THE DETERMINATION OF EXTINCTION AND TEMPERATURE FOR THE CENTRAL STAR OF THE PLANETARY NEBULA NGC 40

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ABSTRACT. NGC 40 is an extended, very inhomogeneous planetary nebula, with a WC8 central star. Very discrepant determinations exist in the literature for the extinction towards this object and the temperature of its nucleus. We review here the various methods which can be used to derive these quantities, discussing the assumptions underlying each method and their inherent limitatons, and the uncertainties that arise when they are applied to this particular object. The results are compared to the values which we derive from far UV spectrophotometry: E(B-V) = 0.50 and $T_* \approx$ 90000K.

1. INTRODUCTION

NGC 40 is characterized by an extremely irregular and inhomogeneous structure. It is classified as a low excitation nebula. As noticed by Aller and Czyzak (1979), however, the excitation level changes dramatically from point to point.

The problem of determining a correct value for the reddening is particularly severe in the analysis of far ultraviolet data: for example, a value of A_V = 1 mag would correspond to an extinction of about 2 to 14 mag. from 300 to 100 nm. Therefore, a small error in E(B-V) can introduce large errors in the UV-line flux corrections and can greatly change the slope of the continuum spectrum, resulting in a wrong color temperature determination.

In the literature, values of E(B-V) ranging from 0.2 to 0.82 can be found for NGC 40. Given these discrepancies and the importance of using a correct value for E(B-V), we shall briefly discuss in Section 2 the uncertainties that can have affected the individual determinations. The resultant E(B-V) has a direct bearing on the determination of the temperature of the central star of NGC 40, which

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TABLE I

Determinations of the extinction towards NGC 40

E(B-V)	Ref.	Method
0.50	this work	UV (IUE) (220nm bump)
0.38	Pottasch et al. 1978	UV (ANS)
0.40	Benvenuti et al. 1982	UV (IUE)
0.34	Clegg et al. 1983	fit of UV nebular continuum
0.49, 0.51	Clegg et al. 1983	avg. Balmer line ratios
0.20	Cahn 1976	avg. Balmer line ratios
0.50	Cahn et al. 1977	radio/H-beta flux
0.45	Pottasch et al. 1977	radio/H-beta flux
⩽ 0.65	Cahn and Kaler 1971	radio/H-beta flux
0.82	Lang 1974	?

is classified as a WC8 star by Hiltner and Schild (1966). We discuss its temperature in Section 3.

2. DETERMINATION OF THE EXTINCTION

In Table I we summarize determinations of the extinction towards NGC 40 that we have found in the literature. We also include our own determination. The individual methods are briefly discussed below.

2.1. Strength of the 220nm extinction bump

The high value of $A_\lambda/E(B-V)$ in the far UV makes the extinction determination very critical, as we stressed in the introduction. Conversely, the non-monotonic shape of the extinction curve in this region, and in particular the strong "bump" at around 220nm due to graphite grains, allow a very precise determination of E(B-V), on the assumptions that (a) the continuum spectrum is smooth across the 220nm band, and (b) that the standard UV extinction law applies.

From the strength of the 220nm dip we derive for NGC 40 E(B-V) = 0.50. In this case, the assumption that the observed spectrum must be smooth in the far UV is supported by the fact that the contribution of the nebular continuum is negligible, as can be seen from the IUE image, where the spectrum is clearly not extended. Also the nebular continuum observed offset from the central star is fainter than the stellar spectrum by about two orders of magnitude.

The possibility should also be investigated that part of the extinction is of circumstellar origin. Circumstellar dust shells are found to surround some WR stars, especially of WC8-9 type. They are revealed by IR excesses measured around 10μ, showing cool (800 to 1800K) blackbody emission, on top of the free-free radiation distribution (see e.g., van der Hucht et al. 1984, van der Hucht et al. 1981 and references therein). If there is a circumstellar component, the standard interstellar extinction law might not apply, especially in the region of the 220nm bump, since this depends on the grain composition. For some WC stars it is argued that the dust could be of iron rather than graphite grains (e.g., Hackwell et al. 1979, van der Hucht et al. 1982). However, in the SWP high resolution spectrum of NGC 40 we do not detect any evidence for the Fe III (UV 34) absorption features which denote the "iron curtain" found by van der Hucht et al. (1982) in two WC9 stars.

