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TIME-DEPENDENT BEHAVIOR AND PHYSICAL CONDITIONS OF THE LMC PLANETARY NEBULA N66

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ABSTRACT

Optical and UV spectrophotometric data for the planetary nebula N66 in the Large Magellanic Cloud gathered in the 1987–1994 interval are analyzed. The central star, which had a featureless weak continuum, has developed intense W-R features and P Cygni profiles that were not present before 1990. He- and N-rich material, processed during the CNO cycle, is being ejected; the ejecta are very H-deficient, with $X/Y < 0.1$. A spectral type of WN4.5 is confirmed for the central object. From the optical broad emission lines a wind velocity of about 3000 km s^{-1} is found in fair agreement with the value $v_\infty = 4200$ km s^{-1} found from the C IV λ1550 P Cygni profile. The intensity of the UV and optical continua have been increasing systematically, and the absolute stellar visual magnitude, M_V, has changed from +1.24 mag in 1987 August to −2.23 mag in 1994 March. The stellar temperature has diminished from ≥120,000 K to ≃50,000 K, while the radius has increased from 0.37 to 1.7 $R_\odot$. The object is probably undergoing a final helium shell flash. The present evolutionary stage of N66 is discussed. On the other hand, the intensities of the nebular emission lines have shown no significant variation in the last 20 years. The nebular chemical abundances, calculated by considering no temperature fluctuations, are He/H = 0.116 ± 0.004, log C/H = 7.45 ± 0.10, log N/H = 7.95 ± 0.12, log O/H = 8.24 ± 0.06, log Ne/H = 7.70 ± 0.06, log Ar/H = 6.12 ± 0.04, and log S/H = 6.70 ± 0.10. N66 shows He and N enrichment, while C appears very depleted relative to LMC H II regions and planetary nebulae; the other heavy element abundances (O, Ne, Ar, and S) are slightly lower than in H II regions, confirming that N66 is a type I planetary nebula. No evidence of C enrichment of the stellar atmosphere due to third dredge-up episode is detected.

Subject headings: Magellanic Clouds — planetary nebulae: individual (LMC N66) — stars: abundances — stars: fundamental parameters — stars: mass loss — stars: Wolf-Rayet

1. INTRODUCTION

N66 (also known as WS 35 and SMP 83) is the most interesting planetary nebula (PN) in the LMC. It is one of the most highly excited LMC PNs, it shows very high expansion velocities, and recently the central star developed a strong wind and W-R features. Extensive studies of the nebula have been made by Dopita, Ford, & Webster (1985), Peña & Ruiz (1988, hereafter PR), Meatheringham & Dopita (1991), and Dopita et al. (1993). These studies have shown that the ionized gas has high N/O and He/H ratios; consequently N66 has been classified as a Peimbert's type I planetary nebula (Peimbert 1978). From the nebular characteristics it has been deduced that the central star is among the most massive PN nuclei. Masses between 0.80 and 1.2 $M_\odot$ have been attributed to this star. From spatially resolved observations Dopita et al. (1993) found that the nebula has a bipolar filamentary structure. The most external filament lies at 1".86 from the central star which represents 0.42 pc (considering a distance modulus of 18.45 for the LMC). Pictures of this object strongly resemble the extraordinary galactic PN NGC 6302.

Torres-Peimbert et al. (1993), based on optical data obtained in 1990, reported an unprecedented variation in the He II λ4686 emission-line profile consisting of the sudden appearance of a weak wide component. This was interpreted as indicative that the central star had developed W-R features in the 1987–1990 interval. Recent UV and optical observations by Peña et al. (1994b, hereafter Paper I) showed that the progenitor of N66 now presents prominent W-R features as well as P Cygni profiles in the N V λ1240 and C IV λ1550 lines. In the optical region, all the He II lines and the N IV λλ3479–84 blend appear very wide and conspicuous, while N V λ4606 and C IV λλ5801, 5012 lines are present but much fainter. Due to these characteristics, which are very unusual in PNs with W-R nuclei, the star was classified as WN4.5. In the galaxy only a few W-R central stars, such as those of A30 and A78, have mixed carbon and nitrogen W-R emission lines (e.g., Heap 1982); however, the central star of N66 shows much fainter C lines and the O lines (λλ1371, 3811, 3834) are not present here, while they are notorious in A30 and A78. All the known W-R nuclei of planetary nebulae in the Galaxy and the Magellanic Clouds show a C-rich photosphere, and they have been classified as WC stars (Heap 1982; Méndez 1991; Tylenda, Acker, & Stenholm 1993; Monk, Barlow, & Clegg 1988; Peña et al. 1994a) except two objects, M1-67 and We21, which show strong N lines and for

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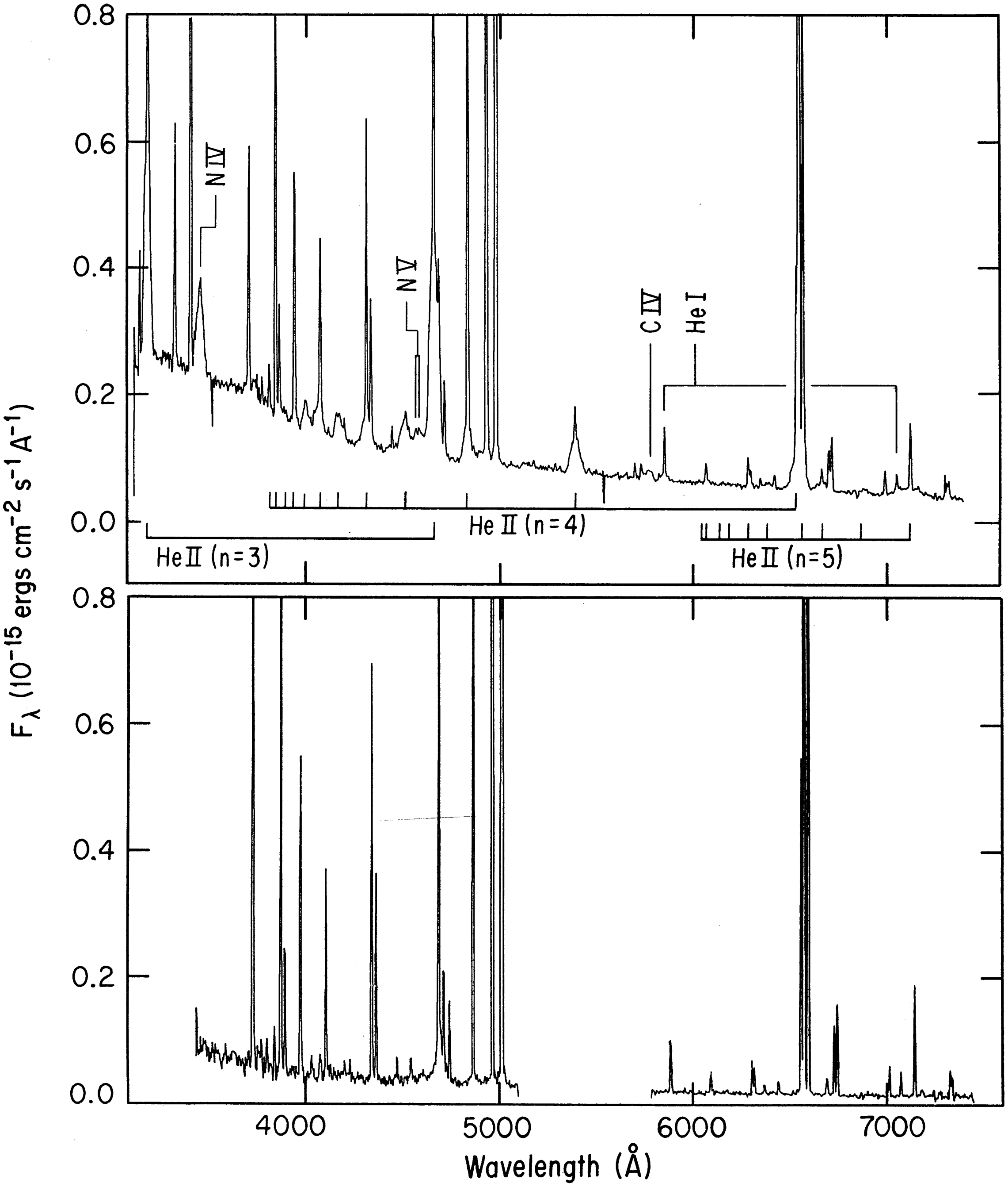

