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A THERMAL PULSE IN PROGRESS IN THE NUCLEUS OF THE LMC PLANETARY NEBULA N66

M. PEÑA,[1,2] S. TORRES-PEIMBERT,[1,2] AND M. PEIMBERT[1]
Instituto de Astronomía, UNAM, Apdo. Postal 70-264, Méx. D.F. 04510, México
AND
M. T. RUIZ[1] AND J. MAZA[1]
Depto. Astronomía, Univ. de Chile, Casilla 36-D, Santiago, Chile
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ABSTRACT

Optical and UV spectrophotometric data, gathered in the 1987–1994 interval, are presented for the planetary nebula N66 (WS 35 or SMP 83) in the Large Magellanic Cloud. These data show that the central star has suffered dramatic changes. Before 1987 it showed a featureless continuum while its present spectrum shows intense W-R features and P-Cygni profiles which resemble a WN4.5 although the N lines are fainter than the He II lines as compared to normal Galactic WN stars. From the C IV $\lambda1550$ P-Cygni profile it is found that $v_\infty = 4200 \pm 500$ km s^{-1}. The intensity of the UV and optical continua have been increasing systematically and the absolute visual magnitude, M_V, has changed from $+1.15 \pm 0.30$ mag in 1987 August to -2.01 ± 0.20 mag in 1994 January. The temperature of the central object has diminished from $120{,}000 \pm 20{,}000$ K to $50{,}000 \pm 10{,}000$. The bolometric luminosity has decreased from $\log L/L_\odot = 4.40 \pm 0.17$ to $\log L/L_\odot = 4.19 \pm 0.12$ while the radius has increased from 0.37 ± 0.07 to $1.7 \pm 0.5\ R_\odot$. The object is probably undergoing a final helium flash. Most of the UV line intensities are 3 times higher in 1993 than in 1983; on the other hand, no significant variations have been detected in the nebular line intensity ratios in this period. The interesting and unusual behavior of N66 should be closely followed.

Subject headings: Magellanic Clouds — planetary nebulae: individual (N66) — stars: evolution — stars: mass loss — stars: Wolf-Rayet

1. INTRODUCTION

N66 (also known as WS 35 and SMP 83) is one of the most interesting PNe in the LMC, due to its extraordinary internal dynamics and its massive central star. Its N/O abundance ratio, greater than 0.5, permits us to classify it as a Peimbert's type I (Peimbert 1978), although not as extreme as N97 or N102 (Monk, Barlow, & Clegg 1988). Extensive studies of this object have been made by several authors (e.g., Dopita, Ford, & Webster 1985; Peña & Ruiz 1988; Dopita et al. 1993). From spatially resolved images, Dopita et al. (1993) found that the nebula shows a bipolar shape with a partially equatorial ring and a bipolar filamentary extension. The most external filament lies at 1.86 arcsec (0.42 pc) from the central star.

Torres-Peimbert et al. (1993) reported an unprecedented variation: the sudden appearance of a weak wide component in the He II $\lambda4686$ emission line profile. The presence of the wide emission was interpreted as indicative of the development of W-R features by the central star in the 1987–1990 interval. In this *Letter* we present recent UV and optical observations that further confirm that interpretation. The central star of N66 has developed intense He II and N IV W-R features as well as P-Cygni profiles. These characteristics are very unusual in PNe with W-R nuclei. In the Galaxy only the central stars of A30 and A78 show some similar spectral characteristics (e.g., Heap 1982) while all the known MC-PNe with W-R features (four in the LMC and two in the SMC) are WC stars (Monk et al. 1988; Peña et al. 1994a). Besides, the short timescale of the phenomenon is a confirmation of the high mass reported for the central star. For the first time 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 that disappeared in a few years (Peimbert et al. 1994), and the central star of the PN Longmore 4 showed WC features that appeared and disappeared in a few months (Werner et al. 1992); FG Sge has varied in spectral type from B to K probably due to a helium flash (e.g., Jurcsik 1993, and references therein).

