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Reddening in the narrow-line region of active galactic nuclei

Z. I. Tsvetanov★ *Department of Astronomy and National Astronomical Observatory, Bulgarian Academy of Sciences, 72 Lenin Blvd, 1784 Sofia, Bulgaria*

I. M. Yancoulova *Department of Astronomy, University of Sofia, 5 Anton Ivanov Str., 1126 Sofia, Bulgaria*

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Summary. We suggest the use of forbidden lines of approximately equal critical density as a reddening indicator for the narrow-line regions of AGN. An R_3/R_6 diagram [line ratios [S II]($\lambda\lambda$6717 + 6731)/[O II]($\lambda\lambda$3726 + 3729) and [S II]($\lambda\lambda$4069 + 4076)/[O II]($\lambda\lambda$7320 + 7330)] is used for reddening estimates in 25 objects taken from the literature. A slight tendency for the reddening of NLR to be higher in type 2 than in type 1 objects is observed. We compare the reddening values derived from the Balmer decrement, the S II/O II and the R_3/R_6 methods.

1 Introduction

When studying the physical conditions in active galactic nuclei (AGN), a precise knowledge of the intrinsic intensities of the emission lines is necessary. The observed emission-line ratios are, however, affected by reddening. Good reddening indicators are ratios of lines from the same ion separated by a wide range in wavelength. The main problem is that there are very few suitable line ratios which can be predicted reliably (see Netzer 1982).

The most commonly used emission-line ratios are those of the hydrogen Balmer series. Recently many authors have pointed out that the intrinsic Balmer decrement can differ from the pure case *B* value due to, amongst other effects, that of an X-ray component in the ionizing spectrum. It has been shown that the Hα/Hβ value is not sensitive to the ionization parameter but is a function of metallicity and the form of the ionizing continuum from the UV to the X-ray region (Halpern 1982; Halpern & Steiner 1983; Gaskell & Ferland 1984; see also Netzer 1982). Based on this, it is recommended that the Balmer decrement can be used as a reddening indicator in the narrow-line regions but that the intrinsic value of Hα/Hβ should be assumed to be about 3.0–3.1 instead of the classical case *B* value of 2.85 (Gaskell 1982; Gaskell & Ferland 1984; Halpern 1982). Also, the Pα/Hβ (Gaskell & Ferland 1984), Pβ/Hα

★Visiting astronomer, European Southern Observatory, Karl-Schwarzschild-Straße 2, D-8046 Garching bei München, FRG.

and $P\beta/H\gamma$ ratios (Ward *et al.* 1987) are almost independent of the assumed physical conditions and, therefore, are good reddening indicators. It should be noted that in many cases significant uncertainties are caused by the blending with the broad-line components, especially for AGN of types 1 and 1.5.

The best reddening indicators are ratios of pairs of forbidden lines arising from a common upper level. If the lines are optically thin, their ratio is a constant which is dependent neither on the density nor the temperature. The ratios of [S II] $\lambda\lambda 4072/10320 = 1.8$ and [O II] $\lambda\lambda 7325/2470 = 1.33$ are good examples, but they include lines in the far-UV and IR regions which are difficult to observe. The ratio of IR to blue sulphur lines was used by Wampler (1968, 1971) and by Ward *et al.* (1987) to estimate the reddening of some classical Seyfert galaxies.

Another possibility is to use line ratios in a more accessible region. In the optical region the forbidden lines of O^+ and S^+ are among the brightest lines in AGN spectra. The use of a combination of [O II] $(\lambda\lambda 7320+7330)/(\lambda\lambda 3726+3729)$ (or R_O) and [S II] $(\lambda\lambda 4069+4076)/(\lambda\lambda 6717+6731)$ (or R_S) ratios as a reddening indicator was suggested by Allen (1979) – the $R_O \times R_S$ versus R_O/R_S diagram. This method was criticized by Michalski & Ferland (1983) who pointed out that "the ratio R_O/R_S is a function of both metallicity and ionization parameter in addition to the reddening". Later, based on his calculations of O^+ and S^+ level populations, Malkan (1983) showed that both ratios are "similar functions of electron density" with the dependence on the temperature being very slight. He used the R_O versus R_S diagram to estimate reddening in a number of AGN he had observed. Both Allen (1979) and Malkan (1983) assume that the narrow emission-line region is homogeneous in density and temperature.

