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Reddening Relations of the *VBLUW* and *UBV* Systems for Objects with Emission Line Spectra

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Summary. For the Walraven *VBLUW* and Johnson *UBV* system we investigate reddening relations for emission line objects: emission nebulae, planetary nebulae, supernova remnants. In contrast with the reddening relations derived empirically for supernova remnants, the reddening relations calculated for planetary nebulae and emission nebulae seem to be different from the known reddening relations derived for stars, i.e. continuum sources.

Key words: photometry – interstellar absorption and extinction – supernova remnants – H II regions – planetary nebulae

Introduction

For photometric observations, reddening corrections are important to obtain absolute colours. Reddening relations are derived from stellar observations and are calculated from extinction laws applied to stellar spectra or black body (BB) radiators (cf. Arp, 1961; Matthews and Sandage, 1963; Lub and Pel, 1977; Buser, 1978). Hence, the known reddening relations are applicable to photometric data of objects emitting dominantly continuous spectra. We have made (Greve and van Genderen, 1977, Paper I; Greve et al., 1982, Paper II) photometric observations of emission nebulae (EN, i.e. H II regions) and supernova remnants (SNR) which emit line spectra with low continuum backgrounds (cf. Osterbrock, 1974). We investigate reddening relations applicable to emission line objects measured in the Walraven *VBLUW* system (Walraven and Walraven, 1960; Rijf et al., 1969; Lub and Pel, 1977) and the *UBV* system (Johnson, 1955). Our observations have been made in the *VBLUW* system. In Sect. I we summarize the photometric relations. In Sect. II we apply the relations to observed spectra of EN, planetary nebulae (PN), SNR, and a BB of 25,000 K to simulate an early type star, i.e. a continuum source. The conclusions are given in Sect. III.

The results of this paper are used in Paper II. This investigation is Paper III on the exploration to derive astrophysical quantities from photometric data of SNR and EN.

I. Photometric Relations

The filter transmission functions (for 1 air mass) of the *VBLUW* and *UBV* systems are taken from Lub and Pel (1977) and Strazys (1977), respectively. The wavelength ranges (λ_s , λ_l -short, long

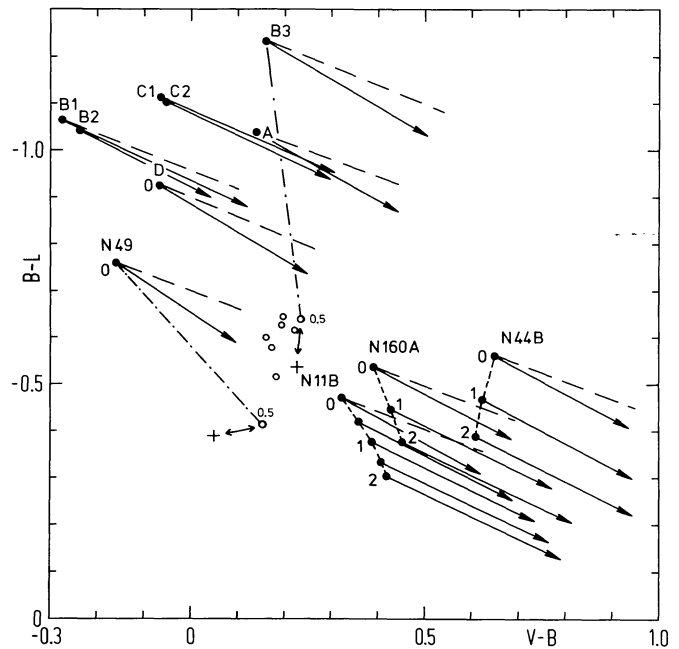


Fig. 1. Theoretical colours for *VBLUW* system (in log intensity scale) and reddening (Table 2a, 2b) of SNR RWC 86: A–C 2, D; SNR N 49, EN N 11 B, N 44 B, N 160 A. No index and index 0: C = 0, pure line spectrum; index 0.5 for SNR: continuum of 0.5 % of $I(H_\beta)$ indicated by small open circles (plus signs are the observations); index 1, 2 for EN: H-continuum of $T=10,000$ K with $C=1, 2$ (Sect. II). Solid lines: reddening of $A_{VJ}=3^m$, dashed lines: reddening of $A_{VJ}=3^m$ with slope for 25,000 K BB source. \circ : RCW 86 and N 49 with continuum $C=0.5$, +: reddening corrected observed colours (Paper II)

wavelength edge, respectively), the effective wavelengths λ_{eff} , and the full halfwidths FHW determined from the filter functions as used in the calculations are given in Table 1. Whenever we use the *UBV* system we write U_J , B_J , V_J , or UJ , BJ , VJ for subscripts.

Assume an object emitting the spectral distribution $I_0(\lambda)$, with λ the wavelength. The radiation emitted within the filter $X(\lambda_s, \lambda_l)$ with transmission function $\phi_X(\lambda)$ is

$$I_{X,0} = \int_{\lambda_s}^{\lambda_l} I_0(\lambda) \phi_X(\lambda) d\lambda. \quad (1)$$

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Table 1. Filters of the *VBLUW* and *UBV* systems used in the calculations (*VBLUW*: Lub and Pel, 1977; *UBV*: Straizys, 1977), in A. Determined for $I(\lambda) = \text{const}$

Filter	W	U	L	B	V
$\lambda_s - \lambda_\ell$	3120–3400	3390–3910	3600–4090	3880–4800	4800–6440
λ_{eff}	3254	3633	3836	4301	5450
FHW	143	239	227	449	719
	U_J			B_J	V_J
$\lambda_s - \lambda_\ell$	3100–4100			3650–5500	4800–7350
λ_{eff}	3642			4448	5505
FHW	450			1010	871

