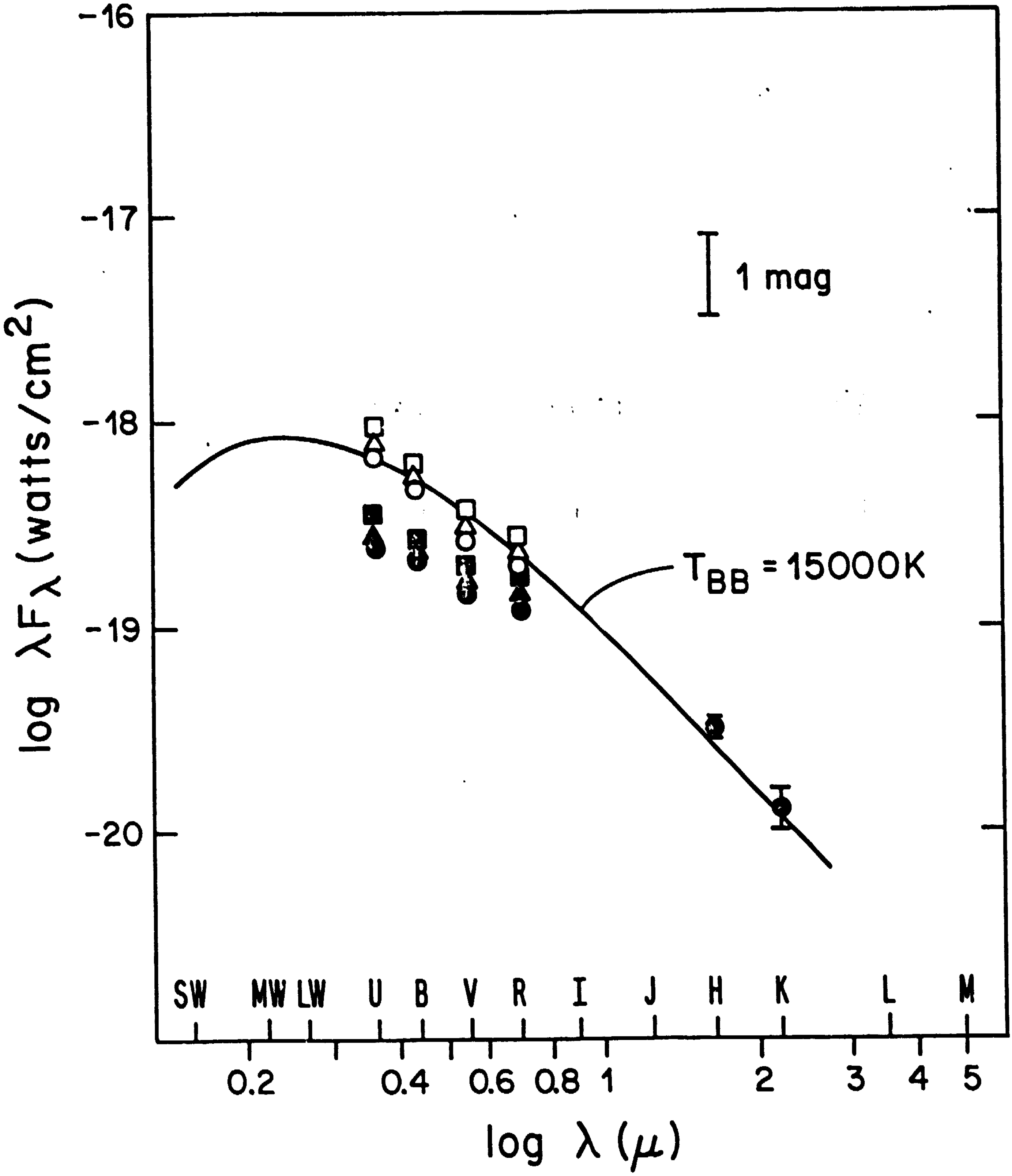

-16
-17
-18
-19
-20
log λF_λ (watts/cm^2)
1 mag
T_{BB} = 21900K
SW
MW
LW
U
B
V
R
I
J
H
K
L
M
0.2
0.4
0.6
0.8
1
2
3
4
5
log λ (μ)

Fig 6 Van