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THE PHYSICAL PROPERTIES OF A SLOW NOVA IN THE BULGE OF M31

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ABSTRACT

Observations are presented of an extremely slow nova that was discovered in the bulge of M31 in 1986. The evolution of the object was monitored with subsequent yearly spectra until 1990, as part of a general spectroscopic survey of novae in M31 underway at McDonald Observatory. The spectra cover the nova's evolution in the nebular phase, and these observations have made this nova the most extensively observed extragalactic nova to date. This has provided a unique opportunity to make the first detailed comparison of the evolution and properties of an extragalactic nova with those in our own Galaxy. Since the nova is situated in the bulge, it is likely that the object represents an outburst associated with an older population of novae, in contrast with Galactic novae which are almost entirely discovered as old disk objects. Although the evolution of this object was unusually slow, the derived mass of the nebula gas of $5 \times 10^{-5}\ M_{\odot}$, electron temperature of 13,000 K, and abundances determined from an analysis of the emission line intensities are typical of those seen in Galactic slow novae: with a close to solar helium abundance (He/H = 0.13 ± 0.02) and roughly solar abundances of oxygen and neon. In a previous study evidence was found for a possible systematic difference in the proportion of the types of observed outbursts between M31 bulge novae and Galactic novae. For individual novae, however, these results indicate that the general disparate properties seen in nova outbursts probably overwhelm the relatively smaller differences that might be expected when comparing novae from different stellar populations. The implications for using extragalactic novae as distance indicators are discussed.

Subject headings: galaxies: individual (M31) — novae, cataclysmic variables — stars: abundances

1. INTRODUCTION

Extragalactic novae are now well studied photometrically, particularly in the LMC (Capaccioli et al. 1990) and in M31 (recently Rosino et al. 1989; Ciardullo et al. 1987, 1990; Capaccioli et al. 1989). Spectroscopic observations have been made of some LMC novae (e.g., Shore et al. 1991; Williams et al. 1991) and a few M31 novae (Ciardullo, Ford, & Jacoby 1983; Cowley & Starrfield 1987). During the period 1987 to 1989 we embarked on a spectroscopic survey of novae in M31, the results of which are reported in Tomaney & Shafter (1992) (hereafter Paper I). The purpose of this survey was to compare the spectroscopic evolution of M31 bulge novae with Galactic novae. Previous photometric surveys of M31 novae have shown that these objects belong primarily to the bulge population (Ciardullo et al. 1987; Capaccioli et al. 1989). Since the majority of Galactic novae are discovered as disk objects one of the aims of the survey was to determine whether there are any systematic differences between novae in the two systems as they represent different populations: the M31 bulge novae are Population II objects and the Galactic disk novae are predominately old Population I objects. Such differences may be manifest in the abundances of the ejecta.

The nebular phase of nova evolution corresponds to a time when the ejecta starts to resemble a photoionized planetary nebula. At this point analytical techniques using emission-line intensities (such as those first used by Ferland & Shields 1978 for V1500 Cyg) can be employed to make some estimates of the abundances and the physical conditions. Unfortunately, only one out of the sample of nine novae presented in Paper I lends itself to such an analysis. The spectra of the other novae have either poor signal-to-noise ratios or have been observed too early in their decline where the densities are very high and conditions are evolving rapidly with time. In particular, three novae in the sample were shown to have emission line intensities that varied on nightly or even hourly time scales, making any kind of abundance analysis problematical.

In this paper observations taken over 4 yr (1987–1990) are presented of a nova that was originally discovered in 1986 during a narrow-band Hα imaging nova survey of the bulge of M31 (Ciardullo et al. 1987 nova no. 32). The nova was rediscovered in 1987 at McDonald Observatory during the McDonald photometric and spectroscopic survey of novae in the bulge of M31 (hereafter, McD87 no. 2). The subsequent yearly spectra obtained reveal an extremely slow nova evolving through its nebula phase. This coverage is the most extensive of any extragalactic nova to date and has provided an ideal opportunity to make the first abundance estimates and properties of a nova outside the Galactic and LMC systems.

2. OBSERVATIONS

The details of the spectroscopic along with photometric observations and reductions employed in the McDonald survey are given in § 2.2. To begin, previous observations of this object will be summarized.

The nova has a projected distance from the nucleus of 4'.7 and was first discovered on a narrow-band Hα CCD image taken at the Wise Observatory, Israel, on 1986 August 16, UT (t_{dis}) (Ciardullo et al. 1987). The coordinates of the nova are

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TABLE 1

Hα PHOTOMETRY[a]

Observatory	Julian Date (+2,400,000)	$m_{H\alpha}$
McD	7762.97	18.33 ± 0.09
McD	7763.84	18.34 ± 0.08
Lag	7793.77	18.19 ± 0.08
Lag	7794.00	18.29 ± 0.12
Lag	7794.99	18.19 ± 0.12
Lag	7795.89	18.36 ± 0.14
McD	7799.74	18.46 ± 0.11
McD	7820.90	18.40 ± 0.13
Lag	7823.67	18.36 ± 0.11
McD	7866.74	18.59 ± 0.05

[a] Supplemental to the observations given in Ciardullo et al. 1990.

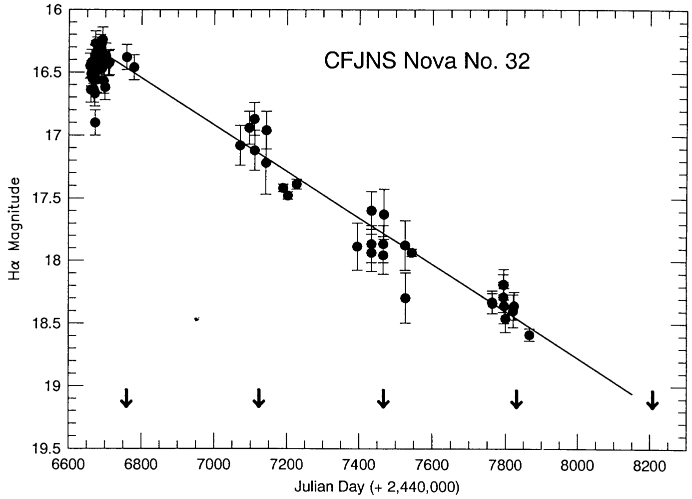

FIG. 1.—The complete Hα of CFJNS nova no. 32 since its discovery. The straight line is least squares fit to the data. The bold arrows indicate the times when the spectra were obtained. The first arrow represents the 1986 spectrum taken by Cowley & Starrfield (1987).

$\alpha(2000.0) = 0^h42^m21\overset{s}{.}3$, $\delta(2000.0) = 41°14'30''$ and agree to within measurement errors with the 1975.0 epoch coordinates given in Ciardullo et al. (1987). Images taken in 1985 at Kitt Peak constrain the nova outburst to have taken place between 1985 October and t_{dis}. The early images showed the object to be a relatively bright Hα source $m_{H\alpha} \sim 16.5$ (where $m_{H\alpha} = 0.0$ corresponds to 1.5×10^{-7} ergs cm^{-2} s^{-1} in a 75 Å filter centered on Hα), but very faint in the continuum ($m_B \sim 19.9$).