In case the radiation passes a medium with optical depth $\tau(\lambda)$, the received radiation is

$$I_X = \int_{\lambda_s}^{\lambda_\ell} I_0(\lambda) \phi_X(\lambda) \exp(-\tau(\lambda)) d\lambda. \quad (2)$$

$\tau(\lambda) = \tau_0 E(\lambda)$ with τ_0 the optical depth at λ_0 , $E(\lambda) \propto \lambda^{-1}$ is the wavelength dependence of the absorption (cf. van de Hulst, 1949; Whitford, 1958). The empirical reddening is usually given in magnitudes $\delta m(\lambda^{-1})$; we derived $E(\lambda)$ from the expression given by Buser (1978), which approximates the Whitford (1958) observation by an analytical function, i.e.

$$\begin{aligned} \delta m &= 0.433 \lambda^{-1} + C_1 \quad \text{for } 3.33 \geq \lambda^{-1} (\mu^{-1}) \geq 2.30 \\ \delta m &= 0.742 \lambda^{-1} + C_2 \quad \text{for } 2.30 \geq \lambda^{-1} (\mu^{-1}) \geq 1.00 \end{aligned} \quad (3)$$

with C_1, C_2 normalization constants. Note that different extinction laws $\delta m(\lambda^{-1})$ exist for different regions of the galaxy or for other galaxies, for instance the LMC (Nandy, 1964–1968; Walker et al., 1969; York, 1971; Honeycutt, 1972; Hayes et al., 1973; Sudzius, 1974; Nandy et al., 1980). We use the generalized Whitford law, Eq. (3), which is often applied for the reduction of spectroscopic data [cf. Osterbrock, 1974, see Sect. II(b)].

For the *UBV* system we use the following relations (cf. Blanco, 1955). The absorption Δm_{XJ} , in magnitudes, in the X passband is

$$\Delta m_{XJ} = -2.5 \log (I_{XJ}/I_{XJ,0}) \quad (4)$$

in particular, $A_{VJ} = \Delta m_{VJ}$. The ratio R_J of the visual and selective absorption is defined by

$$R_J = \Delta m_{VJ} / (\Delta m_{BJ} - \Delta m_{VJ}) = A_{VJ} / E(B-V)_J. \quad (5)$$

The slope CUB_J of the reddening line in the $(U-B)_J - (B-V)_J$ diagram is

$$CUB_J = (\Delta m_{UJ} - \Delta m_{BJ}) / (\Delta m_{BJ} - \Delta m_{VJ}) = E(U-B)_J / E(B-V)_J. \quad (6)$$

Logarithms of intensity are used in the *VBLUW* system. For the X passband we have

$$X - X_0 = \log (I_X / I_{X,0}) \quad (7)$$

in particular, $A_V = V - V_0$. Since the V passbands are nearly identical for both photometric systems (except the low, long wavelength tail of V_J , see Table 1), we have $A_V / A_{VJ} = -0.40$ as verified in the calculations. Equivalent to R_J we define for the *VBLUW* system

$$R = (V - V_0) / [(V-B) - (V-B)_0] = A_V / E(V-B). \quad (8)$$

The slopes CBL, CBU, CUW of the reddening lines in the colour diagrams $(B-L) - (V-B), (B-U) - (V-B), (U-W) - (V-B)$, are

$$CBL = [(B-L) - (B-L)_0] / [(V-B) - (V-B)_0] = E(B-L) / E(V-B) \quad (9)$$

with equivalent expressions for $CBU = E(B-U) / E(V-B)$, $CUW = E(U-W) / E(V-B)$. So far, the expressions are independent of the photometric zero-points.

Colour differences are calculated from the relations

$$(X - Y)_J = -2.5 \log (I_{XJ} / I_{YJ}) + c_{XY} \quad (10)$$

$$(X - Y) = \log (I_X / I_Y) + C_{XY}$$

with the constants c_{XY}, C_{XY} given by Matthews and Sandage (1963) and Lub and Pel (1977), respectively.

For the reddening corrected line spectra $I_0(\lambda)$ we calculated the “apparent” effective wavelength λ_X^* of the X passband

$$\lambda_X^* = \frac{\sum_X \lambda I_0(\lambda) \phi_X(\lambda)}{\sum_X I_0(\lambda) \phi_X(\lambda)} \quad (11)$$

from which we derived $\Delta \lambda(X) = \lambda_X^* - \lambda_{\text{eff},X}$ with $\lambda_{\text{eff},X}$ given in Table 1.

II. Theoretical Reddening Relations

a) Input Data

Using the relations of Sect. I, representative results are given in Table 2a; the data of Table 2a are shown in Fig. 1 except for the Orion nebula (M 42) and PN NGC 7027 in order not to crowd the picture. For comparison we give the data for the 25,000 K BB continuum source. The data of Table 2a (and Table 2b and c; see below) refer to EN (LMC) and SNR of which the reddening corrected spectra $I_0(\lambda)$, as published by various authors (see below), terminate at the [O II] 3727 Å lines. Consequently, except for M 42 and NGC 7027, the ultraviolet colours cannot be calculated and Table 2a (2b and c) contains data only for *VBL* and $V_J B_J$. The data are listed for $A_{VJ} = 0^m$ and 3^m . Between $0 < A_{VJ} \lesssim 7^m$ we found negligible curvature of the reddening slopes. We added to the emission line spectra a weak continuum which, *a priori*, is not negligible in broad band photometry. For the EN we adopted a hydrogen continuum of $T = 10,000$ K and corresponding spectral distribution given by Osterbrock (1974, p. 73). The strength of the continuum is $r = C(I_c(4861 \text{ Å}) / I(\text{H}\beta)) = C 5.10^{-15}$

