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ASTRONOMY
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Absolute Photometry of the Crab Nebula*

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Summary. We give *VBLUW* photometric observations of the Crab nebula. From the data we derive $A_{VJ} = 1^{\rm m}.4$ extinction in the direction of M 1. For positions of the nebula with contaminations by line emission below 2% in the observed fluxes we derive $\alpha = 2.32^{-0.17}_{+0.13}$ for the synchrotron radiation.

Key words: photometry – Crab nebula – synchrotron radiation

Introduction

We have started a program to derive astrophysical quantities of supernova remnants (SNR) and emission nebulae from photometric *VBLUW* observations combined with slit spectroscopy (Greve and van Genderen, 1977, Paper I; 1982, Paper III; Greve et al., 1982, Paper II). We included the Crab nebula (M 1) in the program for the following reasons: 1, the colour of M 1 may give indications to distinguish photometrically SNR with dominant emission line spectra and low continuum backgrounds (see Papers I, and II) from SNR with dominant synchrotron emission, 2, the synchrotron and emission line data published by Woltjer (1958) and Kirshner (1974) indicated that we should be able to derive the synchrotron spectrum for selected areas of the nebula.

There are relatively few photometric observations of M 1 (O'Dell, 1962; Oke, 1969; Scargle, 1969; Miller, 1973; Kirshner, 1974), mostly using narrow passband filters, which avoid emission lines of the filaments, in order to derive the synchrotron spectrum. With the knowledge of the earlier observations we are able to derive the synchrotron spectrum from the broad passband *VBLUW* photometry. In Sect. I we give the *VBLUW* data and describe the reduction, in Sect. II we give the astrophysical results.

Table 1. *VBLUW* Observations of the Crab Nebula

POS.*	V	V-B	B-U	U-W	B-L	V_J*	$\varepsilon_L/\varepsilon_s$	α (1)
	(		log. intensity		)	(magn.)	(%)	
1	-3.494	0.370	-0.054	0.386	-0.037	15.5	16	(2.59)
2	-3.039	0.340	0.027	0.320	-0.005	14.4	10	(2.65)
3	-2.820	0.304	0.047	0.201	0.035	13.9	3	2.22
16	-2.846	0.320	-0.002	0.256	0.006	13.9	8	(2.22)
4	-2.828	0.309	0.058	0.191	0.033	13.9	5	(2.27)
5	-2.669	0.284	0.109	0.154	0.082	13.5	< 2	2.31
6	-2.649	0.272	0.087	0.157	0.077	13.5	< 2	2.15
7	-2.752	0.290	0.050	0.138	0.047	13.7	4	(1.98)
13	-2.775	0.304	0.037	0.236	0.021	13.8	5	(2.28)
8	-2.793	0.306	0.090	0.184	0.063	13.8	3	2.41
14	-2.749	0.297	0.092	0.190	0.066	13.7	2	2.40
9	-2.745	0.301	0.102	0.162	0.077	13.7	< 2	2.38
10	-2.947	0.293	0.133	0.148	0.094	14.2	< 1	2.45
11	-3.270	0.304	0.102	0.084	0.048	15.0	5	(2.12)
12	-3.640	0.362	-0.256	0.388	-0.256	15.9	32	(1.44)
15	-2.845	0.338	-0.058	0.273	-0.054	13.9	13	(2.05)

Notes to Table 1:

Pos.*: for the positions of the measurements see Fig. 1

V_J*: V magnitude of UBV system, Eq. (1)

(1): calculated without eliminating the contribution of line emission. The values α represent the synchrotron radiation only for positions with $\varepsilon_L/\varepsilon_s \leq 3$ % (see Fig. 14 of Paper II).

I. Observations and Reductions

The observations were made on 6, 7 December 1980 with the Walraven *VBLUW* simultaneous photometer attached to the Leiden 90 cm light collector, now part of ESO, La Silla, Chile. The photometric system was slightly changed since the move of the telescope in 1978 to Chile. In order to have data comparable to the results of Papers I–III, the observations discussed here were transformed into the system appropriate for the years 1970–1978 by applying minor corrections provided by Pel (1980, private communication). The effective wavelengths and the FHW of the *VBLUW* passbands for the 1970–1978 system are 5467, 4325, 3838, 3633, 3255 Å and 700, 550, 225, 235, 140 Å, respectively. A description of the photometer and the photometric system is given by Walraven and Walraven (1960), Rijf et al. (1969), and Lub and Pel (1977). We add the subscript *J* when we use *UBV* photometric symbols. From the *VBLUW* data we calculated the apparent visual magnitudes V_J (see Table 1) by using the relation (Pel, 1976)

$$V_J = 6.874 - 2.5[V + 0.065(V - B)]\,. \tag{1}$$

The observational data are given in Table 1. For each observation we used a 16″ diaphragm, the integration time was 192 s. The accuracy of the observations is $\Delta \log(\mathrm{int}) \lesssim 0.01$, i.e. better than 2%. In Fig. 1 taken from Baade, (1956) we show the positions of the measurements of M 1 and the sky background; the sky back-