Recently, the profiles of the narrow lines of AGN have been studied using high-resolution spectra. It was shown that a correlation between FWHM and N_{cr} (critical density at which collisional de-excitation of the transition becomes important, see below) existed in a number of objects (Pelat, Alloin & Fosbury 1981; Atwood, Baldwin & Carswell 1982; Cohen & Marcy 1983; De Robertis & Osterbrock 1984, 1986; Filippenko & Halpern 1984; Filippenko 1985). Although this dependence is strong for some types of AGN (Liners) and not so evident for some others, we can still draw the general conclusion that there are probably clouds of a range of densities (10^2–10^7 cm^{-3}) in most AGN narrow-line regions.

It can be shown that most of the emission in a given line comes from the region where $N_e \approx N_{cr}$ (De Robertis & Osterbrock 1986); consequently, the suggestion in the Allen and Malkan papers that [S II] $\lambda\lambda 4072$, 6725 and [O II] $\lambda\lambda 3727$, 7325 lines were formed under the same conditions (densities and temperatures) is not correct if a range of densities is present. It is preferable that the ratio of transitions of similar critical densities should be used in determining the reddening in the narrow-line region, gaining more confidence that lines are coming from the same region and the intrinsic ratios are predicted reliably. Therefore, we suggest that the following line ratios should be used:

$$\frac{[\mathrm{S\,II}](\lambda\lambda 6717+6731)}{[\mathrm{O\,II}](\lambda\lambda 3726+3729)}, \qquad N_{cr} \approx 10^3\ \mathrm{cm}^{-3}$$

$$\frac{[\mathrm{S\,II}](\lambda\lambda 4069+4076)}{[\mathrm{O\,II}](\lambda\lambda 7320+7330)}, \qquad N_{cr} \approx 10^6\ \mathrm{cm}^{-3}. \qquad (1)$$

2 Calculations

The ground configurations of both O^+ and S^+ are similar and are determined by the $2p^3$ electrons. The equilibrium equations are solved numerically using the five-level atom approximation. The level populations are determined by spontaneous transitions and electron impacts. The Einstein coefficients A_{ik} for spontaneous transitions, the excitation energies of O^+ and S^+ and the collision strengths Ω_{ik} are taken from Pradham (1976, 1978), Zeipen (1982) and Mendoza & Zeipen (1982). A good compilation of atomic parameters is given by Mendoza (1983).

The critical electron density for level (i), $N_{cr}(i)$, above which the collisional de-excitation of the level is important (Osterbrock 1974) is determined by

$$N_{cr}=\sum_{k<i} A_{ik} \Big/ \sum_{i\neq k} q_{ik}, \tag{2}$$

where q_{ik} is the (de)excitation rate of level (i) due to impacts. The transitions in equation (1) have critical densities as follows: first ratio, levels ^2D – [S II] $\lambda6725=3.5\times10^3$ cm^{-3}, [O II] $\lambda3727=4.2\times10^3$ cm^{-3}; second ratio, levels ^2P – [S II] $\lambda4072=2.1\times10^6$ cm^{-3}, [O II] $\lambda7325=6\times10^6$ cm^{-3}. The critical density depends only slightly on temperature, so we can assume for O^+ and S^+ $N_{cr}(^2D)\sim10^3$ cm^{-3} and $N_{cr}(^2P)\sim10^6$ cm^{-3} in the temperature range of interest.