Table 2a. Theoretical colours and reddening relations for EN and SNR (V , B , L and V_J , B_J passbands) (N: number of lines in spectrum between $\sim \lambda$ 3600 and 7027 Å, $\Delta\lambda$ in units of Å)

Object [†]	A_{VJ}	C	V-B	B-L	CBL	R	$(B-V)_J$	R_J
BB 25 000K N	0		-0.070	-0.070			-0.21*	
	3		0.341	0.089	0.39	2.98	0.72	3.29

EN								
N11B ⁽¹⁾ (LMC)21	$\Delta\lambda(L) = -56, \Delta\lambda(B) = -15, \Delta\lambda(V) = -419, \Delta\lambda(B_J) = 267, \Delta\lambda(V_J) = -441$							
	0	0	0.325	-0.474			0.24	
	3	0	0.620	-0.310	0.56	4.60	0.54	11.06
	0	1	0.388	-0.375			0.42	
	3	1	0.736	-0.204	0.49	3.73	0.86	7.33
	0	2	0.422	-0.302			0.54	
	3	2	0.792	-0.128	0.47	3.44	1.06	6.10
N44B ⁽¹⁾ (LMC)22	$\Delta\lambda(L) = -38, \Delta\lambda(B) = -11, \Delta\lambda(V) = -441, \Delta\lambda(B_J) = 364, \Delta\lambda(V_J) = -483$							
	0	0	0.651	-0.566			0.47	
	3	0	0.935	-0.408	0.56	4.80	0.65	19.14
	0	1	0.626	-0.465			0.55	
	3	1	0.941	-0.300	0.52	4.22	0.82	12.31
	0	2	0.610	-0.390			0.61	
	3	2	0.944	-0.221	0.51	3.90	0.95	9.68
N160A ⁽¹⁾ (LMC)23	$\Delta\lambda(L) = -49, \Delta\lambda(B) = -30, \Delta\lambda(V) = -421, \Delta\lambda(B_J) = 265, \Delta\lambda(V_J) = -450$							
	0	0	0.387	-0.538			0.28	
	3	0	0.686	-0.381	0.52	4.54	0.57	11.56
	0	1	0.427	-0.444			0.42	
	3	1	0.769	-0.280	0.48	3.81	0.83	7.94
	0	2	0.450	-0.373			0.53	
	3	2	0.813	-0.204	0.46	3.52	1.01	6.59
Orion N. ⁽²⁾ 68	$\Delta\lambda(L) = -31, \Delta\lambda(B) = -9, \Delta\lambda(V) = -99, \Delta\lambda(B_J) = 63, \Delta\lambda(V_J) = -241$							
(M42)	0	0	0.046	-0.232			-0.02	
	3	0	0.446	-0.071	0.40	3.11	0.71	4.21
	0	1	0.175	-0.180			0.24	
	3	1	0.587	-0.016	0.40	2.98	1.03	3.92

PN NGC7027 ⁽³⁾ 150	$\Delta\lambda(L) = 0, \Delta\lambda(B) = 35, \Delta\lambda(V) = -405, \Delta\lambda(B_J) = 435, \Delta\lambda(V_J) = -434$							
	0	0	0.907	-0.318			0.65	
	3	0	1.183	-0.151	0.61	4.89	0.83	18.41
	0	1	0.804	-0.218			0.67	
	3	1	1.101	-0.050	0.57	4.49	0.91	13.81

SNR								
RCW 86 ⁽⁴⁾ 23	$\Delta\lambda(L) = -81, \Delta\lambda(B) = 7, \Delta\lambda(V) = -333, \Delta\lambda(B_J) = 15, \Delta\lambda(V_J) = -190$							
	0	0	-0.064	-0.925			-0.29	
	3	0	0.249	-0.737	0.60	4.23	0.46	4.13
	0	0.5	0.183	-0.513			0.26	
	3	0.5	0.584	-0.325	0.47	3.06	1.11	3.54
	0	1	0.217	-0.356			0.38	
	3	1	0.626	-0.171	0.45	2.98	1.25	3.46
N49(LMC) ⁽⁵⁾ 35	$\Delta\lambda(L) = -70, \Delta\lambda(B) = -30, \Delta\lambda(V) = -258, \Delta\lambda(B_J) = -53, \Delta\lambda(V_J) = -86$							
	0	0	-0.159	-0.757			-0.32	
	3	0	0.196	-0.589	0.47	3.65	0.58	3.37
	0	0.5	0.153	-0.413			0.26	
	3	0.5	0.565	-0.236	0.43	2.97	1.17	3.32
	0	1	0.199	-0.278			0.38	
	3	1	0.614	-0.101	0.43	2.94	1.29	3.32

[†] Based on spectra by Dufour (1975): (1); Aller (1965): (2); Aller (1965): (3) and continuum measured by Miller and Mathews (1972); Dopita et al. (1980): (4); Osterbrock and Dufour (1973): (5)

* Value from Matthews and Sandage (1963), used for normalization of the calculations.