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* Based on observations collected at ESO, La Silla, Chile

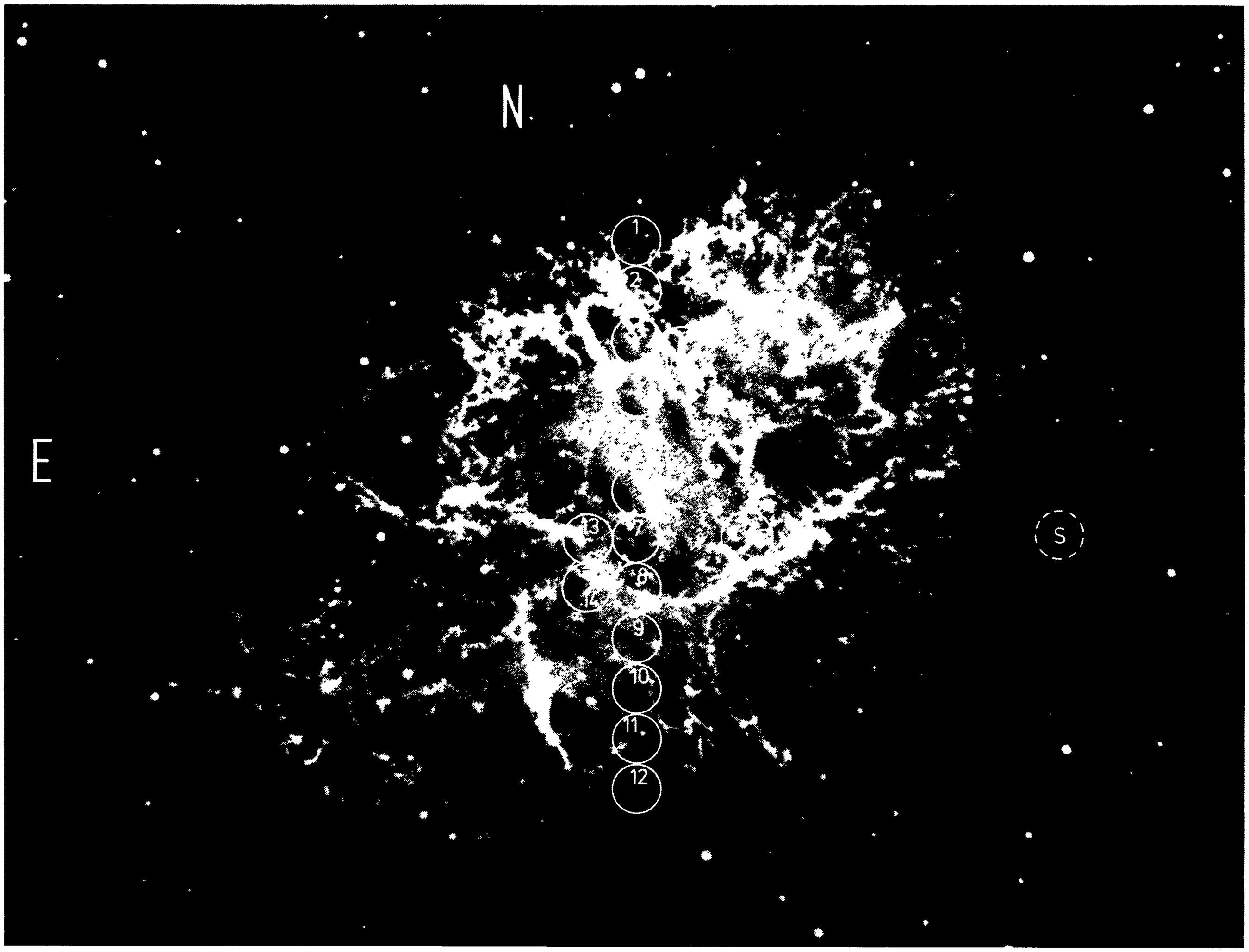

Fig. 1. Distribution of filaments of M 1, line emission of H_α and [N II] (taken from Baade, 1956), and positions of observations. The dashed circle gives the sky background

ground is subtracted from the data of Table 1. Figure 1 shows the distribution of the filaments in the wavelength range λ 6400–6700 Å containing the emission of H_α and [N II]. We selected this plate to illustrate the contamination by line emission in the photometric data; Baade (1956) also gives the plate showing the distribution of the synchrotron emission.