FIG. 1.—Comparison between optical spectra of 1994 January (*upper*) and 1990 August (*lower*). The most important W-R features and the He II emission series have been marked in the 1994 spectrum.

which it has been argued that they lie at longer distances and belong to Population I (see Tylenda et al. 1993). This is not the case of N66 which is a well-known bona fide LMC planetary nebula. This makes the N66 phenomenon a unique event which must be carefully followed.

This is the first time that a change of this nature is observed in a PN in another galaxy. In our galaxy the symbiotic star HM Sge developed W-R features (showing wide N and C lines) that disappeared in a few years (Peimbert et al. 1995), and the central star of the planetary nebula Longmore 4 showed WC features that appeared and disappeared in a few months (Werner et al. 1992); nevertheless the changes in N66 seem to be qualitatively different from those of these two objects, and in Paper I we proposed that N66 could be undergoing a final thermal pulse.

In this work we present new data for the nebula and the central star which are analyzed together with the data presented in Paper I.

2. OBSERVATIONS

2.1. *Optical Region*

Several optical spectra were obtained in 1990 at CTIO with the 4 m telescope equipped with a RC spectrograph and a CCD detector. Blue spectra, covering the range from 3450 to

5100 Å, were obtained using a grating KPGL2 on August 11; the exposure times varied from 150 to 480 s in order to detect the faint lines as well as to measure unsaturated strong lines. Red spectra (5970–7450 Å) were obtained on August 12, using a grating no. 181, the exposure times varied from 60 to 300 s. The spectral resolution was about 6 Å. Spectrophotometric standard stars from the list by Stone & Baldwin (1983) and Baldwin & Stone (1984) were observed to calibrate the data. In all the cases the slit was 2″ wide, oriented E-W.

Two new spectra with the same telescope and spectrograph, a Reticon detector and a grating KPGL2, were obtained in 1994 January 28. The wavelength range observed was 3200–7000 Å, with spectral resolution of about 10 Å, and the exposure times were 100 and 600 s. The slit was 1.″33 wide, oriented along the paralactic angle (60° P.A.) to avoid atmospheric refraction effects. Standard stars from the calibration by Hamuy et al. (1992) were observed for flux calibration. In both cases data reductions were carried out at CTIO La Serena Computing Facilities.

In Figure 1 we present the calibrated spectra of 1990 August and 1994 January, in the 3200–7000 Å interval. They include the nebular and stellar emission. The 1994 spectrum shows prominent W-R features in all the He II lines and in the N IV $\lambda\lambda$3479–84 blend, other weak features such as C IV $\lambda\lambda$5801, 5012, and N V λ4606 are also present and marked in the figure. The continuum flux also increased very notoriously relative to that of 1990. W-R characteristics are already noticeable as a weak wide component in the He II λ4686 emission line in the 1990 spectrum. No evidence of this wide component was detected or reported in previous works; however, it seemed to be already present in a spectrum of 1988 January 17 shown by Meatheringham & Dopita (1991).

To further study the spectacular changes in N66 central star we obtained two additional spectra, with 300 and 1200 s of exposure time, on 1994 March 24, at Las Campanas Observatory, with the 2.5 m Dupont telescope equipped with a modular spectrograph, a grating of 800 l/mm, and a large format TEK CCD detector. The covered spectral range was 4500–7700 Å with 5 Å resolution. The slit was 2″ wide, oriented along the paralactic angle (60° P.A.). Standard stars from the list of Stone & Baldwin (1983) were observed for flux calibration. These new spectra are very similar to those of 1994 January although the nebular emission line fluxes appear more intense as a result of the wider slit employed. A direct image with a V filter (100 s of exposure time) was also obtained with the same telescope and detector to measure the apparent visual magnitude of the whole object (star + nebula) which turned out to be 15.36 ± 0.07 mag. This result is discussed in § 5.

The available nebular and wide component emission-line fluxes were measured in all the spectra. The dereddened nebular intensities, relative to Hβ, are presented in Table 1 for each observing run. We have also included the values reported by PR from observations of 1987. Dereddened line intensities, equivalent widths, and FWHM of the wide component lines are listed in Table 2. These data are discussed in § 4.

The line fluxes were dereddened according to the expression:

$$\log I_\lambda/I(\mathrm{H}\beta) = \log F_\lambda/F(\mathrm{H}\beta) + c(\mathrm{H}\beta) \times f_\lambda . \qquad (1)$$

The logarithmic reddening coefficient at Hβ, c(Hβ), was derived in each case from the Balmer decrement by adopting the recombination theory case B-values (Hummer & Storey 1987), and they have been listed in Table 1 where we also show the values of the galactic reddening law employed, f_λ (Whitford 1958).

