Astronomy & Astrophysics manuscript no.
(will be inserted by hand later)

An ISO and IUE study of Planetary Nebula NGC 2440*

J. Bernard Salas[1,2], S.R. Pottasch[2], W.A. Feibelman[3], and P.R. Wesselius[1]

[1] SRON Laboratory for Space Research, P.O. Box 800, NL 9700 AV Groningen, the Netherlands
[2] Kapteyn Astronomical Institute, P.O. Box 800, NL 9700 AV Groningen, the Netherlands
[3] Laboratory for Astronomy and Solar Physics, NASA–Goddard Space Flight Center, Greenbelt, Maryland 20771

Received date /Accepted date

Abstract. The infrared and ultraviolet spectra of planetary nebula NGC 2440 is presented. The observations were made respectively by the Infrared Space Observatory (ISO) and International Ultraviolet Explorer (IUE). These data, in conjunction with published optical observations have been used to derive electron temperature and density. A trend of electron temperature with ionization potential is found. In particular the electron temperature increases from 11 000 to 18 000 K with increasing IP. The electron density has a constant value of 4500 cm^{-3} in agreement with previous determination. The chemical abundance has been derived for the folowing elements; helium, carbon, nitrogen, oxygen, neon, sulfur and argon. The ionization correction factor turns out to be very small (almost inneccesary) for all species except sulfur.

Key words. ISM: abundances – planetary nebulae: individual: NGC 2440 – Infrared: ISM: lines and bands

1. Introduction

NGC 2440 has a highly and ionized spectrum. It has been of great scientific interest for astronomers for different reasons: The nebula present a complex bipolar or multipolar morphology, effects of stratification (Walker & Aller, 1970), and strong N II lines (Shields et al., 1981). The latter leads to a high nitrogen abundance, that together with the high helium abundance, classify it as Type I nebula (Peimbert, 1978). The earlier studies by Shields et al. (1981) give an electron density of 3000 cm^{-3} and an electron temperature of 14 000 for the O III. Later studies by Hyung & Aller (1998) leaded to a higher density of 5000 cm^{-3} but agree on the electron temperature finding 14 200 K and 10 000 K for O III and N II respectively.

ISO and IUE provide valuable information which allow us to precisely derive the electron density (N_e), temperature (T_e) and the nebular abundance. Infrared lines avoid many problems usually encountered when deriving abundances, especially temperature fluctuations. This is of particular interest because infrared lines are insensitive to this effect, which could be present in the nebula. This and other advantages are briefly discussed in recent papers by Pottasch & Beintema (1999) and Bernard Salas et al. (2001).

The following section of this paper will be devoted to the ISO and IUE observations. The nebula is bigger than both ISO-SWS and IUE apertures and because of dust absorption (although small) the fluxes need to be corrected for extinction. This is discussed in section 3. In section 4 the line fluxes (infrared, optical and ultraviolet) are presented. In section 5 the N_e and T_e are derived as well as the abundance for the nebula. In section 6 a complete discussion of the parameters previously derived, T_e, N_e and abundances is given. The conclusions are given in the last section.

2. ISO and IUE observations

The infrared observations were made with the Short Wavelength Spectrometer (SWS) on board ISO. Information about this instrument can be found in de Graauw et al. (1996). The wavelength range covered by the instrument is from 2.38 to 45.2 μm. The observation used correspond to a SWS01 observing template, TDT number 72501762. This is a fast observation corresponding to Speed 2 and was reduced at a fix spectral resolution of 400. The observations were centered at RA(2000) $07^H41^M55.4^S$ and Dec(2000)-18°12′31.8″. Pointing errors in ISO are uncertain by about 3″. In Fig. 1 the SWS spectrum of NGC 2440 is presented.

Send offprint requests to: J. Bernard Salas
e-mail: J.Bernard@sron.rug.nl

* Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA

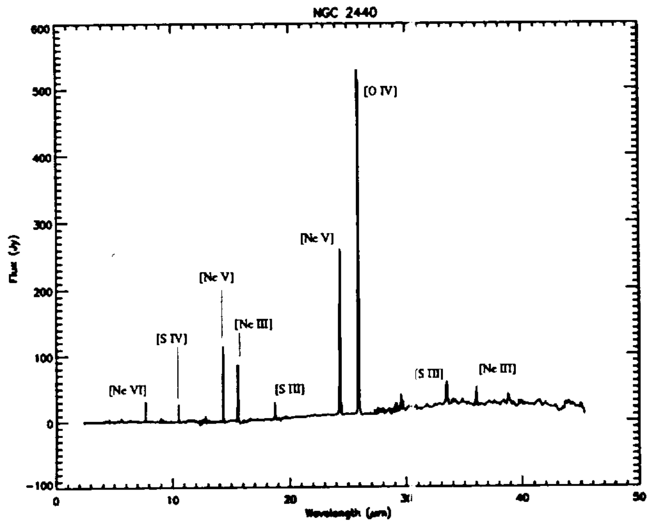

Fig. 1. SWS spectrum of NGC 2440. The continuum is very low. Strong lines are measured and have been labeled. No PAH features are present.

