

# Optical and ultraviolet spectrophotometry of the ONeMg Nova V838 Herculis 1991

Karen M. Vanlandingham,<sup>1★</sup> Sumner Starrfield,<sup>1★†</sup> R. Mark Wagner,<sup>2★‡</sup>  
Steven N. Shore<sup>3★</sup> and George Sonneborn<sup>4†★</sup>

<sup>1</sup>Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287-1504, USA

<sup>2</sup>Department of Astronomy, Ohio State University, 174 W. 18th Avenue, Columbus, OH 43210, USA

<sup>3</sup>Department of Physics and Astronomy, Indiana University South Bend, 1700 Mishawaka Ave, South Bend, IN 46634-7111, USA

<sup>4</sup>Laboratory for Astronomy and Solar Physics, Code 681, NASA/GSFC, Greenbelt, MD 20771, USA

Accepted 1996 April 18. Received 1996 April 12; in original form 1996 March 11

## ABSTRACT

We present an analysis of optical and UV spectra of the fast nova V838 Herculis 1991. *IUE* observations began on 1991 March 25 and continued through 1991 August 20, while optical observations began on 1991 March 29 and continued through 1991 August 20. We determine a value for the reddening of  $E(B - V) \sim 0.5 \pm 0.1$  and a distance of  $\sim 3 \pm 1$  kpc based both on our own observations and on those of other groups. This nova was remarkable in being both fast and optically thick in the UV at maximum light. Our spectra show strong lines of helium, neon, sulphur and nitrogen. In contrast, oxygen lines were never present in our UV spectra and very weak in our optical spectra. We use a new optimization method to perform an abundance analysis of the spectra, and find that carbon, nitrogen, neon, silicon and sulphur are overabundant with respect to solar material by factors ranging from 5 to 37, while helium and oxygen are both underabundant by a factor of 0.3. Our best model is obtained with a luminosity for the central source of  $5.1 \times 10^{36}$  erg s<sup>-1</sup>, indicating that this nova may have turned off by two months after outburst. We also find an ejected mass for this nova of  $M_{ej} \sim 1.8 \times 10^{-4} M_{\odot}$ . Based on both the characteristics of the outburst and our observed abundances, we suggest that this outburst occurred on a very massive ONeMg white dwarf.

**Key words:** stars: individual: Nova Herculis 1991 – novae, cataclysmic variables – ultraviolet: stars.

## 1 INTRODUCTION

Nova V838 Herculis 1991 (hereafter Her 91) was discovered on 1991 March 24 at a visual magnitude of  $\sim +5.0$  (Sugano & Alcock 1991). It was one of the fastest novae on record, with  $t_2 \sim 2$  d and  $t_3 \sim 5$  d as estimated from the composite light curve obtained from the IAU circulars (Fig. 1). The precise position was determined by McNaught (1991) to be RA = 18<sup>h</sup>46<sup>m</sup>31<sup>s</sup>.28, Dec. = +12°14′1″.4 (equinox 2000). Dopita, Ryder & Vassiliadis (1991) suggested that Her 91 was a member of the ‘neon’ class of novae, based on the strength of [Ne III] 3868 Å and [Ne V] 3426 Å in their optical

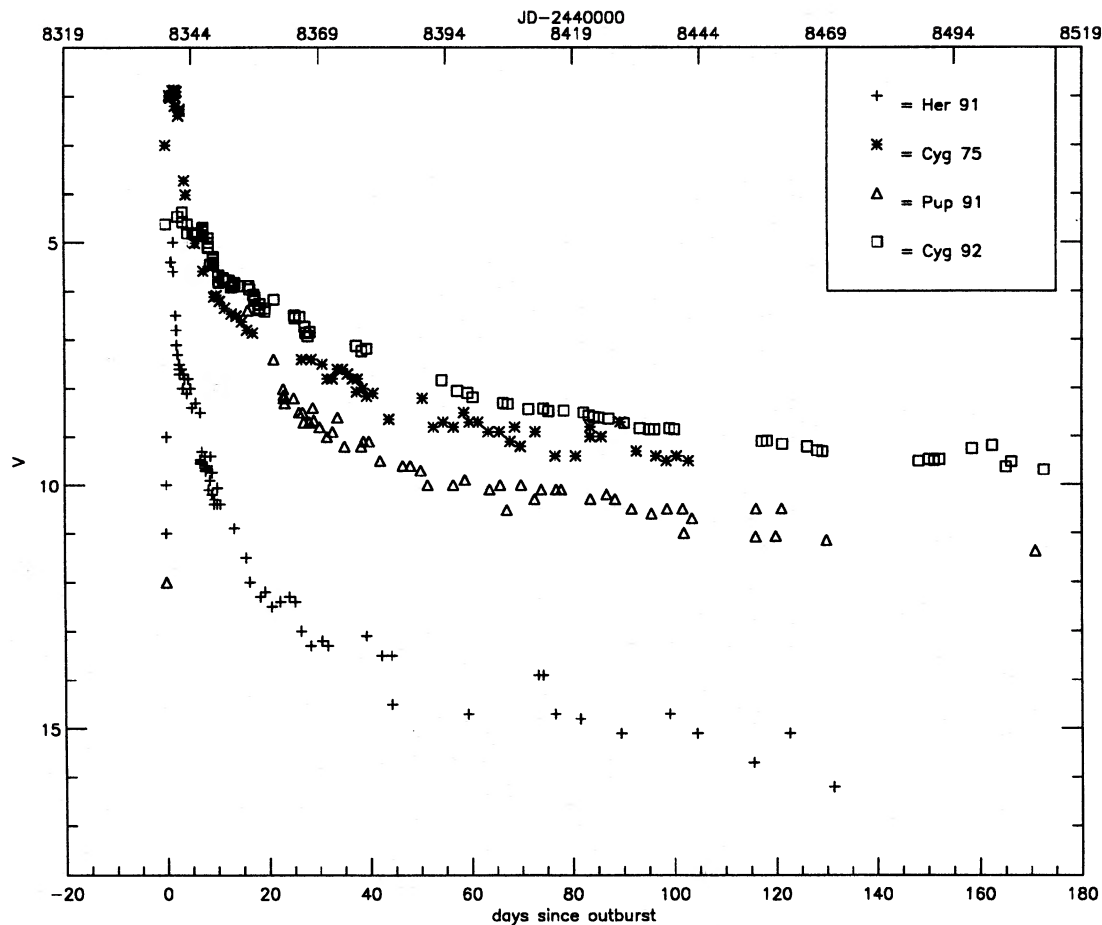
spectra. Neon novae show strong neon emission lines in their spectra, and the velocities of their ejecta are typically higher than those of CO novae (Starrfield, Sparks & Truran 1986). Novae of this type are thought to occur on oxygen–neon–magnesium (hereafter ONeMg) white dwarfs (cf. Politano et al. 1995, and references therein), which are thought to arise from single stars with masses of about 8–12  $M_{\odot}$  on the zero-age main sequence.

Her 91 has been observed in the infrared, optical, ultraviolet and X-ray, and its evolution has proven to be unique in every wavelength regime. Infrared (IR) observations were made by Chandrasekhar, Ashok & Ragland (1992) and Woodward et al. (1992). Woodward et al. observed the IR signature of dust formation less than 10 d after outburst. No other nova has been observed to form dust as early as this in the outburst. Lloyd et al. (1992) detected Her 91 with *ROSAT* on 1991 March 30, far earlier in outburst than any other nova has been detected at X-ray wavelengths. They reported a count rate of  $0.16 \pm 0.01$  s<sup>-1</sup>, with a low-energy

\*karenv@suelee.la.asu.edu (KMV); sumner.starrfield@asu.edu (SS); rmw@altair.lowell.edu (RMW); SShore@paladin.IUSB.Indiana.edu (SNS); sonneborn@stars.gsfc.nasa.gov (GS)

†Guest Observer, *IUE* Observatory.

‡Mailing address: Lowell Observatory, 1400 W. Mars Hill Road, Flagstaff, AZ 86001, USA.



**Figure 1.** Optical light curves of Her 91 (plus signs), Cyg 92 (squares), Cyg 75 (asterisks) and Pup 91 (triangles). The vertical axis is visual magnitude. The horizontal axes are Julian date  $-244\,0000$  (top) and days since outburst (bottom) for Her 91. Notice the steep rise to maximum and fast decline.

cut-off at photon energies of  $\sim 1$  keV. Orbital variations ( $P \simeq 0.297$  d) were found by Leibowitz et al. (1992) in 1991 April. To our knowledge, the only other nova in which orbital variations were seen as early as this in the outburst was V1500 Cygni (Patterson 1979). Matheson, Filippenko & Ho (1993) obtained optical spectra of Her 91 in 1991 August and performed abundance analyses using photoionization models of the ejected material. Their results showed sulphur to be greatly enhanced relative to solar abundances, and nitrogen to be enhanced relative to oxygen. We will discuss this further in Section 5. Their high-resolution spectra revealed detailed velocity structure in the emission lines, probably corresponding to clumps in the ejecta.

In this paper we present our optical and ultraviolet (UV) observations, which have also revealed unexpected properties. A description of the observations is given in Section 2. We have used two independent methods to determine the reddening to Her 91, which are presented in Section 3. In Section 4 we discuss the values we obtained for the distance to Her 91. We have determined abundances for Her 91, using both the optical and UV spectra and a new optimization method. These results are given in Section 5. We compare our abundance results with those of Matheson et al.

**Table 1.** UV observation log.

SWP	Date	JD-2440000	UT	Days	Exp(s)
41180	25 March 1991	8341.3	19.9	1.05	300
41191	27 March 1991	8342.5	0.5	2.24	300
41205	28 March 1991	8344.3	19.0	4.01	240
41210	29 March 1991	8345.1	14.9	4.84	260
41231	30 March 1991	8346.3	19.9	6.05	210
41303	5 April 1991	8352.3	18.2	11.98	360
41318	8 April 1991	8355.3	19.7	15.04	360
41391	15 April 1991	8362.2	16.1	21.89	720
41455	22 April 1991	8369.3	18.7	29.0	1200
41696	25 May 1991	8402.4	21.4	62.11	2940
41747	2 June 1991	8409.8	7.68	69.54	13200
41824	12 June 1991	8419.8	8.4	79.57	13200

(1993) in Section 6. A discussion and summary of our results follow in Sections 7 and 8.