Measurements of the continuum flux at several wavelengths were reported in Paper I. Recalculated and new values are presented in Table 3 where we have listed the dereddened observed flux, I_λ, and the stellar flux, I_*, obtained by subtracting the nebular contribution. The nebular continuum contribution was calculated based on the intensity of Hβ and by adopting an electron density of 2670 cm^{-3}, $N(\mathrm{He}^+)/N(\mathrm{H}^+) = 0.0580$, $N(\mathrm{He}^{++})/N(\mathrm{H}^+) = 0.0578$, $T_e = 16{,}450$ K, and $c(\mathrm{H}\beta) = 0.15$ as derived from the analysis of the nebular lines (§ 3). No attempt to subtract the wind emission contribution to the continuum was made. The values obtained in 1994 March are a factor of 1.5 higher than the values in January of the same year. This could be attributed to differences in the slit width (1.″33 in January and 2″ in March) and observing conditions. We do not expect such a large variation occurring in less than 2 months, but new observations are required to verify this. For the moment we adopted the values obtained in March as representative of the present stellar parameters.

2.2. *Ultraviolet Region*

A short-wavelength, large-aperture, low-resolution *IUE* spectrum was obtained in 1993 November 5 (SWP 49112, 180 minutes of exposure time). Data reductions were performed at IUE Regional Data Analysis Facilities, GSFC. Several low-resolution short- and long-wavelength spectra of N66 are available in the *IUE* archives, and we analyzed all of them by measuring the line intensities and continua of well-exposed *IUE* spectra of different epochs. We found no significant differences in the spectral characteristics from 1982 to 1986 while there are remarkable changes in 1993. Line intensities for different epochs, not corrected by reddening, are presented in Table 4.

A comparison between a spectrum of 1983 (SWP 19905, 183 minutes of exposure time), representative of the epoch before the variation, and the one of 1993 is shown in Figure 2. The new spectrum is very different to the previous ones. The continuum is about 3 times higher, P Cygni profiles at N V λ1240 and C IV λ1550, not present before, are well developed now, and a W-R feature corresponding to N IV λ1718 has appeared. Most of the emission lines are much wider and more intense. This is especially noticeable in the case of N V λ1240 which appears enhanced by a factor of about 8, while the intensities of He II λ1640, N IV] λ1488 and C IV λ1550 are larger by a factor of about 3. The third graph in Figure 2 is the subtraction of both spectra and shows clearly the large increase in the continuum and line intensities mentioned before. It is noticeable that the remaining emission lines are very wide and shifted to the blue, relative to the nebular lines, corresponding to emission by a hot wind very near the stellar surface. It should be interesting to study this effect with higher resolution. A rough estimate of the terminal velocity wind (as proposed by Perinotto, Benvenuti, & Cerruti-Sola 1982) was made in Paper I from the C IV λ1550 P Cygni profile giving $v_\infty = 4200 \pm 500$ km s^{-1}.

Total and stellar dereddened UV continuum fluxes, measured in 1993 and 1983 spectra, are presented in Table 3. To deredden we have assumed that half of the reddening is due to galactic extinction (using the reddening law by Seaton 1979) and half is due to LMC extinction (using the LMC law by Nandy et al. 1981). The stellar continuum is presented after subtracting the nebular component as discussed in § 2.1. These

TABLE 1

Dereddened Nebular Line Intensities Relative to Hβ

			Aug 1987[a] 2"E-W[c]	Aug 1990[b] 1.6"E-W[c]	Jan 1994 1.33"(60° P.A.)[c]	Mar 1994 2.0"(60° P.A.)[c]
λ_0 (Å)	Ion	f_λ	$I(\lambda)/I(H\beta)$	$I(\lambda)/I(H\beta)$	$I(\lambda)/I(H\beta)$	$I(\lambda)/I(H\beta)$
3346	[Ne V]	0.370	...	...	51.8	...
3423	[Ne V]	0.342	...	(127.6)	127.6	...
3726+29	[O II]	0.255	95.5	81.3	53.6	...
3835	H9	0.240	7.24	6.92	7.34	...
3869	[Ne III]	0.235	100.0	97.7	95.2	...
3889	He I + H8	0.225	15.8	18.2	16.4	...
3967+70	[Ne III] + H7	0.205	43.7	44.7	48.5	...
4026	He I + He II	0.185	3.31	...	WR	...
4069	[S II]	0.180	4.37	4.90	...	...
4102	Hδ + He II	0.170	26.3	26.9	29.3+WR	...
4200	He II	0.150	...	...	WR	...
4340	Hγ + He II	0.130	47.8	46.8	48.9+WR	...
4363	[O III]	0.125	21.4	22.4	21.5	...
4471	He I	0.080	2.95	3.02	4.19	...
4541	He II	0.070	2.82	2.63	WR	...
4686	He II	0.040	69.2	64.5	62.6+WR	66.4+WR
4711+13	[Ar IV] + He I	0.030	12.0	10.5	...	...
4725	[Ne IV]	0.030	1.82	1.17	...	...
4740	[Ar IV]	0.025	9.12	8.91	8.78	9.6:
4861	Hβ + He II	0.000	100.0	100.0	100.0+WR	100.0+WR
4959	[O III]	-0.025	309	316	300	332
5007	[O III]	-0.035	912	955	893	997
5200	[N I]	-0.075	1.17	(1.17)	1.06	...
5411	He II	-0.115	4.79	(4.79)	5.0+WR	5.1+WR
5755	[N II]	-0.185	3.16	(3.16)	2.71	2.43
5876	He I + He II	-0.210	8.5	8.30	8.4+WR	8.6+WR
6087	[Ca V]	-0.250	1.78	2.61	3.41	3.11
6300	[O I]	-0.285	3.80	4.57	4.44	4.34
6312	[S III]	-0.295	2.82	3.55	2.43	2.39
6363	[O I]	-0.295	1.74	1.20	1.05	...
6435	[Ar V]	-0.305	1.62	...	1.81	...
6548	[N II]	-0.315	47.8	40.7	32.5	28.5
6563	Hα + He II	-0.320	275	282	288+WR	282+WR
6584	[N II]	-0.325	141.2	117.0	93.3	87.1
6678	He I + He II	-0.340	2.40	2.57	2.3+WR	2.5+WR
6717	[S II]	-0.345	6.46	8.91	7.32	6.21
6731	[S II]	-0.345	8.71	11.5	9.40	7.70
7006	[Ar V]	-0.375	3.39	3.55	3.89	3.94
7065	He I	-0.380	3.72	3.02	2.9+WR	2.8+WR
7136	[Ar III]	-0.390	...	11.0	11.0	10.7
7320+30	[O II]	-0.410	...	5.50	6.21	3.77
$c(H\beta)$			0.18	0.15	0.15	0.10
log $F(H\beta)$[d]			−12.99	−13.00	−13.10	−12.86
EW(Hβ) (Å)			639.6	256.4	51.8	83.4

[a] Fluxes from Peña & Ruiz 1988.