Standard reduction techniques were applied and no major problems were encountered. Information about these tools used to reduce the data, can be found in the interactive analysis software package distributed by the SWS consortium. The observed infrared intensities are given in Table 2.

Maybe Feibelman can comment a little bit more about the IUE observations There are several ultraviolet observations made with the International Ultraviolet Explorer (IUE). Two low resolution spectra and two high ones were used in this paper. When not available ultraviolet measurements from Shields et al. (1981) were also used. The low resolution spectra are labeled SWP 07262 and LWR 06256 and the high ones as SWP 07263 and LWR 10741.The observed ultraviolet intensities are given in Table 3

3. Corrections to line fluxes

All fluxes measured, infrared, ultraviolet and optical, have been corrected for extinction (although the correction in the infrared is very small). Because of the size of the nebula and relative small aperture size of the instruments, aperture corrections have been applied.

3.1. Extinction

In the previous work by Shields et al. (1981) a C_{H_β}=0.63 was found (where $C_{H_\beta}= log(\frac{F(H_\beta)_{predicted}}{F(H_\beta)_{observed}})$), although

In this work the observed lines have been corrected by extinction using C_{H_β}=0.50. This leads to E_{B-V}=0.34. The predicted F_{H_β} has been determined in two ways.

One way to measure the extinction is using the predicted F_{H_β} given by radio fluxes. Applying the following equation:

$$F(H_\beta) = \frac{S_\nu}{2.82\ 10^9\ t^{0.53}\ (1+\frac{He^+}{H^+}+3.7\frac{He^{++}}{H^+})} \quad (1)$$

the expect H_β flux can be found. In eq. 1 S_ν=0.411 Jy at 5 GHz (Pottasch , 1984), t is the temperature of the nebula in 10^4 K (in this case T_e=15 000 is used) and 2.82 10^9 is a conversion factor if the flux density S_ν in Jy and the $F(H_\beta)$ in erg cm^{-2} s^{-1}. The helium abundances are taken from Table 7 and have been derived using the theoretical predictions of Benjamin et al. (1999) at a N_e=10 000 cm^{-3} (using N_e=100 cm^{-3} will lead to the same values). Eq. (1) leads to a predicted H_β of 91.0 10^{-12} erg cm^{-2} s^{-1}. The extinction factor is thus C_{H_β}=0.46. This is in good agreement with what Hyung & Aller (1998) (C_{H_β}=0.53) found. An average of those two ($\overline{C_{H_\beta}}$=0.50) has been used in the present paper to correct for extinction.

3.2. Aperture corrections

NGC 2440 has a measured size (Shields et al., 1981) of 10″ for the main body and a faint envelope that extends up to 30″. ISO-SWS uses different size apertures for the different bands. These sizes range from 14″x 20″(the smallest), to larger apertures 14″x 27″, 20″x 27″ and 20″x 33″. The aperture of the IUE is very similar to ISO-SWS smallest aperture, it's an ellipse of 10″x 23″. It is likely that some of the nebula is missing and, because of the similarity in aperture size, the correction factor in the infrared and ultraviolet will be similar.

In order to correct the infrared lines from apertures effects the SWS measurements have been compared with those from the Infrared Astronomical Satellite (IRAS), which has an aperture big enough to contain the whole nebula. This comparison is shown in Table 1. The SWS and IRAS fluxes (Pottasch , 1986) are shown in columns 4 and 5. In the last column the scale factor to reproduce the IRAS measurements (basically F^{iras}/F^{sws}) is given.

The advantage of this is that the lines IRAS has measured lie on different SWS apertures so that a correction for each one can be applied. As can be seen in Table 1 the IRAS fluxes for Ne VI and S IV is bigger than in the fluxes

Table 1. Comparison of IRAS measurements with ISO–SWS fluxes. Both, IRAS and ISO fluxes are in units of 10^{-12} erg cm^{-2} s^{-1}.