B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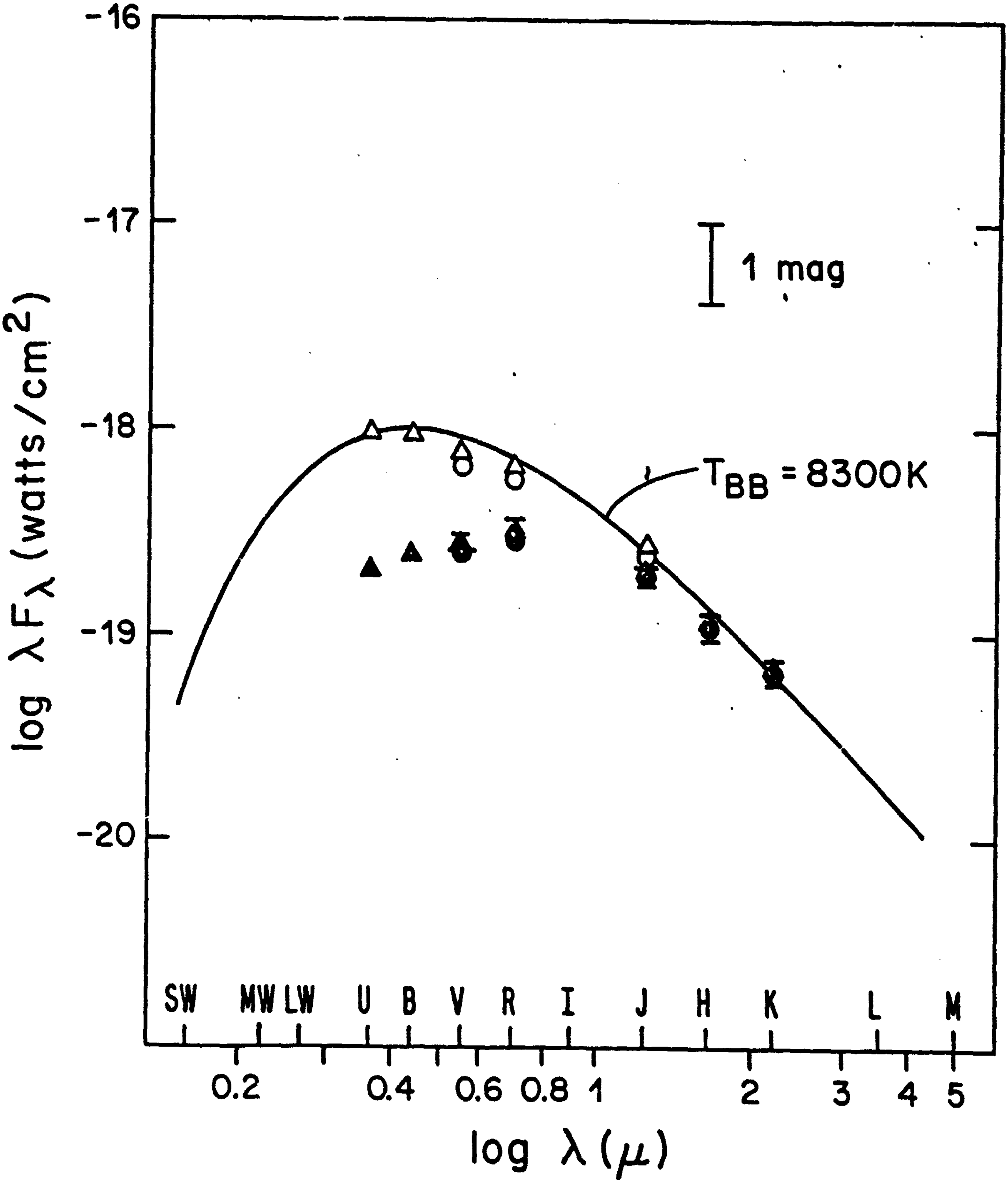
-17
-18
-19
-20
log λF_λ (watts/cm^2)
1 mag
T_BB = 15000K
SW
MW
LW
U
B
V
R
I
J
H
K
L
M
0.2
0.4
0.6
0.8
1
2
3
4
5
log λ (μ)

Fig. 7 AE And.