## 2 SPECTRAL DEVELOPMENT

### 2.1 Ultraviolet observations

Ultraviolet observations were obtained with the *International Ultraviolet Explorer Satellite (IUE)* beginning on

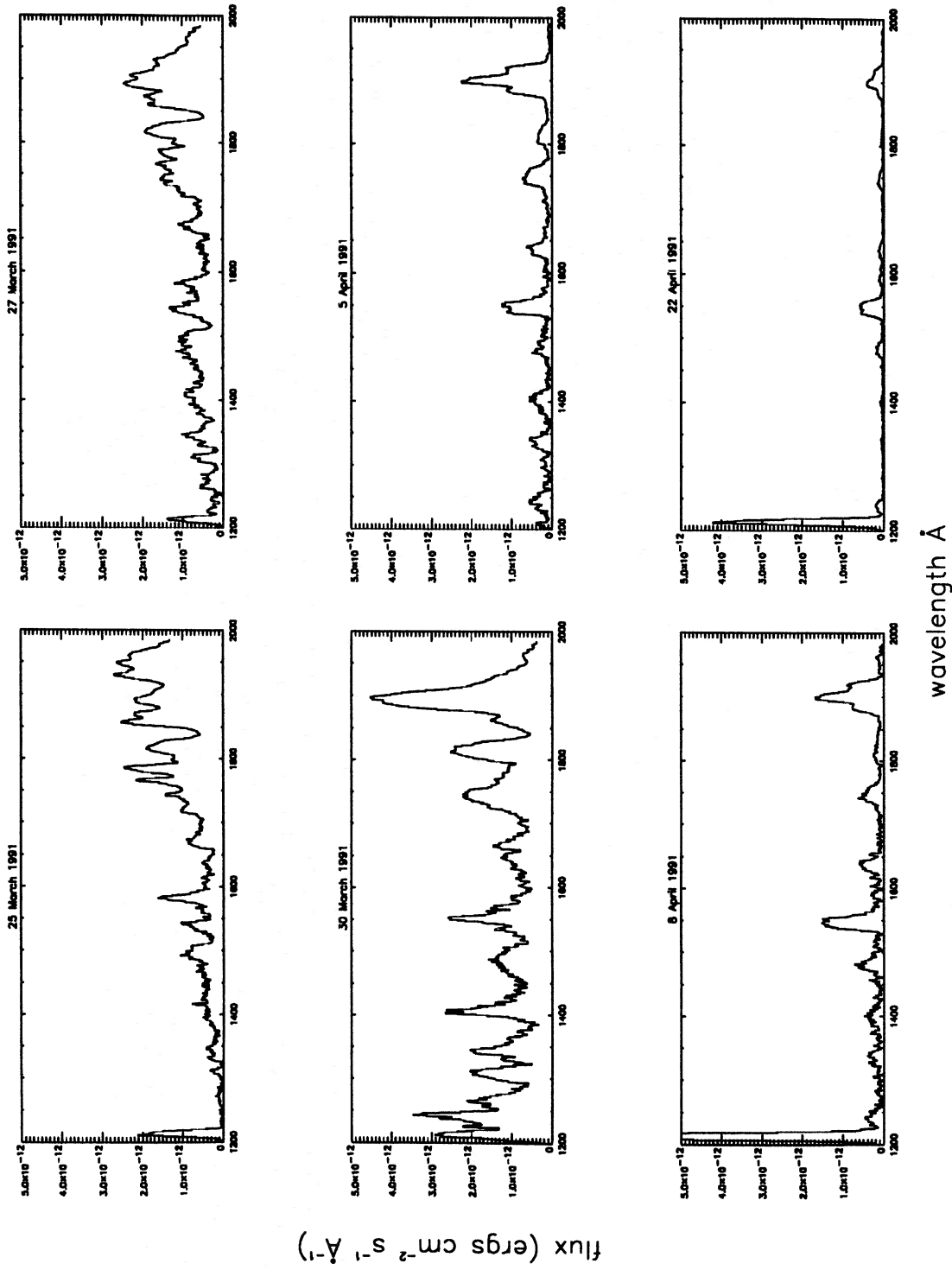


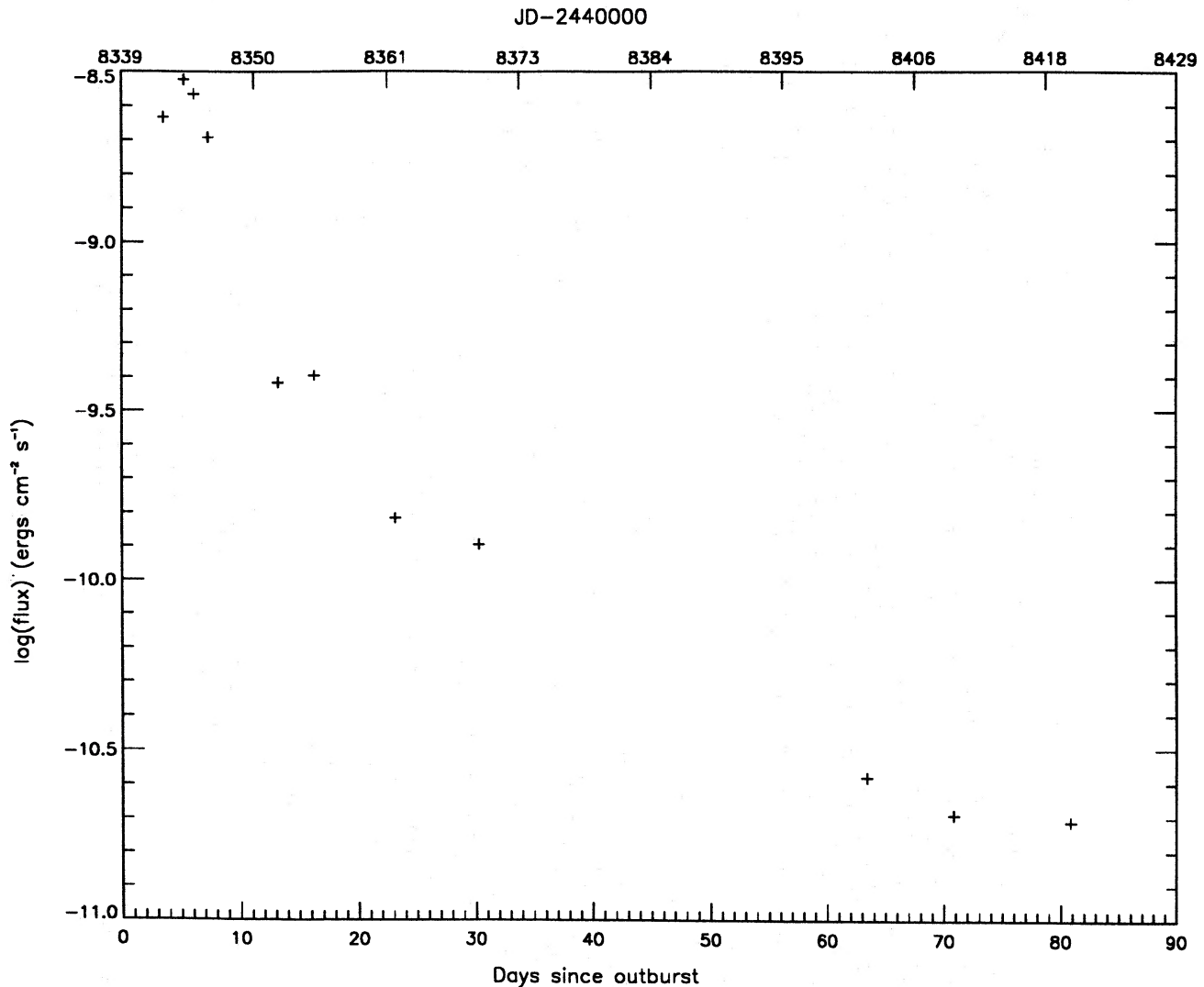
Figure 2. A montage of IUE SWP spectra. The spectra have not been corrected for reddening. The first two spectra show the continuum rising to the red, indicating that the ejecta is optically thick.

1991 March 25 and were continued through 1991 June at which time the nova became too faint for observations. Low-dispersion large-aperture spectra were obtained using both the Long Wavelength Primary (LWP: 2000–3400 Å) and the Short Wavelength Primary (SWP: 1200–2000 Å) cameras (resolution 7 Å). A few high-dispersion spectra were obtained as well. The data were reduced at the Goddard Space Flight Center (GSFC) Regional Data Analysis Facility (RDAF), using standard *IUE* software. We concentrate here on the analysis of the low-dispersion SWP spectra. Table 1 is a summary of the UV observations, including SWP number, date, Julian date – 244 0000, UT date, days since outburst, and exposure time (in seconds).

Fig. 2 shows a montage of the SWP spectra. In contrast to the two other fast ONeMg novae observed in the UV at similar stages of their development (V693 CrA, Williams et al. 1985; LMC 1990 #1, Sonneborn, Shore & Starrfield 1990), the early UV spectra of Her 91 were optically thick at maximum (Hauschildt et al. 1992). By ‘optically thick’, we mean that the spectra obtained on March 25 and 27 showed

a continuum rising to the red, with pseudo-emission lines superimposed on this continuum (Hauschildt et al. 1992, 1994, 1995). The only unambiguous emission line seen in the LWP spectra at this time was the Mg II doublet at 2800 Å, which was blended with Fe II. The feature had a full-width zero intensity (FWZI) of 7300 km s<sup>-1</sup> and a weak blueshifted absorption component with a terminal velocity of ~3000 km s<sup>-1</sup>. At this time the total UV flux, integrated from 1200 to 2000 Å for the SWP and from 2300 to 3400 Å for the LWP, was still increasing and actual lines were beginning to appear. The UV flux peaked ~6 d after outburst (Fig. 3).

By April 5, the continuum level had decreased to the point that we could distinguish emission lines of C II 1335 Å, C IV 1550 Å, N III] 1750 Å, Al III 1860 Å and C III 1909 Å. The line at 1400 Å, commonly attributed to O IV], is probably due to S IV] and Si IV based on the presence of other sulphur and silicon lines in the UV–optical spectra and the absence of the O III] 1660 and 1666 Å lines throughout the outburst. In the April 8 spectrum, the C IV 1550 Å doublet had



**Figure 3.** Ultraviolet light curve of Her 91. The vertical axis is log of the UV flux. The horizontal axes are Julian date – 244 0000 (top) and days since outburst (bottom).

become almost as strong as C III] 1909 Å, and He II 1640 Å and N IV] 1486 Å had appeared. The [Ne IV] 1602 Å line was present but weak. The [Ne IV] 2420 Å line was undetectable due to noise in the LWP spectrum shortward of 2500 Å.

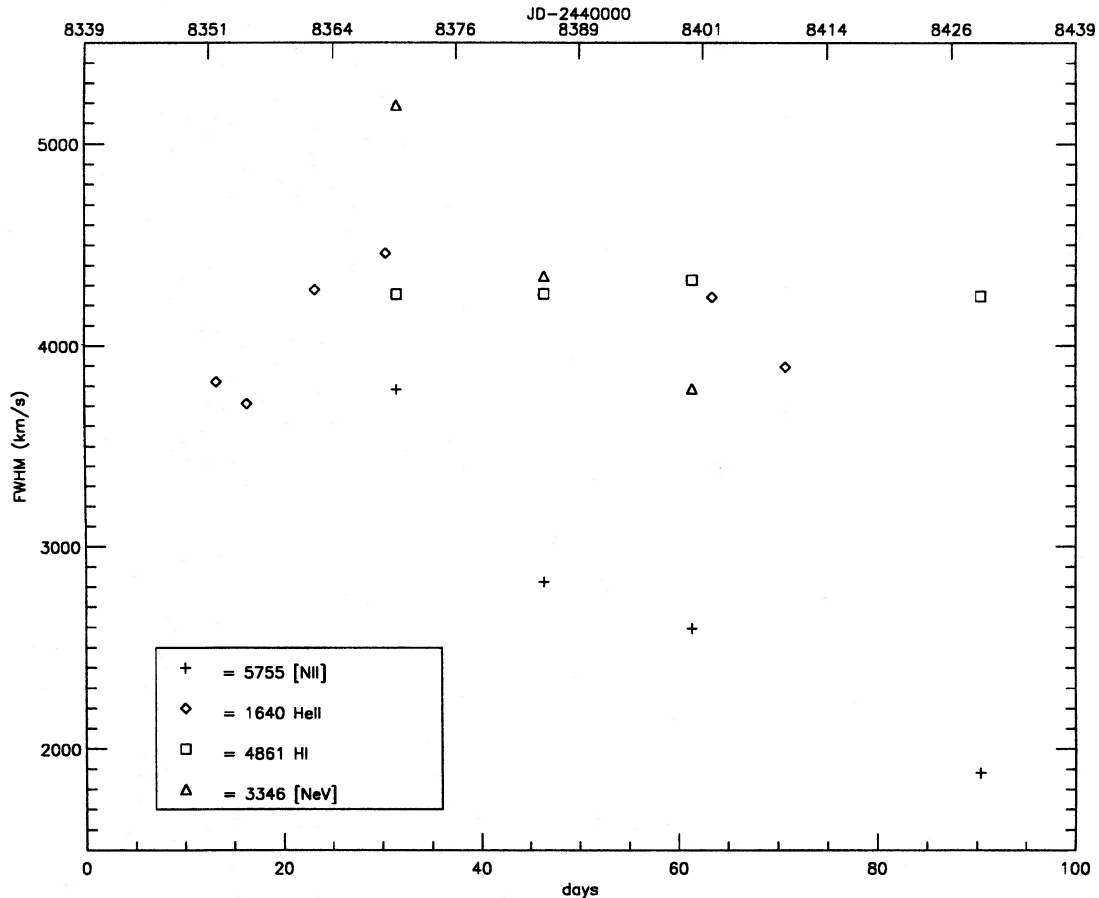
Higher ionization species continued to strengthen through April 22. C IV 1550 Å was the dominant line, and [Ne V] 3346 Å appeared around this time. [Ne V] 1575 Å, if present, was probably blended with C IV, and there was no evidence for the presence of [Ne V] 2976 Å. By May 25, many of the low-ionization species had disappeared, and C IV 1550 Å and C III] 1909 Å were of about equal strength. The June 12 spectrum showed [Ne V] 3346 Å to be the strongest line in the spectrum, while all other lines had either weakened considerably or disappeared. The presence of [Ne IV] 1602 Å and [N V] 3346 Å in the UV spectra combined with the presence of strong neon lines in the optical (Dopita et al. 1991) suggested strongly that Her 91 was a neon nova (Williams et al. 1985; Sonneborn et al. 1990).