λ	Ion	SWS		IRAS	Correc.
(μm)		Aperture	Flux	Flux	factor
7.654	Ne VI	14″x20″	52	70:	1.35
10.52	S IV	14″x20″	29	50	1.72
12.81	Ne II	14″x27″	9.2	8	0.87
14.32	Ne V	14″x27″	96	90	0.93
15.56	Ne III	14″x27″	65	75	1.15
18.7	S III	14″x27″	17	30:	1.80

flux is missing in these apertures. Therefore, all measurements with the large aperture are seeing the whole nebula. Only in the smallest aperture some flux is missing. The aperture correction factor are 1.35 and 1.72 for Ne VI and S IV. Although the Ne VI line from IRAS is noisy an average scale factor of 1.54 is found from both lines. This average factor should be correct within ±0.2.

The Br_α line at 4.043 μm (3.91 10^{-12} erg cm^{-2} s^{-1}) leads to a very low H_β flux (57.0 10^{-12} erg cm^{-2} s^{-1}) because it is being underestimated. This fact can been used to correct the infrared lines by scaling the Br_α line in order to get the proper predicted H_β flux (which is 91.0 10^{-12} erg cm^{-2} s^{-1}). The observed flux for this line is 4.00 10^{-12} erg cm^{-2} s^{-1}. The theoretical prediction given by Hummer & Storey (1987) at T_e=15 000 K and N_e=1000 cm^{-3} (using N_e=10 000 cm^{-3} will lead to the same conclusions) leads to $I(Br_\alpha/H_\beta)=6.86\ 10^{-2}$. Therefore, the expected H_β flux is F_{H_β}=58.3 10^{-12} erg cm^{-2} s^{-1}. If this is compared with the predicted one, an aperture correction factor of 1.56 is found which agrees with the average factor derived before. Therefore a factor of 1.56 has been adopted to correct the measurements done in the smallest SWS aperture (below 12 μm).

To correct the ultraviolet lines the fact that the ratio of the helium lines F(λ1640)/F(λ4686)=6.94 (for a T_e= 15 000 K) has been used. Using the dereddened fluxes listed in Tables 3 and 4 a ratio of 3.54 is found. The scaling factor becomes 1.96, which we shall use.

The optical data used in this study has been taken from Hyung & Aller (1998). These fluxes are only represent part of the nebula, specifically the brightest part of the northern blob using a slit of 4″. Using the entire $H_\beta$flux, they have been scaled to the total flux.

4. Line fluxes

In Table 2, 3, and 4 the infrared, ultraviolet and optical lines are listed.

Table 2. Infrared line intensities for NGC 2440. All fluxes are in units of (10^{-12} erg cm^{-2} s^{-1})

λ	Ident.	Flux		
(μm)		observed	dereddened[1]	corrected[2]
4.051	H I Brα	3.91	4.00	6.24
4.527	[Ar VI]	16.8	17.2	26.8
5.611	[Mg V]	13.5	13.7	16.09
6.986	[Ar II]	3.30	3.34	5.21
7.654	[Ne VI]	52.0	52.7	82.2
7.900	[Ar V]	4.33	4.40	6.86
8.994	[Ar III]	9.37	9.83	15.33
10.512	[S IV]	29.1	30.5	57.6
12.813	[Ne II]	9.18	9.36	9.36
13.101	[Ar V]	4.20	4.28	4.28
14.323	[Ne V]	96.4	97.8	97.8
15.557	[Ne III]	65.2	66.3	66.3
18.712	[S III]	16.7	17.1	17.1
24.321	[Ne V]	121.8	123.5	123.5
25.896	[O IV]	297.9	301.7	301.7
33.479	[S III]	14.8	14.93	14.93
36.017	[Ne III]	9.35	9.42	9.42

[1] Dereddened fluxes using C_{H_β}=0.50
[2] Aperture corrected and dereddened fluxes: Lines up to 12 μm have been applied an aperture correction factor of 1.56 while for the rest of the lines (from 12 μm to 45.2 μm) no aperture correction factor has been applied.

that no weak lines are found. Only one hydrogen line (Br_α) and one helium line at 9.26 μm are found. High ionization stages for Argon (Ar VI), neon (Ne VI) and magnesium (Mg V) have been measured. The strongest line is that of O IV. Argon, neon and sulfur are all present in the most important stages of ionization.

Calibration errors increase at longer wavelength, but on average they amount to about 20%. Fluctuation errors depends on the line strength, and they decrease with line strength. Normally weak lines ($I < 5$, where I is in 10^{-12} erg cm^{-2} s^{-1}) have estimated errors of about 20%, intermediate lines ($5 < I < 10$) of about 10%, while the strongest lines ($I > 10$), have normally less than 5% uncertainty. There is just one exception, the sulfur line at 18.712 at μm, in which both up and down scan differs by 40%.