Table 2b. Variation of theoretical colours for RCW 86, spectra for positions A–C 2 by Ruiz (1981), for position D by Dopita et al. (1980)

Position	C	V-B	B-L	CBL(1) ⁺	R(1) ⁺	(B-V) _J	R _J (1) ⁺	Δλ(L) ⁺⁺	Δλ(B) ⁺⁺	Δλ(V) ⁺⁺	Δλ(B _J) ⁺⁺	Δλ(V _J) ⁺⁺
A	0	0.145	-1.041	0.57	4.48	0.02	6.09	-91	-33	-405	77	-368
	0.5	0.229	-0.611	0.47	3.22	0.34	4.03					
B1	0	-0.272	-1.061	0.51	4.38	-0.61	3.81	-93	-81	-425	-89	-189
	0.5	0.169	-0.575	0.44	2.98	0.24	3.33					
B2	0	-0.236	-1.044	0.48	3.89	-0.52	3.62	-95	-66	-318	-85	-148
	0.5	0.160	-0.600	0.44	2.98	0.24	3.31					
B3	0	0.162	-1.236	0.53	3.97	0.06	4.61	-99	-27	-309	55	-200
	0.5	0.243	-0.646	0.47	3.07	0.40	3.61					
C1	0	-0.064	-1.110	0.44	3.63	-0.29	3.70	-95	-83	-270	-60	-138
	0.5	0.193	-0.625	0.44	2.98	0.29	3.36					
C2	0	-0.053	-1.107	0.49	3.87	-0.24	4.09	-97	-52	-304	-32	-197
	0.5	0.191	-0.643	0.45	3.03	0.30	3.46					
D	0	-0.064	-0.925	0.60	4.30	-0.29	4.26	-81	7	-333	15	-190
	0.5	0.183	-0.513	0.46	3.11	0.26	3.54					
Average	0	-0.054	-1.075	0.52	4.07	-0.27	4.31	-93	-48	-338	-17	-204
RMS	0	0.154	0.087	0.05	0.29	0.23	0.79	5	30	56	62	70
Average	0.5	0.195	-0.602	0.45	3.05	0.29	3.52					
RMS	0.5	0.028	0.051	0.02	0.08	0.05	0.23					

RMS: root mean square

⁺CBL, R, R_J for A_{VJ} = 1^m⁺⁺in A (apparent eff. wavelengths: λ_L^{*} ≈ 3743 ≈ 3727 [O II], λ_B^{*} = 4259, λ_V^{*} = 5112 ≈ 5007 [O III], λ_{BJ}^{*} = 4431, λ_{VJ}^{*} = 5301).**Table 2c.** Theoretical colours dependent on completeness of spectra (N: number of lines between ~λ 3600 and 7330 Å)

Object	C	N	V-B	B-L	R(0.5) ⁺	CBL(0.5) ⁺	(B-V) _J	R _J (0.5) ⁺
Orion N.	0	68 [*]	0.046	-0.232	3.22	0.41	-0.02	4.21
	0	25	0.060	-0.243	3.31	0.42	-0.02	4.78
	1	68 [*]	0.175	-0.180	3.06	0.40	0.25	3.92
	1	25	0.216	-0.172	3.08	0.41	0.30	4.18
N160A	0	25 ^{**}	0.387	-0.538	4.58	0.53	0.28	10.63
	0	68	0.288	-0.439	4.17	0.49	0.24	7.77
	1	25 ^{**}	0.427	-0.444	3.92	0.48	0.42	7.73
	1	68	0.347	-0.368	3.69	0.46	0.39	6.29

^{*}based on spectrum by Aller (1965)^{**}based on spectrum by Dufour (1975)⁺R, CBL, R_J for A_{VJ} = 0.5^m

(Hz⁻¹) as given by Osterbrock (1974, p. 104); the factors *C* are listed in Table 2a (2b and c). The data for *C*=0 represent the colours of the pure emission line spectra. For the SNR we adopted a wavelength independent continuum of strength $C = I_c(4861 \text{ \AA})/I(\text{H}\beta)$; in Table 2a (2b) the corresponding *C* are

given as percent of $I(\text{H}\beta)$. Indications for continua of strength $C \approx 0.2\text{--}1\%$ are given by Miller (1974; see also D'Odorico et al., 1980) for the Cygnus Loop and by Dopita et al. (1980) for SNR 2–6 in M 33. The adopted continua do not necessarily represent the physical conditions of the individual objects, however, for the SNR

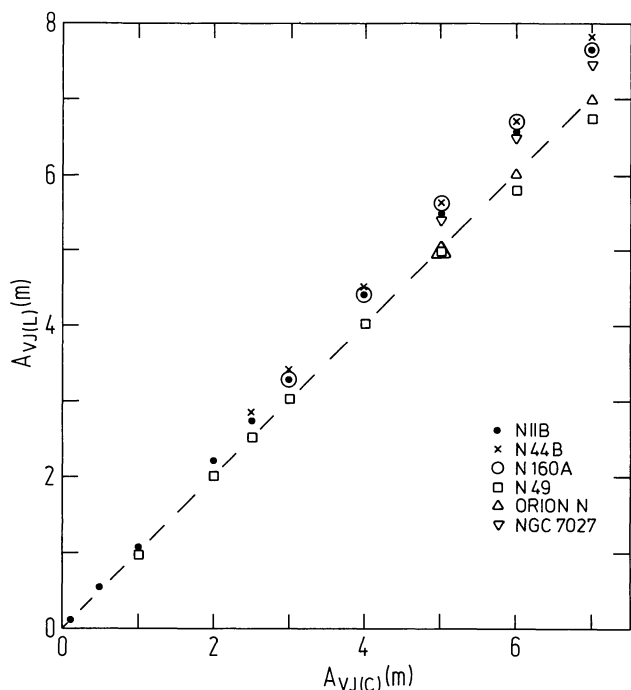


Fig. 2. Relation between extinction derived from continuum source (star), $A_{VJ(C)}$, and derived from pure emission line object, $A_{VJ(L)}$. For emission line objects with continuum ($C=1$) the deviations reduce to $\approx 1/2$ of the shown values

we obtain good agreement between the observations and the calculations; see Fig. 1 (plus signs and open circles respectively) and Paper II.