Before using the photometric data we evaluate the contribution of line emission from the filaments in the observed fluxes. From Kirshner (1974) we take for the observed (uncorrected for reddening) synchrotron spectrum of the entire nebula $f_\nu \propto \nu^{-\alpha}$ with $\alpha = 2.32$. For this spectrum f_ν and the filter functions we calculate the observed flux $S_x \varepsilon_s$ in the filter passband X, with S_x given in relative units and ε_s a factor applicable to all passbands X so that $S_x \varepsilon_s$ is given in absolute flux units. From Woltjer (1958) and Miller (1978) we take representative relative strengths of the emission lines. We recalculate the relative line strengths for $A_{VJ} = 1\overset{m}{.}4$ extinction (see below); we used the extinction curve given by Buser (1978) which approximates analytically the extinction curve determined by Whitford (1958), see Paper III. In a similar way we calculate the observed flux of the emission lines $E_x \varepsilon_L$, with E_x given in relative units and ε_L a factor applicable to all passbands X so that $E_x \varepsilon_L$ is given in the same absolute flux units as $S_x \varepsilon_s$. Following Paper III, the observed colour $V-B$ (and similar for the other colours, except W for which no line data are available) is given by

$$V-B = \log(S_V \varepsilon_s + E_V \varepsilon_L) - \log(S_B \varepsilon_s + E_B \varepsilon_L) + C_{VB} \tag{2}$$

or

$$\begin{aligned} V-B = {} & (V-B)_s + \log[1 + (E_V/S_V)(\varepsilon_L/\varepsilon_s)] \\ & - \log[1 + (E_B/S_B)(\varepsilon_L/\varepsilon_s)] \end{aligned} \tag{3}$$

with $(V-B)_s = \log(S_V \varepsilon_s) - \log(S_B \varepsilon_s) + C_{VB} = 0.296$ the colour of the observed synchrotron spectrum for $\alpha = 2.32$. Figure 2 shows for various values of $\varepsilon_L/\varepsilon_s$ the calculated colours $V-B$, $B-L$, $B-U$. The coincidence of the observed colours, shown in Fig. 2 as solid dots and solid squares, and the calculated colours, Eq. (3), give the corresponding values $\varepsilon_L/\varepsilon_s$. The values $\varepsilon_L/\varepsilon_s$ change only by a few percent for $\pm 10\%$ changes of α and $\pm 10\%$ changes of the line strengths. We find good agreement of the values $\varepsilon_L/\varepsilon_s$ derived from the individual observations and the individual curves $V-B$, $B-L$, $B-U$ of Fig. 2. We adopt the averages of $\varepsilon_L/\varepsilon_s$. In Fig. 2 we omitted coincidences for values $\varepsilon_L/\varepsilon_s \leq 0.01$ since these coincidences are below the accuracy of the observations.