[b] Fluxes in parentheses are taken from other epochs.

[c] Slit width and orientation.

[d] $F(H\beta)$ in ergs cm^{-2} s^{-1}.

continuum measurements together with the optical ones allowed us to estimate the color temperature of the central star (§ 4).

3. NEBULAR PARAMETERS

3.1. *Heavy Element Ionic Abundances*

N66 is a relatively extended bipolar nebula (the outer filament reported by Dopita et al. 1993 is at about 1".86 from the central star), therefore the absolute line intensities observed depend on the slit width and position, this is the reason for the different observed Hβ fluxes presented in Table 1. Nevertheless, the nebular emission-line flux ratios, relative to Hβ, for the different epochs are very similar. The differences among them are less than 0.08 dex for most of the lines. Slight systematic trends, as the decrease of [O II] $\lambda\lambda$3726 + 29 and [N II] $\lambda\lambda$6548, 6583 lines could be attributed to differences in the slit width or slit position (however further observations would be important to verify this). High-excitation lines such as [Ar V] λ7006, He II narrow components, and [O III] λ5007 show no systematic trend. The ratios presented in Table 1 are also very similar to data presented by Monk et al. (1988; from observations carried out in 1975) and Meatheringham & Dopita (1991). We can assume that no significant variations have occurred in the nebular emission in the last 20 years and the stellar changes have not affected the nebular material yet.

We have adopted the line intensity ratios of the observations of 1990 to derive nebular physical conditions and ionic abundances. In the case where some specific line was not measured

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TABLE 2

DEREDDENED WIDE EMISSION LINE FLUXES[a]

		1994 JAN			1994 MAR		
λ(Å)	ION	I_{λ}[b]	EW[c]	FWHM[c]	I_{λ}[b]	EW[c]	FWHM[c]
3204	He II	22.4	50	33	...	...	...
3484b......	N IV	10.7	25	40	...	...	...
4100	He II	2.64	12	36	...	...	...
4199	He II	2.75	15	40	...	...	...
4340	He II	3.76	22	46	...	...	...
4542	He II	2.50	17	42	...	...	...
4606	N V	0.7:	6:	...	...	...	...
4686	He II	24.6	145	46	35.8	165	49
4859	He II	3.18	22	39	4.77	27	43
5411	He II	4.42	43	54	5.16	41	53
5808b......	C IV	0.3:	8	41	0.4:	7:	45:
5876	He I	0.2:	6:	48:	0.3:	6:	47:
6560	He II	5.40	93	71	6.2:	97:	67:
6683	He II	0.6:	8:	38:	0.4:	8:	50:

[a] Dereddening was made using Whitford 1958 reddening law.

[b] Fluxes are in units of 10^{-14} ergs cm^{-2} s^{-1}. The uncertainties are less than 15% in all the lines, except those marked with a colon where it is about 30%. The differences between January and March are probably due to differences in the slit widths.

[c] Equivalent widths and FWHM in Å.

in this epoch, we adopted a value from another observation; these values are shown in parentheses in Table 1. To derive ionic abundances, the contribution of He II λ4859 to the Hβ line was subtracted by estimating it from the He II λ4686 flux.

The available diagnostic lines were analyzed by the usual procedures. Values for the electron temperature and density are presented in Table 5. The physical conditions have been used to derive ionic abundances for the observed ions. We have assumed an electron density of 2670 cm^{-3} and a four-temperature zone model as suggested by Kingsburgh & Barlow (1994), adopting T_e(N II) = 12,300 K for N$^+$, O$^+$, S$^+$, S^{++}, and Ar^{++}, T_e(O III) = 16,450 K for He$^+$ and the other doubly ionized species, T_e(O III) + 1000 K for the triply ionized species, and T_e(O III) + 2270 K for the higher ionized stages. The derived values are presented in Table 5 where the uncertainties listed correspond to the uncertainties in the line intensity measurements and the adopted temperature.

3.2. *The* He *Ionic Abundances*

To derive He$^+$/H$^+$ abundance ratio we took special care to correct for the effects of collisional excitation and self-absorption of the He I 2 ^3S metastable level.

In Table 6 we present the He$^+$/H$^+$ abundance ratios derived from the intensity of four helium lines under various assumptions. For the λ5876/Hβ and λ7065/Hβ ratios we took the average of the 1987 and 1990 observed values and λ6678 was corrected from the He II λ6683 contribution based on the computation by Hummer & Storey (1987). We have defined a factor γ proportional to the population of the 2 ^3S level of He I for which we have considered three cases: (1) when the He I

TABLE 3

DEREDDENED ULTRAVIOLET AND OPTICAL CONTINUUM FLUXES[a]

	1983 MAY SWP 19905 (181 min)		1993 NOV SWP 49112 (180 min)		1987 AUG[b] 2″ E-W[c]		1990 AUG 1″.6 E-W[c]		1994 JAN 1″.33 (60° P.A.)[c]		1994 MAR 2″ (60° P.A.)[c]	
λ (Å)	I_{λ}	I_*	I_{λ}	I_*	I_{λ}	I_*	I_{λ}	I_*	I_{λ}	I_*	I_{λ}	I_*
1300......	2.15	1.88	7.45	7.18	...	...	...	...	...	...	...	...
1500......	1.54	1.19	4.95	4.60	...	...	...	...	...	...	...	...
1750......	1.21	0.89	3.35	3.03	...	...	...	...	...	...	...	...
1850......	1.11	0.80	2.71	2.40	...	...	...	...	...	...	...	...
3500......	...	...	...	...	...	...	12.1	4.53	35.1	29.1	...	...
4000......	...	...	...	...	4.20	2.12	6.60	4.57	22.5	20.9	...	...
4500......	...	...	...	...	3.33	1.51	5.21	3.43	16.7	15.3	28.2:	25.8:
5000......	...	...	...	...	2.24	0.62	4.19	2.61	13.4	12.1	19.4	17.1
5500......	...	...	...	...	1.94	0.51	...	...	10.3	9.18	14.7	12.7
6000......	...	...	...	...	1.63	0.40	2.60	1.40	8.06	7.11	11.5	9.85
6500......	...	...	...	...	1.23:	0.09:	2.29	1.17	6.50	5.61	9.24	7.69
7000......	...	...	...	...	1.10:	0.07:	1.86	0.85	5.09	4.28	7.17	5.76

[a] I_{λ} is the nebular + stellar continuum, I_* is the stellar continuum; a reddening correction, c(Hβ), of 0.15 has been applied to them. UV fluxes are in units of 10^{-14} ergs cm^{-2} s^{-1} Å^{-1}. Optical fluxes, in units of 10^{-16} ergs cm^{-2} s^{-1} Å^{-1}.