The line ratios we suggest as a reddening indicator can be written in the following way

$$\frac{[\mathrm{S\,II}](\lambda\lambda6717+6731)}{[\mathrm{O\,II}](\lambda\lambda3726+3729)}=\frac{N(\mathrm{S})}{N(\mathrm{O})}R_3\frac{X(\mathrm{S}^+)}{X(\mathrm{O}^+)}$$

$$\frac{[\mathrm{S\,II}](\lambda\lambda4069+4076)}{[\mathrm{O\,II}](\lambda\lambda7320+7330)}=\frac{N(\mathrm{S})}{N(\mathrm{O})}R_6\frac{X(\mathrm{S}^+)}{X(\mathrm{O}^+)}, \tag{3}$$

where $N(\mathrm{S})$ and $N(\mathrm{O})$ are sulphur and oxygen relative abundances, and $X(\mathrm{S}^+)$ and $X(\mathrm{O}^+)$ gives the degree of ionization of S and O. R_3 and R_6 stand for

$$R_3=\frac{Y_3(\mathrm{S\,II})\,\chi_{31}A_{31}+Y_2(\mathrm{S\,II})\,\chi_{21}A_{21}}{Y_3(\mathrm{O\,II})\,\chi_{31}A_{31}+Y_2(\mathrm{O\,II})\,\chi_{21}A_{21}}$$

$$R_6=\frac{Y_2(\mathrm{S\,II})\,\chi_{51}A_{51}+Y_4(\mathrm{S\,II})\,\chi_{41}A_{41}}{Y_5(\mathrm{O\,II})(\chi_{53}A_{53}+\chi_{52}A_{52})+Y_4(\mathrm{O\,II})(\chi_{43}A_{43}+\chi_{42}A_{42})}, \tag{4}$$

where $Y_i=N_i/N_1$ are relative level populations of S^+ and O^+, respectively and χ_{ij} are energy differences of the levels. We assume in equation (3) that all singly ionized atoms, S^+ and O^+, are in the ground state, i.e. $N_1(\mathrm{O}^+)\approx N(\mathrm{O}^+)\simeq N(\mathrm{O})X(\mathrm{O}^+)$ and $N_1(\mathrm{S}^+)\approx N(\mathrm{S}^+)\simeq N(\mathrm{S})X(\mathrm{S}^+)$. It is important to note that R_3 and R_6 ratios are functions of N_e, T_e and atomic parameters only and, therefore, their intrinsic values can be tabulated with minimum assumptions of the physical conditions in the narrow-line region.

The equilibrium equations determining the level populations are solved numerically for a range of electron densities (10^2–10^8 cm^{-3}) and temperatures (10^4–2.5×10^4 K). Given the relative level populations one can determine R_3 and R_6 as a function of N_e and T_e. The R_3 ratio does not depend on electron density and decreases with rising temperature. On the other hand, R_6 is slightly changed when the density varies from 10^2 to 10^6 cm^{-3} and also decreases with temperature.

The intrinsic line-ratios are affected by the reddening. Assuming a Whitford reddening curve, as tabulated by Kaler (1976), it can be shown that

$$R_3 = R_3^{(0)}\,10^{+0.971E(B-V)}$$
$$R_6 = R_6^{(0)}\,10^{-0.943E(B-V)}, \qquad (5)$$

where $R_3^{(0)}$ and $R_6^{(0)}$ are the intrinsic values of R_3 and R_6.