One interesting feature was the absence of oxygen emission lines in all of the spectra, even though intercombination and forbidden lines of other elements were present. [O III] was also weak in the optical (see Section 2.2 and Matheson et al. 1993). This suggests an oxygen under abundance in the ejecta, which we will discuss in Section 5.

In Fig. 4 we have plotted the linewidth (FWHM) of He II 1640 Å as a function of time. This line was chosen because it was not obviously blended and was fairly strong throughout most of the evolution of the nova. The width of He II appears to be roughly constant, with a FWHM velocity  $\sim 4300$  km s<sup>-1</sup>. The constant velocity of the line indicates that most of the emission took place at a localized depth in the shell, over which the velocity gradient was very small. This is consistent with the clumpiness of the ejecta (see Section 5). Measurements from the earliest spectra were not used in this plot, since these spectra were still optically thick.

## 2.2 Optical observations

Our optical observations cover the period from 1991 March 29 to August 20. Most of the observations were taken at Lowell Observatory using the Perkins 1.8-m telescope of the Ohio Wesleyan and Ohio State Universities and the Boller & Chivens spectrograph (resolution 9 Å, wavelength range 3200–8200 Å). A 2-arcsec-wide slit and the 150 line per mm grating were used. The April 20 spectrum was taken by Dr Jeff Pier at the USNO 40-inch telescope (resolution 3 Å, range 3350–5600 Å). The June 21 spectrum was taken at the Multiple Mirror Telescope (MMT) on Mt. Hopkins with



**Figure 4.** Full-width half-maximum velocities for various lines in the Her 91 spectra. The vertical axis is FWHM in km s<sup>-1</sup>. The horizontal axes are Julian date - 244 0000 (top) and days since outburst (bottom). The diamonds are He II 1640 Å, pluses are [N II] 5755 Å, asterisks are [N III] 1750 Å, squares are H I 4861 Å, and triangles are [Ne V] 3346 Å.

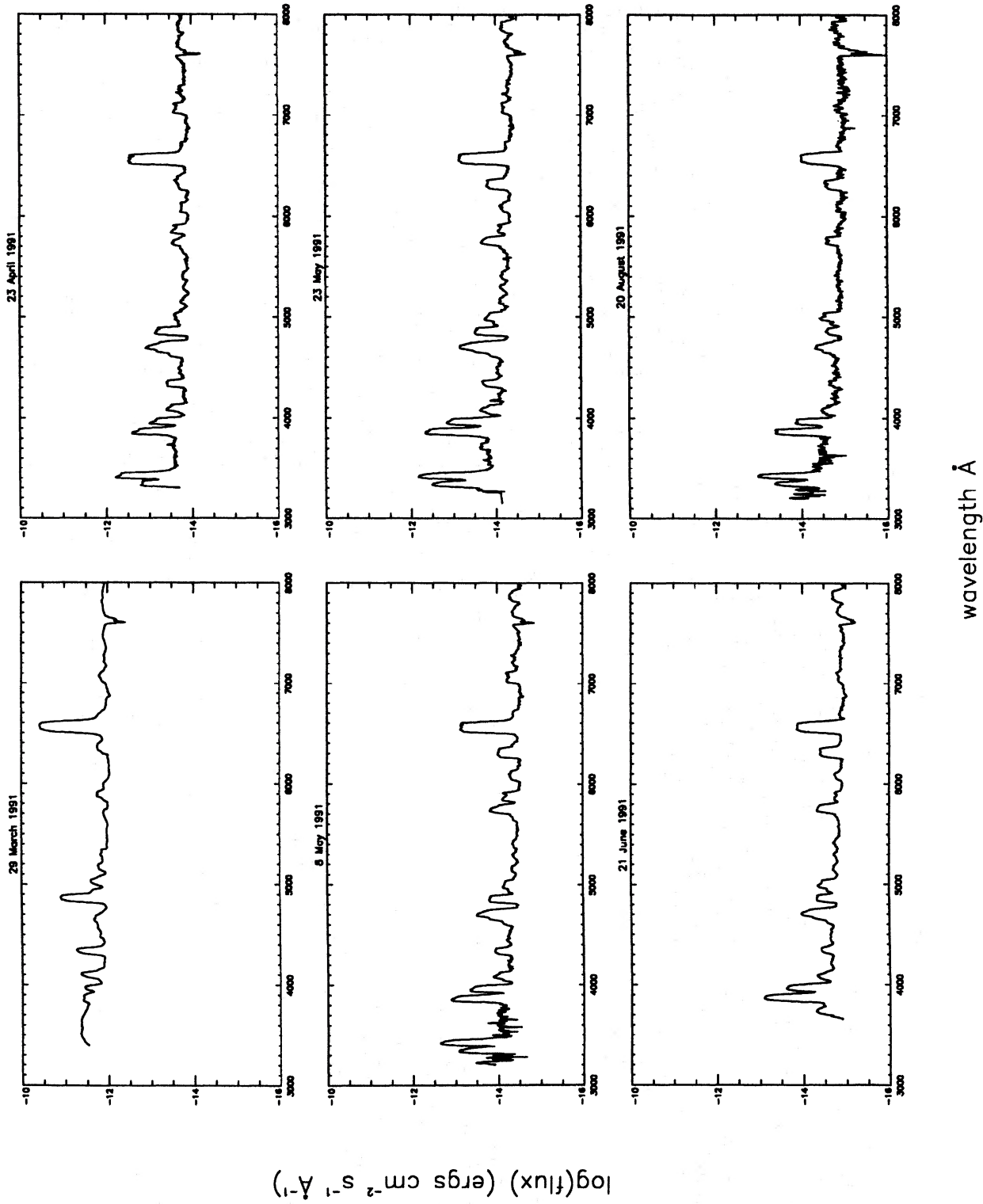


Figure 5. A montage of optical spectra. The spectra have not been corrected for reddening.

Table 2. Optical observation log.

Date	JD-2440000	UT	Days	Obs	Exp(s)	Air
29 March 1991	8345.0	11.0	4.68	Lowell	20	1.334
20 April 1991	8367.0	11.0	26.28	UNSO	3000	1.189
23 April 1991	8370.0	11.0	29.68	Lowell	400	1.11
2 May 1991	8379.0	10.8	38.67	Lowell	1200	1.09
8 May 1991	8384.9	10.6	44.66	Lowell	300	1.09
23 May 1991	8399.9	9.1	59.60	Lowell	600	1.12
21 June 1991	8428.7	4.8	88.42	MMT	180	1.62
20 August 1991	8488.8	6.7	148.50	Lowell	120	1.35

the 150 line per mm grating and the 1.25-arcsec-wide slit (resolution  $6.5 \text{ \AA}$ , range  $3600\text{--}8800 \text{ \AA}$ ). We give a summary of the observations in Table 2. The optical spectra were reduced using standard IRAF routines.

The nova was declining from visual maximum when our observations began (Fig. 1). Fig. 5 shows a montage of our optical spectra, uncorrected for reddening. The earliest spectra strongly resembled those of Nova V1500 Cygni 1975 (Rosino & Tempesti 1977; Wagner et al. 1991). Hydrogen Balmer P Cygni lines dominated, and all showed weak absorption troughs. Other lines present in these early spectra were those of He II  $4686 \text{ \AA}$ , [S III]  $6312, 9069, 9532 \text{ \AA}$  (R. E. Williams, private communication), [Ne III]  $3869, 3967 \text{ \AA}$  and [Ne V]  $3346, 3425 \text{ \AA}$ . The presence of strong neon emission lines supports the identification of Her 91 as an ONeMg nova.

By April 23 the neon lines had grown to be comparable in strength to H $\alpha$ , as had [N II]  $5755 \text{ \AA}$ . Williams et al. (1994) obtained an optical spectrum on April 25, which they classified as N<sub>ne</sub>, using the Tololo classification system. This assignment means that the nebular transition [Ne V]  $3426 \text{ \AA}$  was the strongest non-Balmer line in their spectrum. Our spectra support this classification. In our May 8 observations, the neon lines dominated the spectrum. Williams, Phillips & Hamuy (1994) found that their June 12 spectrum showed that the nova had evolved to the A<sub>ne</sub> class, meaning that the [Ne IV]  $4721\text{-\AA}$  auroral line was stronger than any non-Balmer permitted line. Our spectra at this time showed that the nova was still in the N<sub>ne</sub> phase, but the [Ne IV]  $4721\text{-\AA}$  line in our spectra was blended and an accurate strength was difficult to obtain. By August 20 all lines were decreasing in intensity, with the neon lines still being the strongest.

As in the UV spectra, there was a marked lack of strong oxygen lines. The lines of [O III] at  $4959$  and  $5007 \text{ \AA}$ , as well as [O I]  $6300 \text{ \AA}$ , were extremely weak, if not absent, in all of the spectra. The [O III]  $4363\text{-\AA}$  line was not seen at all, probably due to blending with H $\gamma$ , which was fairly strong. This lack of oxygen lines is in contrast to other fast novae, such as V1500 Cygni (Tomkin, Woodman & Lambert 1976), as well as other ONeMg novae, such as Nova Cygni 1992 (Austin et al. 1996). We will show in Section 5 that the lack of strong oxygen lines is a consequence of a low oxygen abundance in the nova ejecta (relative to solar).

The lines of [Ne V]  $3346 \text{ \AA}$ , H $\beta$ , and [N II]  $5755 \text{ \AA}$  were used for FWHM measurements in the optical spectra (Fig. 4). These lines were chosen because they were not blended and were strong throughout the temporal evolution of the nova. The two forbidden lines show FWHM velocities that steadily decrease with time, while the H $\alpha$  FWHM was more

or less constant throughout the observations at  $\sim 4200 \text{ km s}^{-1}$ . This behaviour agrees with He II  $1640 \text{ \AA}$ , as noted in Section 3.

### 3 REDDENING DETERMINATIONS

We employed two independent methods to obtain the reddening to Her 91. First, the early optical spectrophotometry yields  $B - V \sim +0.5$ . To determine the reddening, we must assume an intrinsic colour for the nova. Based on its similarity to V1500 Cyg, both in spectral features (with the exception of the lack of oxygen lines) and speed class, we assumed that Her 91 had the same intrinsic colours as V1500 Cyg. V1500 Cyg had  $(B - V) = +0.62$  at maximum (Young et al. 1976), and a reddening  $E(B - V) = 0.5$  (Ferland 1977). Thus the intrinsic colour of V1500 Cyg at maximum was  $(B - V)_0 = +0.1$ . Adopting this value for Her 91, we find a colour excess of  $E(B - V) \simeq 0.4$ . Woodward et al. (1992) found a colour excess of  $E(B - V) \simeq 0.3$  using this same method, but they assumed that  $(B - V)_0 = +0.2$ .