A spectrum of the object was obtained by Cowley & Starrfield (1987) with the MMT in 1986 November. Narrow Balmer lines (of HWHM corresponding to ~350 km s^{-1}) and multiplets of Fe II were the principal emission lines detected. These, together with the absence of some other lines such as [O I], [N II] λ5755, and λλ"4640" which appear later in the spectral evolution of novae, were suggestive of a nova about 1–2 mag below maximum light. Furthermore, since the nova was observed ~100 days after its discovery, the narrow lines and the probable stage of evolution indicated that this was a particularly slow nova.

The object was rediscovered the following year during the McDonald survey; it had declined by only ~0.6 mag in Hα. To date its light curve in Hα has been observed extensively at McDonald and Kitt Peak and shows an extremely slow decline of ~0.7 mag in Hα per year. Hα observations taken in 1989 and 1990 at McDonald and Mount Laguna Observatories and supplemental to those given in Ciardullo et al. (1990) are given in Table 1. Figure 1 shows the complete light curve. The decline appears to be linear with time and a least squares fit yields the following equation:

$$m_{H\alpha} = 16.29(\pm 0.07) + 0.0019(\pm 0.0001)(t - t_{dis}) , \quad (1)$$

where t is in days. Low-dispersion spectra were obtained with the large Cassegrain spectrograph at the 2.7 m telescope. The spectral resolution is ~8 Å and the spectral coverage extended from 4000 Å to 6800 Å. In 1989 and 1990 the coverage was extended down to 3600 Å. A journal of spectroscopic observations is provided in Table 2.

Table 3 lists the observed line flux measurements. The errors in the fluxes are the estimates based mainly on the uncertainties in the level of the continuum. A foreground differential reddening to the bulge of M31 of $E(B-V) = 0.11$ (McClure & Racine 1969) and a Seaton (1979) reddening law are adopted in the succeeding analysis. Since the nova is situated inside the bulge, extinction internal to the galaxy toward the nova should be low and it is assumed to be zero, and the foreground reddening should therefore be a close approximation to the total reddening of the nova.

Figure 2 shows the initial spectrum of the nova, obtained in 1987 November; the spectrum shows significant progress in evolution from that seen by Cowley & Starrfield. The disap-

TABLE 2

JOURNAL OF SPECTROSCOPIC OBSERVATIONS

UT Date	Total Integration Time (minutes)	Slit Width	λ Range[a]	Comments
1987 Nov 22.3	195	5"	a	Photometric[b] (epoch 1)
1987 Nov 26.1	60	3	a	Photometric[b] (epoch 1)
1988 Nov 2.2	240	3	a	Photometric[b] (epoch 2)
1989 Oct 31.1	105	3	b	Photometric[b] (epoch 3)
1989 Nov 1.2	240	3	b	Photometric[b] (epoch 3)
1989 Nov 1.4	75	3	a	Nonphotometric (epoch 3)
1990 Nov 13.3	210	3	b	Photometric? (epoch 4)

[a] a = 4000–6800 Å, b = 3600–6300 Å.

[b] Based on consistent lines fluxes (to within 15%) from multiple integration on different nights.

TABLE 3

NOVA FLUX MEASUREMENTS[a]

Spectrum	Primary Identification	Flux[a]	Comments[b]
1987..........	Hα	191.0 ± 1.0	$v_r = -310$
	He I λ5876	11.3 ± 1.2	
	[N II] λ5755	5.8 ± 1.0	
	[O III] λ5007	12.3 ± 0.7	
	[O III] λ4959	6.4 ± 0.4	
	Hβ	21.2 ± 1.3	$v_r = -320$
	He I λ4471	12.1 ± 0.5	Blend
	[O III] λ4363	10.6 ± 0.5	
	Hγ	10.9 ± 0.7	
1988..........	Hα	131.8 ± 1.3	$v_r = -320$
	[Fe X] λ6373	3.9 ± 0.5	
	He I λ5876	9.1 ± 0.5	
	[N II] λ5755	6.3 ± 1.1	
	[O III] λ5007	17.1 ± 1.1	
	[O III] λ4959	5.5 ± 0.5	
	Hβ	19.6 ± 0.8	$v_r = -390$
	He II λ4686	5.6 ± 0.5	
	N III λ4640	7.0 ± 0.5	
	[O III] λ4363	11.6 ± 0.7	
	Hγ	9.0 ± 0.7	
1989..........	Hα	53.1 ± 7.6	$v_r = -370$
	He I λ5876	3.6 ± 0.4	
	[N II] λ5755	1.8 ± 0.2	
	[O III] λ5007	13.9 ± 0.6	
	[O III] λ4959	3.7 ± 0.5	
	Hβ	11.2 ± 0.9	$v_r = -410$
	[Ne IV] λ4716	3.2 ± 0.5	Tentative identification
	He II λ4686	5.2 ± 0.5	
	N III λ4640	3.2 ± 0.3	
	[O III] λ4363	9.3 ± 0.4	
	Hγ	5.8 ± 0.4	
	Hδ	6.7 ± 0.9	Blend with N III (1)
	[Ne III] λ3967	5.8 ± 0.6	Blend with Hε
	[Ne III] λ3869	13.6 ± 0.5	Slight blend with H8
1990..........	[Fe X] λ6375	2.6 ± 0.4	Tentative identification
	He I λ5876	2.4 ± 0.2	
	[N II] λ5755	1.5 ± 0.2	
	[O III] λ5007	19.9 ± 0.7	
	[O III] λ4959	7.4 ± 0.5	
	Hβ	9.2 ± 0.3	$v_r = -620$
	[Ne IV] λ4716	3.7 ± 0.3	Tentative identification
	He II λ4686	7.0 ± 0.5	
	N III λ4640	5.5 ± 0.3	
	[O III] λ4363	9.6 ± 0.5	
	Hγ	4.3 ± 0.3	
	Hδ	4.8 ± 0.5	Blend with N III (1)
	[Ne III] λ3967	7.6 ± 0.5	Blend with Hε
	[Ne III] λ3869	16.1 ± 0.8	Slight blend with H8

[a] In units of 10^{-16} ergs s^{-1} cm^{-2} $Å^{-1}$. Fluxes are not corrected for extinction and errors represent uncertainty in the continuum level around measured lines. Absolute fluxes are accurate to within 30%.

[b] v_r is the "radial" velocity as measured by the difference between the intensity weighted centroid of a line and its rest wavelength.

pearance of the Fe II lines and emergence of the [O III] lines at λ4363, λ4959, and λ5007 signify the nova's evolution into nebular phase. The lines have comparable widths to those seen in the Cowley & Starrfield (1986) spectrum (HWHM ~ 330 km s^{-1}) and comparisons to the night sky lines in the raw spectrum show that the lines are just resolved.

The succeeding spectra show evolution that is typical for a nova in the nebular phase. By 1988 (Fig. 3) the [O III] lines continued to strengthen (both in absolute flux and relative to the Balmer lines). The Balmer lines narrowed and became unresolved (HWHM < 250 km s^{-1}). This was also accompanied by a significant decrease in the Balmer decrement. In 1989 (Fig. 4) and 1990 (Fig. 5) it became possible to exploit an enhanced CCD blue response to detect the [Ne III] nebular lines, λ3869 and λ3967, which were comparable in strength to the [O III] lines.