-16
-17
-18
-19
-20
log λF_λ (watts/cm^2)
1 mag
T_{BB} = 8300K
SW
MW
LW
U
B
V
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I
J
H
K
L
M
0.2
0.4
0.6
0.8
1
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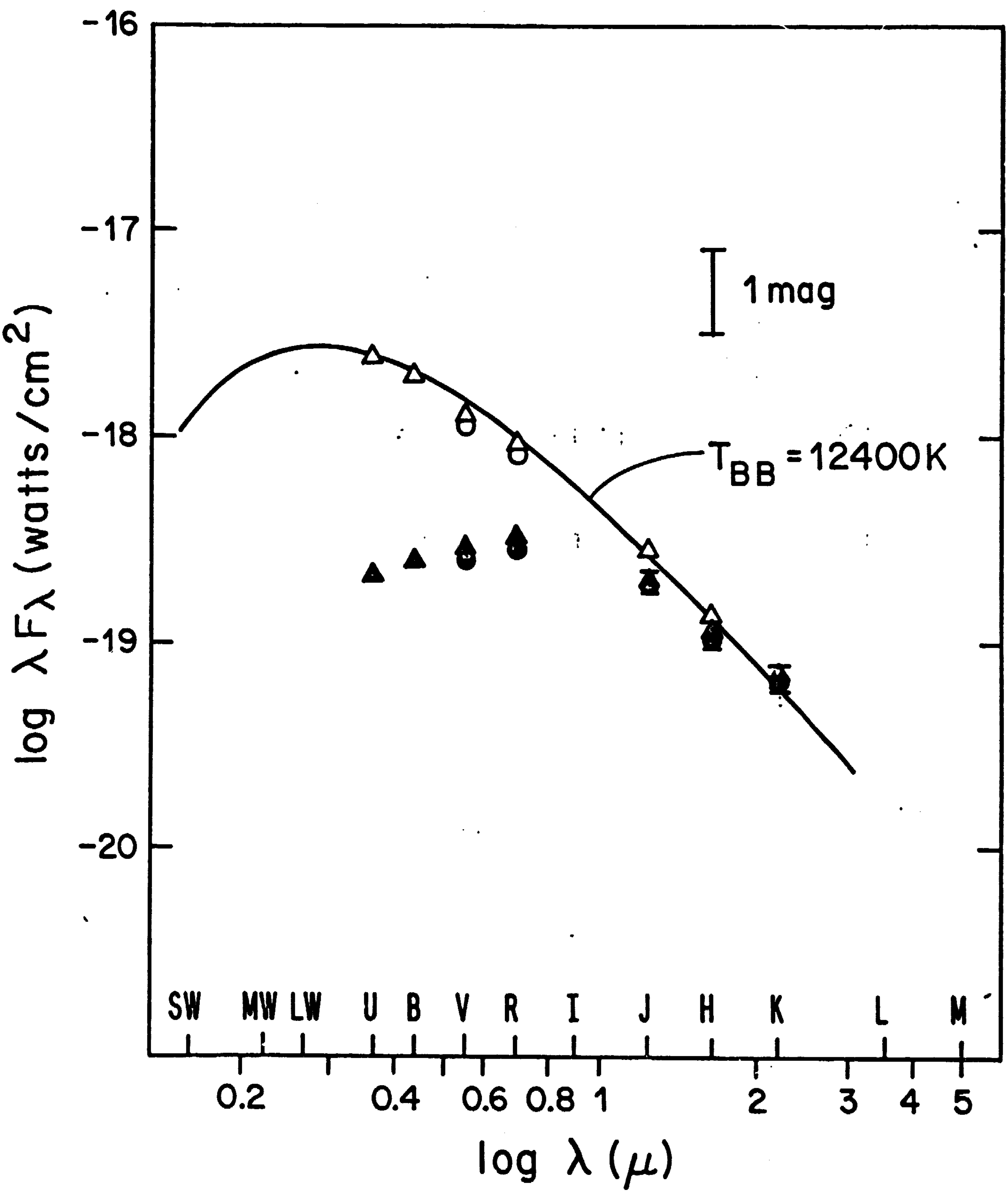