[b] From the observations by Peña & Ruiz 1988.

[c] Slit width and orientation.

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TABLE 4

OBSERVED ULTRAVIOLET LINES INTENSITIES OF N66[a]

λ (Å)	Ion	1983 19905(181)[b] $F_\lambda/F(\lambda1640)$	1986 8083(240)[c] $F_\lambda/F(\lambda1640)$	1993 49112(180)[b] $F_\lambda/F(\lambda1640)$
1240	N V	0.68	...	0.76
1400	Si IV+O IV	0.16	...	0.04
1488	N IV]	0.35	...	0.30
1550	C IV	0.49	...	0.26
1640	He II	1.00	...	1.00
1666	[O III]	0.11	...	0.04
1718	N IV]	...	...	0.07
1750	N III	0.16	...	0.05
1909	C III]	0.16	0.20:	0.04
2426	Ne IV]	...	0.43	...
2734	He II	...	0.07	...
3201	He II	...	0.22	...
log $F(\lambda1640)$[c]		−12.14	...	−11.70
EW(λ1640) (Å)		99.5	...	133.7

[a] Line intensities have not been corrected for reddening. Uncertainties are lower than 15%, except in those marked with a colon.

[b] SWP (min).

[c] LWP (min). The fluxes are relative to $F\lambda1640$ of SWP 19905.

[d] $F(\lambda1640)$ in ergs cm^{-2} s^{-1}.

lines are formed by pure recombination, $\gamma = 0$, that is, there is neither collisional excitation nor self-absorption from the He I 2 ^3S level, (2) when the 2 ^3S level is depopulated by collisional transfers (including collisional ionization) and radiative transitions to the 1 ^1S level, $\gamma = 1$, and (3) when there are additional depopulating processes (like photoionization and charge transfer reactions) to those mentioned in (2), $\gamma < 1$.

The values for $\gamma = 0$ in Table 6 were derived from the Hβ recombination coefficient by Hummer & Storey (1987) and the $\lambda\lambda$4471, 5876, 6678, and 7065 recombination coefficients by Smits (1994). The recombination coefficients derived by Smits are in excellent agreement with those derived by Brocklehurst (1972), with the exception of that for λ7065 due to an error of about a factor of 1.4 in the value presented by Brocklehurst. As can be seen from the $\gamma = 0$ column, the four lines yield different He$^+$/H$^+$ ratios implying the presence of collisional and possible self-absorption effects from the 2 ^3S level.

TABLE 5

PHYSICAL CONDITIONS AND IONIC ABUNDANCES[a]

n_e(S II) (cm^{-3})	1570 ± 300
n_e(O II)[b] (cm^{-3})	2670
T_e(O III) (K)	16450 ± 300
T_e(N II) (K)	12300 ± 500
N$^+$ (λ6584)	−4.90 ± 0.05
O$^+$ (λ3727)	−4.61 ± 0.05
O^{++} (λ5007)	−4.06 ± 0.03
Ne^{++} (λ3869)	−4.72 ± 0.03
Ne^{+3} (λ4725)	−4.78 ± 0.06
Ne^{+3} (λ2423)	−4.77 ± 0.05
Ne^{+4} (λ3423)	−4.83 ± 0.07
S$^+$ (λ6725)	−6.41 ± 0.07
S^{++} (λ6312)	−5.87 ± 0.10
Ar^{++} (λ7136)	−6.42 ± 0.05
Ar^{+3} (λ4740)	−6.34 ± 0.05
Ar^{+4} (λ7006)	−6.81 ± 0.07
(He$^+$/H$^+$)	−1.237 ± 0.013
(He^{++}/H$^+$)	−1.238 ± 0.013

[a] Log of ionic abundances relative to H$^+$.

[b] From Barlow 1987.

In the third column of Table 6 we present the He$^+$/H$^+$ abundances for the case of full collisional effects from the 2 ^3S level by Kingdon & Ferland (1995). From this column it follows that the collisional effects have been overestimated because $\lambda\lambda$4471 and 6679, which depend weakly on the collisional effects, yield abundances higher than those of $\lambda\lambda$5876 and 7065 that depend strongly on these effects. This overestimation has been also seen in other planetary nebulae (Peimbert & Torres-Peimbert 1987a, b). There are three possible solutions to this overestimation: (1) that there is an unknown mechanism that depopulates the 2 ^3S level (case $\gamma < 1$), (2) that the density is smaller than 2670 cm^{-3}, and (3) that the temperature is smaller than 16,450 K.

In the fourth column of Table 6 we present the He$^+$/H$^+$ abundances for $\gamma = 0.6$, which is the value needed to obtain a reasonable agreement from the three determinations based on the $\lambda\lambda$4471, 5876, and 6678 lines. In this case the λ7065 abundance is about 10%–15% higher than that derived from the other lines implying that the self-absorption effect from the 2 ^3S level for $\lambda\lambda$4471, 5876, and 6678 is negligible (Robbins 1968). Clegg & Harrington (1989) have studied different procedures to explain low values of γ and find that photoionization of the 2 ^3S level is only important for compact PNs, which

TABLE 6

He$^+$/H$^+$ ABUNDANCE RATIO

λ	$\gamma = 0$[a]	$\gamma = 1$[b]	$\gamma = 0.6$[c]	$\gamma = 1$[d]	$\gamma = 1$[e]
4471	0.0668	0.0525	0.0575	0.0575	0.0577
5876	0.0739	0.0515	0.0586	0.0584	0.0575
6678	0.0652	0.0571	0.0601	0.0599	0.0574
7065	0.1294	0.0500	0.0663	0.0662	0.0645

[a] Pure recombination, $T_e = 16{,}450$ K, $n_e = 2670$ cm^{-3}.

[b] Full collisional corrections, $T_e = 16{,}450$ K, $n_e = 2670$ cm^{-3}.

[c] Partial collisional corrections, $T_e = 16{,}450$ K, $n_e = 2670$ cm^{-3}.

[d] Full collisional corrections, $T_e = 16{,}450$ K, $n_e = 1100$ cm^{-3}.

[e] Full collisional corrections $T_e = 13{,}300$ K, $n_e = 2670$ cm^{-3}.

