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NEW RESULTS IN PLANETARY NEBULAE WITH WR NUCLEI. THE EVOLUTION OF LMC–N66

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RESUMEN

Se discuten observaciones recientes de la estrella central de la nebulosa planetaria N66 de la Nube Mayor de Magallanes que inició una violenta fase WR hace pocos años. Los datos, acumulados desde 1987 a la fecha, permiten hacer un seguimiento de los cambios de los parámetros estelares y comparar las características estelares actuales con las de otras estrellas WR en nebulosas planetarias. Se encuentra que el evento que ocurre en N66 tiene propiedades espectrales y fotométricas muy diferentes a las de otros núcleos de nebulosas planetarias. La magnitud visual y las características espectrales de N66 son similares a las de estrellas WN débiles de Población I de la Nube Mayor de Magallanes. Se presentan las variaciones mostradas tanto por el continuo estelar como por las líneas fotosféricas entre 1993 y 1995. Se discute la posibilidad de que la estrella central de N66 esté sufriendo un "pulso térmico final".

ABSTRACT

The recent mass-loss event occurring in the central star of the planetary nebula LMC–N66 is analyzed. Data gathered since 1987, showing the evolution of the stellar parameters, are evaluated. The present characteristics of the progenitor are compared with other known WR central stars of planetary nebulae in the LMC and the Galaxy. It is found that the present event in LMC–N66 shows very different spectral and photometric characteristics. The visual magnitude and spectral features of N66 are similar to those of the faint Population I WN stars in the LMC. Spectral variations in the continuum and stellar lines during the period from 1993 to 1995 are presented. The possibility that the central star of N66 is undergoing a "final thermal pulse" is discussed.

Key words: **MAGELLANIC CLOUDS — PLANETARY NEBULAE: GENERAL — PLANETARY NEBULAE: INDIVIDUAL (LMC–N66) — STARS: EVOLUTION — STARS: WOLF-RAYET**

1. INTRODUCTION

Nuclei of planetary nebulae (PNNi) are hot pre-white dwarfs (post-AGB objects) that have recently ejected a substantial amount of mass at low expansion velocity. The mass-loss, consisting of the ejection of an important part of the H-rich atmosphere, occurs principally during the AGB phase. The star leaves the AGB and evolves towards higher effective temperatures, becoming a PNN when the H-rich envelope has been reduced below a certain limit.

Among the known galactic PNNi, about 3% of the sample shows WR characteristics. In these cases, the star seems to be extremely H-deficient and the strong stellar wind is He- and C-rich. All of these objects have been classified as WC-type stars (Méndez 1991; Tylenda, Acker, & Stenholm 1993). In the Large Magellanic

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Cloud (LMC) there are five PNe which are known to have WR-type nuclei (Monk, Barlow, & Clegg 1988; Peña et al. 1994a). This represents 10% of the known LMC-PNe and all these stars are also ejecting He- and C-rich material.

To explain these objects, a removal of the H-rich envelope due to a late He-flash that sends the star back to the AGB (born-again phase) has been invoked (Shönberner 1983; Iben 1984; Renzini 1989; Vassiliadis 1993). The presence of strong massive winds producing WR features in such an advanced evolutionary stage of a low mass star is not very well understood, however WR–PNNi are considered to be He-burning stars situated near the Eddington limit and suffering a radiatively driven strong wind (Méndez 1991). Alternatively, the WR stage has been considered as a phase in the evolution of a binary system (Tylenda & Gorny 1993).

In 1990 the central star of the planetary nebula N66 in the LMC began to show evidence of an incipient mass-loss event (Torres-Peimbert et al. 1993) and in few years, prominent WR features corresponding principally to He and N emission lines appeared to be very well developed. The spectral type corresponds to that of a WN4.5 star. The UV and optical continuum has been increasing systematically since then and the visual stellar brightness has increased by several magnitudes. Peña et al. (1994b; hereafter Paper I) estimated a mass-loss rate of about 4.5×10^{-6} $M_{\odot}$ yr^{-1} and suggested that a "final thermal pulse" could be responsible for such a violent mass-loss event. Previous to the variation, the central star showed a featureless, weak, and extremely hot continuum; a stellar mass of about 1 $M_{\odot}$ was derived from nebular characteristics (Peña & Ruiz 1988; Dopita et al. 1993).