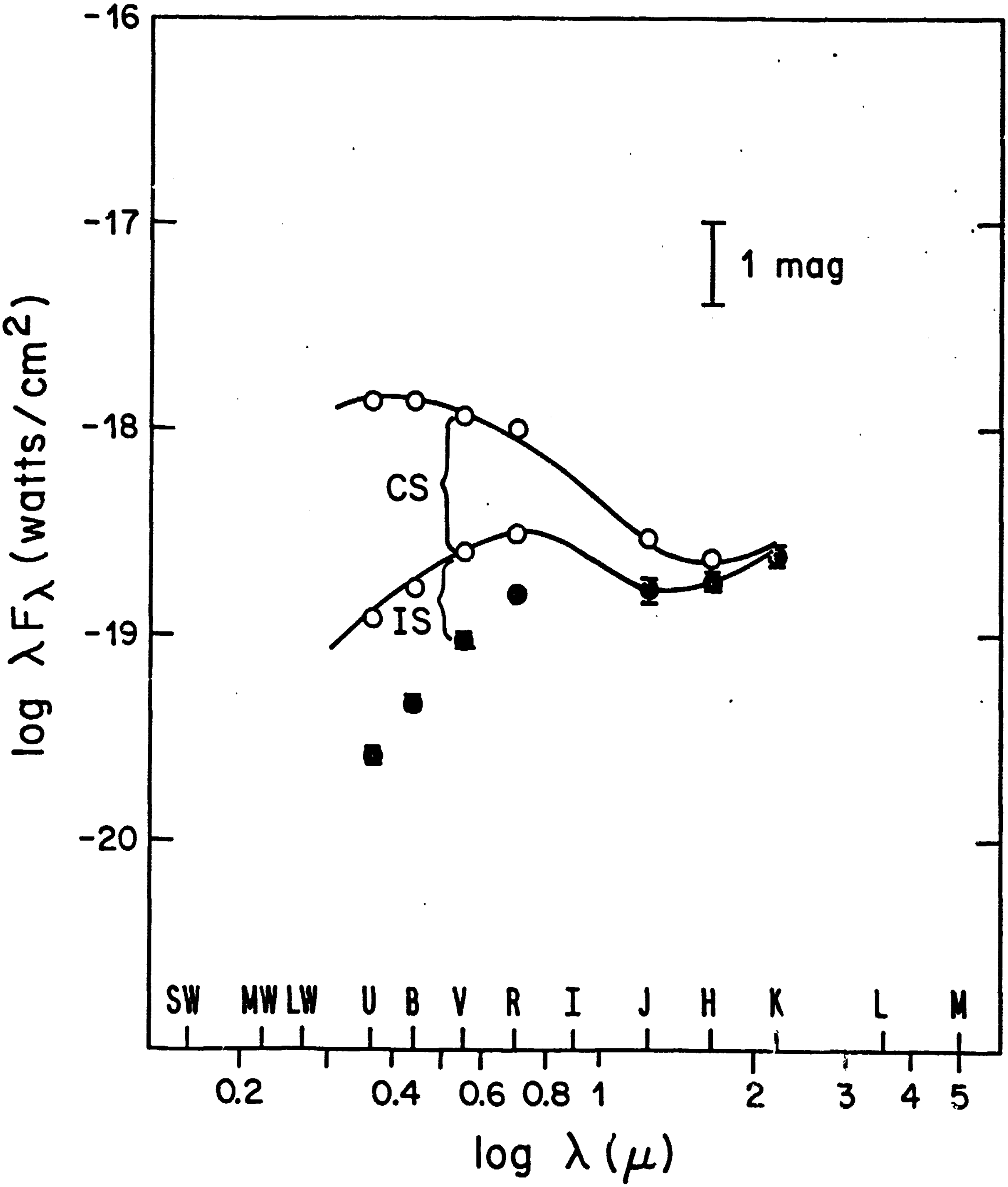
3
4
5
log $\lambda (\mu)$

Fig. 8a Van 15



-16
-17
-18
-19
-20
log λF λ (watts/cm²)
1 mag
T_{BB} = 12400K
SW MW LW U B V R I J H K L M
0.2 0.4 0.6 0.8 1 2 3 4 5
log λ (μ)