The calculated R_3 and R_6 ratios are shown in Fig. 1, where the zero reddening range and some constant reddening lines are also shown. In order to use the R_3/R_6 diagram for reddening determination it is necessary to know the ratio of abundances $N(\mathrm{S})/N(\mathrm{O})$ and the ratio of ionization stages $X(\mathrm{S}^+)/X(\mathrm{O}^+)$ both in the low density ($\sim 10^3$ cm^{-3}) and in the high density ($\sim 10^6$ cm^{-3}) clouds. Different values of $N(\mathrm{S})/N(\mathrm{O})$ and $X(\mathrm{S}^+)/X(\mathrm{O}^+)$ would shift an arbitrary point on the R_3/R_6 diagram along the 45° line which is almost parallel to the constant reddening line. For this reason it is not necessary to know the precise values of $N(\mathrm{S})/N(\mathrm{O})$ and $X(\mathrm{S}^+)/X(\mathrm{O}^+)$, but only whether those two ratios are changed when going from low- to high-density clouds. It is difficult to imagine that the ratio of the abundances vary substantially in relatively close spatial regions. Hence, we will assume that the abundances of the elements are close to the solar values, i.e. $N(\mathrm{S})/N(\mathrm{O}) = 0.34/8.3$ (Lambert 1978; Lambert & Luck 1978). The second important ratio, $X(\mathrm{S}^+)/X(\mathrm{O}^+)$ depends mainly on the form of the ionizing continuum. Supposing that there is no screening and that absorption in the intercloud medium is

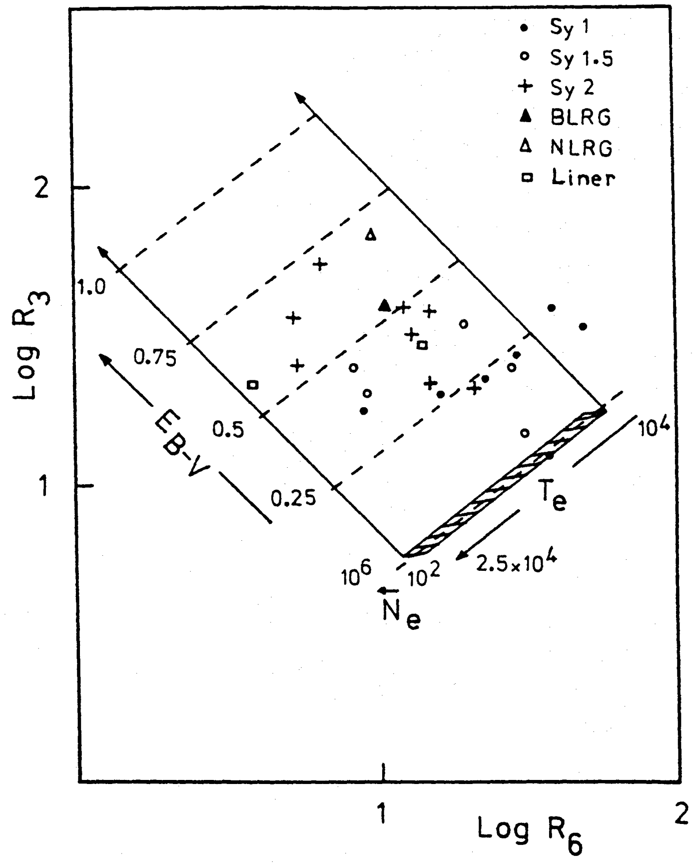

Figure 1. The R_3/R_6 diagram. The dashed lines are loci of constant reddening for $E(B-V) = 0$, 0.25, 0.5, 0.75 and 1.0. The hatched area is the zero reddening range where $10^2 \le N_\mathrm{c} \le 10^6$ cm^{-3} and $10\,000 \le T_\mathrm{c} \le 25\,000$ K. The objects in Table 1 were plotted assuming $N(\mathrm{S})/N(\mathrm{O}) = 0.34/8.3$ (Lambert 1978; Lambert & Luck 1978) and $X(\mathrm{S}^+)/X(\mathrm{O}^+) = 1$.

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negligible, one can assume that the form of the ionizing continuum does not change throughout narrow-line regions and, therefore, the $X(S^+)/X(O^+)$ ratio remains constant. In this paper we will assume $X(S^+)/X(O^+)=1$.