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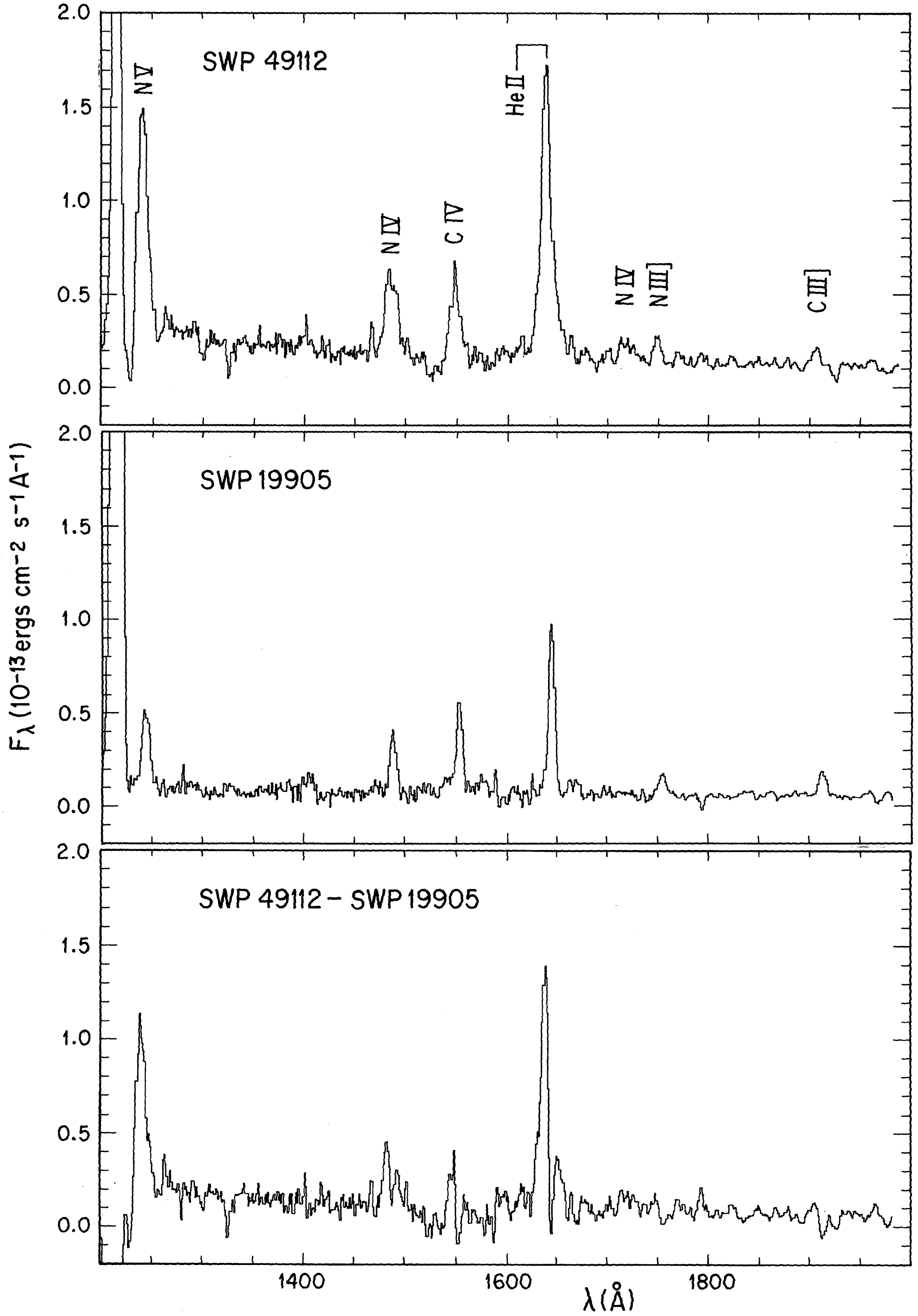

FIG. 2.—Comparison between *IUE* spectra SWP 19905 (1983 May) and SWP 49112 (1993 November). The 1993 spectrum shows very enhanced emission lines and a much larger continuum. The bottom graph represents the subtraction of both spectra.

is not the case of N66. Therefore the $\gamma = 0.6$ solution for this object is not supported by the work of Clegg & Harrington.

In the fifth column of Table 6 we present the He^+/H^+ abundances for $\gamma = 1$, $T_e = 16{,}450$ K, and $n_e = 1100$ cm^{-3}, which is the density needed to derive similar ionic abundances from λλ4471, 5876, and 6678. In the sixth column we present the He^+/H^+ abundances derived for $\gamma = 1$, $n_e = 2670$ cm^{-3}, and $T_e = 13{,}300$ K which also yield a reasonable agreement among the three determinations. We consider that a combination of lower n_e and lower T_e values than those derived from the forbidden lines is needed to correct the He^+/H^+ value. These lower values are expected in the presence of spatial temperature and density fluctuations (Peimbert 1967, 1971). There is strong observational evidence in favor of temperature and density fluctuations in PNs (e.g., Peimbert 1971; Dinerstein, Lester, & Werner 1985; Liu & Danziger 1993; Peimbert, Storey, & Torres-Peimbert 1993; Liu et al. 1994). In particular N66 shows filamentary structure and high expansion velocities that might indicate the presence of shock waves and consequently of a complex density and temperature structure. The He^+/H^+ ratio is given by the average of the λλ4471, 5876, and 6678 values, and from the last three columns of Table 6, it amounts to 0.0587, 0.0586, and 0.0575, respectively; we will adopt a value of 0.0580 ± 0.0018 for N66.

The He^{++}/H^+ ionic abundance was calculated from λ4686/Hβ intensity ratio by using the recombination coefficient in case B by Hummer & Storey (1987) and assuming an electron temperature of 16,450 K and a density of 2670 cm^{-3}.

3.3. *Total Abundances*

Total abundances can be derived by adding all the abundances of the ionic species present in the gas or by using some ionization correction factors to take into account the nonobservable ions. In our case we can obtain directly the Ne abundance from the ionic abundances Ne^{++}, Ne^{+3}, and Ne^{+4}, by assuming that Ne^+ is negligible. C and N ionic abundances cannot be calculated with the new UV data due to the contamination of N V λ1240, N IV] λ1488, N III] λ1750, and C IV λ1550 emission lines by stellar emission. Consequently, for all the elements, except Ne, an ionization correction factor is needed. The formulae for the ionization correction factors have been recently revised by Kingsburgh & Barlow (1994), from where we have extracted the following expressions:

$$O/H = [O^+ + O^{++})/H^+] \times (He/He^{++})^{2/3} , \quad (2)$$

$$N/H = (N^+/O^+) \times (O/H) , \quad (3)$$

$$Ar/H = [(Ar^{++} + Ar^{+3} + Ar^{+4})/H^+][(1 - N^+/N)^{-1}] , \quad (4)$$

$$S/H = \{[1 - (1 - O^+/O)^3]^{-1/3}\}[(S^+ + S^{++})/H^+] . \quad (5)$$

The total abundances derived for N66 are He/H = 0.116 ± 0.004, log N/H = 7.95 ± 0.12, log O/H = 8.24 ± 0.06, log Ne/H = 7.70 ± 0.6, log Ar/H = 6.12 ± 0.06, log S/H = 6.70 ± 0.10. No temperature fluctations have been assumed in these calculations, thus they are lower limits to the real values (Peimbert 1967, 1971). These abundances are equal, within the errors, to the values reported by PR, except for the case of N where they derived a value 0.22 dex higher from the N^+, N^{++}, N^{+3}, and N^{+4} ionic abundances; nevertheless this does not change the conclusions presented here. Larger abundances by a factor of 2.4 in the case of O and Ar and a factor of 4.8 in the case of S were derived by Dopita et al. (1993) from a sophisticated ionization structure model which includes spatially resolved geometry for this nebula but which does not reproduce the temperature-sensitive [O III] λλ4363/5007 intensity ratio observed.