The general trend present in the spectra is one of decreasing density and an evolution toward higher ionization which is most clearly seen with the increasing He II λ4686 to He I λ5876 ratio during later times. The density evolution is revealed by the changing value of the Balmer decrement. Figure 6 shows the evolving reddening corrected Hα/Hβ ratio, starting with the 1986 measurement by Cowley & Starrfield (1987). The high values (~8) seen in 1986 and 1987 compared with the case B value of 2.8 (Osterbrock 1989) are typical for novae in the early decline phase. These values can be affected by blending with [N II] λ6548, λ6584 emission which increases relative to Hα as the nova evolves. This possibility can be eliminated here prior to 1989 with a high-resolution spectrum of the Hα line taken in December of that year which indicated that the FWHM line width was less than 3.9 Å, with no detectable [N II] emission flanking the line.

The steep decrement can be mainly attributed to the large densities in nova shells during the earlier phases of outburst in which the Balmer lines are optically thick and suffer self-absorption. As the nova evolves the densities in the ejecta decrease and the decrement approaches its case B value—as observed, by 1989 the decrement had fallen to 4.2.

Since spectra from 1986 onward (Cowley & Starrfield 1987) have shown that the continuum flux around Hα is very small, the Hα photometry obtained is essentially a measure of the Hα line flux. Figure 7 shows the variation of the Hα flux with time in a log ($j_{H\alpha}$) versus log ($t - t_0$) plot which indicates a $\sim t^{-1.3}$ dependence for $t > t_{dis} + 450$ days with $t_0 = t_{dis}$. With $t_0 = t_{dis} - 300$ days (representing the earliest outburst time constraint), this plot changes to a $\sim t^{-1.8}$ dependence over the same time range. An exponent of 3 is generally attributed to an optically thin expanding sphere (since it will be inversely proportional to the volume). A number of factors could account for the slower decline: Hα emission is optically thick (as implied by the Balmer decrement measurements), mass loss is still continuing, and/or clumping in the ejecta is taking place (e.g., Gallagher et al. 1980; Martin 1989).

3. EMISSION-LINE ANALYSIS

3.1. *Temperature and Densities*

The emission line analysis to determine physical conditions and abundances in the nova ejecta is based on the standard techniques that have been applied to Galactic novae that originated with V1500 Cyg (Ferland & Shields 1978) and have been employed most recently on PW Vul (Saizar et al. 1991). Such analyses are complicated by many factors (for critical reviews see Williams 1977; Collin-Souffrin 1977). In particular, the large ejection velocities of the gas yield broad emission lines, which can be severely blended and difficult to identify. The multiple components seen in emission lines, together with the various absorption systems seen in the early stages of the eruption (see Payne-Gaposchkin 1957; McLaughlin 1960), all indicate that the expanding material can be inhomogeneous and have large-scale deviations from spherical symmetry.

For McD87 no. 2 the narrow line widths make line blending less of a problem (the worst case of this was in the 1987 data

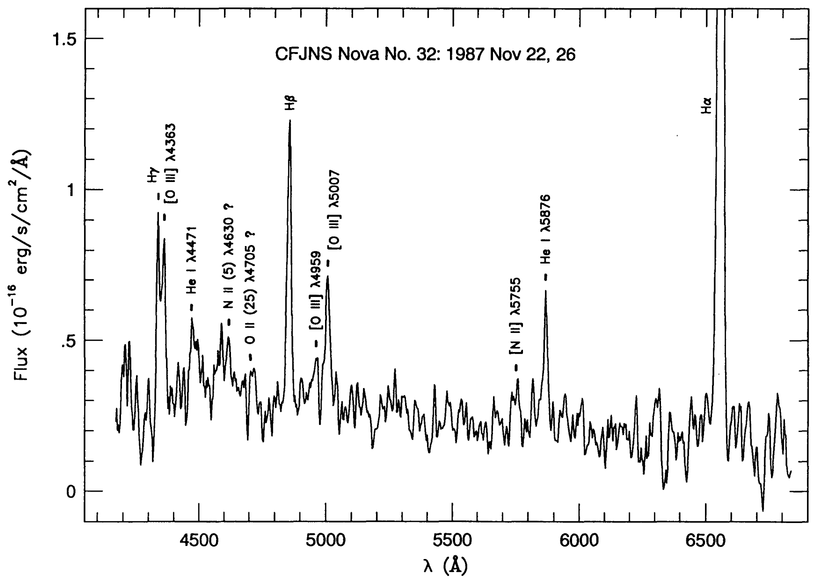

FIG. 2.—Averaged spectrum of CFJNS nova no. 32 from observations taken on 1987 November 22 and 26, UT (epoch 1). The spectrum has been smoothed with a boxcar of width 7 Å.

where the fluxes for the overlapping Hγ and [O III] λ4363 lines were obtained by fitting a pair of velocity-shifted Gaussians). Large-scale inhomogeneities in the ejecta cannot be excluded, but the smooth, symmetric profiles where the lines are resolved in 1986 and 1987 (to within the limitations of the spectral resolution) suggest that this may not be a severe problem in an analysis of this nova.

The most useful line ratios and their functional dependences are

$$\frac{j([\mathrm{O\ III}]\ \lambda\lambda4959,\ 5007)}{j([\mathrm{O\ III}]\ \lambda4363)} = f_1(T_e, N_e)\ , \quad (2)$$

$$\frac{j([\mathrm{O\ III}]\ \lambda\lambda4959,\ 5007)}{j(\mathrm{He\ I}\ \lambda5876)} = \frac{N(\mathrm{O}^{++})}{N(\mathrm{He}^{+})} f_2(T_e, N_e)\ , \quad (3)$$

$$\frac{j([\mathrm{O\ III}]\ \lambda\lambda4959,\ 5007)}{j([\mathrm{Ne\ III}]\ \lambda3869)} = \frac{N(\mathrm{O}^{++})}{N(\mathrm{Ne}^{++})} f_3(T_e, N_e) \quad (4)$$

(Ferland & Shields 1978; Lance, McCall, & Uomoto 1988), where T_e and N_e are the electron temperature and density (both functions of time) and $N(\mathrm{O}^{++})/N(\mathrm{He}^{+})$, $N(\mathrm{O}^{++})/N(\mathrm{Ne}^{++})$ are the ionic ratios. Since O^{++}, He^{+}, and Ne^{++} all have roughly the same ionization potentials their Strömgren spheres are nearly coincident and their ionic ratios are not strongly dependent on temperature and density. Therefore they can be assumed to be roughly constant as the nova evolves (Ferland & Shields 1978).[2]

[2] Relative to similar studies of Galactic novae this assumption is probably particularly reasonable here due to the extremely slow evolution of the nova and the restriction of the analysis to the 1989 and 1990 spectra (see text).