3 Comparison with other methods

A comparison of the reddening in the narrow-line regions of AGN, determined by the different methods mentioned above, for a given sample of objects is of interest. It would be best if the observational data were all obtained with the same telescope and detector. Unfortunately, the observational material existing in the literature very often does not satisfy these requirements. For example, the data given by Osterbrock and collaborators do not include, as a rule, the line [O II] $\lambda 7325$, and for that reason they are not suitable for determining the reddening by Malkan's method or by the method suggested here.

The observational data for the 25 galaxies for which the reddening can be determined by all three methods – Balmer decrement, S II/O II (i.e. Malkan 1983) and by R_3/R_6 – are given in Table 1. The first and the second columns contain the number and the type of object. Columns 3–8 give the intensities of the lines relative to Hβ [$I(\mathrm{H}\beta)=1.0$]. Column 9 gives the value of the reddening by the R_3/R_6 method (see Fig. 1). Columns 10, 11 and 12 give $E(B-V)$ determined as follows: column 10 using the [S II] $\lambda\lambda 4072/10320$ ratio; column 11 by Malkan's method using the R_O/R_S diagram and column 12 by the Balmer decrement. When determining the reddening by the Balmer decrement the intrinsic value of $\mathrm{H}\alpha/\mathrm{H}\beta=3.0$ is used, which supposes that the clouds are influenced by the X-ray part of the central source spectrum (Halpern & Steiner 1983).

The objects in Table 1 are plotted in Fig. 1 assuming solar abundances and unity for the ratio of ionization degrees. No additional assumptions regarding N_e and T_e are made. The

Table 1. Relative line intensities [$I(\mathrm{H}\beta)=1.0$] and reddening in the narrow-line region of some AGN.

Object	Type	[OII] $\lambda 3727$	[SII] $\lambda 4072$	H_α	[SII] $\lambda 6725$	[OII] $\lambda 7325$	[SII] 1.03μ	Reddening, E_{B-V}				References
								R_3/R_6	SII	SII/OII	Ba dec	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
NGC 1068 †	2	0.96	0.20	5.94	1.50	0.32	0.40	0.46	0.42	0.29	0.60	1,2,4,5,14,15
NGC 1275	BLRG	2.03	0.51	10.07	3.29	1.15	2.12	0.53	0.66	0.43	1.07	1,5,15
NGC 3227 †	2	0.79	0.06	5.82	0.79	0.26	0.59:	0.55	0.91	0.47	0.58	2,5
NGC 3783	1	0.08	0.02	2.88	0.08	0.02	-	0.24	-	-	?	19
NGC 4151 †	1.5	1.94	0.33	4.47	1.94	0.30	0.44	0.21	0.29	0.16	0.35	6,7
NGC 5506	2	1.97	0.15	13.57Σ	4.45	0.55	-	0.70	-	-	1.33	18
NGC 5548	1.5	0.98	0.19:	3.46	0.59	0.15	-	0.08	-	0.2:	0.13	11
NGC 7213	Liner	0.30	0.15	6.30	0.37	0.27	-	0.43	-	-	0.65	10
NGC 7469	1	0.15	0.08:	3.7	0.21	0.04	<0.16	0.21	<0.38	0.17	0.18	1,5
Mkn 1	2	1.18	0.41	4.27	1.52	0.76	-	0.44	-	0.38	0.31	8
Mkn 3 *	2	3.00	0.26	5.06	2.68	0.42	0.42	0.32	0.35	0.27	0.46	3
Mkn 6	1.5	1.70	0.17	4.76n	2.44	0.21	-	0.40	-	0.28	0.41	3,8,14
Mkn 79	1.5	1.77	0.12:	3.77	1.88	0.12	-	0.26	-	-	0.20	11
Mkn 176	1	1.70	0.48	6.55	2.73	0.31	-	0.29	-	0.22	0.69	14
Mkn 926	1.5	2.25	0.11	2.94	1.84	0.29	-	0.39	-	-	0.41	11
Mkn 975	1.5	0.46	0.06	4.13	0.46	0.17:	-	0.46	-	-	0.46	11
I Zw 92	1	1.55	0.25	3.71	0.80	0.16	-	0?	-	0?	0.19	9
III Zw 77	1	0.07	0.06	2.70	0.08	0.05:	-	0.25	-	?	?	9
Cyg A	NLRG	2.44	0.14	6.60	6.94	0.35	-	0.70	-	0.70	0.70	17
ESO 103-G35	2	2.61	0.23	9.61Σ	3.91	1.05	-	0.64	-	-	1.03	18
ESO 428-G14	2	2.49	0.19	3.55	2.21	0.22	-	0.25	-	-	0.15	12
Tol 0109-383	2	0.36	0.06	9.84Σ	0.58	0.12	-	0.50	-	-	1.04	16
Tol 1351-373	1	1.07	0.10	10.55Σ	0.89	0.15	-	0.27	-	-	1.11	18
Tol 1506-00	1	0.24	0.01	3.66Σ	0.18	0.03	-	0.36	-	-	0.18	18
PKS 1718-649	Liner	2.50	0.09	7.54Σ	2.19	0.57	-	0.57	-	-	0.81	18