We also used the Balmer decrement to measure the reddening to Her 91. Assuming that the hydrogen lines are emitted in case B conditions, the expected ratio is  $2.74 \leq H\alpha/H\beta \leq 3.04$ , depending on the temperature and electron density of the medium (Osterbrock 1989). For the conditions present in Her 91 (see Section 5), the expected ratio is  $H\alpha/H\beta = 2.8$ . From our observations, we find the ratio to be 5.8 from the April 23 spectrum, 6.7 from the May 8 spectrum, and 5.0 from the June 21 spectrum, with the error of each measurement being less than 20 per cent. This gives us an average value of  $H\alpha/H\beta \sim 5.6$ . H $\gamma$  was not used, since it was severely blended. Comparing the observed ratio to the predicted value, we find a colour excess of  $E(B - V) \sim 0.6$ . By choosing either extreme of the expected  $H\alpha/H\beta$  ratio, the reddening is changed by only  $\pm 0.05$ . Ingram et al. (1992) also measured the reddening, using the Balmer decrement. From their spectra on May 17, 18 and 19 they found the ratio  $H\alpha/H\beta = 5.2$ , which yields  $E(B - V) < 0.54$ . The He II  $4686\text{-\AA}$  line was blended, so that a measurement of the He II  $1640 \text{ \AA}/4686 \text{ \AA}$  ratio was not reliable. We can, however, use the line to determine an upper limit, since in deblending  $4686 \text{ \AA}$  we have probably underestimated the flux. We find the values for the reddening to be 0.54, 0.74 and 0.59 from the combined UV and optical spectra obtained on April 22 and 23, May 25 and 23 and June 12 and 21, respectively. This yields an average reddening of 0.62 which agrees well with the results from our other methods.

Using the equivalent widths of the interstellar sodium D lines, Lynch, Hackwell & Russell (1992) determined the

reddening to be  $E(B-V)=0.53$ . Starrfield et al. (1992) obtained a value for  $E(B-V)$  by taking the ratio of the UV flux of the nova above and below 2000 Å and comparing it to the same ratio for LMC 1990 #1, whose reddening is small and whose distance is known. After the optically thick phase, the spectroscopic development and decline rates for these two novae were very similar. Hence they assumed that the only difference between the flux ratios of the two novae was due to reddening. They found the flux ratios to agree if  $E(B-V)\simeq 0.6$  for Her 91. Table 3 lists our reddening results along with those of other groups. All the values agree fairly well. The majority of the results place the reddening of Her 91 in the range 0.50–0.60. As the measurement of the Balmer decrement makes fewer assumptions than the comparison to V1500 Cygni, we place more weight on our reddening determined from this measurement. This result is also in better agreement with the results of other groups. We will therefore use  $E(B-V)=0.6$ .

We also note that it is possible to combine the absolute magnitude–decay time relationships to determine the reddening to Her 91. A  $t_2$  of  $\simeq 2$  d and the absolute magnitude–decay time relation of Cohen (1985),

$$M_V = 1.76 \log t_2 - 10.42, \quad (1)$$

yield a value for the absolute  $V$  magnitude  $M_V \sim -9.9$ . We can also use the theoretical relation between  $M_B$ , the absolute  $B$  magnitude at maximum and  $t_3$ , the time for the light curve to decay 3 mag from maximum, determined by Livio (1992):

$$t_3 = 51.3 \times 10^{(M_B + 9.76)/10} \times [10^{2(M_B + 9.76)/30} - 10^{-2(M_B + 9.76)/30}]^{3/2}. \quad (2)$$

Using  $t_3 \simeq 5$  d, we solve equation (2) for  $M_B$ . Combining this with the value of  $M_V$  from equation (1), and assuming  $(B-V)_0 = +0.1$ , we find that  $E(B-V)=0.8$ . On the other hand, if we assume  $E(B-V)=0.6$ , then the values of  $M_V$  and  $M_B$  given by the above equations predict an intrinsic colour for the nova of  $(V-V)_0 = +0.3$ . Both of these results

seem too large to be acceptable. We will further discuss the problems associated with these absolute magnitude–decay time relationships in the following section.

#### 4 DISTANCE DETERMINATIONS

The distance to Her 91 was estimated using two different methods. Using the reddening-corrected peak apparent magnitude  $V \simeq +3.1$  [with  $E(B-V)=0.6$ ] and  $M_V$  from  $t_2$ , we find a distance to Her 91 of 4.0 kpc. Due to early dust formation, the absolute magnitude determined in this manner should be corrected for extinction due to circumstellar dust. However, we do not know this correction for Her 91 and, therefore, cannot adjust the determined distance. It has been suggested that observational  $M_V$ – $t_2$  relations, based on all novae, do not correctly predict the distance to a specific ONeMg nova (Starrfield et al. 1992). While these relations show a definite trend, there is a large amount of scatter in the fits, and it is likely that they do not work for as fast an ONeMg nova as Her 91. These relations predict small absolute visual magnitudes for novae with small  $t_2$  values and, hence, result in large distance estimates. This relationship has therefore probably overestimated the distance, and we use this value only to obtain an upper limit on the distance.

Using the theoretical relation between  $M_B$  and  $t_3$  of Livio (1992) given in the previous section, we find  $M_B \sim -9.0$ . As we have assumed  $(B-V)_0 = +0.1$ , this yields  $M_V \sim -8.9$  and a distance to Her 91 of  $\sim 2.5$  kpc.

We can also derive a distance to Her 91 by assuming that its absolute magnitude at maximum was the same as that of V1500 Cyg. V1500 Cyg had an apparent magnitude at maximum of  $\simeq 1.85$  (Young et al. 1976). Its distance is  $1.2 \pm 0.2$  kpc (Lance, McCall & Uomoto 1988), and it has a reddening of  $E(B-V)=0.5 \pm 0.05$  (Ferland 1977). From this we find an absolute magnitude  $M_V = -10 \pm 0.3$ . Using this absolute magnitude and the reddening-corrected peak apparent magnitude for Her 91 of 3.1, we find a distance to Her 91 of  $\simeq 4.2$  kpc.

A third method was used by Woodward et al. (1992). They obtained a distance to the nova by using IR dust emission to derive a temperature and the greybody angular diameter of the dust shell as a function of time. This method makes no assumptions regarding the characteristics of the nova itself. They find a distance of  $\sim 2.8$  kpc. Starrfield et al. (1992) used the LWP/SWP flux ratios of Her 91 and LMC 1990 #1 to determine the reddening of Her 91. Using this

Table 3. Reddening determinations.

Reference	Methods Used	E(B-V)
Ingram et al (1992)	Balmer decrement	$\leq 0.54$
Lynch et al (1992)	Equivalent width of Na	0.53
Starrfield et al (1992)	ratio of UV flux	0.6
this paper	Intrinsic B-V of +0.1	0.4
	Balmer decrement	0.6
Woodward et al (1992)	Intrinsic B-V of +0.2	0.3

Table 4. Distance determinations.

Reference	Methods Used	Distance (kpc)
Chandrasekhar et al (1992)	$M_V$ from $t_3$	$\leq 8.3$
	assuming $L_{edd}$	5.8
Ingram et al (1992)	$M_V \simeq -5.6$ at 15 days	6–12
Kidger et al (1993)	$M_V$ from $t_2$ and $t_3$	7.9
Lynch et al (1992)	distance $\simeq A_V/0.5$	3.4
Starrfield et al (1992)	comparison with LMC90-1	3.4
this paper	$M_V$ from $t_2$	4.0
	$M_B$ from $t_3$	2.5
	assuming $M_V$ from V1500 Cyg	4.2
Woodward et al (1992)	$M_V$ from $t_3$	6.5
	IR photometry	2.8

value and the bolometric fluxes for the two novae, they found a distance to Her 91 of  $\sim 3.4$  kpc. Table 4 lists our results along with those of other groups.

We assume a distance of  $3 \pm 1$  kpc for the rest of the paper. At this distance, the maximum luminosity is  $3.0 \times 10^{38}$  erg s $^{-1}$ , or 1.7 times the Eddington luminosity for a  $1.4-M_{\odot}$  white dwarf. Using a distance of 50 kpc to the LMC (Panagia et al. 1991) and an extinction of  $E(B-V)=0.15$  (Shore, Sonneborn & Starrfield 1990), the maximum luminosity for Nova LMC 1990 #1 was  $\geq 1.6 \times 10^{38}$  erg s $^{-1}$  on 1991 January 18.04. Because of the similarity of these two novae, it seems plausible that Her 91 also exceeded the Eddington luminosity.

## 5 PHYSICAL PARAMETERS

We have used CLOUDY84 (Ferland 1993), in combination with three different minimization routines (discussed below), to model the relative line strengths of Her 91. CLOUDY uses assumed values of the physical conditions (ionization, density, temperature and chemical composition) of the gas to predict the resulting emission-line spectrum. It simultaneously solves the equations of statistical and thermal equilibrium. To use CLOUDY, we input the following parameters: the spectral energy distribution of the continuum source, the temperature and luminosity, the hydrogen density, the density law (given by  $\alpha$ , where  $\rho \propto r^{\alpha}$ ),

the inner and outer radii of the shell, the geometry of the shell, the covering and filling factors of the shell, and the abundances (relative to solar) of He, C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe and Ni.

Most of our analysis has been done using the optical spectrum obtained on May 23 (Fig. 6) in combination with the closest corresponding UV spectrum obtained on May 25 (Fig. 7). Although these spectra were taken a few days apart, we expect little change in the physical conditions between the two observations as they were made two months into the evolution of a very fast nova. In order to account for any systematic differences between the two spectra, we plotted the spectra together and used the overlap area (roughly 3000–3300 Å) to match the fluxes. The best fit in the overlap region was obtained when the optical flux was scaled by 0.4.

We should make a few comments concerning our high-dispersion data. The profile of the 1909-Å feature shows it to be a blend of many lines, probably including lines of sulphur. There is probably, in addition, a component due to Ne II 1916 Å (James, Kanik & Ajello 1995). The deconvolution of this feature is very difficult, and we have probably overestimated the integrated flux of the C III] 1909-Å line. Thus the carbon abundance we have found using this intensity is an upper limit (see below). The N III] 1750-Å and He II 1640-Å lines both show complicated velocity structures, indicating that the ejecta was clumpy. There is a diffuse

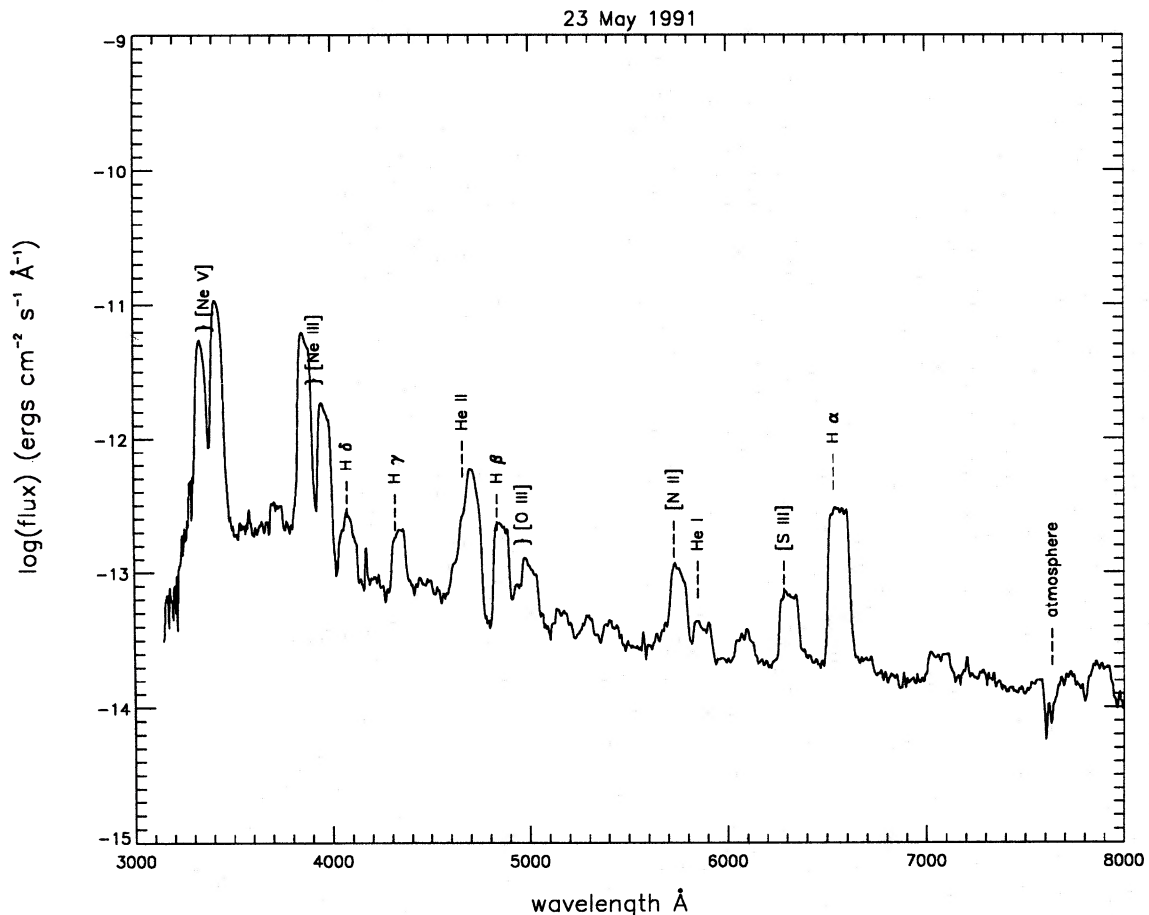


Figure 6. The optical spectrum from 1991 May 23. Relative line strengths were obtained from this spectrum to use with CLOUDY.

