THE ASTROPHYSICAL JOURNAL, 391:L71–L74, 1992 June 1

A PREDICTION OF THE γ-RAY FLUX FROM NOVA HERCULIS 1991

SUMNER STARRFIELD,[1,2] STEVEN N. SHORE,[1,2,3] WARREN M. SPARKS,[4] GEORGE SONNEBORN,[2,5]
JAMES W. TRURAN,[6] AND MICHAEL POLITANO[1]

Received 1992 February 3; accepted 1992 March 13

ABSTRACT

Hydrodynamic simulations of thermonuclear runaways in the accreted hydrogen-rich envelopes on 1.0 $M_\odot$, 1.25 $M_\odot$, and 1.35 $M_\odot$ white dwarfs predict ^{22}Na and ^{26}Al γ-ray emission from ONeMg novae in outburst. We present and discuss the ultraviolet observations made with the *International Ultraviolet Explorer* satellite of Nova Her 1991, the most recent bright ONeMg nova. A distance of 3.4 kpc and reddening of $E(B-V) = 0.6$ to Nova Her 1991 are determined by comparing its UV and optical outburst behavior with those of the extragalactic ONeMg nova LMC 1990 No. 1. Her 1991 was also detected by *ROSAT* five days into its outburst and we argue that a small fraction of the X-rays may be the product of Comptonized 1.2 and 0.5 MeV emission from the decay of ^{22}Na. If the mass of the ejected shell is indeed as high as has been estimated by Woodward et al., $\sim 10^{-4}$ $M_\odot$, then our results predict that ^{22}Na γ-ray emission from the ejecta of Nova Her 1991 should still be detectable by *GRO* in the spring of 1992. The detection level is expected to be $\sim 5\ \sigma$ in a 2 week observation. Such a detection would strongly guide and constrain the hydrodynamic and nucleosynthesis simulations of nova outbursts on massive white dwarfs.

Subject headings: novae, cataclysmic variables — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

A classical nova outburst occurs on the white dwarf component of a close binary system in which the secondary is a cool star which fills its Roche lobe and loses hydrogen-rich material which ultimately arrives on the surface of the white dwarf. Recent studies, based on spectrophotometry done with the *International Ultraviolet Explorer* satellite (*IUE*), have shown that the core material of white dwarfs in nova systems can consist of either carbon and oxygen (CO) or oxygen, neon, and magnesium (ONeMg; Williams et al. 1985; Sonneborn, Shore, & Starrfield 1990 [hereafter: SSS90]; Saizar et al. 1992). Studies have also demonstrated that ONeMg novae might produce significant amounts of both ^{22}Na and ^{26}Al (Weiss & Truran 1990; Nofar, Shaviv, & Starrfield 1991).

Nova Herculis 1991 (Her 1991) was a fast ONeMg nova which was discovered on 1991 March 24 at $V \sim 5$ (Sugano & Alcock 1991). It exhibited one of the fastest declines on record. Early optical spectra showed very strong hydrogen lines in emission, with broad P Cygni profiles extending to a velocity of ~ 7000 km s^{-1} (Della Valle & Turatto 1991). Ultraviolet spectra of Her 1991 obtained with *IUE* on 1991 March 25 revealed an optically thick shell spectrum sharply attenuated shortward of 1700 Å (Sonneborn, Shore, & Starrfield 1991), in contrast to the other fast ONeMg novae observed with *IUE* which were already optically thin at maximum. Mg II λ2800 was in emission, with a FWZI of 7300 km s^{-1}. The line spectrum of the ejecta did not become optically thin until almost a week later. Her 1991 was also detected in the infrared and displayed optically thin dust within a few days of maximum (Woodward et al. 1992). No other fast nova has formed dust this early in the outburst.

