In this paper we describe the evolution of Nova Cas 1993 over the first two months of its outburst. We present an ultraviolet light curve that covers the period from announcement to just after dust began forming in the ejecta (1994 Feb. 15) and IUE spacecraft constraints forced us to halt our observations. We have used spherical, expanding, NLTE stellar atmospheres to compute synthetic spectra and have compared the results to combined ultraviolet (low-resolution 1200–3400 Å and high-resolution 2400–3300 Å) spectra. Our fits show that the effective temperature of the ejecta increased from ~8000 to about ~16 000 K between 1993 Dec. 12 and 1993 Dec. 26. The temperature then increased more slowly to ~24 000 on 1994 Jan. 28. A preliminary abundance analysis shows evidence for hydrogen depletion, as we also found for Nova V1974 Cygni; however we find a larger enhancement of carbon, nitrogen, and oxygen. We also show that the principal mechanism for mass ejection in this nova is a radiation pressure driven wind and that mechanical driving is not necessary.

1. INTRODUCTION

Nova Cas 1993 (hereafter referred to as Cas93), was discovered on 1993 Dec. 7 UT at a photographic magnitude of about 6.5 and announced on 1993 Dec. 11, when it was found to still be at V=6.5 (Kanatsu 1993). Skiff (1993) measured an accurate position for the nova: α2000=23h39m22.36s, δ2000=+57°14'22.9" (α=108:24 deg, δ=-2:67) and also reported the probable identification of the progenitor star on the POSS at B=18 mag and B-R=+1. Using Skiff's identification of the progenitor, we derive an outburst amplitude of about 13 mags, which is reasonable for a classical nova in outburst.

The optical light curve for the first three months of observations is shown in Fig. 1(a). The nova remained at about V=6.5 with only small variations until about 1993 Dec. 18 when it underwent a "flare" to 5.3 mag and a rapid decline back to about 6.5 mag. It underwent smaller flares after this time until about Feb. 15, when at V=9 mag it began a precipitous decline. The light curve shows that if we ignore the flare, Cas93 took about 65 days to fade 2 mag below visual maximum (or, t2=65 days). We cannot determine t3, i.e., the time it took Cas93 to fade 3 mag below visual maximum, directly since that time occurred after dust formed in the expanding material. However, an extrapolation of the pre-decline part of the light curve yields t3~100 days.

We find a remarkable resemblance of Cas93 to those designated as the "DQ Her" class of slow novae by comparing the optical light curve to those assembled in Payne-Gaposchkin (1957). Indeed, its light curve most closely resembles DQ Her 1934 itself. Both novae exhibited a pre-maximum halt, a fast rise to maximum, a several magnitude "flare," and a slow decline of 2 to 3 mag over a period of two to three months. The slow decline is followed by a sharp drop in the optical and, in most recent DQ Her class novae, a concomitant rise in the infrared attributed to the formation of dust (Gehrz 1988, 1990). If the analogy continues to hold, we can expect a gradual increase in visual and UV brightness by about mid-May 1994, as the nova recovers from the deep transition phase.

Early optical spectra of Cas93 show the characteristic lines of an optically thick Fe II nova (Williams et al. 1991), thus enhancing the morphological connection between this nova and DQ Her. Woodward & Greenhouse (1993) report that the infrared Bry line shows a full width half maximum (FWHM) of 1680 km s⁻¹. This value is consistent with the earliest observations of slow novae. Scott et al. (1994) detected 12CO infrared emission on 1993 Dec. 13 with possible evidence for 13CO. Optical spectra at maximum of DQ Her showed CN absorption, so molecules formed early in both novae. Scott et al. (1994) then reported that observations obtained on 1994 Jan. 10 showed 12CO emission and 3.38 μ
emission attributed to polycyclic aromatic hydrocarbons (PAH). They pointed out that the IR evolution of this nova resembled V842 Cen 1986, which exhibited a deep transition and formed dust.

Since its announcement, Cas93 has been observed roughly every four days in the ultraviolet (UV) with the International Ultraviolet Explorer satellite (IUE). Our initial observations showed that the shell was much cooler than we had previously observed for a classical nova. The presence of molecules combined with its close resemblance to DQ Her strongly implied that dust would form in the ejecta of this nova. Just as we were finishing this paper in February 1994, Cas93 began forming dust as we had predicted (Shore & Starrfield 1994; Shore et al. 1993a). We now have the most detailed picture of the early UV evolution of a dust forming nova ever obtained. Although both V842 Cen 1986 and QV Vul 1987 formed dust, only fragmentary data were obtained in the UV.