2. SPECTRAL VARIATIONS

2.1. *Optical Region*

To better study the spectral variation of the N66 nucleus, we obtained two new spectra with the CTIO 4 m telescope, equipped with the RC spectrograph and a Reticon detector in 1994 January 28. The spectral range observed was 3200–7000 Å and the exposure times were 100 and 600 s. A long-slit, 1.33 arcsec wide was used; the slit was oriented along the parallactic angle to avoid atmospheric refraction effects (corresponding to P.A. 60°); seeing was ~1 arcsec. Data reductions were carried out at CTIO La Serena Computing Facilities. The extraction window was 1.33 × 3.5 squared arcsec and the sky was subtracted from part of the slit that showed no evidence of nebular emission. The nebular size is less than 2 arcsec, consequently it is not possible to separate stellar from nebular emission. Part of the 600 s spectrum is presented in Figure 1 where we also show optical spectra obtained with the same telescope in 1987 and 1990. The 1994 spectrum shows prominent stellar W-R features in all the He II lines and in N IV $\lambda\lambda3479$–3484 blend, other weak wide features of C IV and N V are also

[1] Visiting astronomer, Cerro-Tololo Inter-American Observatory, National Optical Astronomy Observatories, which is operated by Associated Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

[2] Guest observer at *International Ultraviolet Explorer* operated by NASA.

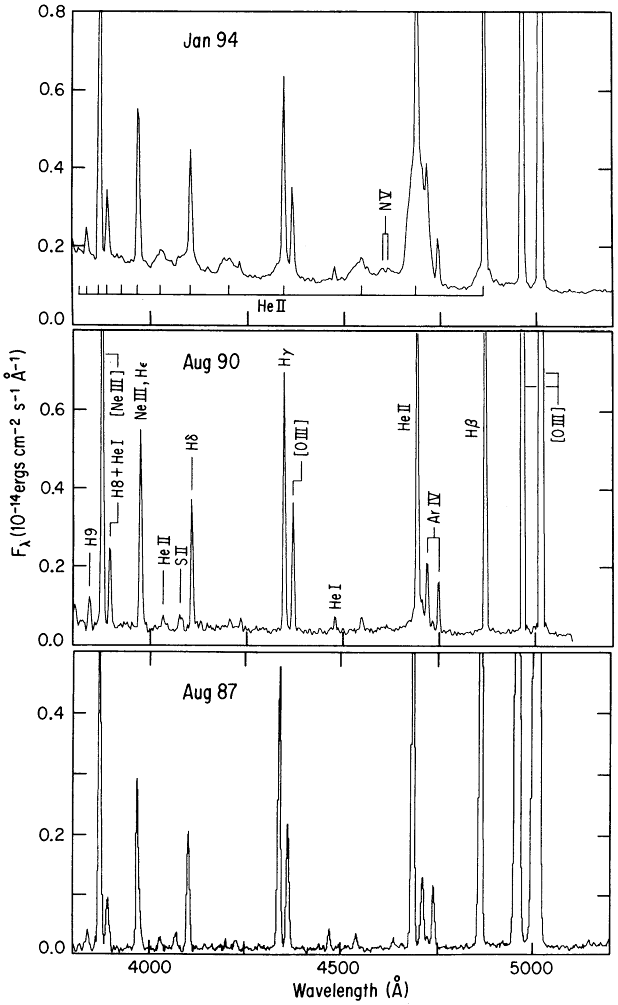

FIG. 1.—Enlargement of the 3800–5200 Å interval in 1994 January, 1990 August, and 1987 August spectra of N66. Faint N v lines (λλ4604, 4620) and strong wide He II features (λλ4859, 4686, 4542, 4339, 4200, 4100, and 4025) are present in 1994; wide λ4686 He II is evident in 1990, and absent in 1987. The change in the continuum intensity is very conspicuous.

present. The presence of the N IV line allows us to classify the object as a WN4.5 according to the classification by Smith (1968), although the N lines are much fainter than the He lines as compared to normal WN stars.