The remarkable changes of the N66 central star have been analyzed in Paper I, by Cowley et al. (1994), and by Peña et al. (1995; hereafter Paper II). In this work, new data obtained in a systematic follow-up of the event are discussed and a comparison of the present spectral characteristics of the N66 central star with other known WR central stars in the LMC and the Galaxy is presented.

No significant variations have been detected in the nebular line intensities in this period, which shows that the stellar mass-loss and the changes in the effective temperature have not influenced the nebula yet. The chemical composition of the nebula corresponds to that of Peimbert's Type I PN (Peimbert 1978); i.e., He- and N-rich. An interesting phenomenon is the fact that many of the optically wide WR features (especially the He lines) always appear redshifted relative to the nebular lines, showing a velocity difference of about 200 km s^{-1}. This seems to be a common phenomenon in WR stars and it has been attributed to the presence of a blueshifted absorption component, too faint to be clearly detected. The possibility of arising from the presence of a close companion as suggested by Cowley et al. (1994) can be discarded.

2. COMPARISON TO OTHER PLANETARY NEBULAE WITH WR NUCLEI

The striking differences of the present WR stage of N66 compared to other WR nuclei of planetary nebulae (WR–PNNi) are presented in this section. The known WR–PNNi in the Magellanic Clouds are: N203, N110, and N133 in the LMC, and N6 in the SMC. All of these show intense photospheric C lines and their effective temperatures are about 40 000 K, therefore they have been classified as WC4.5 to WC5 by Monk et al. (1988). Additionally, Peña et al. (1994a) found that the nucleus of LMC LM1–64 has spectral characteristics of an Of-WC, with an effective temperature of about 100 000 K.

In Figures 1 and 2, sections of the UV and optical spectra of N66 are compared with the spectra of the objects mentioned above. The UV observations were carried out with the *IUE* satellite in 1994 and the optical data were obtained with the 4-m telescope at CTIO during 1994. UV data reduction was performed at *IUE* Regional Data Analysis Facilities, GSFC, NASA, and optical data were reduced using IRAF at the Computer Centers of the Astronomy Department of the University of Chile and the Instituto de Astronomía, UNAM.

In both figures it is seen that the continuum flux of N66, which is mostly of stellar origin, is much more intense than the fluxes of the other objects. This difference amounts to one order of magnitude in the UV (at λ1300) and about a factor of 3 at λ5500, showing that the nucleus of N66 is intrinsically much brighter than the others. Other remarkable differences are: (a) the presence of intense He II lines in N66 that are not detectable in the other WR–PNNi, and (b) the absence or weakness of the C lines (C IV λ5808, C III λ4650, etc.) in N66 while they are very obvious in the other objects. From the point of view of the nebulae, all the LMC WR-PNe except N66 are extremely C rich, with C/O abundance ratios in the range of 1.7 to 5 (Peña, Ruiz, & Torres-Peimbert 1995). This is evidence that the nebular material in these objects was contaminated with freshly made C; this is not the case of N66 which is an N-rich nebula with low C abundance (Peña & Ruiz 1988).

When compared with galactic WR–PNNi, N66 also shows striking differences. First, as previously stated, it is the only WR-PNN classified as WN-type while all the galactic objects of this kind have been classified