Both the optical light curve and UV behavior of this nova are different from V1974 Cyg. Since V1974 Cyg was an ONeMg nova (Hayward et al. 1992; Hauschildt et al. 1994), our studies of Cas93 are providing data on a completely different class of nova. Although we have not completed an abundance analysis, we expect that the analogy of Cas93 with DQ Her will continue and it will be found to be a CNO enriched nova and not ONeMg enriched.

In the next section we discuss the UV observations of Cas93 and compare and contrast them to UV observations of V1974 Cyg. We follow with an atmospheric analysis of Cas93, and end with a discussion.

2. EARLY ULTRAVIOLET EVOLUTION

The rapid response capability of IUE made it possible for us to obtain our first UV spectra of Cas93 within a few hours of the announcement (Kanatsu 1993). We obtained several exposures with the long wavelength primary (LWP, 2000–3400 Å) and short wavelength primary (SWP, 1200–2000 Å) cameras. We chose our initial exposure times based on our experiences with previous novae and found that Cas93 was much fainter in the UV than expected. Although there was a possibility that the nova was highly reddened, the extracted spectra showed that, in fact, it was quite cool. Additional data obtained over the next few days showed that we had caught Cas93 at UV minimum. As discussed in detail in our studies of V1974 Cyg (Shore et al. 1993b, 1994; Hauschildt et al. 1994; Starrfield & Shore 1994), this is the stage when a large number of overlapping absorption lines from the iron group elements, mainly Fe II, block most of the UV light and virtually all of the emitted radiation escapes in the optical. UV spectra showing this phase of the evolution of a nova are
presented in Shore et al. (1993a) and Hauschildt et al. (1994).

Our first spectrum in shown in Fig. 2 along with a synthetic spectrum (upper curve). Note that it is virtually featureless and shows no detectable flux shortward of ~1700 Å. It seems clear that we missed the fireball stage by several days. Our fits to this spectrum (discussed in the next section) require an effective temperature of ~8000 K. This is much lower than the value of 15 000 K obtained for the first spectrum of V1974 Cyg (Hauschildt et al. 1994) and also cooler than those obtained at UV minimum for that nova. Our first LWP spectrum also differed from that of V1974 Cyg. The region around 2800 Å, which is a blend of both Fe II and Mg ii, displayed a pseudo-P Cygni profile with a broad absorption through that extended to ~1600 km s\(^{-1}\). In Fig. 3 we show an IUE spectrum obtained on 1994 Feb 11, just at the time of beginning dust formation and compare it to a synthetic spectrum with \(T_{\text{eff}}=26\ 000\ K\). The Journal of IUE observations can be found in Tables 1 and 2.

In Fig. 1(a) we display the UV spectrophotometric evolution of the nova, showing the integrated flux in each camera. Unlike the evolution of V1974 Cyg, in which the UV flux rose very rapidly in the UV after minimum (Shore et al. 1994), the UV flux in Cas93 rose only after an extended minimum and remained virtually constant for nearly 40 days. The rise in the UV can be explained by a very slow increase in the effective temperature of the shell. At higher electron temperatures the relative abundance of Fe ii, which is the species with the largest number of strong lines in the UV, is smaller in the inner parts of the photosphere and the UV flux increases. At the same time, the lines forming in the outer photosphere switch from pure absorption into P-Cygni profiles, due to a change in the gradient of the source function. This leads to a much higher emergent flux in the UV and the appearance of “true” emission lines in the UV spectrum. In this phase of the UV development, the first semiforbidden or forbidden lines gradually appear in the spectrum, formed above the photosphere in the low density ionized region.

3. EXTINCTION AND DISTANCE

The extinction and distance are required to understand the energetics of the outburst. We are still very early in the outburst, however, and at this time we can only utilize indirect methods. For example, we have not seen the transition stage to a nebular spectrum so emission line ratios cannot be used to determine the reddening. However, observations have confirmed the theoretical prediction that the nova, during the initial outburst, evolves at constant bolometric luminosity (Shore et al. 1994), and we find that bolometric constancy is achieved [to within about 10\% until the start of the dust-forming episode; see Fig. 1(b)] assuming that \(E(B-V)=0.5\) with a likely range of \(\pm 0.1\). This uncertainty will be reduced once the shell becomes optically thin.