From these observations and data collected in the literature (Monk et al. 1988; Peña & Ruiz 1988; Meatheringham & Dopita 1991) we conclude that no significant variations have occurred in the nebular emission line ratios from 1975 to 1994. On the other hand, the systematic increase in the optical continuum intensity is very noticeable. Measurements of the continuum at several wavelengths are presented in Table 1 where we have listed the dereddened observed flux, I_λ and the stellar flux, I_*, obtained by subtracting the nebular contribution. The nebular continuum due to two-photon emission and hydrogen and helium bound-free continua has been computed following standard procedures (e.g., Aller 1984, pp. 98–106; Osterbrock 1989, pp. 86–93). The determination of the nebular contribution was based on the intensities of Hβ and λ4686 and on the adoption of $N_e = 2000$ cm^{-3}, $N(\mathrm{He}^+)/N(\mathrm{H}^+) = 0.0551$, $N(\mathrm{He}^{++})/N(\mathrm{H}^+) = 0.0578$, $T_e = 16{,}400$ K and $C(\mathrm{H}\beta) = 0.15$ (Peña et al. 1994b). The fluxes were dereddened using the

TABLE 1

DEREDDENED ULTRAVIOLET AND OPTICAL CONTINUUM FLUXES[a]

	1983 19905(181)[b]		1993 49112(180)[b]	
λ_0 (Å)	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
log F(He II 1640) .	−12.16		−11.70	
EW(He II 1640) ...	99.5		133.7	

	Aug 1987[c] 2″ E-W[d]		Aug 1990 1″.6 E-W[d]		Jan 1994 1″.33 (60° P.A.)[d]	
λ_0 (Å)	I_λ	I_*	I_λ	I_*	I_λ	I_*
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
5000	2.24	0.62	4.19	2.61	13.4	12.1
6000	1.63	0.40	2.60	1.40	8.06	7.11
6500	1.23:	0.09:	2.29	1.17	6.50	5.61
7000	1.10:	0.07:	1.86	0.85	5.09	4.28
log F(Hβ)	−12.99		−13.00		−13.10	
EW(Hβ)	639.6		256.4		51.8	

[a] I_λ is the nebular + stellar continuum, I_* is the stellar continuum; a reddening correction of $C(\mathrm{H}\beta) = 0.15$ has been applied to them. UV continuum fluxes are in units of 10^{-14} ergs cm^{-2} s^{-1} Å^{-1}; optical continuum fluxes in 10^{-16} ergs cm^{-2} s^{-1} Å^{-1}; $F(\mathrm{H}\beta)$ and $F(\mathrm{He\ II})$ in ergs cm^{-2} s^{-1}.

[b] SWP(min).

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

[d] Slit width and orientation.

extinction law by Whitford (1958) for a $C(\mathrm{H}\beta) = 0.15$. The absolute visual magnitude of the nucleus, as estimated from the stellar flux at 5480 Å, has changed from $M_V = +1.15$ in August 1987 to $M_V = -2.01$ in 1994 January (where a distance modulus of 18.45 was adopted for the LMC). The decrease in the $F(\mathrm{H}\beta)$ value presented in Table 1 from the 1994 observations is due to the smaller entrance slit used, and not to a change in the total flux emitted by the nebula at Hβ. Dopita et al. (1993) reported a stellar flux at Hα of 2.07×10^{-17} ergs cm^{-2} s^{-1} Å^{-1} observed in 1991 May; this flux is 5 times smaller than the stellar flux near Hα that we observed in August 1990 and 20 times smaller than the flux observed in 1994 January. This could be an indication of very short time variability of the star.

W-R characteristics, presented in Figure 1, are already noticeable as a weak wide component in the He II λ4686 emission line in the August 12 1990 spectrum reported by Torres-Peimbert et al. (1993). We have found that this wide feature was already present in a spectrum of 1988 January 17 published by Meatheringham & Dopita (1991) although not mentioned by them. No evidence of this wide component was detected nor reported in previous works.