4.2. Ultraviolet spectrum

In the IUE spectra fifty lines were measured. Nitrogen, oxygen, carbon, magnesium an silicon lines are abundant. In Table 3 the observed fluxes are listed in column 3. The extinction law applied (Fluks et al. , 1994) is given in col-

Table 4. Optical line fluxes. Observed values were taken from Hyung & Aller (1998). The dereddened fluxes were derive using an interstellar extinction of $C_{H\beta}$=0.50 (E_{B-V}=0.34). Fluxes are in units of 10^{-12}erg cm^{-2} s^{-1}.

Wavelength (nm)	Ident.	Measured Fluxes	Dereddened Fluxes
342.68	[Ne V]	25.3*	118
372.60	[O II]	15.17	64.1
372.97	[O II]	7.59	32.0
386.87	[Ne III]	27.2	111.3
436.32	[O III]	7.29	26.6
447.15	He I	0.99	3.51
468.57	He II	23.5	78.1
471.15	[Ar IV]	2.29	7.56
474.00	[Ar IV]	2.46	8.05
486.10	H_β	31.6	99.54
500.68	[O III]	522.4	1572
519.17	[Ar III]	0.10	0.28
519.80	[N I]	1.69	4.81
520.03	[N I]	1.17	3.33
551.76	[Cl III]	0.64	0.52
553.79	[Cl III]	0.23	0.60
575.46	[N II]	4.80	12.02
575.46	[N II]	4.54†	11.37
587.57	He I	3.10	7.60
630.03	[O I]	6.53	14.9
631.20	[S III]	0.66	1.50
658.33	[N II]	383.7	841
658.33	[N II]	263.1†	576.7
671.64	[S II]	1.96	4.21
673.08	[S II]	3.13	6.71
700.59	[Ar V]	1.39	2.87
726.29	[Ar IV]	0.149	0.296
732.00	[O II]	3.14	6.196
733.03	[O II]	2.63	5.18

* taken from Rowland et al. (1993)
† taken from Perinotto & Corradi (1998) (see text)

if not possible data form Shields et al. (1981) was used. The low resolution spectra was preferred because the calibration is better.

Maybe Feibelman want to comments something about errors or something

4.3. Optical data

Together with the infrared and ultraviolet data, optical lines were also used to derive the physical parameters of the nebula, and to have information in some stages of ionization that weren't observed neither in the infrared nor ultraviolet. The observed fluxes were taken from Hyung & Aller (1998), and corrected for reddening. The Ne V line S III, Ar III, O III, Ne III and Ne V. The helium lines were used to derive the helium abundance. The rest of the ion were included to have information on several missing stages of ionization.

For the N II the average values for the lines at 575.5 and 658.4 nm. given by Perinotto & Corradi (1998) have been included. They measure the flux in different regions of the nebula from the center (*cen*), to positive increasing distances from the center (*p1,p2, etc..*) and negative increasing distances (*n1,n2, etc..*). The different values given by Hyung & Aller (1998) and Perinotto & Corradi (1998) leads to different T_e which can slightly affect the relative abundances derived for low ionization potentials (IP) ions.

5. Physical parameters and abundance

5.1. Electron density

N_e has been derived for nine ions. A T_e=15 000 K has been assumed and a justification for this choice is given in the following subsection. The N_e is shown in Table 5, and as can be seen, N_e seems to be constant for all the ions except for S III and Ar V. For comparison, the N_e found by Keenan et al. using the R-matrix method in successive papers in 1996, 1997, 1998 and 1999 for S II, Ar IV, Ne IV and O II respectively have been included in the table. An average of about 4000 cm^{-3} is found. In the paper by Hyung & Aller (1998) an average N_e of 5000 cm^{-3} is found. If the average N_e is derive from Table 5, but excluding the S III and Ar V ratio, a value of 4500 cm^{-3} is found. This is in good agreement with the N_e given by Hyung & Aller (1998) and Keenan et al. (1996,1997,1998,1999) and therefore has been adopted to derive the T_e and abundances.

Table 5. Electron density. T_e=15 000 K is used.

Ion	IP (eV)	Lines used (nm)	Observed ratio	N_e (cm^{-3})	Other Meas.[1]
S II	10.4	673.1/671.6	1.59	4260	3100 [a]
O II	13.6	372.6/372.9	2.00	4890	5000 [d]
S III	23.3	33 470/18 700	0.87	871:	
Cl III	23.8	553.8/551.8	1.15	4900:	
C III	24.4	190.7/190.9	1.35	4360	
Ar IV	40.7	472.4/472.5	1.04	4900	
Ar IV	40.7	471.1/474.0	0.94	5200	4000[b]
Ar V	59.8	13 100/7900	0.62:	34 500:	
Ne IV	63.4	242.4/242.2	1.11	3400	4000[c]

[1]Values taken from Keenan et al. 1996[a], 1997[b], 1998[c], 1999[d]
: Large uncertainty

are noisy and the error in their line flux determination is larger than in any other ion.