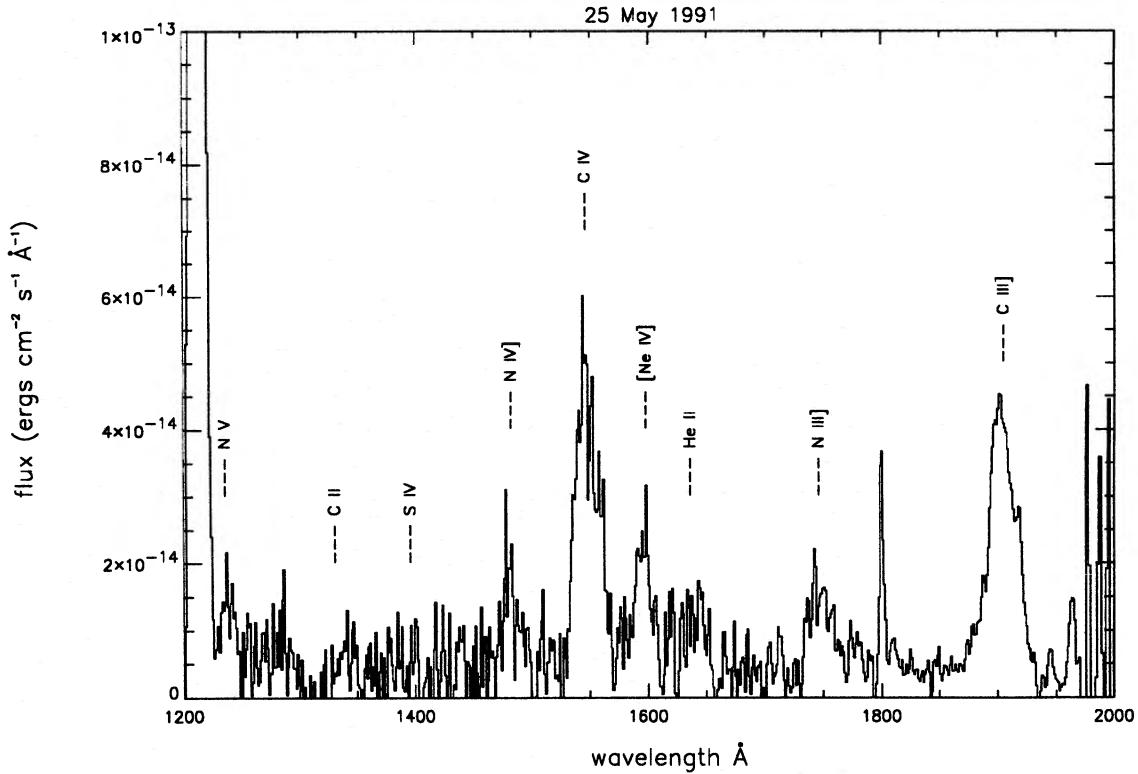


Figure 7. The IUE SWP spectrum from 1991 May 23. Relative line strengths were obtained from this spectrum to use with CLOUDY.

component to the profiles as well, although most of the material is contained in the clumps. The number of distinct components is difficult to determine from our spectra; however, other groups have done more detailed analyses of the shell structure (Matheson et al. 1993). The presence of these clumps indicates that the filling factor of the ejecta is much less than unity (Harrison & Stringfellow 1994). We describe our choice of filling factor in more detail below.

We chose a range of temperatures for the underlying photoionizing source (assumed to be a blackbody for most of our runs) based on studies of other ONeMg novae (Nova LMC 1990 #1, Sonneborn et al. 1990; V1974 Cyg 1992, Austin et al. 1996). We also ran models using MacDonald's (private communication) hot white dwarf model atmospheres as the continuum source. This, however, did not produce any significant differences in the results. In future work we plan to use Werner's non-LTE model planetary nebula nuclei atmospheres (Werner & Heber 1991).

CLOUDY requires only the hydrogen density of the ejecta, not the electron density. Due to the presence of a strong high-ionization line and few neutral lines, however, the assumption that hydrogen is completely ionized is probably accurate. We therefore set the hydrogen density equal to the electron density. Due to the lack of oxygen lines, we could not use them to determine the electron density of the shell. We therefore chose a range of densities based on studies of other novae. From our measured expansion velocities and time since outburst, we estimated an inner and outer radius. Harrison & Stringfellow (1994) find that, if the ejecta is assumed to be composed of spherical, optically thick clumps, the filling factor,  $\phi$ , is given by

$$\phi = N_{\text{cl}} V_{\text{cl}} / V_{\text{shell}} = 8 N_{\text{cl}}^{-1/2} \tau^{3/2}, \quad (3)$$

where  $N_{\text{cl}}$  is the number of clumps,  $V_{\text{cl}}$  and  $V_{\text{shell}}$  are the volume of the clumps and shell respectively, and  $\tau$  is the fraction of the spherical shell intercepted by the clumps. The shell intercepted 5 per cent (Woodward et al. 1992) of the luminosity of the central source at maximum; thus  $\tau = 0.05$  and  $\phi = 0.089 N_{\text{cl}}^{-1/2}$ . This shows that the filling factor must be less than 0.1. We therefore assumed a filling factor of  $\sim 10$  per cent. We assumed a spherical shell and a covering factor of unity. Our spectra lack lines of the other elements which CLOUDY requires for modelling (i.e., Ni, Ca, Ar, etc.). Fortunately, these elements are trace species and do not contribute much to the electron density. Setting their abundances to zero did not affect our results. An upper limit for their abundances could have been found by increasing their abundances until CLOUDY predicted the presence of lines that were not seen in the spectra. Again this did not seem reasonable, since their presence, or absence, did not change our results. We have therefore left them at their solar values.

We initially used individual CLOUDY runs, adjusting the parameters between the runs, to obtain a rough fit to the observations. To determine the goodness of the fit, we used the  $\chi^2$  of the model:

$$\chi^2 = \sum_i \frac{(M_i - O_i)^2}{\sigma_i} \quad (4)$$

where  $M_i$  is the modelled line flux ratio,  $O_i$  is the observed line flux ratio, and  $\sigma_i$  is the error in the measurement of the

observed flux for each line (Austin et al. 1996). Once this rough fit ( $\chi^2 < 100$ ) was obtained, we then used one or more of our minimization routines to fine-tune the model. From our observations, we had 18 emission lines on which to base our fit. Of the 23 input parameters in CLOUDY we fixed nine (the covering factor and eight abundances for which we had no data). Thus we had 14 free parameters, resulting in four degrees of freedom. Following the general rule that a good

fit should have a  $\chi^2$  equal to the number of degrees of freedom, we attempted to find fits with  $\chi^2 \sim 4$ .

We used three separate minimization routines. The first routine used was the Metropolis algorithm described by Austin et al. (1996). This routine uses Monte Carlo simulations to fit the observations, and has been successful in modelling other ONeMg novae (Nova Cyg 92, QU Vul; Austin et al. 1996). However, when we applied the Metrop-

Table 5. Model parameters.

Parameter	Simplex	Migrad	Migrad Lower Limit	Migrad Upper Limit
$T_{eff}$	$3.2 \times 10^5$ K	$3.2 \times 10^5$ K	$2.7 \times 10^5$	$3.6 \times 10^5$
$L$	$7.9 \times 10^{36}$ (erg s $^{-1}$ )	$5.1 \times 10^{36}$ (erg s $^{-1}$ )	$2.3 \times 10^{36}$	$2.0 \times 10^{37}$
density	$3.7 \times 10^6$ cm $^{-3}$	$4.2 \times 10^6$ cm $^{-3}$	$2.4 \times 10^6$	$8.1 \times 10^6$
density law, $\alpha$	$-1.9 \times 10^{-3}$	$-7 \times 10^{-4}$	-0.55	1.10
inner radius	$2.5 \times 10^{14}$ cm	$6.0 \times 10^{14}$ cm	$6.01 \times 10^{13}$	$1.09 \times 10^{15}$
outer radius	$4.0 \times 10^{15}$ cm	$3.2 \times 10^{15}$ cm	$1.66 \times 10^{15}$	—
filling factor	0.1	0.17	0.09	0.47
filling factor law	0.39	0.40	-0.5	2.5
geometry	sphere	sphere	—	—
He	0.3	0.3	0.1	0.8
C	4.6	5.2	1.8	11.0
N	13.7	15.3	6.2	24.8
O	0.3	0.3	0.1	0.5
Ne	28.5	37.0	26.8	52.2
S	6.9	6.7	1.7	12.3