2.2. *Ultraviolet Region*

We obtained an *IUE* spectrum in the 1200–2000 Å range in 1993 November 5 (SWP 49112, 180 minute exposure time). Data reductions were performed at *IUE* Data Analysis Center located at GSFC. The new spectrum is very different to previous ones of the same object; the basis of comparison is SWP 19905, the best well exposed spectrum available in the *IUE* archives. P-Cygni profiles at N V λ1240 and C IV λ1550, not present before, are well developed now. The emission lines

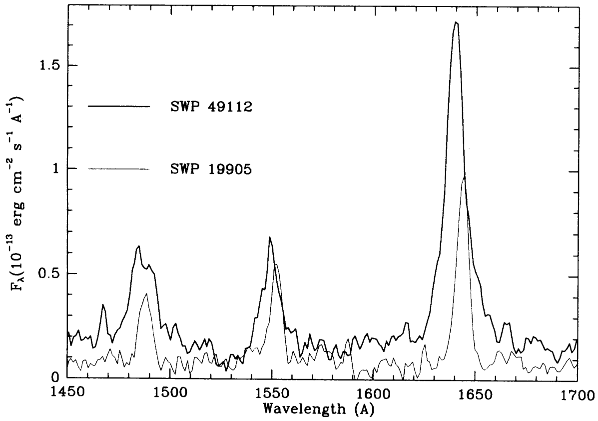

FIG. 2.—Comparison of a portion of the *IUE* spectra SWP 49112 (1993) and SWP 19905 (1983). There are appreciable changes in the continuum flux, emission line intensities and widths and the appearance of P-Cygni profiles in the $\lambda1550$ line.

appear wider, more intense and shifted to lower wavelengths (N v $\lambda1240$, N iv] $\lambda1488$, C iv $\lambda1550$, and He ii $\lambda1640$); a section of the UV spectra of 1983 and 1993 is presented in Figure 2. The line intensities (Peña et al. 1994b) are larger by a factor of approximately 3 in 1993 than in previous years. An estimate of the terminal velocity wind from the C iv P-Cygni profile gives $v_\infty = 4200 \pm 500$ km s^{-1}.

In Table 1, we present dereddened total and stellar UV continuum fluxes measured in 1993 and 1983. To deredden we have assumed that half of the reddening is due to galactic extinction (using the reddening law from Seaton 1979), and half is due to LMC extinction (using the LMC law from Nandy et al. 1981). An increase in the stellar continuum of a factor of about 3 is observed in 1993, compared with the previous observation, taken in 1983. These continuum measurements together with the optical ones allow us to estimate the color temperature of the central star.

3. STELLAR PARAMETERS

From the He ii $\lambda4686$ emission line intensities, published by Peña & Ruiz (1988) and the 1983 UV continuum measurements presented here we have determined a Zanstra temperature of 120,000 ± 20,000 K for the central star. A color temperature greater than 150,000 K is derived from the continuum measurements (UV to visible) previous to the variation. We have adopted the He Zanstra temperature as representative of the effective temperature of the star at that epoch. This temperature, combined with the stellar flux at 1300 Å, gives a bolometric luminosity of $\log L/L_\odot = 4.40 \pm 0.17$ and a stellar radius of 0.37 ± 0.07 $R_\odot$. Before 1987, the central star of N66 was very hot and luminous. The mass derived by comparing these values with evolutionary H-burning tracks by Wood & Vassiliadis (1993) is 0.95 $M_\odot$. Dopita et al. (1993) determined a temperature of 170,000 K $\log L_*/L_\odot = 4.50$ and a mass of 0.98 $M_\odot$ for H-burning and of 1.2 $M_\odot$ for He-burning tracks.

From the 1993 observations, an analysis of the color temperature using the color indices $\lambda\lambda1300/1750$ and 1500/1850 (as proposed by Kaler & Feibelman 1985) gives $T_* \simeq 60{,}000$ K, and the color temperature obtained from the whole spectrum (1993 UV to 1994 optical) gives $T_* \simeq 40{,}000$ K. We adopted 50,000 ± 10,000 K as the temperature of the star, which is consistent with the spectral type of WN4.5 discussed before. The bolometric luminosity derived from this temperature and the 1993 stellar flux at 1300 Å (for a BB approximation), is $\log L/L_\odot = 4.19 \pm 0.12$ and the radius is 1.7 ± 0.5 $R_\odot$. The present derived temperature and radius correspond to the parameters of the optically thick expanding envelope. However, the bolometric luminosity is the corresponding stellar value for an optically thick envelope. In conclusion, the stellar luminosity seems to have diminished by about 0.2 ± 0.15 dex. The changes from 1987 to 1993 are presented in Table 2.