5.2. Electron temperature

To derive T_e the ratio of lines originating from levels that differ by several electron volts are needed. An N_e=4500 cm^{-3} has been assumed.

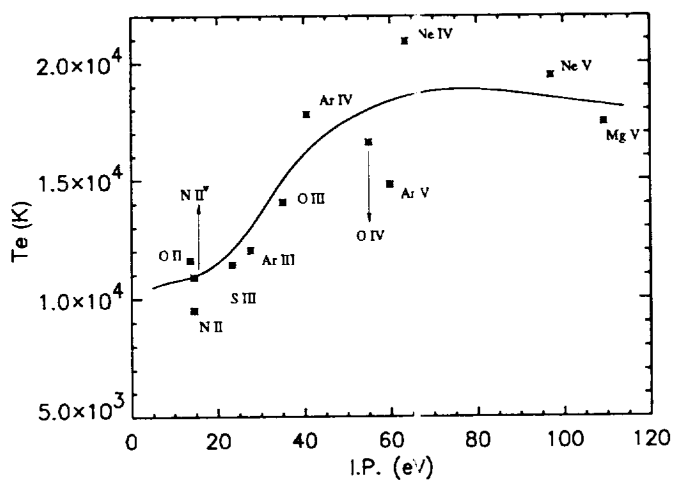

Fig. 2. Electron temperature versus ionization potential. The ratios used for each ion are indicated. The N II$^{\psi}$ has been derive using the lines fluxes given by Perinotto & Corradi (1998). The shape of the assumed curve is in accordance with the expected physical behavior (see discussion Sect. 6.2.)

The T_e for twelve different ions has been derived and are shown in Table 6. These temperatures are plotted against the ionization potential in Fig. 2. The curve represent the trend of the T_e with the ionization potential (IP).

The values given by Keenan et al. (1997, 1998, 1999) are also shown in Table 6 The T_e derive for the N II differs by 1400 K whenever the optical lines from Hyung & Aller (1998) or Perinotto & Corradi (1998) are used. In Fig. 2 these values have been plotted with the exception of the T_e determined with Ne III and S III (using the 33.4 μm line). The Ne III have been excluded because in other nebulae studies (Pottasch & Beintema (1999); Bernard Salas et al. (2001)) it usually gives a lower T_e. Probably this has something to do with the atomic parameter data. The T_e derive from the S III (631.2/33400) is not included because the infrared line is very noisy , instead the ratio 631.2/18700 has been used. It also should be notice that the S III ratio is sensitive to the adopted N_e and this could

Table 6. Electron temperature. N_e=4500 cm^{-3} is used.

Ion	IP (eV)	Lines used (nm)	Obs. ratio	T_e (K)	Other Meas.[1]
O II	13.6	732.0/372.6*	0.177	11 700	11 700[1c]
N II	14.5	575.5/658.4	0.0143	9500	
N II	14.5	575.5/658.4	0.0197	10 900†	
S III	23.3	631.2/18 700	0.088	11 400[2]	–
S III	23.3	631.2/33 400	0.100	8700	–
Ar III	27.6	519.2/8990	0.018	12 000	
O III	35.1	436.3/500.7	0.0169	14 060	
Ar IV	40.7	726.3/471.1	0.039	17 800	17 650[1a]
Ne III	41.0	386.8/15 500	1.68	13 800	
O IV	54.9	140.0/25 900	0.148	16 600	
Ar V	59.8	700.5/7900	0.39	14 800	
Ne IV	63.4	472.4/242.2*	0.012	20 900	19 800[1b]
Ne V	97.1	342.6/24 300	0.95	19 400	
Mg V	109.3	278.3/5610	0.61:	17 500	

[1]Values taken from Keenan et al. 1997[a], 1998[b], 1999[c]
† Using the line fluxes given by Perinotto & Corradi (1998)
* The lines used are; (732.0+773.0)/(372.6)
* The lines used are; (472.4+472.6)/(242.2+242.6)
: Very noisy

5.3. Chemical abundances

The element abundances for carbon, nitrogen, oxygen, neon, magnesium, argon and sulfur have been derived. Unfortunately for silicon and chlorine only one stage of ionization was measured which is not enough to properly derive the element abundance. The determination of the ionization correction factor (ICF) should have been too uncertain. The ions for which abundance have been derive are listed in Table 7

The equation used to determine these ionic abundances was:

$$\frac{N_{ion}}{N_p} = \frac{I_{ion}}{I_{H_\beta}} N_e \frac{\lambda_{ul}}{\lambda_{H_\beta}} \frac{\alpha_{H_\beta}}{A_{ul}} \left(\frac{N_u}{N_{ion}}\right)^{-1} \quad (2)$$

In the equation N_p is the density of the ionized hydrogen; I_{ion}/I_{H_β} is the measured intensity of the ionic line, normalized to H_β; λ_{ul} is the wavelength of the line and λ_{H_β} is the wavelength of H_β; α_{H_β} is the effective recombination coefficient for H_β; A_{ul} is the Einstein spontaneous transition rate for the line and finally N_u/N_{ion} is the ratio of the population of the level from which the line originates to the total population of the ion.