Fig. 8b Var 15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IS
log λFλ (watts/cm²)
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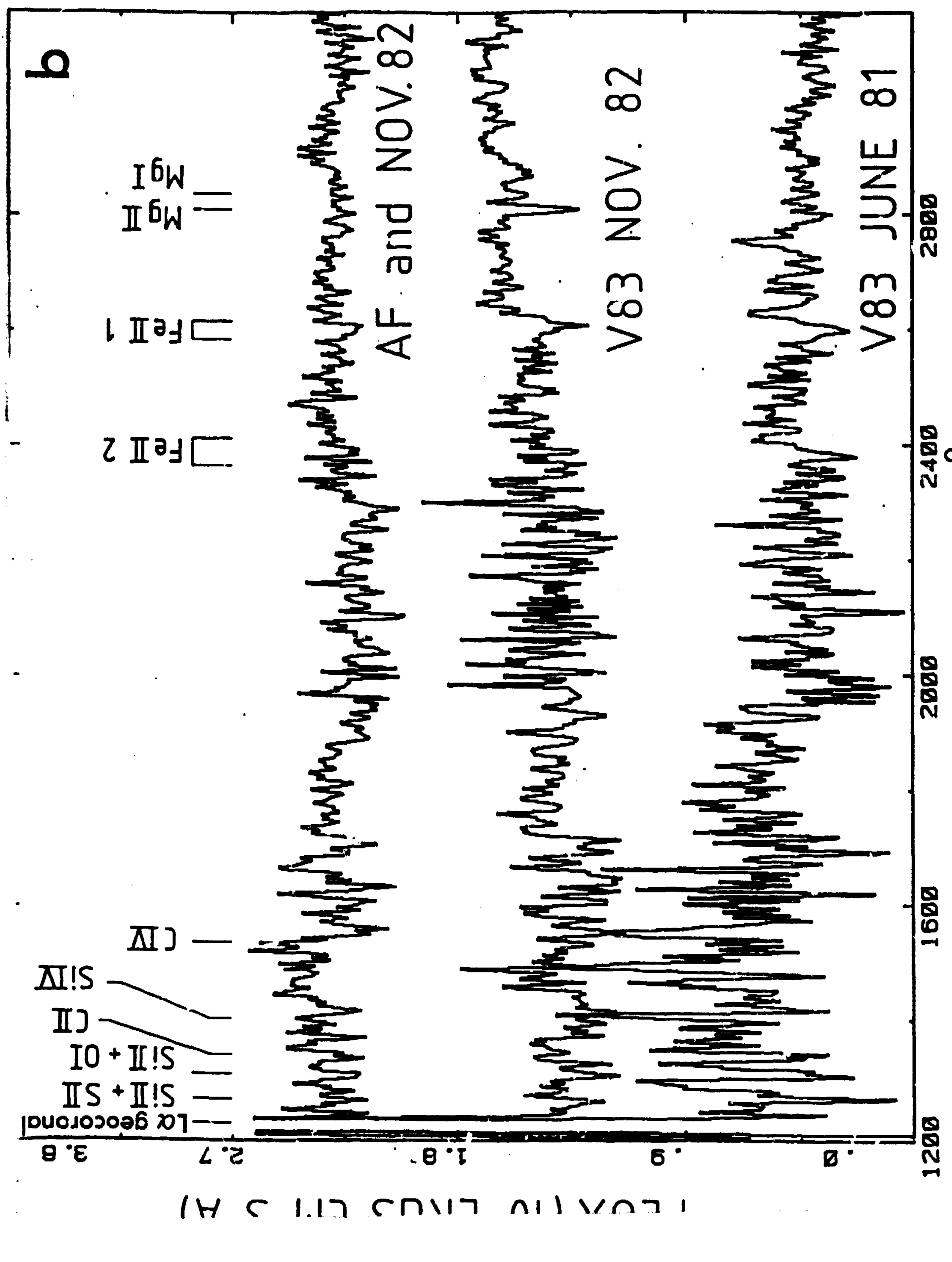
Fig. 9 Var A


b
AF and NOV.82
V83 NOV. 82
V83 JUNE 81
WAVELENGTH (Å)
1200
1600