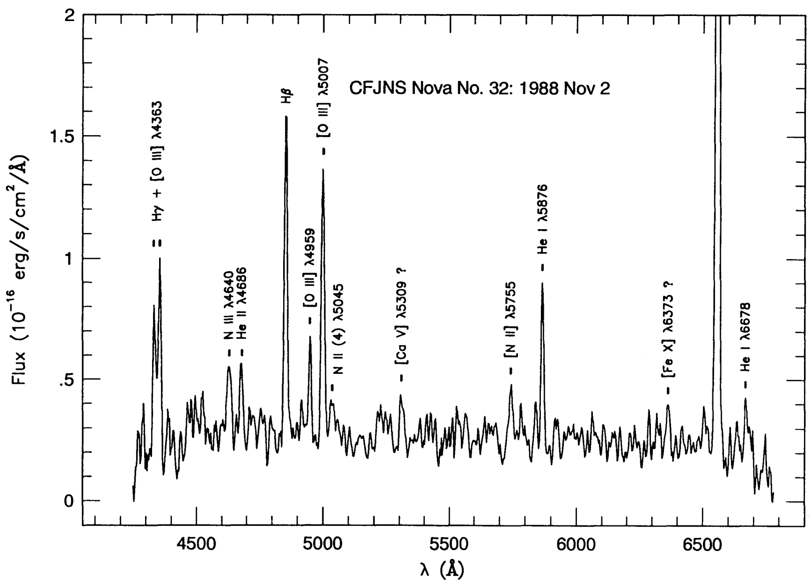

FIG. 3.—Averaged spectrum of CFJNS nova no. 32 from observations taken on 1988 November 2, UT (epoch 2). The spectrum has been smoothed with a boxcar of width 7 Å.

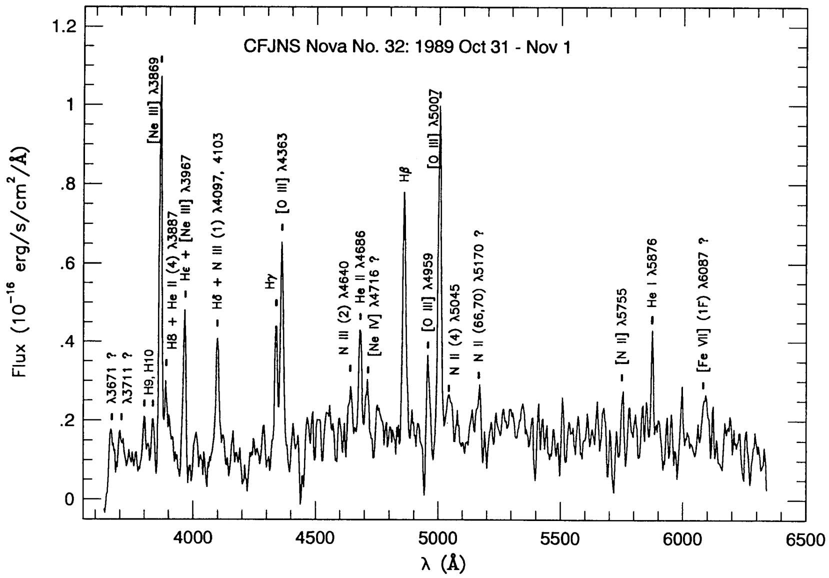

FIG. 4.—Averaged spectrum of CFJNS nova no. 32 from observations taken on 1989 October 31 and November 1, UT (epoch 3). The spectrum has been smoothed with a boxcar of width 7 Å.

Figure 8 shows the de-reddened j([O III] $\lambda\lambda$4959, 5007)/j([O III] λ4363) time evolution from 1987 through 1990. For the first 3 yr the ratio was observed to be constant at a value of $\sim$1.7. By 1990, however, the ratio increased abruptly to a value of $\sim$2.7. This can be directly attributable to the decreasing density: at $N_e \sim 2.6 \times 10^7$ cm^{-3} the critical density for λ4363 is reached for nebular temperatures of 10^4 K (Martin 1989). At this time the λ4363 (auroral) line fades relative to the λ4959, 5007 (nebular) lines, since radiative depopulation begins to exceed collisional de-excitation in determining the excitation equilibrium for the line. The line emissivity then evolves from an N_i dependence (the ionic density) to a more rapid $N_i N_e$ dependence. In addition, the 1989 and 1990 measurements of [O III] λ(4959 + 5007)/[Ne III] λ3869 show a small change from $\sim$1.2 to $\sim$1.5, indicating that the nova is close to the critical density of λ3969, which is slightly lower than that of [O III] λ4363 at 7.9×10^6 cm^{-3} (Osterbrock 1989).

Thus the 1989 and 1990 measurements place constraints on the density which the previous epochs do not, and these spectra allow for enough measurements to solve for the six parameters associated with the line ratios in equations (2) to (4) (N_e and T_e for both epochs and the two ionic ratios). Although the $N(O^{++})/N(He^+)$ ionic ratio is expected to be relatively insensitive to temperature changes for a fixed abundance (see above), the abundance determination is particularly sensitive to uncertainties in the temperature determination. The derived ionic ratio changes by over two orders of magnitude for typical nebular temperatures in the range 10^4 to 2×10^4 K, making it very sensitive to uncertainties in the measurements. Since this ratio is crucial to the analysis, it was decided to solve for the

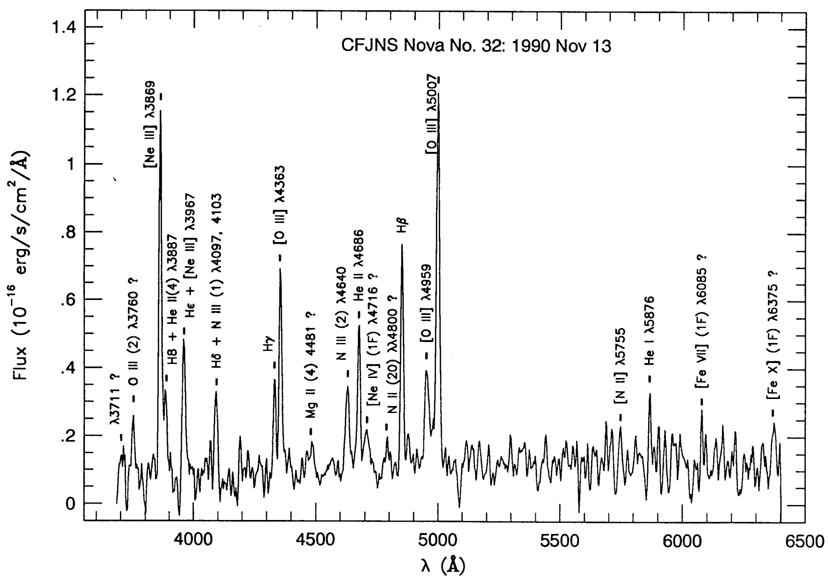

FIG. 5.—Averaged spectrum of CFJNS nova no. 32 from observations taken on 1990 November 13, UT (epoch 4). The spectrum has been smoothed with a boxcar of width 7 Å.

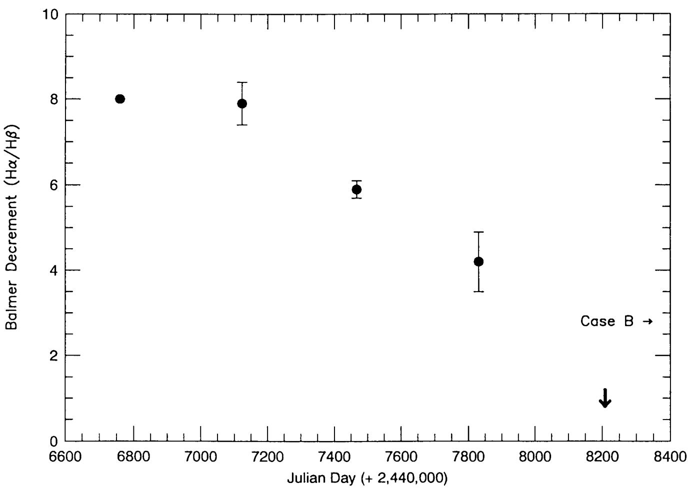

FIG. 6.—The dereddened $j(H\alpha)/j(H\beta)$ ratio (Balmer decrement) showing the evolution since discovery. The first point is the 1986 spectrum taken by Cowley & Starrfield (1987). The arrow indicates when the McDonald 1990 spectrum was obtained.