As can be seen in Table 7 the ICF is 1 or 1.1 in all cases but sulfur. This shows how powerful it can be to combine

6. Discussion

6.1. Electron density

The N_e has been derived for several ions which have different IP. This value seems to be constant, about 4500 cm^{-3}, there is no trend with the IP. This could means that the ejection of the outer layers has been constant with time. This supports the supposition made before, that the nebula is homogeneous.

6.2. Electron temperature

A trend of the T_e is found with the IP. As previously studied by Bernard Salas et al. (2001) for NGC 7027, this agree with a simple picture of the nebula where the high states of ionization are reached closer to the central star so they give higher temperatures, and the low states of ionization give lower T_e because they are formed further away. As mentioned, to derive the abundances an /tes has to be assumed, that in this case is determined by the curve in Fig. 2. As can be seen in Fig. 2 the trend at high IP not as well determined as at low IP, where this assumption is more important. For ions with low IP the abundance has been derive mainly with ultraviolet or optical data, and these lines are sensitive to the T_e adopted, where the curve is well determined. On the other hand abundances of ions at high IP have been derived from infrared and therefore are insensitive (or very little) in the adopted T_e.

6.3. Comparison of abundances

The abundances derived have been compared to those found in the Sun, O, B stars and previous literature (see Table 8 for references). Helium and carbon agree with those found by Kwitter & Henry (1996). The carbon abundance found by Hyung & Aller (1998) seems too little. The nitrogen is half that found by the same authors. The ICF used by Hyung & Aller (1998) seems too large. On the other hand the oxygen and neon abundance agree quite well. The sulfur abundance is between those reported by Hyung & Aller (1998) and Kwitter & Henry (1996) and finally the argon derived from Hyung & Aller (1998) is smaller than the present study. From the three elements carbon, nitrogen and oxygen, only oxygen is less abundant than in the Sun and O, B stars. Maybe some oxygen has been converted into carbon and nitrogen via cycle CNO. Neon and argon are smilar to O, B stars which could mean that the nebula hasn't formed any of these elements during its evolution. The sulfur is less abundant but the reason for this is not clear.

Other interesting possibility is the comparison of the ratio of carbon, oxygen and/or nitrogen. This is shown in Table 9. The N/O ratio is 3 times bigger than in NGC 7027

Table 9. Comparison of the abundance ratios of C, N and O

	NGC 2440	NGC 7027[1]	Sun	O Stars
N/O	1.23	0.39	0.15	0.15
C/O	1.89	1.46	0.48	0.42
$\frac{(C+N+O)}{H}$	1.47(-3)	1.24(-3)	1.19(-3)	6.56(-4)

[1] From Bernard Salas et al. (2001)

is twice as big as any other source. The progenitor star of NGC 2440 must be much more massive than the Sun or NGC 7027 (3-4 $M_\odot$, Bernard Salas et al. (2001)). This is also supported by the helium abundance which is also larger than any of these comparison sources.

7. Conclusions

Acknowledgements.

References

Anders, E., Grevesse, N., 1989, Geochem. Cosmo. 53, 197
Benjamin, R.A., Skillman, E.D., Smits, D.P., 1999, ApJ 514, 307
Bernard Salas, J., Pottasch, S.R., Beintema, D.A. et al, 2001, A&A 367, 949
Fluks, M.A., Plez, B., Thé, P.S., et al., 1994, A&AS, 105, 311
de Graauw, T., et al., 1996, A&A 315, L49
Gies, D.R., Lambert D.L., 1992 ApJ 387, 673
Grevesse, N., Noels, A., 1993, In:Prantos N., et al. (eds.) Origin of the Elements. Cambridge University Press, p. 15
Hummer, D.G., and Storey, P.J., 1987, MNRAS 224, 801
Hyung, S. and Aller, L.H. 1998, PASP 110, 466
Keenan, F.P., Aller, L.H., Bell, K.L., et al., 1996, MNRAS 281, 1073
Keenan, F.P., McKenna, F.C., Bell, K.L., et al., 1997, ApJ 487, 457
Keenan, F.P., Aller, L.H., Bell, K.L., et al., 1999, MNRAS 304, 27
Keenan, F.P., Aller, L.H., Bell, K.L., et al., 1999, MNRAS 304, 27
Killian-Montenbruck J., Grehen T., Nissen P.E., 1994, ApJ 291, 757
Kwitter, K.B. and Henry, R.B.C., 1996, ApJ 473, 304
Peimbert, IAU Symp. 76, Plan. Neb., ed. Y. Terzian, p. 215
Perinotto, M. and Corradi, R.L.M., 1998, A&A 332, 721
Pottasch, S.R. 1984, Planetary Nebulae, D-Reidel, vol 107
Pottasch, S.R. 1984, A. Preite-Martinez, F.M. Olnon et al., 1986, A A 161, 363
Pottasch, S.R. and Beintema, D.A., 1999, A&A 347, 975
Rowland, N., Houck, J. R., Skrutskie. M. F. et al., 1993, PASP 105, 1287