ROSAT detected Her 1991 in outburst at a flux of 0.16 ± 0.01 counts s^{-1} on 1991 March 30 (Lloyd et al. 1992). *No nova has been detected in X-rays this early in the outburst*, although other novae have been detected later in their outbursts (Ögelman, Krautter, & Beuermann 1987; Mason et al. 1986). Recent theoretical studies of nova outbursts predict EUV or soft X-ray thermal emission from the white dwarf surface at the time the nova first reaches *bolometric* maximum light (Starrfield et al. 1991). However, the *ROSAT* detection of Her 1991, which was more than 1 week after the explosion, was too late for the X-rays to have been produced by this mechanism. The possibility that the X-rays were produced by a shock running through an extended stellar envelope, as was the case for the X-rays observed during the outburst of RS Oph (Mason et al. 1986; Bode & Kahn 1985), seems unlikely since Her 1991 was found to have a short orbital period of $0^{\rm d}.29764$ (Leibowitz et al. 1992). Such a small binary system leaves insufficient room for the envelope of a red giant as is the case for RS Oph ($P \sim 1$ yr; S. J. Kenyon 1991, private communication). The cause of this early X-ray emission is, therefore, unknown.

This *Letter* proposes that Her 1991 may be emitting γ-rays at an intensity that makes this nova detectable by *GRO* in the spring of 1992.

2. THE OUTBURST AND THE DISTANCE TO NOVA HERCULIS 1991

2.1. *Description of the Outburst*

Ultraviolet spectra were obtained for Her 1991, using the *IUE* satellite, from 1991 March 24 until 1991 July 24 when it faded below the *IUE* detection threshold. The initial spectra showed that the expanding envelope was optically thick, with strong iron peak absorption dominating the spectral appearance (SSS90; Hauschildt et al. 1992). Peak UV brightness

[1] Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287-1504.
[2] Guest Investigator, *International Ultraviolet Explorer Satellite*.
[3] GHRS Science Team, Computer Sciences Corporation, Code 681, NASA/GSFC, Greenbelt, MD 20771.
[4] Applied Theoretical Physics Division, Los Alamos National Laboratory, Los Alamos, NM 87545.
[5] Laboratory for Astronomy and Solar Physics, NASA/GSFC, Code 681, Greenbelt MD 20771.
[6] Department of Astronomy and Astrophysics and Enrico Fermi Institute, University of Chicago, Chicago, IL 60637.

occurred on about 1991 March 31, 1 week after the first *IUE* spectrum was obtained and after optical maximum. The ejecta became completely optically thin in the UV emission lines ∼50 days into the outburst.

The strongest emission lines in the UV spectra were due to carbon and nitrogen. [Ne III] λ3868 appeared in the optical in early 1991 April, along with [Ne V] λ3426, indicating that this nova was a member of the ONeMg class (Dopita, Ryder, & Vassiliadis 1991). The strengths of the neon lines and He II λ4686 increased until they exceeded Hβ later in the outburst. Neon was also detected in the UV, with [Ne V] λ1575 and [Ne IV] λ1602 appearing in mid-April shortly after the start of the optically thin phase. A striking feature of this outburst was the total absence of *any* emission lines that could be attributed to oxygen. Specifically, [O III] λ1667, O III λ3133, and [O III] λλ5007, 4959 were neither present in our UV spectra nor our contemporaneous optical spectra (R. M. Wagner 1991, private communication). An emission feature at 1400 Å was probably due to S IV, rather than Si IV or O IV, since optical spectra showed unusually strong sulfur lines in this nova (R. M. Wagner 1991, private communication).

The behavior described above differed from that of Nova LMC 1990 No. 1 (hereafter; LMC 1990-1) the first extragalactic ONeMg nova (SSS90). Her 1991 exhibited a slow rise in the UV and the initial spectra were optically thick so that they resembled those of CO classical novae (Hauschildt et al. 1992). In contrast, the ejecta of LMC 1990-1 never exhibited an optically thick phase and P Cygni line profiles were observed for all UV resonance transitions, in particular C IV λ1550 and Si IV λ1400, from the first UV observations. An important distinction between these two novae is that all of the UV carbon lines (C II λ1335, C III] λ1910, and C IV λ1550) appear stronger in Her 1991 than in LMC 1990-1 at the same stage in the outburst. As we discuss below, the enhanced carbon, reduced oxygen, and enhanced sulfur are an indication that the white dwarf in Her 1991 is more massive than the one in LMC 1990-1, even though the energetics of the two explosions were quite similar.