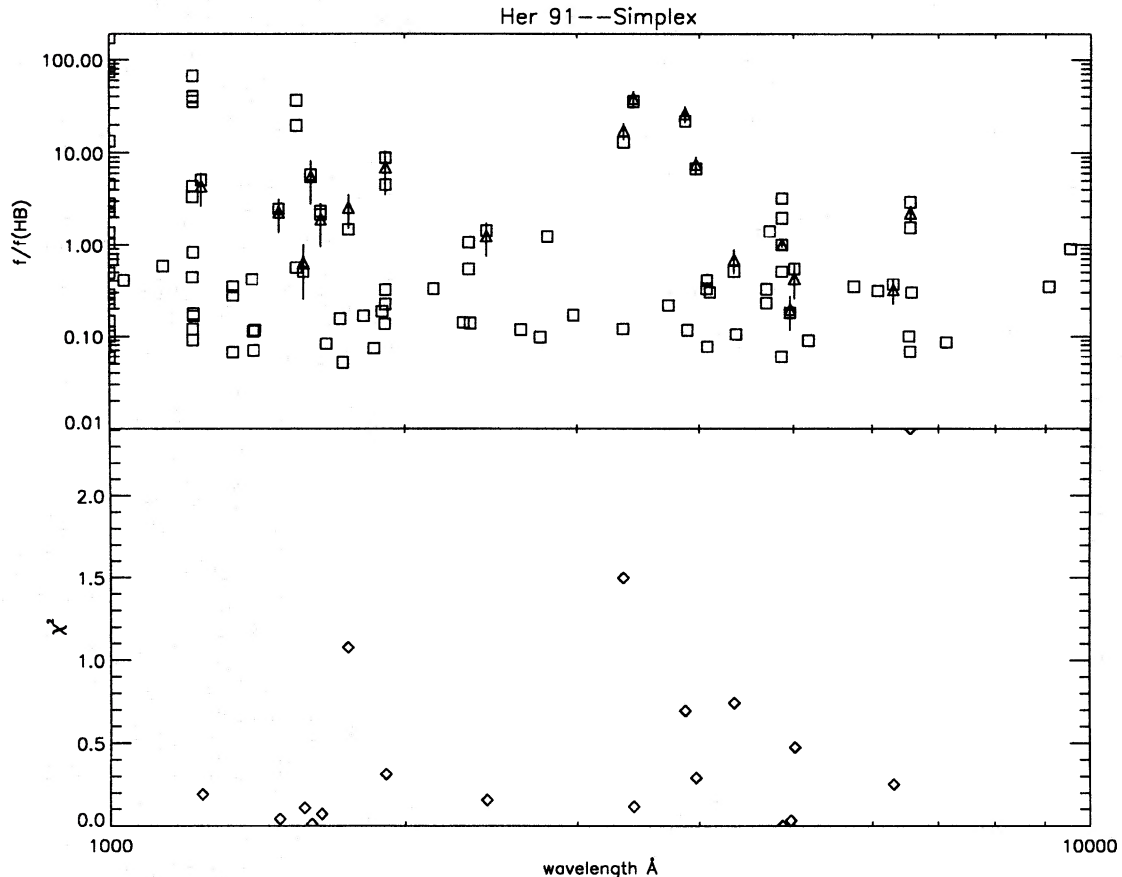


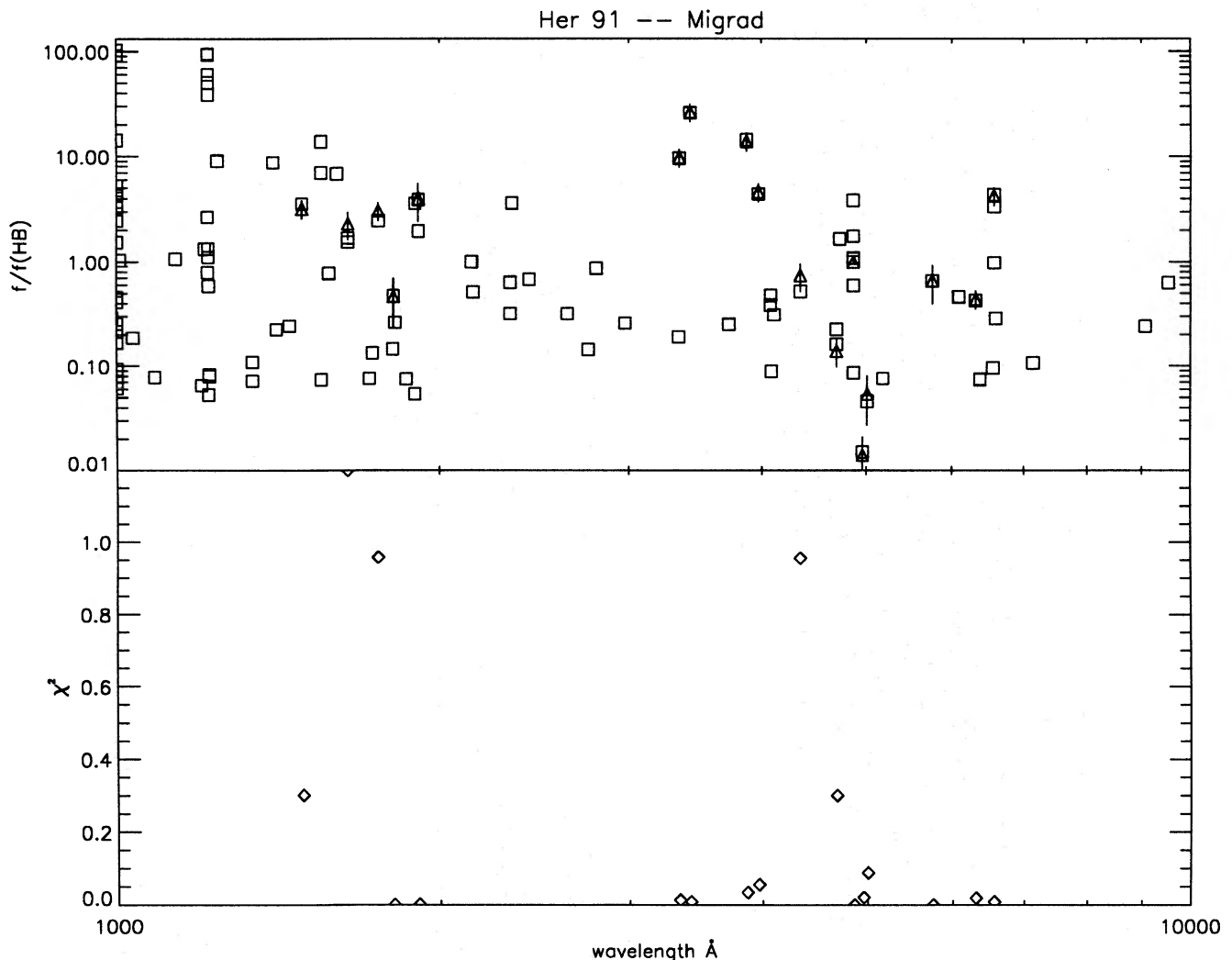
Figure 8. Simplex best-fitting results. The top frame shows the flux of the strongest lines compared to that of H $\beta$ . The triangles represent the observations, while the squares are the model predictions. The bottom frame is the  $\chi^2$  for each observed line.

olis algorithm to Her 91, it converged to a solution with unphysical parameters [e.g.,  $\log(N_{\text{H}})=9.5$ , filling factor = 1.0] and  $\chi^2 \sim 56$ . We interpret the routine's inability to fit our data as an indication that the true minimum is in an isolated, narrow valley in the 14-fold parameter space. With the stepping routine that Metropolis uses, we estimate that it would take many iterations ( $\gg 10\,000$ ) for it to find the true minimum.

We therefore obtained the minimization routine `MINUIT` from the CERN program library (James & Roos 1993). `MINUIT` has the ability to run two types of minimizations which do not use random stepping but rather step in the direction of lower  $\chi^2$ , thereby using the shape of the parameter space to find the minima. These are the simplex and Migrad routines.

The simplex routine uses the method of Nelder & Mead (1965). The method uses function evaluations, not derivatives. Given starting points and initial step sizes ( $\sim 10$  per cent of the starting point), this routine will change each parameter individually and thus map out the parameter space. Simplex then steps to the lowest  $\chi^2$  and varies the parameters again. In this way the routine works its way

down the valleys of the parameter space. We were forced to place limits on our parameters in order to prevent the routine from choosing values outside of the boundaries set by `CLOUDY` (e.g., negative abundances). Using our rough fit as a starting point, the simplex routine converged to a fit of  $\chi^2 = 8.48$ . The values of the parameters at this fit are listed in Table 5. Since the routine stops once a minimum is found without sampling the rest of the parameter space, it is possible to become stuck in a local minimum. To ensure that our solution was the true minimum, we re-ran the routine many times with different starting points. Each time a solution was found, but none with a lower  $\chi^2$  than the original fit ( $57 \leq \chi^2 \leq 137$ ). Fig. 8 shows a plot of the model results. The upper frame of Fig. 8 shows the flux of the strongest lines relative to  $\text{H}\beta$ . The squares represent all lines calculated by `CLOUDY`, and the triangles represent the observations. The lower frame shows the  $\chi^2$  for each observed line.  $\text{C IV } 1549 \text{ \AA}$  was not included in our model at first, since `CLOUDY` has difficulty in reproducing the flux of this resonance line (Austin et al. 1996). Nevertheless, the predicted strength of the line was only 50 per cent too large, and when we did include it our  $\chi^2$  increased only to 10.87.



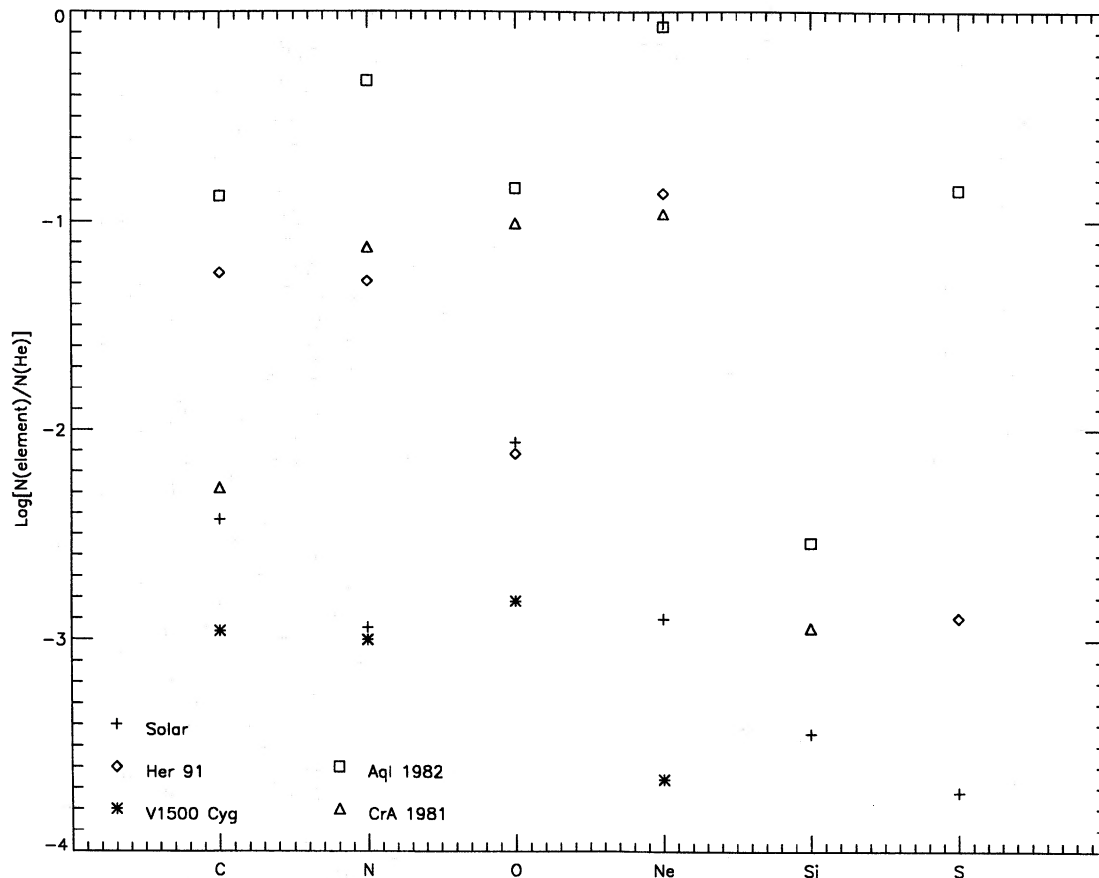
**Figure 9.** Migrad best-fitting results. The top frame shows the flux of the strongest lines compared to that of  $\text{H}\beta$ . The triangles represent the observations, while the squares are the model predictions. The bottom frame is the  $\chi^2$  for each observed line.

The most powerful method available to us is the Migrad routine, which uses the Davidson–Fletcher–Powell (DFP) variable-metric algorithm, a quasi-Newton’s method (Press et al. 1986). This routine is more complete and efficient than the simplex routine, since it maps out the parameter space and finds the shortest path to the minimum. Migrad uses not only the function values but their derivatives as well, finding the steepest slope in parameter space and hence the quickest descent to the minimum. Just as with the simplex method, we input starting points, step sizes, and limits. With our rough fit as the starting point, Migrad converged to a fit of  $\chi^2 = 5.96$ . As with simplex, we then re-ran it with various starting points to confirm our minimum. All other fits had much larger  $\chi^2$  than the original ( $43 \leq \chi^2 \leq 162$ ). The results of the Migrad routine are given in Table 5, and the model results are plotted in Fig. 9. Again C IV 1549 Å was not included in our model, although the addition of this line only raises the  $\chi^2$  to 8.84.

The Migrad solution has the lowest  $\chi^2$ . The prediction of the flux from each line matches the observations better than any of the other models we tried, and hence we choose those values of the physical parameters as our best fit. We have placed error bars on the parameters corresponding to the amount the parameter could be changed (all others held constant) and still give less than a factor of 2 change in  $\chi^2$ . These errors are listed in Table 5. It can be seen that the

results of the simplex and Migrad routines are very similar, with the simplex values falling within the error bars of the Migrad solution.