2000
2400
2800
Lα geocoronal
Si II + S II
Si II + OI
C II
Si IV
C IV
Fe II 2
Fe II 1
Mg II
Mg I
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3.6

Fig 6b

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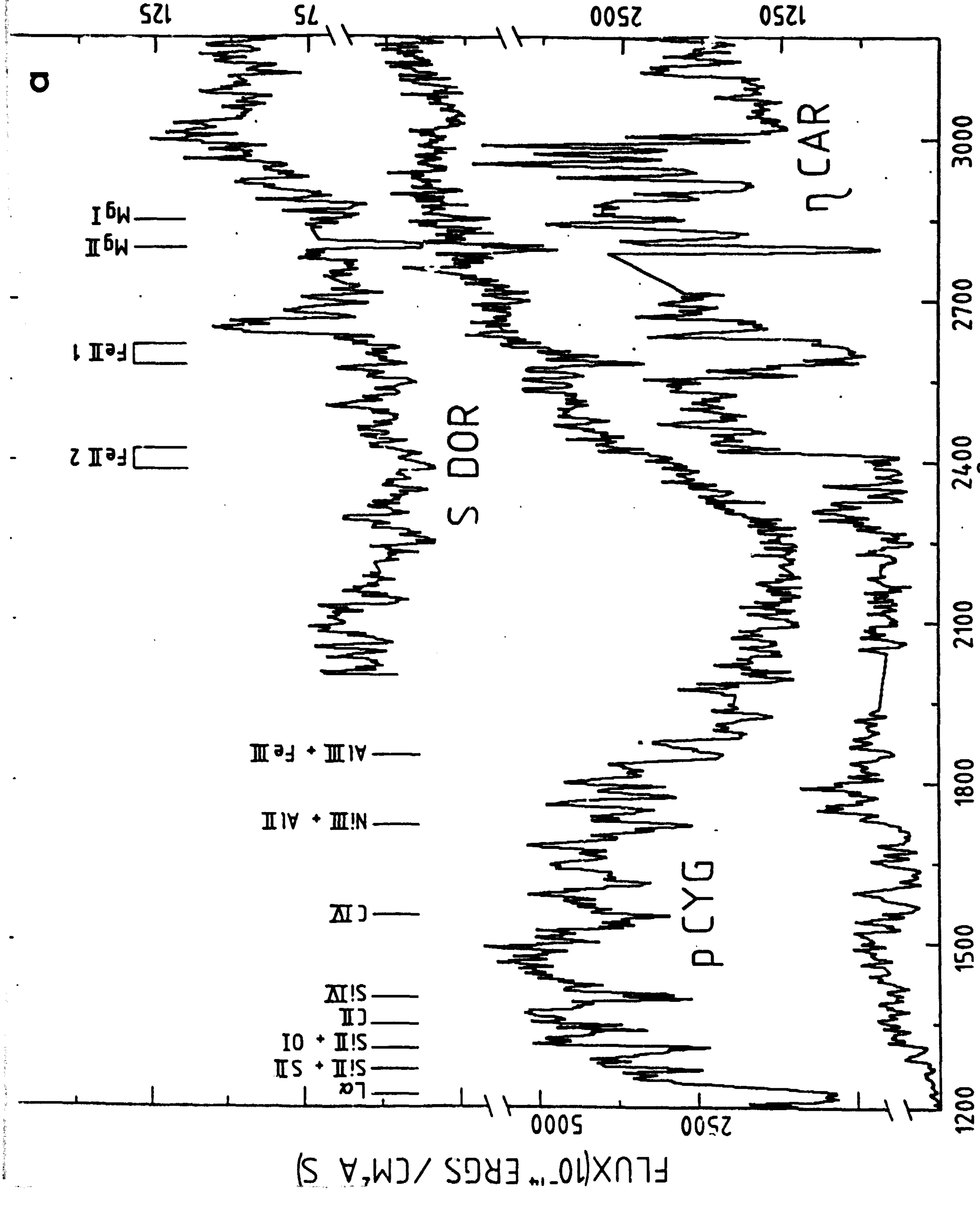