Peak UV brightness occurred, for LMC 1990-1, during the first two days of observations which was ∼2 days after optical maximum. In contrast, the UV peak for Her 1991 occurred ∼1 week after optical maximum. The UV flux for Her 1991 declined rapidly following maximum and within the next week its rate of decline approximated that observed for LMC 1990-1. Temporal scaling of the UV photometric evolution implies that perhaps an order of magnitude more mass was ejected by Her 1991 than LMC 1990-1.

The Her 1991 UV light curve (Fig. 1) was initially similar to those of CO novae except that in the early phase, when the line spectrum was optically thick, was shorter. However, once the ejecta became optically thin the two novae evolved nearly identically. In addition, both showed ejection velocities (∼8000 km s^{-1} for LMC 1990-1 and ∼7300 km s^{-1} for Her 1991) similar to other ONeMg novae and much higher than those observed for typical CO novae.

2.2. *Distance to Nova Herculis 1991*

Woodward et al. (1992) used the $M_{V,\max} - t_3$ relation to estimate a distance of 6.5 kpc and also obtained a value of the extinction for Her 1991 ($A_v \sim 0.9$ mag). From IR photometry they derived a graybody angular diameter for the dust shell

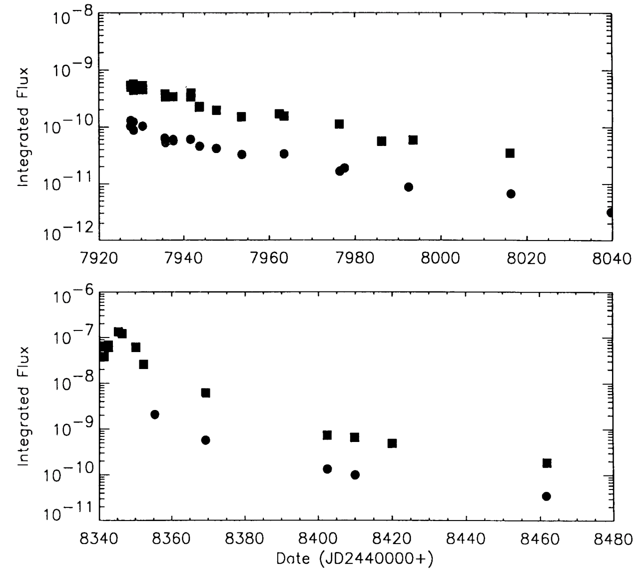

FIG. 1.—Light curves for Nova LMC 1990 No. 1 (*top*) and Nova Her 1991 (*bottom*). Reddening corrections of $E(B-V) = 0.15$ and $E(B-V) = 0.60$ have been applied, respectively (see text). The filled squares are the SWP data and the filled circles are the LWP data. Each data point is obtained by integrating the spectrum from the respective *IUE* camera.

which yielded a distance of ∼2.8 kpc. They preferred the smaller distance.

We have developed a new distance method which is based on our spectrophotometric studies of novae in the LMC and an assumed distance to the LMC of 55 kpc. Here, we compare the evolution of the UV spectrum of Her 1991 with LMC 1990-1 (SSS90). Both novae were observed before UV maximum and well-spaced UV observations of each nova extended to ∼100 days after discovery. The UV data for LMC 1990-1 are consistent with a luminosity at the peak that is comparable to the Eddington limit (solar abundances) for a 1.4 $M_\odot$ white dwarf (SSS90).