To estimate the distance, we have employed the interstellar lines, in particular the Na I D doublet from unpublished optical spectra by Gordon and Aufdenberg (1993) and the Mg ii 2800 Å resonance doublet from the high resolution IUE spectra. The Na I lines each show discrete absorption extending to \(-50\ \text{km s}^{-1}\) (see Shore & Starrfield 1994). These lines are relatively weak and probably unsaturated, so the velocity centroid of each cloud is well determined. The Mg ii doublet components are saturated. They have mean velocities of \(-35\ \text{km s}^{-1}\) but extend to nearly \(-60\ \text{km s}^{-1}\). Comparing the measured velocities with the galactic H I rotation curves by Burton (1988) suggests distances ranging from 3 to 6 kpc. Hobbs (1969) shows the high resolution Na I profiles for several stars at similar galactic coordinates.
at distances of order 1 kpc. These do not show any absorption blueward of $-25 \text{ km s}^{-1}$, although this is a weak lower limit on the distance because of the sparseness of the sample.

A range from 3 to 6 kpc is inconsistent with values derived using either the $M_V - t_2$ or $M_V - t_3$ relations (cf. Livio 1994). For example, the observed $t_2$ and $t_3$ imply $M_V \approx -6.8$. For $E(B-V) = 0.5$ and a peak $V \approx 6.2$ (we ignore the flare to $V = 5.4$ mag), we arrive at a distance of order 2 kpc. A distance of 2 kpc cannot be reconciled with the measured interstellar absorption line velocities. Moreover, the Galactic H I measurements would require components at velocities greater than $-25 \text{ km s}^{-1}$ in order for this distance to be correct and these are not observed.

Another method is to take advantage of the analogy with DQ Her and scale its distance and outburst parameters to those of Cas93. DQ Her is at a distance of 560 pc (Herbig & Smak 1992) and reached a maximum of $V = 1.3$ mag with $t_3 = 94$ days (Payne-Gaposchkin 1957). Its extinction is $E(B-V) = 0.1$ (Weight et al. 1994). These results imply $M_V = -7.8$ mag at optical maximum. Since Cas93 is evolving more rapidly and exhibited higher velocities than DQ Her, we expect that it will turn out to be brighter at maximum. Nevertheless, using $M_V = -7.8$ and $E(B-V) = 0.5$, we obtain a distance to Cas93 of $\approx 3.2$ kpc. The maximum luminosity of this nova was then $\approx 6 \times 10^4 L_\odot$. This is approximately the Eddington luminosity for a 1 $M_\odot$ white dwarf and is not unreasonable considering the speed class of this nova. IR observations give a lower limit for the luminosity of $\approx 4 \times 10^3 L_\odot$ (Mason & Gehrz 1994), therefore, the luminosity of the nova is well constrained.

4. MODEL ATMOSPHERES

We used the computer code PHOENIX (Version 4.7), to compute model atmospheres and synthetic spectra for Cas93. This is an updated version of the code used for the analyses of the early spectra of Nova Cygni 1992 (Hauschildt et al. 1994) and SN 1993J (Baron et al. 1994), and it is described in some detail in these papers. However, in order to calculate fully self-consistent atmospheres with $T_{\text{eff}} \approx 10^4$ K, we now include the water vapor line list of Miller et al. (1994, see also Allard et al. 1994).

The model atmospheres are characterized by the following parameters (see Hauschildt et al. 1992, 1994; details. The reference radius $R$ (where the continuum optical depth equals unity at 5000 Å) is chosen and the effective temperature $T_{\text{eff}}$ [defined by the luminosity, $L$, and the reference radius, $R$, $T_{\text{eff}} = (L/4 \pi R^2 \sigma)^{1/4}$ where $\sigma$ is Stefan's constant]
is specified. We parametrize the density structure using a free parameter, \( N, [\rho(r) \propto r^{-N}] \). We also specify the maximum expansion velocity, \( v_0 \), the density at the outer edge of the envelope, \( \rho_{\text{out}} \), the microturbulent velocity \( \xi \) (e.g., Gray 1992), treated as a depth-independent isotropic Gaussian turbulent velocity, and the element abundances.