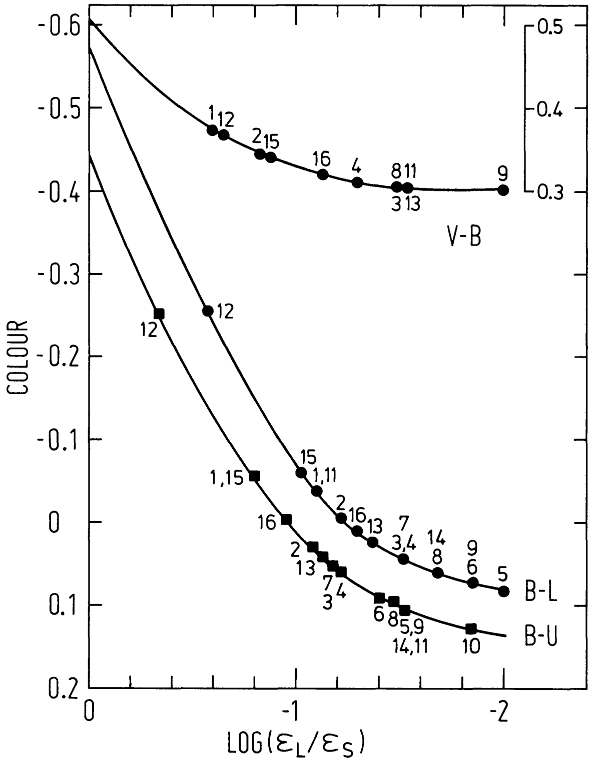

Fig. 2. Determination of the contamination $\varepsilon_L/\varepsilon_s$ by line emission, see Sect. I. Left hand scale for $B-L$ and $B-U$, right hand scale for $V-B$. Observations are indicated by solid dots and squares. Coincidences are not shown for values $\varepsilon_L/\varepsilon_s<0.01$

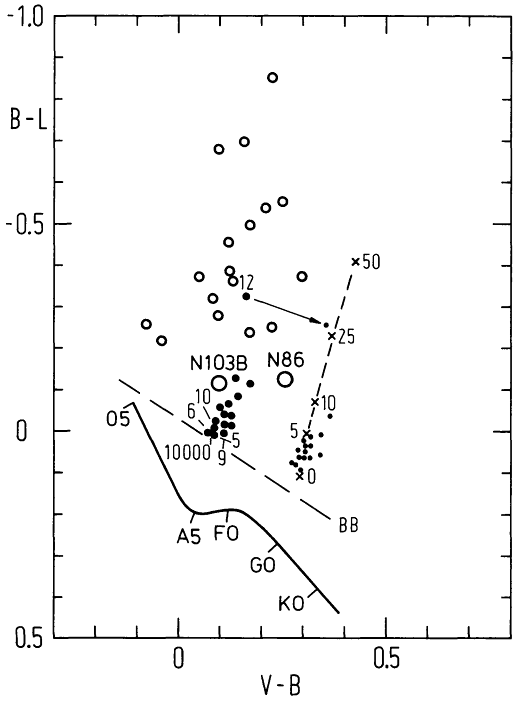

Fig. 3. Two colour diagram. Large solid dots: reddening corrected ($A_{VJ}=1^{\rm m}.4$) colours of M 1, small dots: observations of M 1; dashed line: relation of Eq. (3) for values $\varepsilon_L/\varepsilon_s\times 100$ as indicated; open circles: reddening corrected observations of other SNR (Paper II). Black body (BB) line and main sequence line are shown

Since $E_V/S_V=1.2$ for $\alpha=2.32$ and the line strengths given by Woltjer (1958) and Miller (1978), for the V passband the value $(\varepsilon_L/\varepsilon_s)\times 100$ is the percentage of contamination by line emission in the observed flux $f(V)$. Whenever we speak of $\varepsilon_L/\varepsilon_s$ in percentages we refer to the V passband, the corresponding values $\varepsilon_L/\varepsilon_s$ are given in Table 1. For the other passbands the contamination may increase to $\lesssim 3$ times the percentage of the V passband.

The photometric observations must be corrected for extinction. From observations of [S II] line ratios, Miller (1973) derived the value $A_{VJ}=1.6\pm0^{\rm m}.2$; this value is adopted by Kirshner (1974). For a discussion of extinction values derived from stellar observations (O'Dell, 1962; Brodskaya, 1963) see the publication by Miller. Following Paper III, our calculations show that the reddening relations derived for stars (continuum sources) are applicable to the *VBLUW* colours of the intrinsic (reddening corrected) synchrotron spectrum $f_\nu\propto\nu^{-\alpha^*}$ with the additional line emission. The reddening corrected observations by Kirshner (1974) give a good fit for $\alpha^*=0.41$ when using $A_{VJ}=1^{\rm m}.6$. Using the observations at position 5, 6, 9, 10, for which the line contamination is below 2%, and calculating the reddened synchrotron colours for $\alpha^*=0.41$ we find agreement with the observations for $\langle A_{VJ}\rangle=1.35\pm0^{\rm m}.1$ (see Fig. 13 of Paper II). For $\alpha^*=0.65$ and $\alpha^*=0.17$, which correspond with the observations by Kirshner corrected for $A_{VJ}=1^{\rm m}.4$ and $A_{VJ}=1^{\rm m}.8$, respectively, we find $\langle A_{VJ}\rangle=1.20\pm0^{\rm m}.1$ and $\langle A_{VJ}\rangle=1.55\pm0^{\rm m}.1$. We adopt the value $A_{VJ}=1^{\rm m}.4$ which agrees with the lower limit derived by Miller (1973).