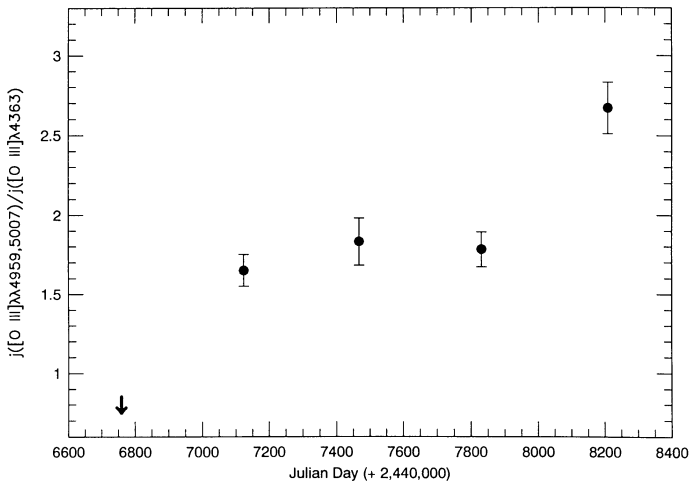

FIG. 8.—The dereddened j([O III] $\lambda\lambda$4959, 5007)/j([O III] λ4363) ratio evolution from 1987 to 1990. The increase in 1990 is due to the decreasing the electron density which has just fallen below the critical density of [O III] λ4363 (see text). The arrows shows when the 1986 spectrum was taken by Cowley & Starrfield (1987).

parameters with a Monte Carlo simulation. In this way the formal errors of the solutions were ensured to properly reflected the uncertainties in the input measurements.

We proceeded by generating 10,000 input data sets based on the 1989 and 1990 line ratios and their estimated errors (Table 3).[3] The explicit form of equations (2)–(4) given in Lance et al. (1988) was used in the analysis (their eqs. [5a]–[5c]) along with the latest determinations of atomic constants reported therein. By taking the ratio of the epochs for equations (3) and (4) the ionic ratios were eliminated (with the assumption that they are constant in time) yielding four equations (including the two epochs for equation [2]) that were functions only of temperature and density. The solutions were constrained by assuming a constant temperature between the two epochs. The results (based on this subset of solutions) are given in Table 4 and are consistent with those obtained by allowing the temperature to vary between the two years, although their formal errors are smaller. (Note that the logarithmic distribution of Monte Carlo solutions for the electron densities and the $N(O^{++})/N(He^{+})$ ratio was found to closely approximate a Gaussian distribution and therefore their mean and standard deviation derived from their logarithmic distributions are quoted in Table 4). The derived density of $\log_{10}(N_e) \sim 7.5$ for 1989 is consistent with the high density implied by the Balmer decrement for that year. Figure 9 shows the probability distributions for the solutions given in Table 4.

[3] The He I λ5876 line intensity in the 1990 spectrum was somewhat weak; in this analysis this line was assigned a conservative 40% uncertainty. For the other lines used in the analysis the error in their intensity is dominated by the uncertainty in the continuum level around the line (Table 3). A change from 10% to 40% uncertainty in the He I line intensity for that year results in an 80% increase in the error uncertainty of the key ionic ratio, $\log_{10} N(O^{++})/N(He^{+})$. For larger uncertainties in He I the error in this ionic ratio does not change significantly.

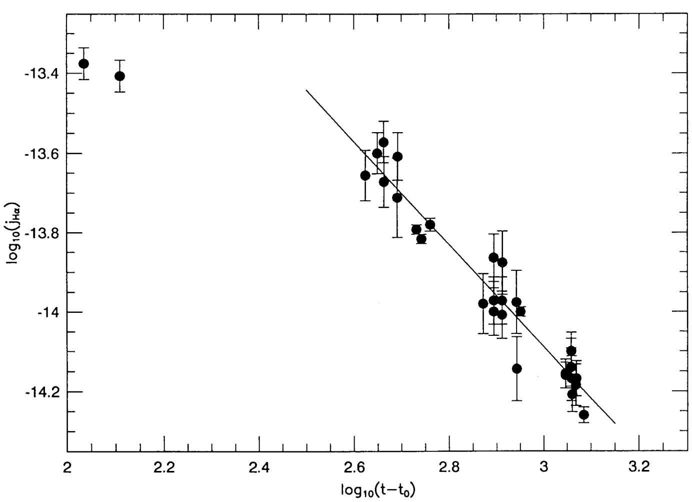

FIG. 7.—A log $(j_{H\alpha})$ − log $(t - t_0)$ plot with $t_0 = t_{dis}$, showing a power-law time dependence for the Hα intensity from t_{dis} + 450 days onward.

3.2. *Helium Abundance*

To determine the helium abundance initially the arguments outlined in Ferland (1978, 1979) were followed. The helium abundance can be estimated via helium to Balmer line ratios by first assuming that these lines form solely through radiative recombination. The effective recombination coefficients, α_λ, of H I, He I, and He II lines are almost independent of density and the ratios of helium to hydrogen recombination coefficients have a very weak dependence on temperature (Brocklehurst 1971, 1972). From the ratio of line emissivities, j_λ, the number abundance of helium with respect to hydrogen can be obtained

TABLE 4

MONTE CARLO SOLUTIONS TO 1989 AND 1990 DATA

Parameter	Solution
1989 $\log_{10}\{N_e\}$ (cm^{-3})	7.52 ± 0.30
1990 $\log_{10}\{N_e\}$ (cm^{-3})	7.16 ± 0.22
T (K)	12,800 ± 2400
$N(O^{++})/N(Ne^{++})$	3.88 ± 0.53
$\log_{10}\{N(O^{++})/N(He^{+})\}$	−2.40 ± 0.51