To increase the statistical significance we included more objects in the calculations. The spectra (all terminating at λ 3727 Å) are taken from Dopita et al. (1980): RCW 86, RCW 103, SNR of LMC and M 33, EN of M 33; Ruiz (1981): RCW 86; Osterbrock and Costero (1973): Vela; Miller (1974) and D'Odorico et al. (1980): Cygnus Loop; Osterbrock and Dufour (1973): N 49 (LMC); Lasker (1981): SNR and EN of LMC; Peimbert and Torres-Peimbert (1974, 1976), Dufour (1975): EN of SMC and LMC.

b) Accuracy Estimates

For the investigated emission spectra the observed line ratios, $I(\lambda)$, and the reddening corrected line ratios, $I_0(\lambda)$, are given in the literature. Whenever the value A_{VJ} was given, which was applied to obtain $I_0(\lambda)$ from $I(\lambda)$, we checked that the extinction law Eq. (3) reproduced the ratios $I(\lambda)$ when applied to $I_0(\lambda)$. The differences between the published and reproduced values did not exceed 10%. For this reason we do not apply another extinction law, in particular we do not apply a specific extinction law for the objects of the LMC and M 33.

The extinction A_{VJ} may be derived either from observed line ratios compared with model calculations (cf. Ruiz, 1981; Dopita et al., 1980), or may be derived from extinction measurements of stars near the object of investigation (cf. Paper II). Let $A_{VJ(C)}$ be the extinction derived from stellar observations (i.e. continuum sources). Dependent on the distribution of emission lines in the V_J passband, the value $A_{VJ(L)} = -2.5 \log(I_{VJ}/I_{VJ,0})$ calculated from

the line ratios $I_0(\lambda)$ by applying Eq. (3) and the corresponding value $A_{VJ(C)}$, may be different from the observed value $A_{VJ(L)}$. For a number of objects we show in Fig. 2 the relation between $A_{VJ(L)}$ and $A_{VJ(C)}$; the differences do not exceed 10% also in case continua are included for the emission line objects.

The wavelength positions of the filter functions may not be known exactly. We introduced random shifts of up to ± 30 Å in the filter positions which produced the following standard deviations (for $C=0$ and $C=1$): $\text{rms}(V-B) \approx \text{rms}(B-L) \approx 0.06$, $\text{rms}(R) \approx 0.07$, $\text{rms}(B-V)_J \approx 0.10$, $\text{rms}(R_J) \approx 1.5$. Similar uncertainties are observed for uncertainties of 20% in the line ratios.

To illustrate the variation of theoretical colours calculated for spectra taken at various positions of the same object, we give in Table 2b data for RCW 86 derived from the observations by Ruiz (1981) and Dopita et al. (1980). The data of Table 2b are also shown in Fig. 1.

Motions of the objects with respect to the observer result in Doppler-shifted spectra. For the spectra of the objects of Table 2a and a velocity of $\pm 100 \text{ km s}^{-1}$ we obtain changes $\Delta(V-B) \approx \Delta(B-L) \approx \mp 0.05$, $\Delta(B-V)_J \approx \mp 0.10$.

The completeness of the observed spectra is an important question; Table 2c gives relevant data. The photometric values of M 42 are calculated for the spectrum given by Aller (1965); this spectrum contains $N=68$ lines between $\sim \lambda$ 3600 Å and $\sim \lambda$ 7330 Å. From this spectrum we selected 25 bright lines, i.e. the lines observed in N 160 A by Dufour (1975), and calculated the photometric data for the reduced M 42 spectrum. The photometric data of N 160 A are calculated for the spectrum given by Dufour, i.e. $N=25$. Since both nebulae have temperatures $T \approx 10,000$ K, though being different in abundance, we added to the observed 25 lines of N 160 A the additional weak lines observed in M 42. In Table 2c the data are given for $C=0$, pure emission line spectrum, and $C=1$, with additional H-continuum of $T=10,000$ K. For M 42 the changes in colour are small (at constant C). For N 160 A we obtain differences $\Delta(V-B) \approx \Delta(B-L) \approx 0.10$ and $\Delta(B-V)_J \approx 0.04$.

c) Reddening Relations

To understand quantitatively the reddening relations, we calculated for the emission line spectra the values R , R_J which may be used to derive $E(V-B)$, $E(B-V)_J$ in case A_V , A_{VJ} are known. For the pure emission line spectra ($C=0$) we find considerable variations of R , R_J which we attribute to corresponding changes in the apparent effective wavelengths λ_{eff}^* , Eq. (11). We find good correlations when plotting R , R_J against $\lambda_{\text{eff}}^* - \lambda_{\text{eff}}^*$, $\lambda_{\text{eff},J}^* - \lambda_{\text{eff},J}^*$, respectively, as shown in Figs. 3 and 4 for $A_{VJ} = 0^m.5$. For $A_{VJ} = 3^m$, the values R , R_J are $\sim 10\%$ lower. We observe that $R \rightarrow R(\text{BB})$ for $\lambda_{\text{eff}}^* - \lambda_{\text{eff}}^* \rightarrow \lambda_{\text{eff},V} - \lambda_{\text{eff},B}$; the same holds for the UBV system. In Figs. 3 and 4 we also show the influence of the additional continuum (see Sect. IIa). In particular, for the PN NGC 7027 we used the spectrum given by Aller (1965) and the continuum measured by Miller and Mathews (1972). The continua decrease the values R , R_J , i.e. R , R_J approach $R(\text{BB})$, $R_J(\text{BB})$; however, the influence of the emission lines may remain noticeable as evident from Figs. 3 and 4.