The reddening corrected data can be obtained from the data of Table 1 by using $A_V=0.4\ A_{VJ}=0.4\times1.4=0.560$ and applying the reddening relations given by Lub and Pel (1977), hence

$$E(V-B)=0.190\,,$$

$$E(B-U)=0.121\,,$$

$$E(U-W)=0.085\,,$$

$$E(B-L)=0.082\,.$$

II. Astrophysical Results

a) (V–B) –(B–L) Colour Diagram

In Fig. 3 we show the observed and the reddening corrected ($A_{VJ}=1^{\rm m}.4$) values of Table 1 plotted in the $(V-B)-(B-L)$ diagram; the other colour diagrams are similar. We find that the colour of M 1, and in particular the colour of the synchrotron radiation, is neither similar to a G 2 star (Oort and Walraven, 1956) nor to a F 0 star (Woltjer, 1958). The colour of the synchrotron radiation is similar to the colour of a black body of ~10,000 K as illustrated in Fig. 3 by the values for positions 5, 6, 9, 10. The dashed line in Fig. 3 shows the reddening uncorrected relation $V-B$ of Eq. (3) calculated for $\alpha=2.32$ and various values $\varepsilon_L/\varepsilon_s$.

Inserted into Fig. 3 are the reddening corrected colours of other SNR of the Galaxy, LMC and SMC as discussed in Paper II. Note that the colour of M 1 at position 12 coincides with the colour region of the other SNR, although the other SNR have very low continuum backgrounds (Paper II) while the observation at position 12 contains ~70% synchrotron radiation. As shown in

Table 2. Values α^* of the optical synchrotron spectrum $f_\nu \propto \nu^{-\alpha^*}$ for various values $A_{VJ}(m)$

Pos.	$A_{VJ} = 0$	$A_{VJ} = 1.4$	$A_{VJ} = 1.6$	$A_{VJ} = 1.8$
5	2.31	0.52	0.27	0.08
6	2.15	0.36	0.12	(−0.13)
9	2.38	0.59	0.33	0.09
10	2.45	0.67	0.42	0.17
Average	$2.32^{-0.17}_{+0.13}$	$0.53^{-0.17}_{+0.14}$	$0.28^{-0.16}_{+0.14}$	0.11
Entire Nebula (Kirshner, 1974)	2.32	0.64	0.41	0.17

Fig. 3, the colours of N 86 of the LMC, and in particular the colour of N 103 B of the LMC, coincide with the colour region of the synchrotron radiation of M 1. The slopes of the radio spectra (Milne et al., 1980) of N 86 and N 103 B are α(0.408–14.7 GHz) = 0.37 and $\alpha = 0.44$, for M 1 we have $\alpha = 0.26$ (see Kirshner, 1974, and references therein). For the moment, the similarity of the photometric data is not conclusive.

b) Optical Synchrotron Radiation

Using the effective wavelengths and FHW of the filter passbands, we derive the values α of the reddening uncorrected synchrotron radiation $f_\nu \propto \nu^{-\alpha}$. From the data obtained for the positions 5, 6, 9, 10, for which the contamination is below 2%, we obtain $\langle\alpha\rangle = 2.32^{-0.17}_{+0.13}$. This value agrees with the value α derived by Kirshner (1974) for the entire nebula; the deviations from the average value α may be interpreted as intrinsic changes in α for various positions of the nebula. For a region 5″ away from the pulsar, Oke (1969) gives $\alpha = 2.28$, for regions close to the positions 5, 6, Scargle (1969) gives $\alpha \simeq 2.33$.

In Table 2 we give the values α^* for the positions 5, 6, 9, 10 corrected for extinctions of $A_{VJ} = 1^{\mathrm{m}}.4$, $1^{\mathrm{m}}.6$, $1^{\mathrm{m}}.8$, respectively. Note that for $A_{VJ} = 1^{\mathrm{m}}.8$ at position 6 we obtain $\alpha^* < 0$, i.e. a spectrum which increases with increasing frequency. Within the limits of accuracy, our values agree with the values given by Kirshner (1974).