Table 3. IUE intensities for the high and low resolution spectra for NGC 2440. All fluxes are in units of 10^{-12} erg cm^{-2} s^{-1}. When a flux from low resolution spectra is followed by a " means that this line is blend with the wuotated ones.

λ (nm)	Ident.	Flux[1] HR	Flux[1] LR	A_{H_β}/E_{B-V}	Flux[2]	Flux[3]
116.86	C IV	3.60		10.613	99.9	195.8
123.92	N V	1.33	2.74	9.747	28.1	55.2
124.21	?	0.63		9.73	13.25	26.0
124.31	N V	1.45		9.718	30.4	59.6
130.06	C III		0.39$^\sharp$	9.198	6.95	13.6
132.77	C II		0.42:$^\sharp$	8.961	6.95	13.62
137.09	O V	0.55	0.32	8.641	8.23	16.13
140.13	O IV]	0.78	2.74	8.442	10.97	21.5
140.51	O IV]	0.57		8.420	7.96	15.60
140.73	O IV]	0.28		8.409	3.90	7.64
148.36	N IV]	3.75	10.14	8.162	48.3	94.7
148.68	N IV]	2.38		8.156	30.6	60.0
154.86	C IV	11.99	27.36	8.131	153.0	299.8
155.12	C IV	7.24		8.131	92.4	181.0
157.50	Ne V	0.630*		8.136	8.05	15.78
160.24	[Ne IV]		0.58$^\sharp$	8.117	7.37	14.44
164.07	He II	22.36	23.43	8.031	276.5	541.9
166.10	O III	0.44	2.96:	7.941	5.29	10.37
166.64	O III	1.06		7.927	12.69	24.87
171.10	Si II	0.630*		7.850	7.36	14.43
171.68	S III?		0.42$^\sharp$	7.839	4.89	9.58
174.71	N III]	0.48	10.1	7.784	5.49	10.77
174.90	N III]	0.71		7.780	8.11	15.90
175.00	N III]	4.07		7.779	46.5	91.2
175.24	N III]	2.19		7.776	25.0	49.0
175.43	N III]	0.45		7.773	5.13	10.06
180.49	[Ne III]		0.450$^\sharp$	7.756	5.10	10.00
180.80	Si II	0.160*		7.758	1.82	3.56
187.54	Si III]		0.390$^\sharp$	7.90	4.63	9.07
190.70	C III]	24.29	41.92	8.027	300.0	588.0
190.91	C III]	17.7		8.041	219.6	430.3
229.80	C III	0.26	0.61	8.795	4.08	8.00
232.65	C II]	1.46		8.639	21.84	42.8
232.81	C II]	0.65	0.37?	8.621	9.67	18.95
238.66	He II	0.31		8.082	3.89	7.63
242.30	[Ne IV]	3.38	7.47$^{\sharp,\dagger}$	7.814	39.1	76.5
242.56	[Ne IV]	3.79		7.791	43.5	85.2
242.74	[Ne IV]		7.47$^{\sharp,\dagger}$	7.776	85.3	167.1
247.15	[O II]	0.56	1.04	7.462	5.79	11.36
251.24	He II	0.58	1.04	7.226	5.57	10.92
273.46	He II	1.13	1.62	6.215	7.91	15.51
278.42	[Mg V]	0.66:	0.87	6.089	4.44	8.71
279.73	Mg II	0.23		6.058	1.53	3.00
280.45	Mg II	0.13		6.041	0.86	1.69
283.00	O IV?	0.20		5.982	1.30	2.55
283.77	O III	0.72	0.59	5.962	4.66	9.13
285.51	Mg I	0.31		5.923	1.98	3.88
286.96	?	0.13		5.889	0.82	1.61
290.14	C IV	0.12		5.821	0.74	1.46
292.95	[Mg V]	0.21		5.759	1.27	2.50
302.50	O III	0.21		5.570	1.20	2.35
303.11	O III		0.15$^\sharp$	5.558	0.85	1.68
304.86	O III	1.03	1.22	5.526	5.81	11.39
313.44	O III	7.15	7.88	5.371	38.4	75.3
320.47	He II	2.69	3.88	5.252	13.93	27.31

Flux[1]: Observed flux; HR= High Resolution Spectra; LR= Low ResolutionSpectra
Flux[2]: Dereddened flux
Flux[3]: Dereddened and aperture corrected flux (Aperture factor is 1.96)

Table 7. Ionic and element abundances.