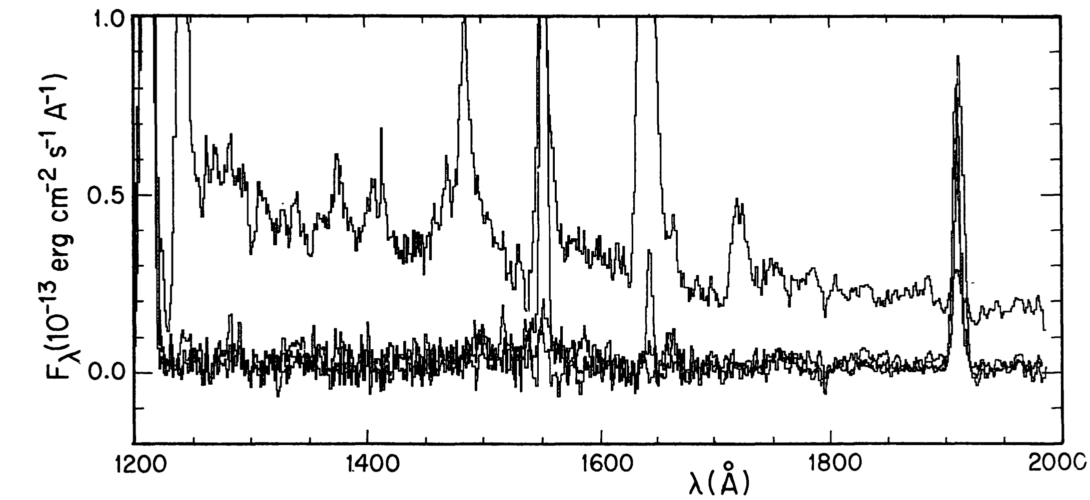

Fig. 1. Comparison of the *IUE* calibrated spectra of N66 with the spectra of the WR–PNNi N203, N110, N133, and LM1-64 in the LMC and N6 in the SMC. N66 is much more luminous than the others and shows impressive stellar features.