Our method depends on the fact that absolutely calibrated fluxes are provided by the *IUE* Observatory and relies on the ratio of the UV flux above and below 2000 Å. This method assumes that the observed differences in the LWP/SWP flux ratio, at late times in the outburst, are caused only by differences in the reddening to each nova. Note that this ratio is *independent* of distance. We assume, here, that the dereddened values should be the same for both novae since the spectroscopic development and decline rates were very similar (Fig. 2). Fortunately, the reddening to the LMC is both small and well known (Fitzpatrick 1986). The ratio of the LWP to SWP integrated fluxes for LMC 1990-1, corrected for reddening with $E(B-V) = 0.15$ and the Fitzpatrick (1986) extinction law, reached an asymptotic value of 0.19. The LWP/SWP flux ratio for the Her 1991 spectra also approached an asymptotic value. Comparing the asymptotic value of the ratio for Her 1991 with that of LMC 1990-1, allows us to rule out $E(B-V) < 0.5$ (the LWP/SWP ratio for Her 1991 would exceed 0.25) and $E(B-V) > 0.7$ (the LWP/SWP ratio for Her 1991 would be smaller than 0.14). Agreement in the LWP to SWP flux ratio between Her 1991 and LMC 1990-1 is obtained for $E(B-V) = 0.6 \pm 0.1$ mag. Using this value plus ratio of the bolometric fluxes for the two novae, we derive a distance of 3.4 ± 1.6 kpc to Her 1991.

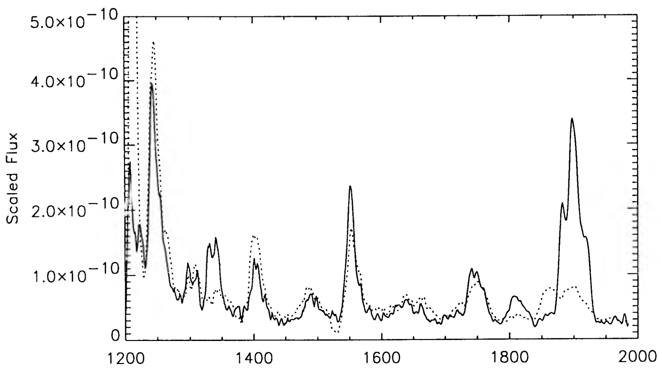

FIG. 2.—A spectrum of Nova Her 1991 (SWP 4182), dereddened by 0.6 mag (*solid line*), compared with Nova LMC 1990 No. 1 (SWP 38090) (*dashed line*) dereddened by 0.15 mag and scaled by the flux ratio (factor of 270) (see text for discussion).

TABLE 2

EJECTED ABUNDANCES (Mass Fraction)

Sequence	1	2	3
X	0.33	0.30	0.27
Y	0.17	0.19	0.20
$^{12}C + {}^{13}C\,(10^{-2})$	0.94	4.3	3.4
$^{16}O + {}^{17}O\,(10^{-2})$	11.8	7.0	1.1
$^{20}Ne + {}^{21}Ne + {}^{22}Ne\,(10^{-3})$	0.25	0.23	0.17
$^{22}N\,(10^{-3})$	0.05	1.7	5.7
$^{24}Mg + {}^{25}Mg + {}^{26}Mg\,(10^{-2})$	5.9	3.8	4.4
$^{26}Al\,(10^{-3})$	19.6	9.4	7.4
$^{27}Al\,(10^{-2})$	1.4	1.6	1.9
$^{28}Si + {}^{29}Si + {}^{30}Si\,(10^{-2})$	1.6	5.8	5.3
$^{31}P\,(10^{-4})$	0.02	40.2	202
$^{32}S\,(10^{-4})$	1.1	29.4	289
$^{36}Ar\,(10^{-5})$	1.9	2.1	40.9