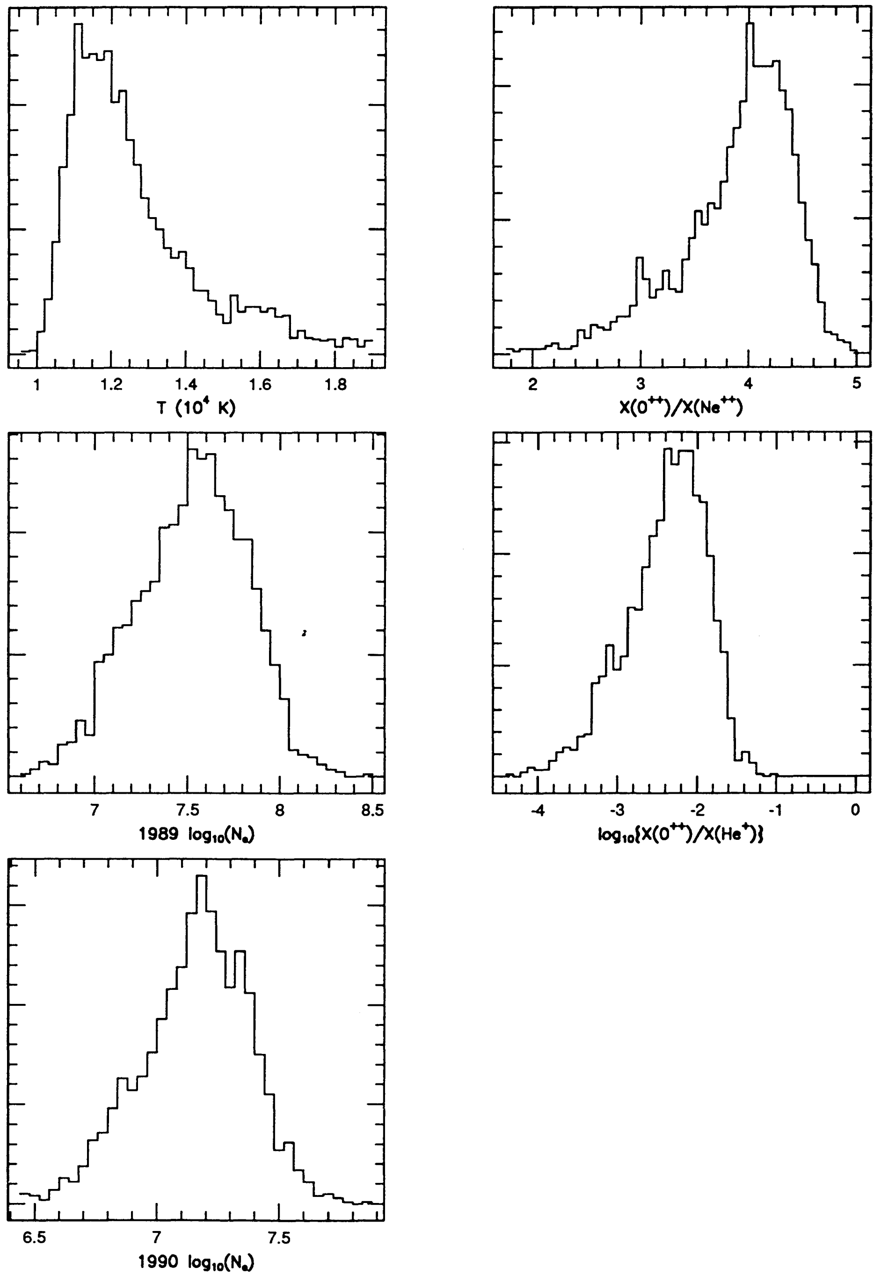

FIG. 9.—The probability distributions for the solutions given in Table 4 for the temperature, density (for both 1989 and 1990) and ionic ratios, $\log_{10}\{N(O^{++})/N(He^{+})\}$ and $N(O^{++})/N(Ne^{++})$ from the Monte Carlo analysis.

from

$$\frac{j_{\rm He\,I}}{j_{\rm H\,I}} = \frac{\alpha_{\rm He\,I}(T)}{\alpha_{\rm H\,I}(T)}\,\frac{\lambda_{\rm H\,I}}{\lambda_{\rm He\,I}}\,\frac{N({\rm He}^+)}{N({\rm H}^+)}\,, \tag{5}$$

$$\frac{j_{\rm He\,II}}{j_{\rm H\,I}} = \frac{\alpha_{\rm He\,II}(T)}{\alpha_{\rm H\,I}(T)}\,\frac{\lambda_{\rm H\,I}}{\lambda_{\rm He\,II}}\,\frac{N({\rm He}^{++})}{N({\rm H}^+)}\,. \tag{6}$$

There are a number of caveats to this analysis. First, self-absorption effects in the Balmer lines must be taken into account. Ferland (1978) notes that calculations by Netzer (1975) for self-absorption conditions indicate that the strength of Hα is never enhanced by more than 20%, whereas Hβ can be weakened by over 50%. Thus line ratios of the helium lines with respect to Hα give a lower limit for the helium ion abundance which is close to the true value in the pure radiative recombination case. The detections of λ5876 and λ4686 can be used to derive the abundances of He$^+$ and He^{++}, respectively. However, the intensities of triplet lines such as He I λ5876 are influenced by collisional excitation from the metastable 2^3S state. Only a fraction, $R/(C + R)$, of all λ5876 photons are the result of pure recombination (R), the remainder come from collisional excitation (C). The observed line intensity must be multiplied by this fraction to correct for collisions before equation (5) can be used. Values of C/R were determined from the formulae given in Clegg (1987). The λ5876 line intensities were modified for each of the 4 yr by assuming the electron tem-

TABLE 5

HELIUM ABUNDANCE DETERMINATIONS

Year	He^+/H^+	He^{++}/H^+	He/H
1987............	0.091 ± 0.010	...	0.091 ± 0.010
1988............	0.106 ± 0.006	0.012 ± 0.001	0.118 ± 0.006
1989............	0.104 ± 0.019	0.028 ± 0.005	0.132 ± 0.020
1990[a]...........	0.126 ± 0.011	0.067 ± 0.005	0.193 ± 0.016

[a] Upper limit based on $j(\mathrm{He})/j(\mathrm{H}\beta)$ instead of $j(\mathrm{He})/j(\mathrm{H}\alpha)$ line ratios.

perature of 12,800 (± 2400) K derived above, corresponding to an $R/(R+C)$ value of 0.70 (± 0.12). Using the He I $\lambda 5876$/Hα and He II $\lambda 4686$/Hα line ratios and the effective recombination coefficients for these lines interpolated from values given in Brocklehurst (1971, 1972) the derived ionic and total helium abundances for 1987 to 1989 are shown in Table 5.

The absence of any He II recombination lines in the 1987 data is suggestive of an effective temperature (see below) of less than 7×10^4 K for the central source. Ferland (1978, 1979) points out that in this situation a correction needs to be made to the abundance estimate in the above analysis since the outer edges of the Strömgren spheres of He II and H II are not coincident, leading to an underestimate of the helium abundance. This explains the systematically lower abundance determination for 1987 compared with 1988 and 1989.

For 1990 no spectrum was obtained that included Hα; however, the helium abundance derived with respect to Hβ is listed. The significantly higher value of ~ 0.20 compared with ~ 0.13 for 1988 and 1989 is attributable to self-absorption effects which more strongly affect Hβ. Thus optical depth effects in the Balmer lines are still important as late as 1990. Since self-absorption reduces the intensity of Hβ this estimate provides an upper limit to the helium abundance in this nova.

The unweighted average (since the 1989 measurement will be affected less by self-absorption) of the 1988 and 1989 helium estimates yields He/H = 0.125 (± 0.030) for the nova (this estimate also includes the uncertainty in the collisional correction). The corrections that have been discussed, namely self-absorption and any further correction for underestimated extinction, would all act to revise this estimate upward.

3.3. *Oxygen and Neon Abundances*

No detection was made of [O I] $\lambda 6300$ or [O II] $\lambda 3727$ during the observations, and it is likely that most of the oxygen is in the form of O^{++} or higher ionization stages. Such an assumption is reasonable since V1500 Cyg (Ferland & Shields 1978; Lance et al. 1988) and a recent analysis of PW Vul (Saizar et al. 1991) have shown that these ions are less than 10% of the $N(O^{++})$ fraction for a similar range of effective and electron temperatures and densities as this nova. Since O^{++} and He^+ have roughly the same ionization potentials, then $N(O^{++})/N(He^+) \sim N(O)/N(He)$. From the Monte Carlo simulation a value of $\log_{10}\{N(O^{++})/N(He^+)\}$ of -2.51 ± 0.51 was obtained. This value needs to be corrected for the effect of collisions on the intensity of the $\lambda 5876$ line as discussed above (unappreciated at the time of the Lance et al. analysis). Applying the same correction factor as used in the helium abundance analysis yields O/He = 5.7 (+12.3; −6.0) $\times 10^{-3}$ and thus O/H = 7.1 (+15.9; −4.9) $\times 10^{-4}$ from the derived helium abundance.