References: [1]Wampler (1971), [2]Wampler (1968), [3]Malkan & Oke (1983), [4]Shields & Oke (1975a), [5]Anderson (1970), [6]Osterbrock & Koski (1976), [7]Boksenberg *et al.* (1975), [8]Neugebauer *et al.* (1976), [9]Kunth & Sargent (1979), [10] Filippenko & Halpern (1984), [11]Cohen (1983), [12]Bergvall, Johansson & Olofsson (1986), [13]Morris & Ward (1985), [14]Koski (1978), [15]Shields & Oke (1975b), [16]Fosbury & Sansom (1983), [17]see Gaskell (1982), [18]Morris & Ward (1988), [19]Ward & Morris (1984).

n – Narrow component only.

⋆ – $E_{B-V}=0.24$ from [OII] $\lambda 2470/\lambda 7325$ line ratio. Data taken from Malkan & Oke (1983).

Σ – Sum of H_α + [NII] lines.

† – Average E_{B-V} from Ward *et al.* (1987): NGC 1068 – 0.41, NGC 3227 – 0.53, NGC 4151 – 0.22.

uncertainty of $E(B-V)$ due to N_e is negligible, while different T_e may lead to an error of up to ~ 0.05 mag in the reasonable temperature interval 10 000–25 000 K. The internal accuracy of the suggested R_3/R_6 method is expected to be ~ 0.1–0.15 mag, the main contributor being our simplifying assumption of constant $X(S^+)/X(O^+)$. For several objects in Table 1 (marked with a Σ) lines [N II] ($\lambda\lambda 6548+6584$) are not deblended from Hα. For these objects only upper limits of the reddening can be estimated from the Balmer decrement. Note that for the type 1 objects broad components may introduce significant error in the narrow-line region reddening estimate.

Fig. 2 shows a comparison of the reddening estimated by the three methods. It is clearly seen that Malkan's method gives lower reddening in comparison with the R_3/R_6 method. This is due most probably to the assumption of a single, homogeneous narrow-line region in the R_O/R_S method. In inhomogeneous regions [S II] $\lambda 4072$ and [O II] $\lambda 7325$ come from substantially denser gas than [S II] $\lambda 6725$ and [O II] $\lambda 3727$. As Malkan (1983) noted, "to make the artificial requirement that these two densities agree requires lowering the reddening below its true value". The mean difference between R_3/R_6 and R_O/R_S values is 0.08 ± 0.05, but one should also mention that all Malkan's points (except one) are below the 45° line in Fig. 2. On the other hand, the values determined by the hydrogen lines are on average higher. We suppose this is partly due to the contribution of broad components, but other intrinsic reasons may also be important. A similar effect is noticed by Gaskell (1982).