Our best Migrad model ( $\chi^2 = 5.96$ ) has a blackbody continuum at  $T = 320\,000$  K. Since a blackbody is a poor assumption, in a future paper we will replace the blackbody with a non-LTE model atmosphere (Werner & Heber 1991). We find the luminosity to be  $L \sim 5 \times 10^{36}$  erg s<sup>-1</sup>, which is lower than expected for a typical nova at two months after outburst. We discuss the implications of this result in Section 7. The inner and outer radii of the model correspond to expansion velocities of  $\sim 1000$  and  $\sim 7000$  km s<sup>-1</sup>, respectively. These velocities agree with those measured from our spectra. Our model indicates a uniform density ( $\alpha = -7 \times 10^{-4} \sim 0$ ) of  $N_{\text{H}} = 4.2 \times 10^6$  cm<sup>-3</sup>. Given the thinness of the shell and the high expansion velocities, a constant density is quite acceptable. We did find minima at higher densities, but these values were  $\geq 10^9$  cm<sup>-3</sup>. The value of the filling factor, 0.15, is near the upper limit of the range determined by Harrison & Stringfellow (1994). Our model shows helium and oxygen to be underabundant relative to solar by a factor of 0.3 each. Carbon, nitrogen, neon and sulphur are all overabundant by factors of 4.6, 13.7, 28.5 and 6.9, respectively. We have plotted our abundance determinations (relative to helium), along with the abundances determined for other ONeMg novae, in Fig. 10.



**Figure 10.** Elemental abundances relative to He for Her 91 (this paper), Sun (Cameron 1973; Lambert 1978), CrA 1981 (Williams et al. 1985), V1500 Cyg (Ferland & Shields 1978), and Aquil 1982 (Snijders et al. 1987).

## 6 THE ABUNDANCE COMPARISON WITH MATHESON, FILIPPENKO & HO

Matheson et al. (1993) also used `CLOUDY` to perform an abundance analysis of Her 91. The spectrum they modelled was obtained on 1991 August 20, three months after our primary spectra, which makes a direct comparison between their results and ours difficult. However, we do not expect the abundances to vary with time and thus, while the temperature and density will be necessarily different, the abundances should be the same. We find little agreement with our results. We find helium underabundant, while they found a value of 4 times solar. Matheson et al. modelled the neon lines with a neon abundance only 10 times solar, while we found a neon abundance of 37 times solar was needed. Although Matheson et al. obtained a sulphur abundance of 100 times solar, we were able to fit the sulphur lines with an abundance of only 6.7 times solar. We believe that these discrepancies are a result of different input parameters for `CLOUDY`, in particular, the value of the luminosity. Matheson et al. used a luminosity of  $10^{38}$  erg s $^{-1}$ , a factor of 20 times greater than our value, even though the spectrum they analysed was obtained three months after ours. Another difference between our parameters and theirs is the choice of filling factor. Matheson et al. used a filling factor of 1.0, while we used a value of 10 per cent based on the structure of the lines. This seems more reasonable, since novae do not eject material in smooth, uniformly filled shells (Shore et al.

1993) and the line profiles shown in Matheson et al. imply clumpy ejection. They also used an aluminium abundance of 200 times solar (we chose a solar abundance). If we use this value in our model, we find the predicted Al III 1860-Å and Al II] 2669-Å line strengths to be far in excess of those lines in the observed spectra.

In order to compare the models more directly, Matheson et al. kindly sent us their spectra. We have obtained a fit for their spectrum of 1991 August 20, using the input parameters stated in their paper. This fit is shown in Fig. 11. Their model assumed a solar oxygen abundance. They stated, however, that this was probably overestimating the true abundance. While their model predictions do fit some of the optical observations, Matheson et al. obtained only optical spectra. From Fig. 11 we can see what `CLOUDY` predicts for the UV wavelengths with the given abundances. As we do not have any UV data for this date, we could not determine whether or not the UV predictions were correct. We then combined Matheson et al.'s 1991 May 5 optical spectrum with our closest corresponding UV spectrum of 1991 April 22 (using the overlap in wavelength coverage to correct for any systematic flux differences) and applied their model, adjusting the blackbody continuum temperature and hydrogen density within the acceptable ranges stated in their paper to get the best fit to the observations. The best fit, using Matheson et al.'s abundances, was obtained with a continuum blackbody temperature of  $T \sim 3.0 \times 10^5$  K and a hydrogen density of  $1 \times 10^8$  cm $^{-3}$ . The results are shown in

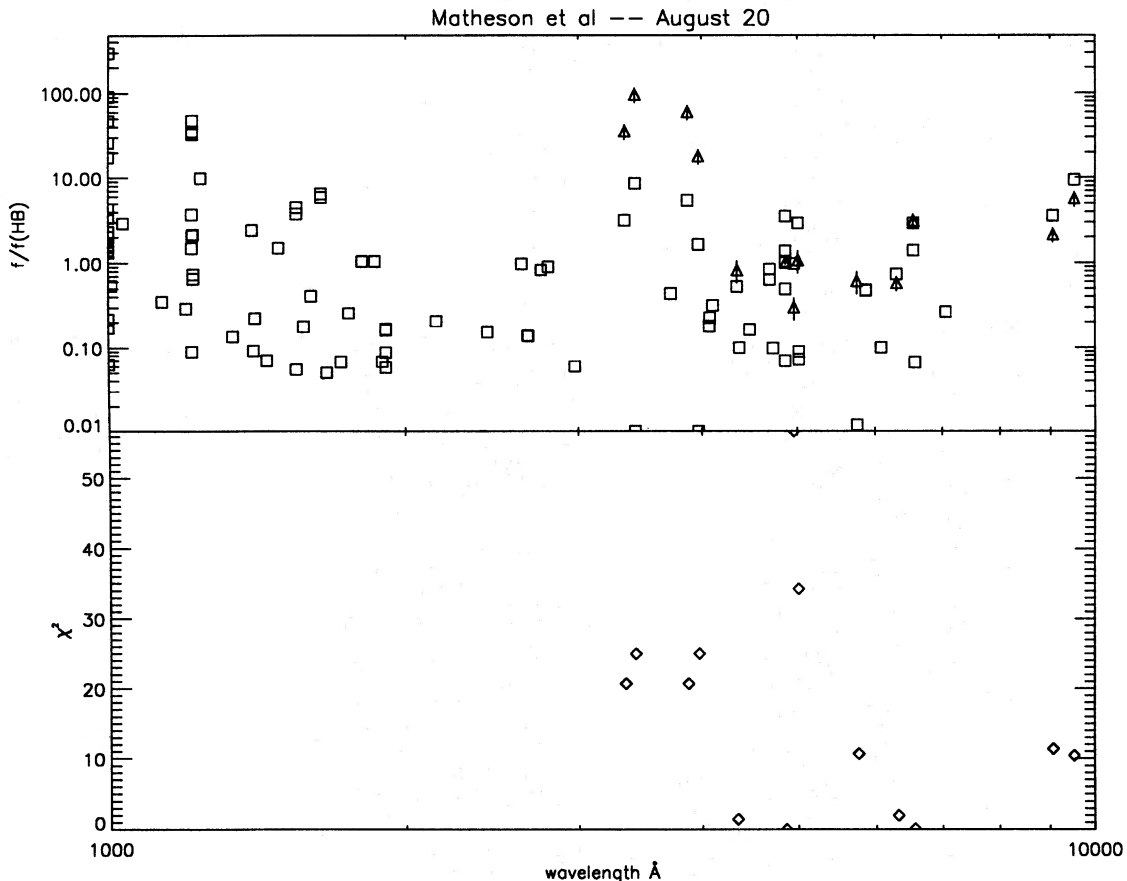
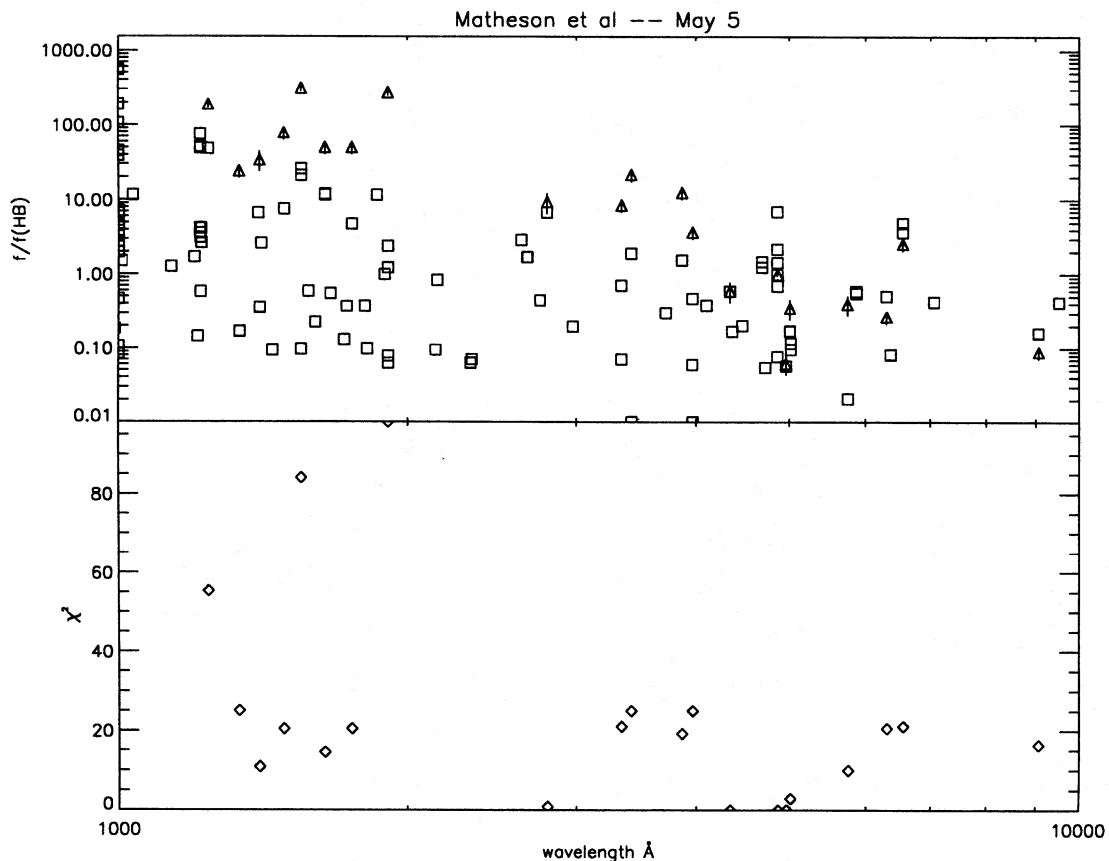


Figure 11. Matheson et al.'s best-fitting model as described in their paper.



**Figure 12.** Matheson et al.'s model as applied to their optical spectrum of 1991 May 5 combined with our UV observation of 1991 April 22.

Fig. 12. While their model again roughly fits the optical observations, it fails to fit any of the UV lines. This demonstrates that UV data are *crucial* in determining accurate elemental abundances for novae.

## 7 DISCUSSION OF MODEL RESULTS

One of the more interesting results of our study is the low value of the luminosity,  $L \sim 10^{36}$  erg s $^{-1}$ . A typical nova, even a fast one, is expected to be at or near the luminosity it had near maximum light, two months after outburst. We attempted to fit the observations using a luminosity of  $\sim 10^{38}$  erg s $^{-1}$ . At this luminosity, however, the value of the outer radius was  $\sim 10^{16}$  cm, which would have required an expansion velocity greater than 18 000 km s $^{-1}$ . With smaller values of the outer radius, a model with such a high luminosity overpredicts the strengths of the high-ionization lines. Our model predicts the IR luminosity to be  $L_{\text{IR}} = 4.8 \times 10^{32}$  erg s $^{-1}$  and the X-ray luminosity to be  $L_{\text{X-ray}} = 4.6 \times 10^{34}$  erg s $^{-1}$ . It therefore appears that, at only 62 d after outburst, Her 91 had *turned off!* *ROSAT* observations made by Szkody & Hoard (1994) 1.5 yr after outburst show the X-ray luminosity to be  $L_{\text{X-ray}} \sim 10^{32}$  erg s $^{-1}$ . A short observation (4425 s) taken about 1 yr after outburst was also analysed by Szkody & Hoard, and it also indicated a low level of X-ray emission. If Her 91 had indeed turned off after two months, this would be the fastest turn-off time ever observed (Shore, Starrfield & Sonneborn 1996). This would imply that the

progenitor star is a white dwarf of mass greater than  $1.3 M_{\odot}$ , which is consistent with the fast decline of Her 91 (Krautter et al. 1996). Since a massive white dwarf will accrete and eject very little material, we therefore expect the ejected mass of the nova shell to be small. Our results are supported by the observations of eclipses in Her 91 by Leibowitz et al. (1992). Their observations were made in 1991 May and indicate that one could see through the ejected shell to the accretion disc by this date. Using our value of  $L \sim 5 \times 10^{36}$  erg s $^{-1}$  and  $T \sim 3 \times 10^5$  K, we find a radius for the white dwarf of  $R \sim 8 \times 10^8$  cm. This is close to the pre-outburst radius for a white dwarf, and is in agreement with the accretion disc being reestablished. With a luminosity of  $\sim 10^{38}$  erg s $^{-1}$ , the radius of the white dwarf would be  $R \sim 4 \times 10^9$  cm, almost an order of magnitude larger.