3. THEORETICAL STUDIES OF OUTBURSTS ON OXYGEN-NEON-MAGNESIUM-NOVAE

Weiss & Truran (1990) and Nofar, Shaviv, & Starrfield (1991), have reported the results of calculations which simulate the synthesis of ^{22}Na and ^{26}Al in ONeMg-rich novae. Their calculations were performed with large nuclear reaction networks which utilized temperature, density, and time profiles obtained from earlier hydrodynamic simulations of CO outbursts. The results of both their studies can be summarized as follows: (1) extremely low levels of ^{26}Al and ^{22}Na are expected to be formed in nova envelopes with a solar composition. (2) Enrichment of only the CNO nuclei does not significantly increase the production of ^{22}Na or ^{26}Al. (3) Greatly increased ^{22}Na and ^{26}Al production does result from envelopes with substantial initial enhancements of elements in the range from neon to aluminum. (4) Novae with ejecta rich in material from an ONeMg white dwarf may represent an important source of ^{26}Al in our Galaxy. The results from the nucleosynthesis studies must be verified by hydrodynamic evolutionary studies since convective mixing carries material from the surface layers into the nuclear burning region.

We have used a one-dimensional hydrodynamic computer code which incorporates a large nuclear reaction network to follow the changes in abundance of 78 nuclei up to ^{40}Ca (Kutter & Sparks 1972; Politano et al. 1992). We evolved thermonuclear runaways in the accreted hydrogen-rich layers of white dwarfs with masses of 1.0 $M_{\odot}$, 1.25 $M_{\odot}$, and 1.35 $M_{\odot}$. Some of the model parameters and abundance results are given in Tables 1 and 2. The rate of accretion onto the white dwarf, in all cases, was 10^{17} g s^{-1} (1.6×10^{-9} $M_{\odot}$ yr^{-1}) and the initial abundances of the ONeMg nuclei total 50% of the envelope material (by mass). The remaining 50% consisted of a solar mixture of the elements. It is assumed that this composition resulted from the mixing of the accreted layers with core material.

TABLE 1

MODEL RESULTS

Sequence	1	2	3
Mass ($M_{\odot}$)	1.00	1.25	1.35
M_{acc} (10^{-5} $M_{\odot}$)	10.5	3.2	1.5
ϵ_{nuc}(peak) (10^{17})	0.21	1.0	1.9
T_p (10^6 K)	224	290	356
L_p (10^5 $L_{\odot}$)	0.22	0.43	1.63
T_{eff} (10^5 K)	3.40	6.42	9.02
M_{ej} (10^{-6} $M_{\odot}$)	9.3	2.7	10.1

Our simulations show that the violence of the outburst increases as the mass of the white dwarf increases and, for a 1.35 $M_{\odot}$ white dwarf, the peak temperature is high enough ($T = 3.56 \times 10^8$ K) for significant nucleosynthesis. This is confirmed by an examination of the abundances given in Table 2. Note that the abundance of ^{26}Al declines and ^{22}Na increases as the mass of the white dwarf increases, and they are both much larger than reported in the nucleosynthesis calculations. This suggests that these ONeMg novae, which exhibit the largest production of ^{26}Al, may not be the same novae that produce enhanced ^{22}Na. As we proceed to higher white dwarf masses, the abundances of ^{31}P, ^{32}S, and ^{36}Ar increase to very large values. All of these nuclei are produced by proton captures on ^{20}Ne and ^{24}Mg over the few minutes of the explosion and are thoroughly mixed in the ejecta.

We also call attention to the behavior of the light nuclei in our results. ^{12}C increases in abundance with white dwarf mass, but ^{16}O decreases in abundance. In contrast, the total neon abundance remains virtually constant. This may explain the puzzling feature that all of the observed ONeMg novae show strong neon lines even when the Mg or Al lines are weak. The observations of Her 1991 imply that oxygen is depleted, in this ONeMg nova, while sulfur may be enhanced. We interpret these data as implying that the explosion occurred on a very massive white dwarf but the fact that it may have ejected more mass than the typical ONeMg nova implies that it either had a lower luminosity, lower accretion rate, or both.