In the same way we understand the variation of the reddening slope CBL , Eq. (9), for which the calculations are not affected by the ultraviolet cut-off of the spectra. Figure 5 exhibits a good correlation between the calculated CBL , for $A_{VJ} = 0^m.5$, and the ratio $(\lambda_{\text{eff},B}^* - \lambda_{\text{eff},V}^*) / (\lambda_{\text{eff}}^* - \lambda_{\text{eff}}^*)$. For $A_{VJ} \gtrsim 3^m$, the corresponding values CBL are $\sim 5\%$ lower. In Fig. 5 we also show the influence of the additional continuum.

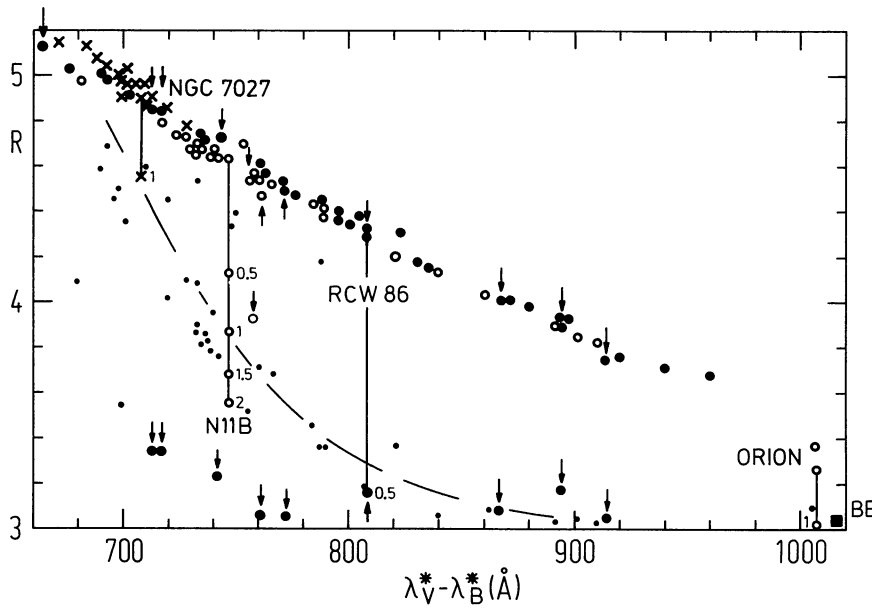


Fig. 3. Values R plotted at positions $\lambda_V^* - \lambda_B^*$ of pure line spectra ($C=0$) for the $VBLUW$ system: SNR: \bullet , EN: \circ , PN: \times , 25,000 K BB: \blacksquare . The influence of a continuum is indicated for SNR RCW 86: $C=0.5$, EN N 11 B: $C=0.5, 1, 1.5, 2$, Orion Nebula: $C=1$, PN NGC 7027: continuum of Miller and Mathews (1972); small dots: addition of H-continuum ($T=10,000$ K, $C=1$) for EN and PN, dashed line: adopted curve with continuum. Arrows indicate SNR, EN discussed in Paper II [Table 1(B)], with continua derived there. All data for $A_{VJ} = 0^m.5$

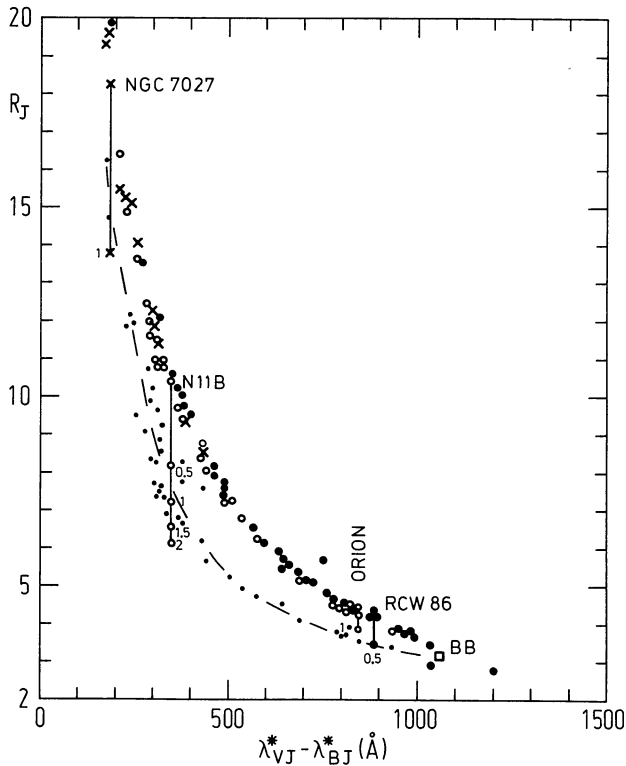


Fig. 4. Similar to Fig. 3 but for the UBV system; all data for $A_{VJ} = 0^m.5$

To investigate the ultraviolet colours we selected from the compilation by Kaler (1976) a number of PN for which the spectra extend to $\sim \lambda 3000$ Å. We also used the spectrum of M 42 and PN NGC 7027 (Aller, 1965). We added a H-continuum of $T=10,000$ K, $C=1$, not necessarily representing the actual physical conditions, but sufficient to demonstrate the influence of continua. The values R , R_J and CBL of the PN and M 42 are also shown in