Given our density law, shell radii, filling factor and abundances of our best Migrad model, we find  $M_{\text{ej}} \sim 1.8 \times 10^{-4} M_{\odot}$ . The upper and lower limits on our parameters give values of the ejected mass  $M_{\text{ej}} \sim 9.6 \times 10^{-3} M_{\odot}$  and  $\sim 1.6 \times 10^{-7} M_{\odot}$ , respectively. Most of the ejected mass that we are seeing at this time in the outburst is the mass contained in the denser knots of slower moving material. If we use this fact that the ejecta were opaque for the first few days, then we can estimate the column density to be at least  $\sim 10^{22}$  cm $^{-2}$ , implying an ejected mass of  $\sim 5 \times 10^{-6} M_{\odot}$ . Hence, at early times we are not seeing very far into the shell, and it is only at later times that the densest material can be seen. The value for the

ejected mass,  $M_{\text{ej}} \sim 1.8 \times 10^{-4} M_{\odot}$ , strongly implies an outburst on a massive white dwarf. We predict, based on the fast decline from maximum light and the value of the ejected mass, that the mass of the underlying white dwarf is  $M_{\text{WD}} > 1.25 M_{\odot}$ . In contrast, Szkody & Ingram (1994) estimate the mass of the white dwarf, from their velocity curves of the H $\alpha$  emission line, and find that  $M_{\text{WD}} = 0.75\text{--}0.99 M_{\odot}$ . While this is higher than the average white dwarf mass, it is not massive enough to support our results. However, Szkody & Ingram state that a good mass estimate of Her 91 was hindered by a close companion as well as emission from the accretion disc. Our value for the ejected mass of Her 91 exceeds those values for V1974 Cyg 92 (Austin et al. 1996) and Pup 91 (Saizar et al. 1996). This is a puzzling result, since these two ONeMg novae were considerably slower than Her 91, implying that the explosion took place on a lower mass white dwarf. This, in turn, would imply that a larger amount of material should be accreted and later ejected. However, another indication of a massive progenitor is an increased N/O ratio and an enhanced sulphur abundance (Starrfield et al. 1992; Politano et al. 1995). Our model abundances show nitrogen to be enhanced by a factor of 15 over solar, oxygen to be underabundant by a factor of 0.3, and sulphur to be enhanced by 6.7 with respect to solar.

Our analysis of the ejected material from the outburst of Her 91 is in excellent agreement with the hydrodynamic predictions of Starrfield et al. (1986) and the abundance predictions of Politano et al. (1995; see also Starrfield et al. 1992). Starrfield et al. (1986) studied accretion of oxygen-enriched material on to massive white dwarfs and found that the entire accreted shell was ejected during the explosive phase of the outburst. They also found that the bolometric luminosity was never constant, but began declining immediately after maximum. Politano et al. (1995) also studied accretion on to massive white dwarfs, but used a much larger nuclear reaction network. They found that a thermonuclear runaway in oxygen, neon material enriched in magnesium on a  $1.35\text{-}M_{\odot}$  white dwarf resulted in a violent outburst, and that the ejected material was enriched in sulphur and depleted in oxygen.

## 8 SUMMARY AND DISCUSSION

From our combined UV and optical observations, we have determined the reddening of Her 91 to be  $0.4 < E(B - V) \leq 0.6$ , with the most likely value being closer to 0.6. This is in good agreement with values obtained by Lynch et al. (1992) and Starrfield et al. (1992). We have placed an upper limit on the distance to Her 91 at 4.2 kpc. The lower limit we determined to be 2.5 kpc. Comparing our results to the distances of Starrfield et al. (1992) and Woodward et al. (1992), the true distance is probably around 3 kpc, closer to the lower limit we have determined.

Our abundance determinations indicate that the ejecta are enhanced in carbon, nitrogen, neon and sulphur. Neon is enhanced by 37 times solar, indicating that Her 91 is a member of the neon novae class. The weakness of the oxygen lines in our spectra, which is unusual for a nova, is due to an actual underabundance of oxygen in the ejecta. Our best fit requires that oxygen be 0.3 times solar. We find an

overabundance of sulphur, giving rise to strong sulphur lines in the near-IR, of order 6.7 times solar. Starrfield et al. (1992) found in their models of nova outbursts that the N/O ratio increased with increasing white dwarf mass, as did the mass fraction of sulphur. The high N/O ratio that we observed and the enhanced sulphur abundance imply that Her 91 is probably a result of mass accretion on to a massive ONeMg white dwarf. This is supported by the low value we find for the ejected mass,  $M_{\text{ej}} \sim 1.8 \times 10^{-4} M_{\odot}$ .

The low luminosity that we found at two months after outburst leads us to believe that Her 91 had turned off by this time, which again implies that the outburst took place on a very massive white dwarf (Starrfield et al. 1986). From our early spectra, when the total optical plus UV output was at a maximum, we find the integrated luminosity to be  $1.8 \times 10^{38} \text{ erg s}^{-1}$ . This implies that Her 91 was super-Eddington at maximum, which agrees with observations of LMC 1990 #1, another fast ONeMg nova.

## ACKNOWLEDGMENTS

We thank T. Matheson and A. Filippenko for numerous discussions and for providing us with their spectra for comparison. We also thank R. E. Williams for providing us with optical spectra to use in our analysis, J. MacDonald for supplying us with his hot white dwarf model atmospheres, as well as the people at CERN for making MINUIT available to us. We also thank the referee for helpful comments. This work has been supported in part by NSF and NASA grants to ASU. We are grateful to the *IUE* Observatory for their support in obtaining the *IUE* data necessary for this study.

## REFERENCES

- Austin S. J., Wagner R. M., Starrfield S., Bertram R., Shore S. N., Sonneborn G., 1996, *AJ*, 111, 869  
 Chandrasekhar T., Ashok N. M., Ragland S., 1992, *MNRAS*, 255, 412  
 Cohen J. G., 1985, *ApJ*, 292, 90  
 Dopita M., Ryder S., Vassiliadis E., 1991, *IAU Circ. No. 5262*  
 Ferland G. J., 1977, *ApJ*, 215, 873  
 Ferland G. J., 1993, Department of Physics & Astronomy Internal Report (Univ. of Kentucky)  
 Harrison T. E., Stringfellow G. S., 1994, *ApJ*, 437, 827  
 Hauschildt P. H., Wehrese R., Starrfield S., Shaviv G., 1992, *ApJ*, 393, 307  
 Hauschildt P. H., Starrfield S., Austin S., Wagner R. M., Shore S. N., Sonneborn G., 1994, *ApJ*, 422, 831  
 Hauschildt P. H., Starrfield S., Shore S. N., Allard F., Baron E., 1995, *ApJ*, 447, 829  
 Ingram D., Garnavich P., Green P., Szkody P., 1992, *PASP*, 104, 402  
 James F., Roos M., 1993, MINUIT, CERN Program Library D506  
 James G. K., Kanik I., Ajello J. M., 1995, *ApJ*, 455, 769  
 Kidger M. R., Martinez-Roger C., 1993, *A&A*, 267, 111  
 Krautter J., Ogelman H., Starrfield S., Wichmann R., Pfeiffermann 1996, *ApJ*, 456, 788  
 Lambert D. L., 1978, *MNRAS*, 183, 79  
 Lance K., McCall M. L., Uomoto A. K., 1988, *ApJS*, 66, 151  
 Leibowitz E. M., Mendelson H., Mashal E., Prialnik D., Seitter W. C., 1992, *ApJ*, 385, L49  
 Livio M., 1992, *ApJ*, 393, 516  
 Lloyd H. M., O'Brien T. J., Bode M. F., Predehl P., Schmitt J. H. M. M., Trümper J., Watson M. G., Pounds K. A., 1992, *Nat*, 356, 222

- Lynch D. K., Hackwell J. A., Russell R. W., 1992, *ApJ*, 398, 632  
 Matheson T., Filippenko A. V., Ho L. C., 1993, *ApJ*, 418, L29  
 McNaught R. H., 1991, *IAU Circ. No.* 5222  
 Nelder J. A., Mead R., 1965, *Computer Journal*, Vol. 7, p. 308  
 Osterbrock D. E., 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*. University Science Books, California  
 Panagia N., Gilmozzi R., Macchetto F., Adorf H. M., Kirshner R. P., 1991, *ApJ*, 380, L23  
 Patterson J., 1979, *ApJ*, 231, 789  
 Politano M., Starrfield S., Truran J. W., Weiss A., Sparks W. M., 1995, *ApJ*, 448, 807  
 Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P., 1986, *Numerical Recipes*. Cambridge Univ. Press, Cambridge  
 Rosino L., Tempesti P., 1977, *SvA*, 21, 291  
 Saizar P., Pachoulakis I., Shore S. N., Starrfield S., Williams R. E., Rotschild E., Sonneborn G., 1996, *MNRAS*, 279, 280  
 Shore S., Sonneborn G., Starrfield S., 1990, *IAU Circ. No.* 4949  
 Shore S. N., Sonneborn G., Starrfield S., Riestra-Gonzalez R., Ake T. B., 1993, *AJ*, 106, 2408  
 Shore S., Starrfield S., Sonneborn G., 1996, *ApJ*, 463, L21  
 Snijders M. A., Batt T. J., Roche P. F., Seaton M. J., Morton D. C., Spoelstra T. A. T., Blades J. C., 1987, *MNRAS*, 228, 329  
 Sonneborn G., Shore S. N., Starrfield S., 1990, in Rolfs E., ed., *Evolution in Astrophysics – UV Astronomy in the Era of New Space Missions*. ESA SP-310  
 Starrfield S., Shore S. N., Sparks W. M., Sonneborn G., Truran J. W., Politano M., 1992, *ApJ*, 391, L71  
 Starrfield S., Sparks W. M., Truran J. W., 1986, *ApJ*, 303, L5  
 Sugano M., Alcock G., 1991, *IAU Circ. No.* 5222  
 Szkody P., Hoard D. W., 1994, *ApJ*, 429, 857  
 Szkody P., Ingram D., 1994, *ApJ*, 420, 830  
 Tomkin J., Woodman J., Lambert D. L., 1976, *A&A*, 48, 319  
 Wagner R. M., Bertram R., Ali B., Starrfield S., 1991, *IAU Circ. No.* 5227  
 Werner K., Heber U., 1991, in Crivellari L., Hubney I., Hummer D. G., eds, *Stellar Atmospheres: Beyond Classical Models*. Kluwer, Dordrecht, p. 341  
 Williams R. E., Ney E. P., Sparks W. M., Starrfield S. G., Wyckoff S., Truran J. W., 1985, *MNRAS*, 212, 753  
 Williams R. E., Phillips M. M., Hamuy M., 1994, *ApJS*, 90, 297  
 Woodward C. E., Gehrz R. D., Jones R. J., Lawrence G. F., 1992, *ApJ*, 384, L41  
 Young P. J., Corwin H. G., Jr, Bryan J., de Vaucouleurs G., 1976, *ApJ*, 209, 882