Moreover, our spectrum appears very smooth when dereddened using the average galactic extinction law, and can be fitted very well with a blackbody distribution (see next section) so that it seems justified to use the standard extinction law in the present case. For a more detailed discussion see Grewing and Bianchi (1984) and Bianchi and Grewing (1984).

2.2 Balmer line ratios

E(B-V) can be derived from the Balmer line intensities, using the known relation

$$E(B-V) = 2.5 \log (\hat{I}_i/\hat{I}_{i,o}) / (X_i-X_\beta),$$

where $\hat{I}_i$ and $\hat{I}_{i,o}$ are the theoretical and observed intensities normalized to $H\beta$, and $X_i = A(\lambda_i)/E(B-V)$. In this method, it is essential to use line intensities that apply to the nebula proper, avoiding any contribution from the central star, if the pure recombination theory is applied. Even then, however, the observations of NGC 40 do not give a unique answer. This can be seen e.g., by comparing the intensities (from Minkowski and Aller 1956) for a weak and a strong knot in the nebula. In Table II we list the relative intensities and the E(B-V) values derived using theoretical predictions for the line ratios for $T = 10^4$K.

The numbers clearly illustrate the uncertainties involved. If we ignore the values derived from the H-alpha fluxes because these might be affected by [NII] emission, the averages become E(B-V) = 0.48 and 0.12 in front of the weak and the strong knot, respectively. The first result is consistent with our previous result and the ones derived from the radio/H-beta ratio discussed next; the second result clearly is not.

This difference in extinction is too large to be simply explained as an extinction variation across the object. Using the standard relation between E(B-V) and the hydrogen column density N(H), the latter would have to vary by as much as $\Delta N(H) = 2\times10^{21} cm^{-2}$, which seems improbable.

TABLE II

Relative Intensities and Colors

	Relative intensities					E(B-V)			
	F(Hα)	F(Hβ)	F(Hγ)	F(Hδ)	F(Hε)	Hα	Hγ	Hδ	Hε
weak knot	581	100	37.2	19.8	12.0	0.64	0.55	0.46	0.42
strong knot	904	100	44.0	24.1	15.1	1.04	0.15	0.12	0.08

2.3. Flux ratio F(radio)/F(H-beta)

By comparing the ratio of the observed 10 cm and H-beta fluxes with theoretical predictions, Cahn and Kaler (1971) derived E(B-V) $\leqslant$ 0.65 assuming an electron temperature of T_e = 5000K and taking the value of the fractional ionization of helium from Kaler (1970). Using the same method but a different T_e Cahn (1976) derived E(B-V) = 0.50, and Pottasch et al. (1977) found E(B-V) = 0.45, using a larger value for H-beta.

In this method, the possibility exists that the radio flux is contaminated by unresolved nearby sources. Also, the H-beta flux can be contaminated by emission from the central star atmosphere; this is particularly true in the present case given the relative strength of the stellar and the nebular component (see e.g., Aller 1968 and Bianchi and Grewing 1984). Indeed, three values for the H-beta line absolute intensity are quoted in the literature (e.g., Higgs 1971, Carrasco et al. 1983). Further sources of uncertainties are the electron temperature and the abundance and fractional ionization of Helium. The ratio of the free-free radio continuum observed at 6 cm wavelength to the H-beta flux for an optically-thin nebula can be expressed as (cf. e.g., Milne and Aller 1975),

$$S(6cm)/F(H\text{-}beta)=1.15\cdot 10^{7}\cdot T^{0.4}\cdot(\ln T-3.08)\cdot(1+He^{+}/H^{+}+3.7He^{++}/H^{+})$$

if there is no extinction. In this equation S is measured in Jy, F(H-beta) in erg/cm^{2}s, and T in K. As S and F have the same density dependence, the ratio is independent of density fluctuations, a fact which is particularly important for such an inhomogeneous object. The two quantities do, however, differ slightly in their temperature dependence. Moreover, the fractional ionization of He enters explicitly into the calculation of S.