Figs. 2–5. For the PN and M 42 we show in Fig. 6 the calculated reddening slopes C_{BU} and C_{UW} , see Eq. (9), for $A_{VJ}=0^m.5$, plotted against $(\lambda_B^* - \lambda_U^*)/(\lambda_V^* - \lambda_B^*)$ and $(\lambda_U^* - \lambda_W^*)/(\lambda_V^* - \lambda_B^*)$, respectively. For $A_{VJ} \gtrsim 3^m$, the values C_{BU} and C_{UW} are $\approx 5\%$ lower. The correlation is good, however, for C_{UW} there exists a strong influence of the continuum probably caused by the increased strength of the continuum shortwards of the Balmer jump.

For the PN and M 42 we show in Fig. 7 the calculated reddening slope C_{UBJ} , Eq. (6), of the UBV system plotted against $(\lambda_{BJ}^* - \lambda_U^*)/(\lambda_{VJ}^* - \lambda_{BJ}^*)$. The correlation is good, however, there exists a noticeable dependence on the value A_{VJ} and the continuum background. We believe that the correlations shown in Figs. 6 and 7 also hold for ultraviolet spectra of EN and SNR. For the homogeneous sample of 14 PN shown in Fig. 7 we calculated from the emission line spectra $I_0(\lambda)$ of the average values $\langle \lambda^* \rangle$ and the standard deviations rms. The values are: $\langle \lambda_{VJ}^* \rangle = 3875$ Å, rms = 73 Å; $\langle \lambda_{BJ}^* \rangle = 4746$ Å, rms = 65 Å; $\langle \lambda_U^* \rangle = 5042$, rms = 72 Å. The values $\langle \lambda^* \rangle$ show the strong influence of the strong lines [O II] $\lambda 3727$ Å, [O III] $\lambda 4959$ Å, [O III] $\lambda 5007$ Å, respectively.

In Figs. 3–7 we used the apparent effective wavelengths λ^* calculated from the reddening corrected line ratios $I_0(\lambda)$. We used $I_0(\lambda)$ since in both photometric systems the values $(\lambda_V^* - \lambda_B^*)$, $(\lambda_U^* - \lambda_B^*)/(\lambda_V^* - \lambda_B^*)$, calculated for the reddened line ratios $I(\lambda)$, may change by $\approx 40\%$ for values $0 < A_{VJ} \lesssim 7^m$, so that a complete representation of the reddening relations for various values of A_{VJ} requires many figures.

III. Conclusions

The analysis reveals that reddening relations derived for stars are not necessarily applicable to emission line objects like EN, PN, SNR. The scatter of the data shown in Figs. 1–7 demonstrates the difficulty, though not impossibility, to group classes of objects (EN, PN, SNR) together with respect to the values $\Delta\lambda(X)$, $(\lambda_V^* - \lambda_B^*)_{(J)}$, or $(\lambda_U^* - \lambda_B^*)/(\lambda_V^* - \lambda_B^*)_{(J)}$, so that each object must be analyzed individually.

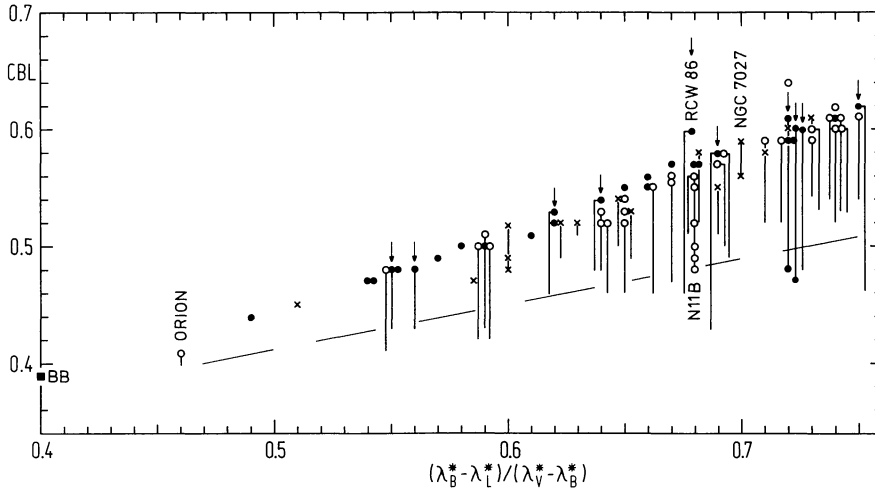


Fig. 5. *VBLUW* system. Reddening slope *CBL* of pure line spectra for SNR: ●, EN: ○, PN: ×, 25,000 K BB: ■, for $A_{VJ} = 0^m.5$. Lower endpoints of vertical lines is *CBL* with continuum background added (see Sect. IIa); dashed line: adopted relation with continuum included. Arrows indicate SNR, EN discussed in Paper II with continua derived there