Objections may be raised against the method to derive α by using effective wavelengths λ_{eff} and filter FHW, i.e. by using broad passband photometry in general. Several checks and error estimates are made. For inaccuracies $\Delta(V-B) = \ldots = \Delta(B-L) = \pm 0.002$ we have $\Delta\alpha = \pm 0.01$. From theoretical colours of the synchrotron radiation $(V-B)_s, \ldots, (U-W)_s$ calculated for various values α we reconstructed α with an accuracy $\Delta\alpha = \pm 0.03$. The values λ_{eff} and FHW may be inaccurately known, for $\lambda_{\mathrm{eff}} = \pm 10$ Å we find $\Delta\alpha \leqq 0.01$, for Δ(FHW) = ±10 Å we find $\Delta\alpha = \pm 0.06$. The upper limit of the combined inaccuracies is $\Delta\alpha = \pm 0.10$.

c) Absolute Intensities

Following Paper II, we use the calibration of the *VBLUW* system (Lub et al., 1979; private communication, 1980) to derive absolute intensities of the synchrotron radiation and the H_β line. The calibration of the *VBLUW* system gives fluxes at the top of the Earth's atmosphere; which are converted into specific intensities I at the surface of M 1. For M 1 we use the observations of the V passband and correct the values for $A_{VJ} = 1^{\mathrm{m}}.4$. The reddening corrected intensities of the synchrotron radiation are shown in Fig. 4; the values refer to the center frequency $\nu^* = 5.56\,10^{14}$ Hz of the V passband. The values of Fig. 4 are corrected for the contamination from line emission by using Eq. (3) and the factors $\varepsilon_L/\varepsilon_s$ of Table 1. The distribution shown in Fig. 4 agrees well with the values of the photographic isophotes published by Woltjer (1957); we normalized the values given by Woltjer to the observation at position 6. In Fig. 4 we also show the intensity of the line emission of the filaments received within the V passband as calculated from Eq. (3). Adopting the emission line spectrum given by Woltjer (1958) and Miller (1978), the values of Fig. 4 multiplied by 0.15 (i.e. the ratio of the line intensities in V with respect to the relative intensity of H_β) give the intensities of the H_β line; a representative average is $\langle I(H_\beta)\rangle = 3\,10^{-5}$ erg cm^{-2} s^{-1} sterad^{-1}.

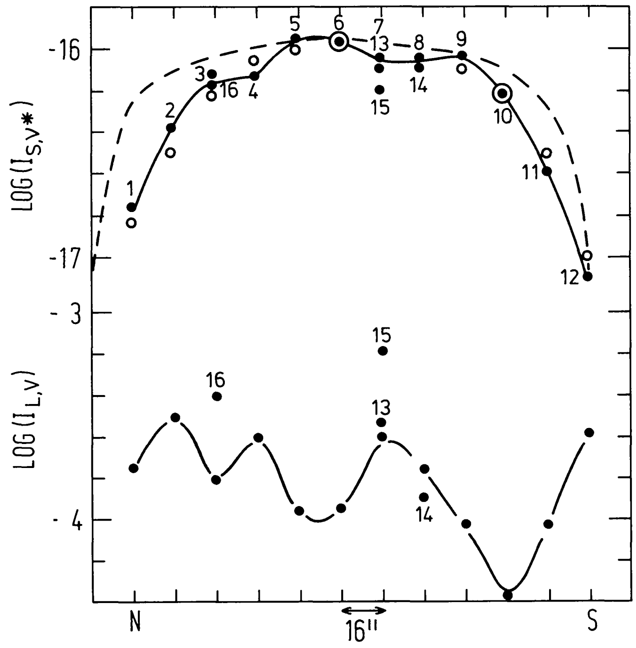

Fig. 4. Absolute intensities derived from V passband fluxes, corrected for $A_{VJ} = 1^{\mathrm{m}}.4$. The upper curves give the intensity $I_{s\nu^*}$ of the synchrotron radiation for the frequency $\nu^* = 5.56\,10^{14}$ Hz at the center of V passband, intensity in erg cm^{-2} s^{-1} Hz^{-1} sterad^{-1}. Solid dots: derived from observations of this paper, open circles: taken from Woltjer (1957) and normalized to the intensity at position 6; dashed line: emission of a homogenous, optically thin sphere. Lower curve: line intensity $I_{L,V}$ received in V passband, in erg cm^{-2} s^{-1} sterad^{-1}

Conclusion

The astrophysical quantities derived for M 1 from the broad passband *VBLUW* observations agree with other determinations. This agreement is obtained by the possibility to determine the contribution of emission line radiation in the observations. The photometric system may be used to observe with smaller diaphragms ($\gtrsim 5''$) small scale details of M 1, for instance the synchrotron emission of the wisps and the line emission at positions where spectral data are given by Woltjer (1958).

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