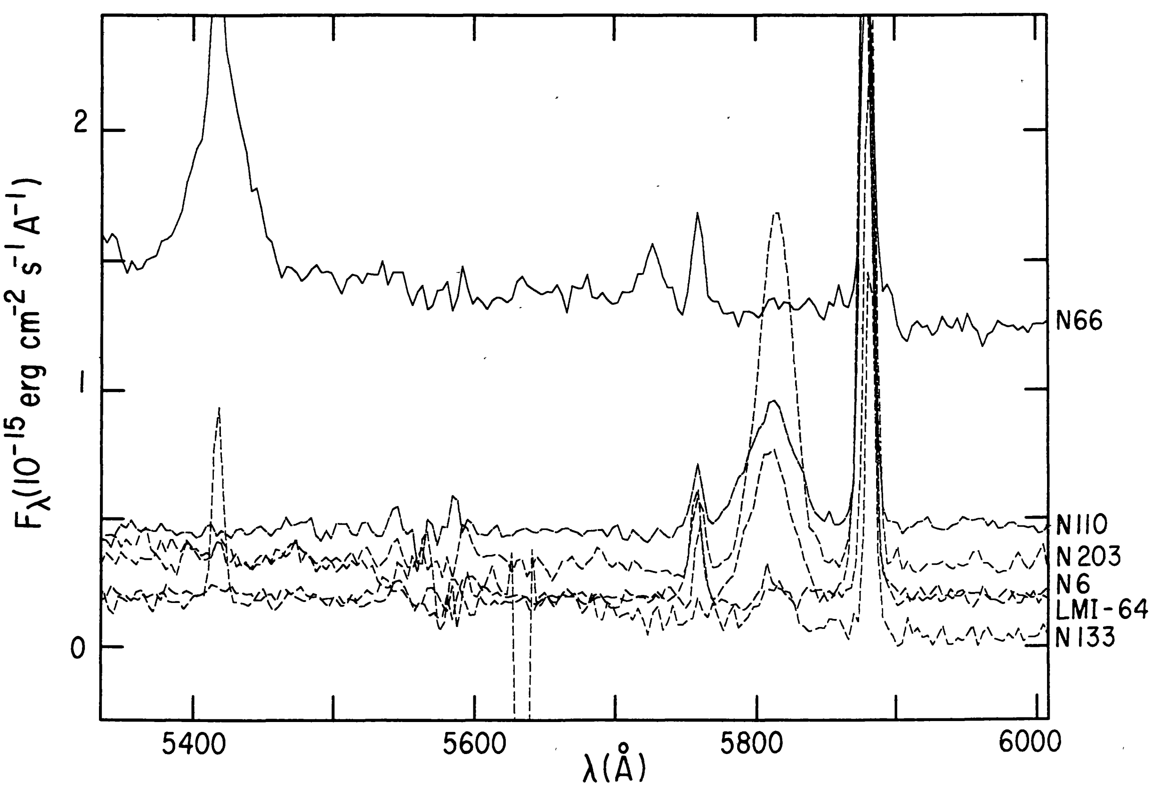

Fig. 2. Sections of the calibrated spectra of N66, N203, N110, N133, LM1–64 and N6 (SMC). The zone around the He II λ5411 emission line is shown. This line is very prominent in N66 and absent in the other objects. N66 does not present C IV λ5808 emission. The continuum of N66 is 3 times higher than the other continua. All the spectra were obtained in Dec/94 with the CTIO 4-m telescope.

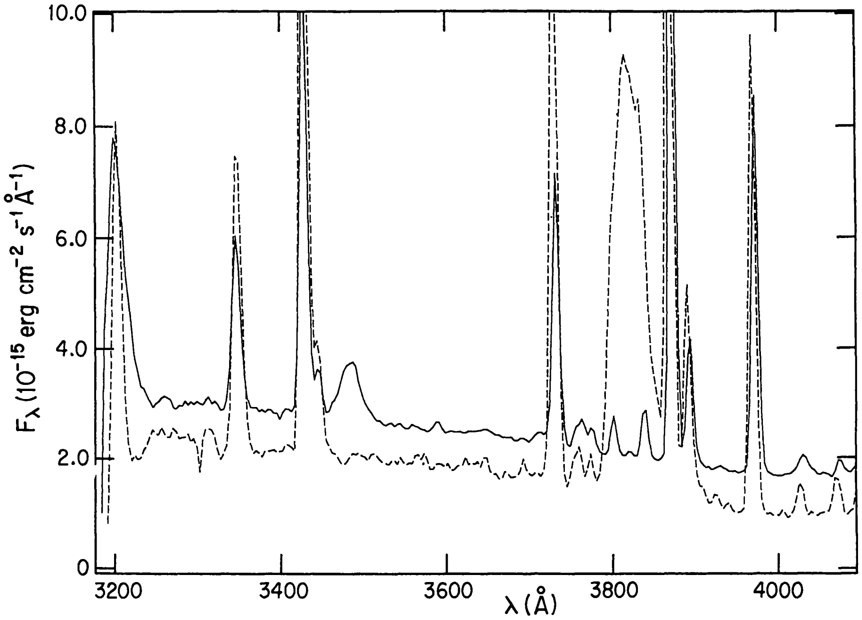

Fig. 3. Comparison between the optical spectra of N66 (filled line) and PB6 (broken line). PB6 in a hot WR nucleus of a galactic planetary nebula classified as WC3. It shows impressive O IV λλ3811, 3834 emission that is absent in N66.

as WC-type. In Figure 3 we compare the optical spectrum of N66 with that of PB6. The latter is a galactic Type I PN with one of the hottest WR nuclei (classified as WC3 by Tylenda et al. 1993). Kaler et al. (1991) deduced an effective temperature higher than 100 000 K and a bolometric luminosity between 3800 and 7800 $L_\odot$ for this object. In Figure 3 N66 appears brighter than PB6 (even being an object in the LMC) and shows more intense He II emission lines and a stronger wind. On the other hand, the nucleus of PB6 has an impressive O VI λλ3811, 3834 emission blend that is completely absent in N66.