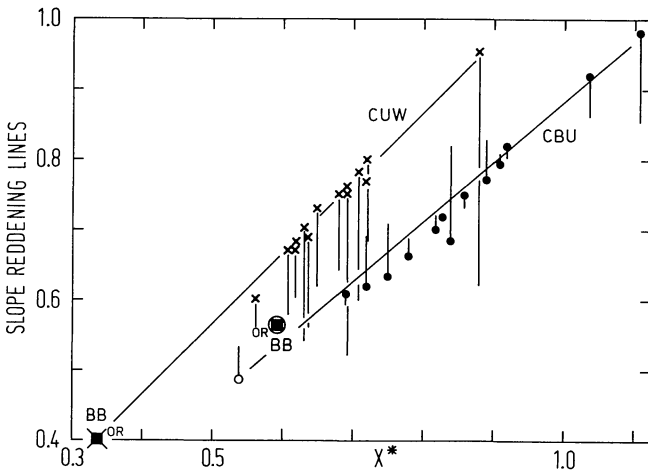


Fig. 6. *VBLUW* system. Reddening slopes *CBU* (●) and *CUW* (×) of pure line spectra plotted against $X^* = (\lambda_B^* - \lambda_V^*) / (\lambda_V^* - \lambda_B^*)$ and $X^{**} = (\lambda_V^* - \lambda_W^*) / (\lambda_V^* - \lambda_B^*)$, respectively, for PN and the Orion Nebula: OR, and 25,000 K BB: ■, for $A_{VJ} = 0^m.5$. Endpoints of vertical lines is *CBU*, *CUW* with H-continuum ($T = 10,000$ K, $C = 1$) added

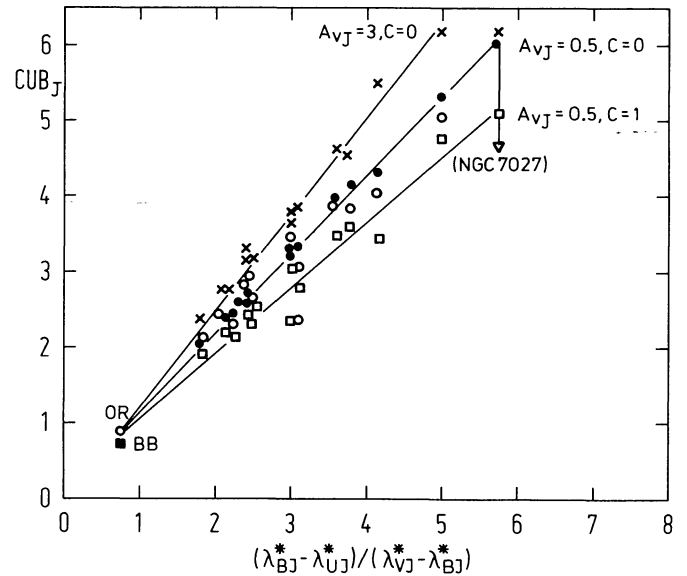


Fig. 7. *UBV* system. Reddening slope CUB_J for PN, Orion Nebula: OR, 25,000 K BB: ■. Pure line spectra, $C = 0$, for $A_{VJ} = 0^m.5$: ●, and $A_{VJ} = 3^m$: ×. Line spectra with H-continuum ($T = 10,000$ K, $C = 1$) added, for $A_{VJ} = 0^m.5$: □, and $A_{VJ} = 3^m$: ○. PN NGC 7027 with continuum of Miller and Mathews (1972), for $A_{VJ} = 0^m.5$: ▽

The reduction of photometric data of emission line objects require spectra to derive apparent effective wavelengths for the various filter passbands. Table 2c and the analysis of the PN in Fig. 7 indicate that only the stronger lines (like [O II] λ 3727 Å, [O III] λ 4959 Å, λ 5007 Å) are important for the reduction.

For pure emission objects ($C = 0$), which do not exist in nature so that this discussion represents a limiting case, drastic changes of the reddening relations occur as exhibited in Figs. 1–7. The changes increase for increasing deviations of the values $(\lambda_V^* - \lambda_B^*)_{(J)}$, $(\lambda_X^* - \lambda_V^*)_{(J)}$ from the values $(\lambda_{\text{eff},V} - \lambda_{\text{eff},B})_{(J)}$, $(\lambda_{\text{eff},X} - \lambda_{\text{eff},V})_{(J)}$, valid for objects with dominant continuum emission.

For emission line objects with continuum backgrounds the modifications of the reddening relations are considerably reduced,

or even negligible, unless the values $(\lambda_V^* - \lambda_B^*)_{(J)}$, $(\lambda_X^* - \lambda_V^*)_{(J)}$ considerably deviate from the corresponding values for the continuum source. A typical example is PN NGC 7027, at least with respect to data used in the analysis. Unfortunately we do not yet have sufficient photometric data, and corresponding spectroscopic data, for EN (and PN) to substantiate this statement with observations.

Figure 1 and the previous Paper II show that our observational data of SNR (plus signs in Fig. 1) are reproduced when appropriate continuum backgrounds are included in the calculation of colours (small circles in Fig. 1). Because of these backgrounds, and the particular values $(\lambda_V^* - \lambda_B^*)$, $(\lambda_X^* - \lambda_V^*) / (\lambda_V^* - \lambda_B^*)$, the required reddening relations deviate only slightly from the values applicable to a continuum source. The objects of our observations are indicated in Figs. 1, 3, and 5.

At present we are inclined to agree with the statement by Aller and Liller (1968) made for PN that "conventional *UBV* filters supply gibberish, unless supplemented by careful spectrophotometry". However, a sufficiently large statistical sample of photometric observations may reveal correlations with astrophysical parameters, as for instance line strengths of dominant lines in the various filter passbands. A search for such correlations is useful in order to establish and extend classifying photometric work to emission line objects in, for instance, nearby galaxies.

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