4. γ-RAY LUMINOSITY OF NOVA HERCULIS 1991

^{22}Na has a half-life of $\tau_{1/2} = 2.6$ yr and produces a γ-ray with an energy $E_{\gamma} = 1.275$ MeV in its decay to ^{22}Ne. Based upon our results for ^{22}Na production, we find that the luminosity of the nova in ^{22}Na γ-ray photons is

$$n_{\gamma} = 4 \times 10^{-5} \times \left(\frac{M_{ej}}{10^{-5}\ M_{\odot}}\right) \times \left(\frac{X_{^{22}Na}}{10^{-3}}\right) \times \left(\frac{D}{\mathrm{kpc}}\right)^{-2} e^{-t/3.75\ \mathrm{yr}}\ \mathrm{cm^{-2}\ s^{-1}}\ ,$$

where $X(^{22}Na)$ is the mass fraction of ^{22}Na in the ejecta, M_{ej} is the ejected envelope mass, and D is the distance in kiloparsecs.

Table 2 shows that the γ-ray photon emission can reach ~ 15 $L_\odot$ for a 1.35 $M_\odot$ white dwarf which ejects a mass of 10^{-5} $M_\odot$ (Starrfield et al. 1992). The measured *ROSAT* count rate corresponds to $\sim 2 \pm_1^2 \times 10^{34}$ ergs s^{-1}, assuming a distance of 3.4 kpc. The mass quoted by Woodward et al. (1992) of $\sim 7 \times 10^{-5}$ $M_\odot$ is an upper limit to the mass of the shell. Combining this value with the shell radius, $\sim 3 \times 10^{14}$ cm at the time of the X-ray detection, we find that the Compton optical depth for 1.275 MeV photons at the time of the *ROSAT* observation was greater than unity. Therefore, Compton scattering, which degrades the energy of the ^{22}Na γ-rays down to X-ray energies where they can photoionize the ejecta (Pinto & Woosley 1988), is probably responsible for only a small fraction of the X-ray emission from Her 1991.

5. SUMMARY AND DISCUSSION

This paper has reported four important results with respect to the outburst of Nova Her 1991.

First, the distance to this nova is ~ 3.4 kpc and the reddening is about $E(B-V) \sim 0.6$ based on a new method which compares *IUE* spectra of this nova to those obtained during the outburst of LMC 1990-1. This distance, in combination with the distance of Woodward et al. (1992) of 2.8 kpc, shows that the $M_{V,\max} - t_3$ distance method has failed for this nova.

Second, Her 1991 and LMC 1990-1 were ONeMg novae with very similar outbursts. The fact that Her 1991 was optically thick at maximum implies that this nova ejected more mass than a typical fast ONeMg nova and possibly as much as QU Vul, the only slow ONeMg nova so far observed and studied (Saizar et al. 1992).

Third, our simulations imply that the amount of ^{22}Na produced in the outburst increases as the mass of the white dwarf increases and for the 1.35 $M_\odot$ simulations it can reach $\sim 6 \times 10^{-3}$ (by mass). This is a significant increase over the results reported in nucleosynthesis calculations.

Fourth, the amount of ^{22}Na produced in our 1.35 $M_\odot$ simulation, in combination with the observed value for the mass ejected in the outburst of Her 1991 of $\sim 7 \times 10^{-5}$ $M_\odot$ (Woodward et al. 1992), suggests that a small fraction of the X-rays detected by *ROSAT* were caused by Compton scattering of γ-rays from ^{22}Na decay. Our UV spectra of Her 1991 show that its envelope was optically thick to the γ-rays from this decay at the time of the X-ray detection. However, by the spring of 1992, when the expanding material will have become optically thin to γ-rays, *GRO* should be able to directly detect the radioactive decay of ^{22}Na from Her 1991. Our predicted photon flux *using the most optimistic values of all the parameters*, during a 2 week pointing, should be $\sim 1.2 \times 10^{-4}$ cm^{-2} s^{-1}. This value is to be compared with the 3 σ line sensitivity given in Appendix G of the "*GRO* as a Guest Investigator Facility" of $\sim 10^{-4}$ cm^{-2} s^{-1} (OSSE) and 6×10^{-5} cm^{-2} s^{-1} (Comptel). Finally, we note that any X-rays observed at this time should come from thermal emission by the photosphere and not from Compton scattered γ-rays.