In conclusion, the massive wind that happens in the nucleus of N66 seems to be of a very different chemical composition compared to those occurring in galactic and LMC WR–PNNi. Additionally, the central star of N66 is, at present, intrinsically much brighter and shows more intense He II emission lines than the others. With an absolute visual magnitude of about −2.5 (see Table 2) and a He II λ4686 equivalent width of ≈ 150 Å, the nucleus of N66 appears similar to AB9 and AB15, which are the faintest LMC early–WN stars reported by Conti & Massey (1989) in their study of Population I WR stars in the LMC. The present characteristics of N66 correspond better to those of the low-luminosity end of the Population I WN stars than to "normal" planetary nebula WR nuclei.

3. RECENT VARIATIONS IN UV AND OPTICAL WAVELENGTHS OF THE CENTRAL STAR OF N66

Systematic spectrophotometric observations in the UV and optical wavelengths have been carried out to follow the evolution of the stellar characteristics.

In Figure 4 three low-resolution calibrated UV spectra, observed with *IUE* satellite in Nov/93, Sept/94, and Jan/95 are presented. In Nov/93 the WR stellar features were already very well developed and prominent P-Cygni profiles were observed in N V λ1240 and C IV λ1550. Previous UV spectra did not show any WR feature and the continuum was a factor of 10 lower (see Paper I). The spectra presented in Fig. 4 show that from 1993 to 1995 the UV continuum suffered remarkable changes, increasing by a factor of about 2 (as measured at λ1300) from Nov/93 to Sept/94 and decreasing back in Jan/95. Simultaneously the photospheric UV emission lines varied by significant amounts (see Table 1).

Sections of optical spectra obtained at CTIO with the 4-m telescope and the RC spectrograph, in about the same epochs as the *IUE* observations, are presented in Figure 5. The optical stellar continuum has not changed as much as the UV (although it has been increasing systematically), but some stellar features —especially the

TABLE 1
EVOLUTION OF STELLAR EMISSION LINES[a]

		1993		1994		1995	
λ	ion	F_λ	EW	F_λ	EW	F_λ	EW
1240	N V	151.0	64	105.0	22	135.1	64
1488	N IV	60.7	34	112.0	32	65.4	37
1550	C IV	52.8	36	96.2	26	50.8	26
1640	He II	200.0	134	306.0	117	174.0	89
1718	N IV	14.0	8	14.0	6	12.2	10
3484	N IV	6.7	25	9.8	36	3.0	13
4606	N V	0.5:	6:	1.5	12	1.5	11
4686	He II	171.0	145	177.0	150	173.0	148
5808	C IV	0.2:	8:	1.5	17	0.4:	4

[a] F_λ (not corrected by reddening) in units of 10^{-14} erg cm^{-2} s^{-1}, EW in Å.

N IV blend at λ3480— have varied by a large amount (Figure 5). In Dec/94 λ3480 was more than 3 times weaker than in August/94.

The most important photospheric line intensities are presented in Table 1. The UV lines are from the spectra shown in Fig. 4 and the optical ones are from spectra taken in about the same epochs as the ones with *IUE*. In Table 1 we see that the intensities of He II (λ1640), C IV (λ1550 and λ5808) and N IV (λλ1488, 1718, and 3484) showed a behavior similar to the continuum: they increased by factors of 1.5 to 2 from the end of 1993 to the middle of 1994 and decreased back by the beginning of 1995. The only exceptions are: N V λ1240 which did the opposite, decreased and increased back, and He II λ4686, which did not vary significantly. These variations in the photospheric lines can be interpreted as evidence of changes in the effective temperature and/or optical depth of the wind. A complete discussion of these data will be presented elsewhere.

TABLE 2
EVOLUTION OF STELLAR CHARACTERISTICS

Parameter	Aug 1987	Aug 1990	Mar 1994	Sept 1994	Jan 1995
m_V^*	19.69 ± 0.20	18.23 ± 0.20	16.22 ± 0.07	16.06 ± 0.08	15.88 ± 0.07
M_V^{*a}	1.24 ± 0.20	−0.22 ± 0.20	−2.23 ± 0.10	−2.39 ± 0.10	−2.57 ± 0.10
$T_*(10^3 K)$	120 ± 20	...	50 ± 10	60 ± 10	40 ± 10
$\log L_*/L_\odot$	4.40 ± 0.17	...	4.19 ± 0.12	4.57 ± 0.15	3.95 ± 0.12
R_* $(R_\odot)$	0.37 ± 0.07	...	1.7 ± 0.5	1.8 ± 0.5	2.0 ± 0.5
Spec. Type	...	...	WN4.5	WN4.5	WN4.5

[a] A distance modulus of 18.45 was assumed for the LMC.