Ward *et al.* (1987) investigated the reddening of NLR and BLR for three objects of Table 1 (NGC 1068, 3227 and 4151 – marked with a †). The averages of the reddening from several different methods are in good agreement with our values obtained using the R_3/R_6 method assuming $A_V = 3.2\ E(B-V)$.

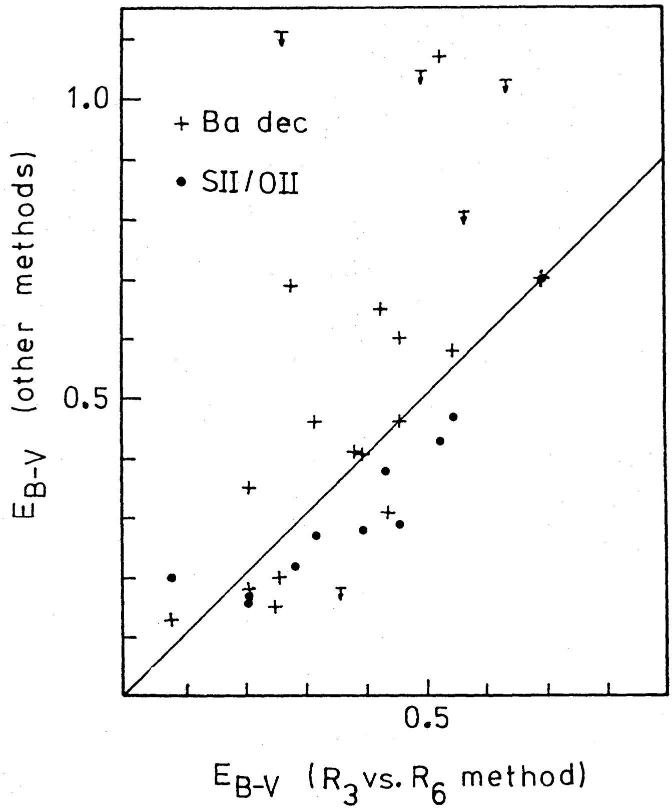

Figure 2. Comparison of reddening estimated via the S II/O II method (all data taken from Malkan 1983), (filled circles); via the Balmer decrement (crosses); and via the R_3/R_6 method.

4 Conclusions

The R_3/R_6 method suggested here is an attempt to account for the inhomogeneous emitting region using line-ratios of similar critical density. This is prompted by the recently established FWHM/N_{cr} dependence and the generally accepted photo-ionization picture of the narrow-line regions. The small number of assumptions is an advantage in addition to the optical line-ratios used. Detailed modelling of the intrinsic ratios in different conditions, abundances, ionizing radiation, etc., could improve the method.

An important effect is seen in Fig. 1. A slight tendency is present for the galaxies of type 1 to have smaller reddening as compared to that of type 2 galaxies. The effect has been noticed by other authors, e.g. Gaskell (1984). Our sample consists of 11 type 2 objects (8 Sy 2, 2 Liners and 1 NLRG) and 13 type 1 (7 Sy 1 and 6 Sy 1.5). NGC 1275 has been excluded because of its controversial type and Liners have been put to Sy 2 while Sy 1.5 have been put to Sy 1. Although one could argue against such a rough division we hope this will not affect the general conclusion. The means of the two subsamples are $E(B-V)=0.51\pm0.14$ ($n=11$) and 0.26 ± 0.12 ($n=13$), respectively, and they are different at over the 99 per cent confidence level (t-test). The Kolmogorov–Smirnov two-sample test rejects the null hypotheses that the two distributions are identical at the 99 per cent level of significance. Thus, we can conclude that there is a trend of increased reddening of the narrow-line regions when going from type 1 to type 2 objects. It is important to demonstrate this effect on a larger sample of objects with more precise estimation of the type of each galaxy. This may contribute to establishing that the differences between different types of AGN are due, at least in part, to different degrees of nuclear obscuration.

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