TABLE 2

STELLAR CHARACTERISTICS

Parameter	1987	1990	1993
M_V	$+1.15 \pm 0.30$	-0.35 ± 0.20	-2.01 ± 0.20
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

It is possible to make a rough estimate of the mass-loss rate in the wind, corresponding to the wide emission lines observed in 1994. From the dereddened flux of the wide component of He ii $\lambda4686$, $F(4686)$, the total luminosity in the line, $I(4686) = 4\pi d^2 F(4686) = 4.1 \times 10^{34}$ ergs s^{-1} = 10 $L_\odot$, can be derived. For an optically thin region the line luminosity is $I(4686) = \int f N_e N(\mathrm{He}^{++}) \alpha h\nu \, dV$; and the mass of the emitting region is $M = \int f N(\mathrm{He}^{++}) 4 m_{\mathrm{H}} \, dV$ (considering that the wind is essentially helium twice ionized). For a spherical shell and a density law $N \propto 1/r^2$ the emitting matter is concentrated close to the stellar surface. For $R_* = 1.7$ $R_\odot$, an electron temperature of 20,000 K, a filling factor $f = 1$ and an average wind velocity $v = v_\infty/2 = 2100$ km s^{-1}, the following parameters can be derived: the density at the surface $N(\mathrm{He}^{++})_{R_*} = 1.2 \times 10^{12}$ cm^{-3}, with a corresponding mass loss rate $\dot{M} = N(\mathrm{He}^{++})_{R_*} 4 m_{\mathrm{H}} (4\pi R_*^2 v) = 4.5 \times 10^{-6}$ $M_\odot$ yr^{-1}. The value of the mass loss rate is an order of magnitude estimate because a smaller filling factor would decrease $\dot{M}$, while an optically thick He ii $\lambda4686$ would increase $\dot{M}$.

4. DISCUSSION

The sudden appearance of P-Cygni profiles in the UV lines and the wide components of the He ii lines as well as the continuum changes are a confirmation that the N66 nucleus has developed a strong wind in a short time scale. No evidence of nebular variations can be found in the data reported in the literature for this object during the previous 15 years. The increase in the FWHM and in the intensities of the high excitation emission lines N v $\lambda1240$, C iv $\lambda1550$ and He ii $\lambda\lambda1640$ and 4686 indicate that these lines have been partially emitted in regions close to the stellar photosphere.

The W-R nature of the star means that at present its surface is H-poor and that is undergoing He-burning. There is no information on the photospheric abundances prior to 1988 and we do not know if before this epoch it was undergoing H- or He-burning. Dopita et al. have discussed these two possibilities. The H-burning case that undergoes a final thermal pulse after departure from AGBs has been studied by several authors (e.g., Iben et al. 1983; Schönberner 1983; Iben 1984, 1987; Wood & Faulkner 1986; Vassiliadis 1993). In this case the star follows a wide loop in the H-R diagram, characterized by a significant drop in T_{eff}. Since we are observing a decrease in T_{eff} of a factor of about 2.4, it seems reasonable to suggest that the star is experiencing a final thermal pulse. If this is the case we would predict a further decrease of T_{eff} in the next few years. The thermal pulse could be responsible of the radiation pressure that might be driving the observed mass loss. Other possibilities to explain the observed changes, like perturbations due to a close companion, should be explored.

The optical line intensity ratios have been constant showing that the central star mass loss and intensity variations have not influenced the ionized gas yet. However the drastic changes in the central star activity should be apparent in the nebula in the next few years because the nebula is about 0.4 pc in radius and the recombination time is about 50 years.

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