4. EVOLUTION OF STELLAR PARAMETERS

Stellar parameters such as color temperature, bolometric luminosity, and radius can be derived from the stellar continuum observed for each epoch, by assuming a black body behavior. The procedure was described in Paper I. The values calculated from 1987 to the present are listed in Table 2 where we have included data from Papers I and II. The stellar characteristics for 1987 (before the mass-loss event) were derived from nebular parameters.

The stellar temperature (as derived by fitting a black body to the dereddened stellar continuum) and the bolometric luminosity seem to have been decreasing systematically (except in Sept/94) while the radius has increased correspondingly. These changes indicate that at present we are seeing a "false photosphere" produced by an optically thick expanding wind. This false photosphere is growing in radius and getting cooler with time.

The evolution of the stellar parameters in an H-R diagram corresponds to a track from the high temperature, high luminosity extreme, towards a much lower temperature (≈ 40 000 K) and lower luminosity zone (with a

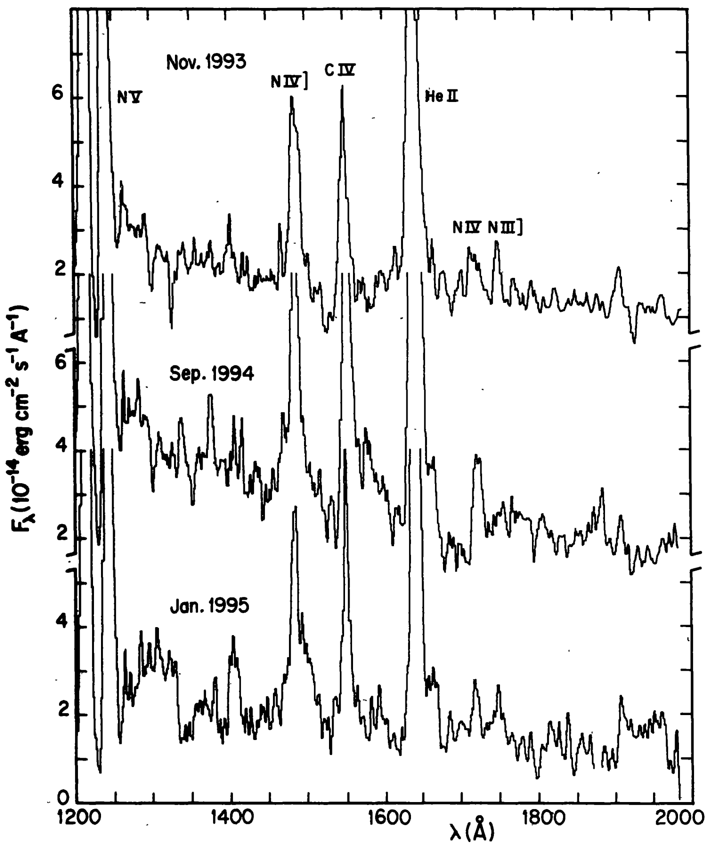

Fig. 4. UV calibrated spectra corresponding to images SWP 49112 (Nov. 5, 1993, 180 min), SWP 52223 (September 26, 1994; 90 min) and SWP 53256 (January 2, 1995; 90 min). In Sept/94 the stellar continuum was higher by a factor of two relative to the other two spectra. The behavior of the lines is discussed in the text.