By comparing the N66 chemical abundances derived in this work with the average values for the LMC H II regions (Dufour 1984; Russell & Dopita 1992; Garnett et al. 1994), we found that the Ne, Ar, and S abundances in N66 are systematically lower by 0.08 dex than the H II region values, while O is lower by 0.15 dex. That is, oxygen seems to be slightly deficient in N66 (however, this could be an artifact of the ionization correction factor used). On the other hand, He and N are larger than the LMC interstellar medium values, by 0.12 and 0.90 dex, respectively, showing that the N66 progenitor ejected a He- and N-rich envelope (with a N/O ratio of 0.51). In relation to C, its abundance was calculated by PR previously to the present stellar W-R phase. They determined log C/H = 7.45 ± 0.10, which is much lower than the average value, log C/H = 7.90, derived for H II regions and the value of 8.70 ± 0.30 reported for LMC PN by Barlow (1991). The C/O ratio in this nebula is a factor of 2 lower than the ratio log C/O = −0.48 obtained by Garnett et al. (1994) for the H II region in 30 Dor. Consequently we found that in N66 He and particularly N are enhanced by large factors, while O is slightly deficient and C is highly depleted. This is a common occurrence in type I planetary nebulae although N66 is not as extreme as the planetaries P7 and P9 which show much higher He/H and N/O ratios (Aller et al. 1987). Additionally we found that the (C + N)/H abundance ratio in N66 is equal to (C + N)/H in H II regions, thus the C and N abundances observed are consistent with CN-processing taking place in the original material already there. There is no evidence of envelope-burning of freshly created C dredged up from the nucleus as suggested for type I PNs by Barlow (1991) and Kingsburgh & Barlow (1994). The present high-mass-loss event in N66 does not show C enrichment either (see § 4); thus all seems to indicate that the third dredge-up did not occur in N66.

4. STELLAR VARIATIONS

Prominent W-R features in He II and N IV permitted lines were developed by the central star from 1987 to 1994. Some He I wide lines are also barely detected underlying the nebular lines, and we only present measurements of He I λ5876, which is the most intense of them. Dereddened intensities, equivalent widths, and FWHM of these features were given in Table 2, after subtraction of the nebular components. The uncertainties in these measurements are less than 15% with the exception of those marked with a colon which are more uncertain. A first result from these line measurements is that the FWHM of all the lines is consistent with a wind velocity of about 3000 km s^{-1}, in fair agreement with the value derived from the C IV λ1550 P Cygni profile.

Before the change, the central star flux was too weak to detect any stellar feature and to classify the object. The present spectral type of the star was classified as a WN4.5 in Paper I due to the presence of the intense N IV λ3480 feature, the weakness of the C IV λλ5801, 5812, and the lack of O VI and O V emission lines that are usually seen in early WC stars. The classification schemes by Smith (1968), van der Hucht et al. (1981), and Conti, Leep & Perry (1983) were employed. To confirm this classification we have compared the line intensities and equivalent widths of the N66 W-R features with those presented by Conti & Massey (1989) for galactic and

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LMC WN stars. It is found that the N IV λ3480 blend and the He II λ4686 line in N66 fit very well the correlation found for WN stars. On the other hand, N66 shows a weaker C IV λ5808 doublet. The equivalent widths of the wide component of He II lines (λλ1640, 4686, and 5411) also follow very well the correlations presented by Schmutz (1991) from atmospheric model calculations. This behavior of N66 W-R features confirms the spectral classification given in Paper I for this star.

From the previous discussion, it is evident that, as in WN population I stars, the central star of N66 is also ejecting He- and N-rich material processed during the CNO cycle. It is important to examine if the expelled material is H-deficient or not. To do this we have followed the semiquantitative procedure developed by Conti et al. (1983) which consists of calculating the Balmer-Pickering decrement to detect the presence of Balmer hydrogen lines mixed with the even members of the He II Pickering series. The H/He ratio can be estimated from the possible excess by assuming an optically thin or optically thick case. Using the data tabulated in Table 2 we found that the Balmer-Pickering decrement is marginally higher than the odd Pickering members decrement by less than 0.1 dex, therefore we estimate that the H/He ratio in N66 stellar wind is less than 0.4 by number (it corresponds to $X/Y < 0.10$) in the optically thick case and less than 0.26 in the optically thin case. That is, the present mass ejection in N66 consists of CNO processed material highly H-deficient.

In Paper I several stellar parameters, previous to the variation, were calculated for the central star of N66 from the nebular characteristics. We found that the He II Zanstra temperature (derived from the He II λ4686 which has not varied yet) was ≥120,000 K, and the bolometric stellar luminosity and radius were about 25,000 $L_\odot$ and 0.37 $R_\odot$, respectively. The mass derived by comparing these values with H-burning evolutionary tracks by Wood & Vassiliadis (1993) is 0.95 $M_\odot$, while it is higher for a He-burning object. The present stellar temperature can be derived from the UV stellar continuum by using the color indices λλ1300/1750 and 1500/1850 as proposed by Kaler & Feibelman (1985); this gives a color temperature $T_* \simeq 60{,}000$ K. Furthermore, the color temperature can be derived from the whole spectrum (UV from 1993 observations and optical from 1994 March data) giving $T_* \simeq 40{,}000$ K; nevertheless this last temperature is very uncertain due to nonsimultaneity of both spectra. Alternatively, we can estimate the present effective temperature using the procedure developed by Schmutz, Hammann, & Wessolowski (1989). This consists in comparing the equivalent widths of He II and He I wide lines with the predictions of a spherically symmetric expanding atmosphere model. From the equivalent widths of He II λ5411 and He I λ5876 as given in Table 2 and the models by Schmutz et al. (1989), we have derived an effective temperature of 52,000 K, which is in very good agreement with the values derived with the other methods and with the spectral type of WN4.5 determined before. From all these estimates we adopted 50,000 ± 10,000 K as the present effective temperature of the star. The stellar bolometric luminosity and the radius derived from this temperature and the stellar flux at 1300 Å, as given in Table 3, are ≃15,500 $L_\odot$ and ≃1.7 $R_\odot$, respectively. The dramatic drop in temperature and increase in radius show that currently we are seeing a false photosphere due to the presence of an optically thick wind.