Assuming T_e = 10^4 and using S(6 cm) = 0.57 Jy and F(H-beta) = 2.3x 10^{-11} erg/cm^2 s, we find:

$$A_\lambda(H\beta) = 2.02 \text{ for } He^{+} = He = 0.1\ H^{+}(\text{case I})$$

$$= 2.26 \text{ for } He^{++} = He = 0.1\ H^{+}(\text{case II})$$

Using a ratio R = A_V/E(B-V) = 3.2, the two values correspond to E(B-V) = 0.46 (case I) and E(B-V) = 0.53 (case II). As helium is likely to be partially in the form of He^+ and He^{++}, the true value should be

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bracketed by these numbers, and it is then consistent with the value we derived from the UV spectrum.

3. DETERMINATION OF THE CENTRAL STAR TEMPERATURE

A detailed discussion of the resulting temperature of the central star of NGC 40 cannot be given here in view of the limited space available (see, however, Grewing and Bianchi, 1984). Here we confine ourselves to summarizing some of the results.

3.1. Comparison with blackbody distribution

The IUE spectrum dereddened for E(B-V) = 0.50 is very well represented by a blackbody distribution with temperature between 80000 and 100000K. The spectrum and the fit is shown in Bianchi and Grewing (1984), Fig. 1. This temperature is in agreement with theoretical predictions based on evolutionary calculations.

3.2. Comparison with model atmospheres

In principle, this method should give more precise information than the blackbody approximation. However, model atmospheres for WR stars should take into account the effects of the dense extended atmosphere, the high Helium abundance, and the high mass-loss rate (not hydrostatic, but expanding atmosphere). Unfortunately, very few such models exist in the literature, and they are all flatter than our observed spectrum (see Grewing and Bianchi 1984, for further discussion). Moreover, the existing calculations show that models with very different T_{eff} can have similar emerging flux distributions, depending on the extension of the atmosphere. Therefore, in the case of WR stars this method does not give unique results, unless the physical parameters of the atmosphere can be determined independently.

3.3. Energy-balance methods

For low excitation nebulae, the temperature of the central star can be inferred from the [O III] 5007/[O II] 3727 line ratio (see e.g., Köppen and Tarafdar 1978), or with the Zanstra method. However, this can be applied only to nebulae which are optically thick in all directions, which is not the case here. For NGC 40, in fact, this method would give a temperature T_* around 35000K, which is discrepant with the previous determination.

3.4. Excitation-class

Webster (1976) finds that the excitation class is primarily determined by the temperature of the central star and by the optical depth of the nebula, and gives a relation between T and the excitation class for optically thick nebulae. In the case of NGC 40, which is not optically thick, this method must be applied with caution, also in

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view of the very large inhomogeneities within the nebulae. The temperature of the central star one would find from the Webster relation is 40000 - 50000K, which must be considered as a lower limit.

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DISCUSSION

TOBIN: How much does the secular change in IUE LWR sensitivity affect estimates of E(B-V) obtained by "ironing out" the 2200 Å bump, and how can someone using IUE fluxes correct for the LWR sensitivity changes?

BIANCHI: In the particular case of the data I have shown, these were taken soon after the data on which the revised absolute calibration is based (Bohlin and Holm, 1980). In general, to know the amount of change in sensitivity at the time of given observation, one can see the reports on IUE sensitivity monitoring which appear in the IUE newsletter. The overall sensitivity degradation from the time of the acquisition of the calibration data to now is at maximum about 20% in the LWR and less than 5% in the overall range of the SWP camera.

BOHLIN: The use of mean extinction curves to determine the amount of reddening by "ironing out" the 2200 Å feature can lead to rather large errors in corrected flux distributions because of large variations in the UV extinction curves, even for stars without any evidence for dust that could be associated with the star itself. For example, in the case of E(B-V) = 0.5, I estimate that different observed extinction curves could give UV fluxes that are different by more than one magnitude, while equally well ironing out the 2200 Å bump.

BIANCHI: The possibility that some of the extinction is of circumstellar origin is discussed by Grewing and Bianchi (1984). If circumstellar dust shells are present surrounding the central star, they can be detected by IR observations or UV high-resolution observations. Moreover, in the case that the interstellar extinction law deviates from the average galactic one, usually the largest difference is in the shape of the 2200 Å bump. Therefore, one can realize that the extinction curve is wrong because the dereddened spectrum would never look smooth.