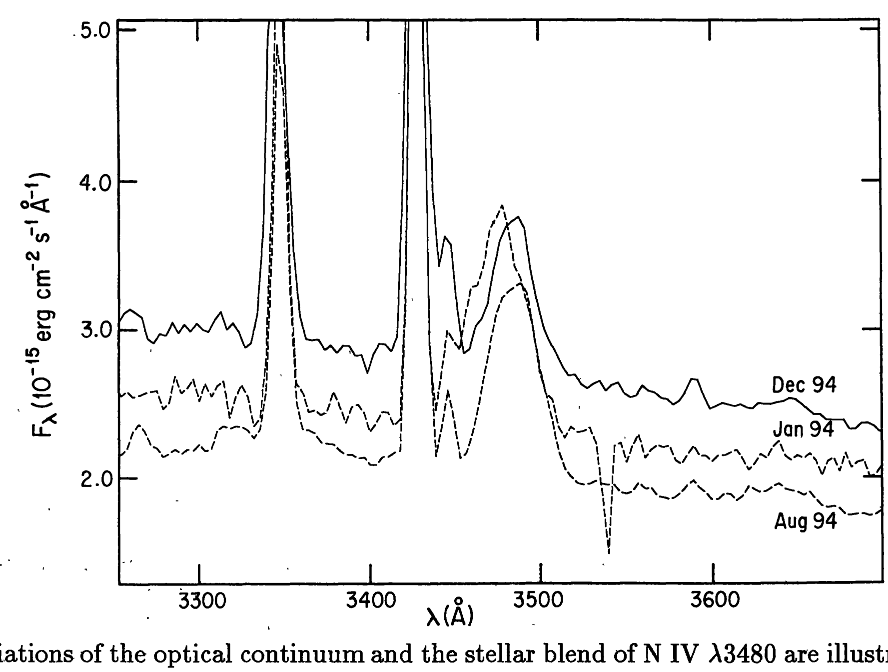

Fig. 5. The variations of the optical continuum and the stellar blend of N IV λ3480 are illustrated in this figure.

small loop of few months in 1994). Except for a "thermal pulse" event, there is no other known phenomenon that can produce such behavior in an evolved low-mass star. According to models of "final thermal pulses" (e.g., Schönberner 1983; Iben 1984, 1987; Wood & Faulkner 1986; Vassiliadis 1993) a star in this situation follows a wide loop in the H-R diagram, characterized by a significant drop in T_{eff} with a slight variation in bolometric luminosity. This is very similar to what we are observing in the N66 central star (although the evolution time has been very short, probably due to the high stellar mass) and, if this is the case, a further decrease of T_{eff} should be expected in the next few years. The thermal pulse could be responsible for the radiation pressure that might be driving the observed wind.

5. CONCLUSIONS

From UV and optical spectrophotometric data it is found that the WR characteristics of the central star of N66 are very different from those of known WR–PNNi in the Magellanic Clouds and the Galaxy; the chemical composition of the ejecta in both cases are very different and the visual luminosity and spectral features of N66 resemble more those of faint Type I WN stars in the Large Magellanic Cloud. Therefore, the nature of the present WR event in N66 seems to be very different from what is occurring in other WR–PNNi.

In our Galaxy the symbiotic star HM Sge developed WR features (showing He II and C lines) that disappeared in a few years (Peimbert et al. 1995), and the central star of the PN Longmore 4 showed WC features that appeared and disappeared in a few months (Werner et al. 1992), but these seem to have been a different kind of phenomenon. The evolutionary track of the N66 nucleus resembles the behavior of a star undergoing a "final thermal pulse", although the timescale of the event in N66 is much faster than the predictions for lower mass stars. It is possible that a similar (but much slower) phenomenon occurred in FG Sge, the central star of the planetary nebula He 1–5, which showed large brightness changes 60 years ago and evolved from a spectral type of B4 I to A5 Ia in an interval of 15 years (Montesinos et al. 1990).

The new UV and optical observations presented here show that the spectral characteristics of the star are varying on timescales of few months. The WR features and UV continuum got stronger in the middle of 1994 and have been decreasing since then.

All this seems to indicate that new and unexpected events in N66 are still coming. We will keep observing.

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