TABLE 7

STELLAR CHARACTERISTICS

Parameter	1987 Aug	1990 Aug	1994 Mar
m_V^*	19.69 ± 0.20	18.23 ± 0.20	16.22 ± 0.07
M_V^*	1.24 ± 0.20	−0.22 ± 0.20	−2.23 ± 0.07
$T_*(10^3$ K)	120 ± 20	...	50 ± 10
log ($L_*/L_\odot$)	4.40 ± 0.17	...	4.19 ± 0.12
$R_*(R_\odot)$	0.37 ± 0.07	...	1.7 ± 0.5
$\dot{M}(M_\odot$ yr^{-1})	...	...	4.5×10^{-6}

The absolute visual magnitude of the central star, as derived from the dereddened stellar continuum at 5480 Å presented in Table 3, changed from +1.24 in 1987 to −2.23 in 1994 (for the adopted distance modulus of 18.45 for the LMC). In Table 7 we list the changes of the central star parameters from 1987 to the present. We have included the mass loss estimated in Paper I from the He II λ4686 wide emission line.

5. DISCUSSION

From the observations presented here and data collected in the literature we conclude that no significant variations have occurred in the nebular emission line intensities of N66 from 1975 to 1994 in spite of the drastic drop of effective temperature of the central star (from ≥120,000 to 50,000 K) and the change in luminosity. The apparent visual magnitude of all the object (star + nebula) is 0.3 mag brighter, as derived from our V direct image where we measured $V = 15.36$ in contrast with $V = 15.66$ reported by Westerlund & Smith (1966). This means that at present half of the visual flux comes from the central star in contrast with the value of 1966 where most of the visual emission came from the intense nebular [O III] and Hβ lines while the central star contribution to this flux was less than 3%. The spectacular changes in the central star activity should be apparent in the nebula in the next few years because the recombination time of the nebula is about 50 years and the nebula is about 0.4 pc in radius.

Physical conditions and ionic abundances of the ionized gas were derived from spectrophotometric analysis of the nebular lines. The He^+/H^+ abundance ratio was calculated by taking into account the collisional excitation of the He I 2 ^3S metastable level. It was found that the He I λλ4471, 5876 and 6678 line intensities yielded discordant values of the He^+/H^+ ratio by assuming that: (1) the 2 ^3S level is depopulated only by collisional transfers and by radiative transitions to the 1 ^1S level and (2) that N66 is a homogeneous nebula with constant n_e and T_e values. A concordant value among the three lines can be reached if (1) there is an unknown additional mechanism depopulating the 2 ^3S level to 60% ($\gamma = 0.6$), (2) there are spatial density fluctuations present such that the average electron density is 1100 cm^{-3} instead of 2670 cm^{-3}, or (3) there are spatial temperature fluctuations such that the average electron temperature is 13,300 K instead of 16,450 K. It is suggested that the discrepancy can be solved by a combination of possibilities (2) and (3).

Chemical abundances of He, C, N, O, Ne, Ar, and S were derived for the nebula. It is found that the nebular gas is He- and N-rich, while C appears highly depleted. The chemical abundances derived are consistent with a scenario where the ejected envelope was enriched with He and N produced during CN-burning where the N abundance was enhanced at the expense of the C already present. No evidence of C enrichment due to a third dredge-up episode was found.

The sudden appearance of P Cygni profiles in the resonant N V and C IV ultraviolet lines and the wide components of the

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He II lines as well as the visual and UV continuum enhancement are a confirmation that the central star of N66 has developed a strong wind (with $v_\infty \approx 4200$ km s^{-1} and $\dot{M} \simeq 4.5 \times 10^{-6}$ $M_\odot$ yr^{-1}) in a short timescale. In a period of a few years this object has developed a W-R atmosphere although no evidence of stellar variations has been reported during the 20 previous years.

The fast variations in bolometric luminosity, temperature, and radius of the central star are similar to those predicted by theoretical models for stars undergoing a final helium flash (Iben et al. 1983; Iben 1987, 1989; Shönberner 1983; Vassiliadis 1993). The predictions (made for a nucleus of $M \leq 0.6$ $M_\odot$) suggest that stars in this stage would evolve making a wide loop in the H-R diagram, characterized by a significant drop in T_* at about constant luminosity. The star would become a red giant before coming back to the PN region on the H-R diagram (born-again AGB phase). The present spectral evolution of the central star of N66 would correspond to the initial phase of this phenomenon, although the evolution time has been faster than predicted for objects with $M \simeq 0.6$ $M_\odot$. This is consistent with the high mass of this PN nucleus, and it should be a very short timescale phenomenon as it has not been observed in any other planetary nebula.

A fundamental difference between this star and other planetary nebulae with W-R nuclei is that N66 is presently ejecting He- and N-rich material instead of He- and C-rich. We have verified that the ejecta are highly H-deficient. Consequently the present evolutionary stage of N66 central star is that of a highly evolved H-deficient star with a C-O core and a He-burning shell surrounded by a He- and N-rich atmosphere which is being ejected in a strong wind. As in the ionized nebula, there is no evidence of C enrichment with freshly made C from the nucleus in the presently He- and N-rich photosphere. In this sense, N66 presents spectral characteristics that are unique in PN nucleus studies, as all the known planetaries with W-R nuclei (even those found in type I PNs) have been classified as WC stars.

According to current ideas in the W-R field (e.g., Willis 1991), WC spectral types correspond to more evolved stages where stars are showing, in their surface, products of He burning. Applying these ideas to the evolutionary stages of N66, as well as to those of A30 and A78 (which have been classified also as "born-again" planetary nebulae), it could be said that N66 seems to be less advanced than the other two which are showing a C-rich envelope, and that in a near future N66 probably will change from WN to WC. Another possible explanation for this phenomenon could be attributed to the high core mass of N66 (which is higher than 0.95 $M_\odot$). The evolution of low to intermediate mass stars (1–10 $M_\odot$) and the photospheric abundances in the post-AGB phase have been discussed by Iben (1991) who argues that stars with high core masses (≥ 0.8 $M_\odot$) do not become carbon stars because they do not live long enough to dredge up substantial amounts of fresh C to the He envelope in order to exceed the abundance of O there. Furthermore, the dredged-up C could be easily converted to N at the base of the convective envelope by CN burning.

From the previous discussion, we expect more spectacular changes of the central star and the nebula of N66 in the next few years.

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