As in Ferland & Shields (1978) the similarity of the O^{++} and Ne^{++} ionization potentials is used to make an approximation of the ionic fractions, $N(O^{++})/N(Ne^{++}) \sim N(O)/N(Ne)$. Thus from Table 4, O/Ne = 3.9 ± 0.5 and Ne/H = 1.8 (+4.1; −1.3) $\times 10^{-4}$.

Table 6 compares the abundances derived in this nova with solar values (from Anders & Grevesse 1989). These essentially solar abundances are quite typical of slow novae and their implications are discussed in section § 3.4, below.

3.4. *Effective Temperature*

The increasing effective temperature of the photoionizing radiation as a nova evolves through the nebular phase can be seen clearly in this nova. Novae of all speed classes are thought to evolve at constant bolometric luminosity during outburst (e.g., Shara 1989; McDonald, Fujimoto, & Truran 1985). Bath & Shaviv (1976) describe the outburst as a radiation pressure driven, optically thick wind from the surface of the white dwarf. As the mass loss decreases, the density of the wind decreases and the photospheric radius contracts. At constant bolometric luminosity the effective temperature of the central source is seen to increase as the flux is redistributed from the visual toward the UV. The strengthening of He II $\lambda 4686$ at the expense of He I $\lambda 5876$ from 1987 to 1990 can be understood in terms of this model.

The He I $\lambda 5876$ and He II $\lambda 4686$ recombination lines can be used to make rough estimates of the effective temperature of the ionizing source (e.g., Ferland 1978, 1979; Krautter & Williams 1989). If the number of He I $\lambda 5876$ and He II $\lambda 4686$ photons formed through recombination is assumed to equal the number of photoionizing photons for He I (of energies in the range 1.8–4.0 rydbergs) and He II (of energies greater than 4.0 rydbergs) respectively, then the measured ratio of the two lines (with $\lambda 5876$ corrected for collisional effects discussed above) can be described by an equivalent continuum temperature for the central ionizing source (Osterbrock 1989),

$$\frac{j_{\lambda 4686}}{j_{\lambda 5876}} = \frac{5876}{4686}\frac{\alpha_{\lambda 4686}}{\alpha_{\lambda 5876}}\frac{\alpha_B(\mathrm{He}^0)}{\alpha_B(\mathrm{He}^+)}\frac{\int_{4\nu_H}^{\infty}(F_\nu/h\nu)d\nu}{\int_{1.8\nu_H}^{4\nu_H}(F_\nu/h\nu)d\nu}\,. \tag{7}$$

With the approximation that the radiation field, F_ν, is equal to a uniform blackbody, the 1988, 1989, and 1990 measurements yield effective temperatures of 1.8, 3, and 4×10^5 K, respectively. The lack of a detection of He II $\lambda 4686$ in 1987 is consistent with an effective temperature less than 7×10^4 K.

3.5. *Ionized Mass*

Some estimates of the mass of nebular gas in the ejecta can be made by assuming that the Balmer flux is solely the result of recombination and the hydrogen is fully ionized. Thus the total number of protons in a volume V is given by

$$N(\mathrm{H}^+)V = \frac{4\pi d^2 j(\mathrm{H}\alpha)}{\alpha_{\mathrm{H}\alpha}^{\mathrm{eff}}(T)N_e h\nu_{\mathrm{H}\alpha}}\,. \tag{8}$$

TABLE 6

COMPARISON OF NOVA AND SOLAR ABUNDANCES

Element[a]	Nova	Solar[b]	Nova/Solar
He/H	0.125 ± 0.030	0.098 ± 0.008	1.3 ± 0.3
O/H	$7.1^{+15.9}_{-4.9}(-4)$	$8.5 \pm 0.7(-4)$	$0.8^{+1.9}_{-0.5}$
Ne/H	$1.8^{+4.1}_{-1.3}(-4)$	$1.2 \pm 0.3(-4)$	$1.6^{+3.4}_{-1.1}$

[a] By number.

[b] From Anders & Grevesse 1989.

The Hα line flux has been chosen for this measurement since it is less affected by self-absorption than the other Balmer lines. The measurements of the Hα flux (Table 3) together with determinations of the electron density and temperature for 1989 (Table 4) are used as input to equation (8). Correcting the Hα flux for extinction with $E(B-V) = 0.11$, adopting a distance, d, to M31 of 725 kpc (van den Bergh 1991) and an effective recombination coefficient, $\alpha_{\mathrm{H}\alpha}^{\mathrm{eff}}(T)$, interpolated from values given in Brocklehurst (1971), a total of 4×10^{52} protons in the nebula is obtained. With a helium abundance of 0.13 and the assumption that other heavy elements are essentially solar in abundance and contribute negligibly to the ejecta mass, the mass of nebula gas in the ejecta is estimated at $5 \times 10^{-5}\ M_{\odot}$. This lies in the range of typical estimates seen for Galactic novae of 10^{-4}–$10^{-5}\ M_{\odot}$ (Gallagher & Starrfield 1978).

This is a simplified estimate for the ejected mass, since if the ejecta consists of clumps the electron density derived above will be mainly sensitive to the local conditions in the nebula which dominate the contribution to the observed line fluxes. In this case, the electron density used will be slightly higher than the integrated mean electron density for the whole medium that contributes to the line flux. The ejecta may also consist of a coronal component as well as a neutral component, thus the ionized mass estimate represents a lower limit to the total mass. It should be noted that there is weak evidence for a coronal component to the ejecta in this nova (see below). Recently, Saizar et al. (1991) determined that the coronal gas was the dominant component in the total mass of the ejecta of PW Vul. A lack of detectable [O I] λ6300 indicates that the neutral component of this gas may be quite small since this line is a strong indicator of neutral hydrogen (Martin 1989).

3.6. *Other Lines*

There are detections of N III λ4640 in the 1988 to 1990 spectra; however, since this line is probably formed by continuum or Bowen fluorescence (Paper I) it is difficult to compare with recombination or forbidden lines to derive an abundance. Unfortunately, there are no measurements of [O II] λ7325 which is useful in deriving a nitrogen abundance from the relation $N(\mathrm{O}^+)/N(\mathrm{O}) \sim N(\mathrm{N}^+)/N(\mathrm{N})$ with the ratio of [N II] λ5755 and [O II] λ7325 (e.g., Ferland & Shields 1978; Saizar et al. 1991). It should be noted that high overabundances of nitrogen in novae are quite common (e.g., Escalante & Dalgarno 1991; Truran & Livio 1986) and are thought to be the result of incomplete burning through the CNO cycle during outburst (Shara, Prialnik, & Shaviv 1980; Williams 1982).