We are grateful to M. Bode, P. Hauschildt, S. Kenyon, J. Krautter, I. Nofar, G. Shaviv, C. Shrader, R. M. Wagner, and R. Wehrse, for valuable discussions. We are also grateful to the referee, P. Pinto, for his efforts in improving this paper. This work was supported in part by NSF and NASA grants to the University of Illinois and ASU and by the DOE.

REFERENCES

Bode, M. F., & Kahn, F. D. 1985, MNRAS, 217, 205
Della Valle, M., & Turatto, M. 1991, IAU Circ., No. 5223
Dopita, M., Ryder, S., & Vassiliadis, E. 1991, IAU Circ., No. 5262
Fitzpatrick, E. 1986, AJ, 92, 1068
Hauschildt, P. H., Wehrse, R., Starrfield, S., & Shaviv, G. 1992, ApJ, in press
Kutter, G. S., & Sparks, W. M. 1972, ApJ, 175, 407
Leibowitz, E. M., Mendelson, H., Mashal, E., Prialnik, D., & Seitter, W. 1992, ApJ, 385, L49
Lloyd, H. M., O'Brien, T. J., Bode, M. F., Predehl, P., Schmitt, J. H. M. M., Trumper, J., Watson, M. G., & Pounds, K. A. 1992, Nature, 356, 222
Mason, K. O., Cordova, F. A., Bode, M. F., & Barr, P. 1986, in RS Oph and the Recurrent Nova Phenomenon, ed. M. F. Bode (Utrecht: VNU Science Press), 167
Nofar, I., Shaviv, G., & Starrfield, S. 1991, ApJ, 369, 440
Ögelman, H., Krautter, J., & Beuermann, K. 1987, A&A, 177, 110
Pinto, P., & Woosley, S. 1988, ApJ, 329, 820
Politano, M., Starrfield, S., Truran, J. W., & Sparks, W. M. 1992, in preparation
Saizar, P., Starrfield, S., Ferland, G. J., Wagner, R. M., Truran, J. W., Kenyon, S. J., Sparks, W. M., Williams, R. E., & Stryker, L. L. 1991, ApJ, 367, 310
Saizar, P., Starrfield, S., Ferland, G. J., Wagner, R. M., Truran, J. W., Kenyon, S. J., Sparks, W. M., Williams, R. E., & Stryker, L. L. 1992, ApJ, submitted
Sonneborn, G., Shore, S. N., & Starrfield, S. 1990, in Evolution in Astrophysics: *IUE* Astronomy in the Era of New Space Missions, ed. E. Rolfe (ESA SP-310; Noordwijk), 439
———. 1991, IAU Circ., No. 5226
Starrfield, S., Truran, M., Politano, M., Sparks, W. M., Nofar, I., & Shaviv, G. 1992, in Proc. Workshop to Honor W. A. Fowler on his 80th Birthday, ed. S. Woosley, in press
Starrfield, S., Truran, J. W., Sparks, W. M., Krautter, J., & MacDonald, J. 1991, in Physics of Classical Novae, ed. A. Cassatella and R. Viotti (Heidelberg: Springer), 306
Sugano, M., & Alcock, G. 1991, IAU Circ., No. 5222
Weiss, A., & Truran, J. W. 1990, A&A, 238, 178
Woodward, C. E., Gehrz, R. D., Jones, T. J., & Lawrence, G. F. 1992, ApJ, 384, L41
Williams, R., Ney, E., Sparks, W., Starrfield, S., & Truran, J. 1985, MNRAS, 212, 753