Ion	λ (nm)	N_{ion}/N_p	$\sum N_{ion}/N_p$	ICF[1]	$N_{elem.}/N_p$
He^+	587.7	0.0554 [a]			
He^{++}	468.6	0.0639 [a]	0.119	1	0.119
C^+	(232.6, 232.8)[b]	6.10(-5)			
C^{++}	190.9	5.68(-4)			
C^{3+}	154.9	3.75(-5)	6.66(-4)	1.01	6.73(-4)
N^0	519.8, 520.0	7.88(-6)			
N^+	658.3	1.14(-5)	used		
N^+	658.3[†]	7.80(-6)			
N^+	575.5	8.21(-5)			
N^{++}	1750	3.09(-4)			
N^{3+}	148.5	9.39(-5)			
N^{4+}	123.9	1.50(-5)	4.37(-4)	1	4.37(-4)
O^0	630.0	2.45(-6)			
O^+	372.7, 373.0	3.54(-5)			
O^{++}	500.8, 436.3	1.82(-4)			
O^{3+}	25 900	1.06(-4)	3.26(-4)	1.1	3.56(-4)
Ne^+	12 810	1.10(-5)			
Ne^{++}	15 500	4.10(-5)			
Ne^{3+}	242.5,472.5	2.26(-5)			
Ne^{4+}	14 320	8.99(-6)			
Ne^{4+}	24 300	1.65(-5)			
Ne^{5+}	7650	1.02(-5)	1.10(-4)	1	1.10(-4)
Mg^+	280.0	–			
Mg^{4+}	5610	3.42(-6)	–	–	–
Si^+	34 800				
Si^{++}	189.2		–	–	–
S^+	671.6, 673.1	3.24(-7)			
S^{++}	18 710	1.80(-6)			
S^{3+}	10 510	1.10(-6)	3.22(-6)	1.47	4.72(-6)
Cl^{++}	553.8, 551.8	4.51(-8)			
Ar^+	6980	3.58(-7)			
Ar^{++}	8990	1.31(-6)			
Ar^{3+}	471.1, 474.0	7.09(-7)			
Ar^{4+}	7900, 207.2	1.22(-7)			
Ar^{5+}	4527	3.58(-7)	2.86(-6)	1.07	3.06(-6)

[1] ICF = Ionization Correction Factor
[a] Using the predictions for the helium emission lines given by Benjamin et al. (1999)
[b] Using the high IUE resolution spectra
[†] Value from citetperinotto

Table 8. Comparison of abundances in NGC 2440

Element	Present abund.	Sun[1]	O,B Stars[2]	Hyung[3] ICF-M	Hyung[3] Model	Kwitter[4] Model
Helium	0.119	0.098		0.126	0.11	0.12
Carbon	6.73(-4)	3.55(-4)	1.74(-4)	3.40(-4)	4.0(-4)	6.34(-4)
Nitrogen	4.37(-4)	9.33(-5)	6.46(-5)	9.98(-4)	9.0(-4)	8.22(-4)
Oxygen	3.56(-4)	7.41(-4)	4.17(-4)	4.41(-4)	3.5(-4)	5.71(-4)
Neon	1.10(-4)	1.20(-4)	1.23(-4)	9.51(-5)	7.0(-5)	7.42(-5)
Magnesium	–	3.8(-5)	2.40(-5)	2.00(-6)	2.0(-6)	
Silicon	–	3.55(-5)	2.40(-5)	1.74(-6)	1.9(-6)	
Sulfur	4.72(-6)	1.86(-5)	1.23(-5)	1.72(-6)	2.0 (-6)	
Chlorine	–	1.86(-7)	1.86(-7)	1.35(-7)	1.2(-7)	
Argon	3.09(-6)	3.63(-6)		2.02(-6)	2.2(-6)	

[1]Solar abundance from Grevesse et al. (1993) and Anders & Grevesse (1989)
[2]O, B star abundances are the average of Gies Gies & Lambert (1992) and Killian–Montenbruck et al. (1994)
[3] Abundances by Hyung & Aller (1998) determined using the ICF method
[4] From Kwitter & Henry (1996)