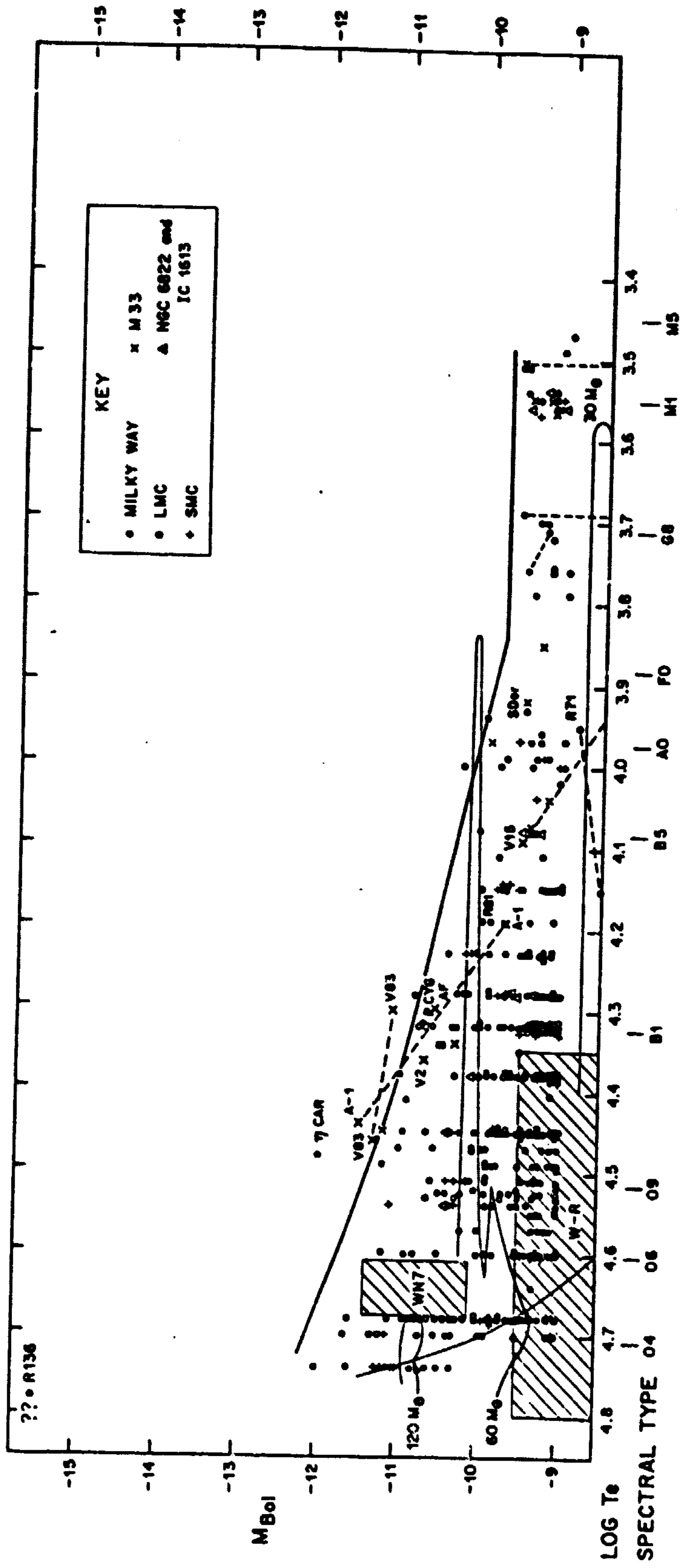
Fig 10a

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A0
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Fig. 11

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Madrid, Spain