The spectra do not have sufficient S/N to detect useful lines for the determination of a carbon abundance (assuming the carbon abundance is near solar). These lines include C II λ4267 and C III λ4187 as well as C III $\lambda\lambda$4647, 4650, 4651 (Ferland & Shields 1978). In the latter case the lines are usually blended with the N III λ4640 feature, although in this nova the narrow width of λ4640 is not suggestive of their existence. The relations $N(\mathrm{C}^{++})/N(\mathrm{H}^+) \sim 0.36\ j(\lambda4267)/j(\mathrm{H}\alpha)$ and $N(\mathrm{C}^{+++})/N(\mathrm{H}^+) \sim 1.4\ j(\lambda4187)/j(\mathrm{H}\alpha)$, provided by Ferland & Shields, can be used to place some upper limits on the carbon abundance in this nova. For the 1989 spectrum, which has good S/N in the region of these lines, their intensity is estimated to be less than $0.03\ j(\mathrm{H}\alpha)$. Assuming that C^{++} and C^{+++} are the dominant states, the upper limit for C/H is less than 0.05. Thus carbon would have to be enhanced by over an order of magnitude above solar to be detectable in this nova.

Finally, Benjamin & Dinerstein (1990) have argued that all novae probably evolve through a coronal phase; however, the evidence for any coronal emission in this object is very weak: there is a suggestion of [Fe X] λ6374 emission in both the 1988 and 1990 spectra, and possibly [Fe VII] λ6087 in the 1989 spectrum. It is likely that the nova was followed for an insufficient amount of time to observe this phase develop fully.

4. DISCUSSION

The extremely slow evolution of this object has been exploited to make the first abundance estimates and detailed study of a nova outside the Galactic and LMC systems using the standard techniques that have been applied to Galactic novae. This nova is of particular interest, since it is situated in the bulge of M31 and it may be associated with a Population II system. This compares with Galactic novae which are almost exclusively discovered as disk objects and have been associated with the old disk (Population I); it is reasonable that some influence due to the difference in populations may be expected when comparing nova outbursts in the two systems. However, the analysis does not reveal any substantive difference between the outburst characteristics of this nova and that of a typical slow Galactic nova. In particular, slow novae are characterized with solar CNO abundances (as opposed to fast novae which can show enhancements of up to hundreds of times solar; for a review see Truran & Livio 1986). This is consistent with what is observed for O and Ne. The He abundance of $\sim$0.13 is close to a solar value of 0.10, and again is not unusual compared with recent determinations, particularly for slow novae (Truran & Livio 1986; Whitney & Clayton 1989) which show solar to slightly enriched He abundances.[4]

The derived abundances for O and Ne, although near solar, are sufficiently uncertain that lower metallicities for these two elements are not ruled out. Nevertheless it is worth considering the possibility that the nova is in fact a disk object superposed near the bulge. From the bulge and disk parameters given in Walterbos & Kennicutt (1988) it is estimated that the disk contributes significantly (nearly 25% of the total light) in both B and V at the isophotal position of the nova. However, with the Ciardullo et al. (1987) and Capaccioli et al. (1989) results for the specific nova rates, $\rho_{\mathrm{Bulge}}/\rho_{\mathrm{Disk}} > 10$, it would appear that the likelihood that this is a disk nova is quite small.

The value O/Ne $= 3.9 \pm 0.5$ derived here is of some interest. This value is relatively well determined, especially since it is not too sensitive to large changes in the electron temperature, T_e, derived in § 3.3. Henry (1989) has shown in an analysis of 171 planetary nebulae, which included objects in the Galaxy (both disk and some halo planetary nebulae), the Large and Small Magellanic Clouds, and M31, that the ratio of O/Ne appears to be independent of the parent galaxy. Since his average ratio for O/Ne (5.9 ± 2.1, by number) is close to that observed in H II regions, he suggests that the abundances of O and Ne are not affected by nucleosynthesis in intermediate-mass stars and are therefore probably representative of their abundances at the time of birth of the star.

Nova ejecta abundances are thought to be influenced by three sources: the accreted material from the low-mass second-

[4] The electron temperature of $\sim$13,000 K is also typical of that found in planetary nebulae; such temperatures reflect solar and subsolar metallicities since the extreme metal rich ejecta of fast novae (e.g., V1500 Vyg, Lance et al. 1988) tend to exhibit electron temperatures as low as $\sim$9000 K due to the effect of enhanced cooling channels provided by collisionally excited lines from the more abundant metals.

ary, synthesis during the thermonuclear runaway, and convective and/or diffusive mixing of the envelope with the core material during the time between outbursts (for a comprehensive review see Shara 1989). In particular, however, it has been the detection of extreme overabundances of metals such as Ne and Mg in the ejecta of some novae that has led authors to suggest that the high metallicity of these ejecta envelopes must be the result of convective and/or diffusive mixing with the core material of the white dwarf prior to outburst. Since slow novae are thought to take place on the surface of low-mass CO white dwarfs (e.g., Shara et al. 1980; Shara 1989), this nova and other slow novae are unlikely to have their O and Ne abundances influenced by prior stellar nucleosynthesis if Henry's (1989) hypothesis is correct. It follows that the O/Ne ratio may not be significantly altered by mixing with core material prior to outburst, and thus it is not too surprising that the O/Ne ratio determined in this nova is consistent with Henry's global estimate of O/Ne.

The absolute abundances of O and Ne are less reliably determined, however; mixing of envelope and core material could easily overwhelm the relatively smaller differences in metallicity we would expect to be present between the different halo and disk nova populations. Given the disparate properties of nova outbursts in general it is likely that population differences are hidden when comparing novae on an individual basis. Thus the implication is that the effects of population in nova outbursts are unlikely to be seen except when comparing large samples of well-studied objects from different systems.

In Paper I it was shown that there appears to be a systematic difference between the distribution of *observed types* of outbursts in seen in the bulge of M31 and the Galactic disk. No evidence was found of the fast, violent outbursts associated with explosions in nova systems containing a high-mass ONeMg white dwarf in the M31 spectoscopic sample observed to date, unlike the high frequency of such outbursts seen in the Galactic disk. Further spectroscopic observations of M31 novae, together with more detailed analyses of their ejecta, are particularly desirable if it is to be ascertained whether this result represents a real systematic effect due to the difference in parent populations of novae in the two systems.

Such a study is warranted for other reasons: as shown by Arp (1956), de Vaucouleurs (1978), van den Bergh & Pritchet (1986), and most recently Capaccioli et al. (1989, 1990), novae are useful standard candles for extragalactic distance determinations. The most dramatic use of novae in distance determinations was Pritchet & van den Bergh's (1987) measurement of the distance to the Virgo cluster. These authors used six well-sampled *B*-band light curves of novae in the giant Virgo elliptical's NGC 4365, NGC 4472, and NGC 4649 to derive a distance of 19.5 ± 3.9 Mpc^{-1}. As acknowledged by Pritchet & van den Bergh themselves, one of the principal uncertainties in their study was their implicit assumption that the nova light curves in these early-type galaxies were similar to those observed in M31. If the properties of these novae were found to differ in a clear and systematic way from those in older stellar populations, it would bear directly upon the usefulness of novae as distance indicators; in particular, the maximum-magnitude, rate of decline, MMRD (or equivalent), relations calibrated in the Galaxy to derive distances to extragalactic Population II objects such as M31's bulge, or the Virgo ellipticals. Ignoring potential differences in nova light curves between differing stellar populations could then lead to systematic errors that would diminish the precision of the distance measurements.

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