We have computed a grid of co-moving frame NLTE nova model atmospheres with the following set of parameters:

\[
L = 7 \times 10^4 L_\odot, \quad N = 3, \quad \xi = 50 \text{ km s}^{-1}, \quad 5000 \lesssim T_{\text{eff}} \lesssim 60000 \text{ K}, \quad v_0 = 2000 \text{ km s}^{-1} \quad \text{and solar abundances.}
\]

We then computed Eulerian frame synthetic spectra for each of the model atmospheres in the grid and used these synthetic spectra to estimate the \( T_{\text{eff}} \) corresponding to the observed IUE spectra. The fit to the observations was iteratively improved by changing the parameters of the model atmospheres, in particular \( v_0 \) and the abundances. A detailed description of the models and fits to both optical and UV spectra will appear elsewhere (Hauschildt et al. 1994).

Our analysis shows that we must increase the metal abundances, i.e., all elements with \( Z > 2 \), by about a factor of two over solar abundances in order to obtain good agreement with the UV and optical spectra of Nova Cas 1993. The agreement is substantially improved below 1600 Å if we use about 100 times the solar abundances of carbon and oxygen. In the following discussion, however, we will describe only the results from the models with twice solar abundances for the metals and defer a discussion of the more detailed models to a later paper.

In Fig. 4 we show the time dependence of the derived \( T_{\text{eff}} \). The effective temperatures rise rather slowly with time as compared to V1974 Cyg, and we find that the earliest effective temperature is approximately 8000 K. Nova atmospheres with such a low \( T_{\text{eff}} \) form molecules in their outer layers. In fact, our model for the earliest epoch of Cas93 predicts emission by infrared CO first overtone lines, as was observed by Scott et al. (1993). At the higher effective temperatures, the temperature range in the line forming region increases to the point where lines of very different ionization stages are simultaneously present in the spectra. This is typically observed in novae. The IR observation of diffuse band emission at about 3.4 µm is also expected if PAH or related molecules formed in the outermost layers. This emission is pumped by absorption of UV photons and their subsequent redistribution through the many available vibrational modes of a variety of species of intermediate mass molecules of the polycyclic aromatic hydrocarbons (Desert et al. 1986; Puget & Leger 1989). In order for infrared emission to occur, however, there must be a sufficiently strong UV radiation source.
Fig. 4. Evolution of the effective temperature of Nova Cas 1993 as a function of time ("+" symbols). The full curves indicate our estimate for the error in the derived $T_{\text{eff}}$. In addition, we plot the electron temperatures at $\tau_{\text{ne}}=10^{-3}$ ("diamond" symbols) and at $\tau_{\text{ne}}=1$ ("*" symbols).

and our UV observations show that this did not occur until after the recovery from UV minimum in early 1994 Jan. This is just when such emission was detected.

The mechanism responsible for mass ejection is a central question of this study. Mass ejection from a nova may not proceed in a single explosive event but in an explosion plus a wind. Unlike a normal stellar wind, however, the time scale for luminosity evolution during the initial stages is very fast and it may not be possible to establish a steady state wind. Thus, the very high luminosity and temperature that typifies the fireball may initiate a fast wind that quickly shuts off, leading to a secondary phase of lower terminal velocity. The fastest material reaches low temperatures first, and it is this part of the outflow that is responsible for the early CO overtone emission that was observed in Cas93. Subsequently, during the constant bolometric luminosity stage, radiative acceleration may drive a steady state outflow.

In order to demonstrate this, we plot in Fig. 5. the ratio of the outward acceleration due to radiative forces (both lines and continua), $a_{\text{rad}}$, to the inward gravitational acceleration, $a_{\text{grav}}$, due to an assumed 1.25 $M_\odot$ central star. For the coolest model, $T_{\text{eff}}=8000$ K (1993 Dec 13), there is a region where $a_{\text{rad}}<a_{\text{grav}}$. This zone is rather small and above the region where most of the material is accelerated. In most of the inner regions of the model, $a_{\text{rad}}$ is larger than $a$ by a factor of 10. In the hotter models, $T_{\text{eff}}=16000$ K (26 Dec 1993) and $T_{\text{eff}}=24000$ K (28 Jan 1994), $a_{\text{rad}}$ always exceeds $a_{\text{grav}}$. The gravitational acceleration is much larger in the hotter models than in the cooler ones because we have assumed the same bolometric luminosity of $7.0\times10^4 L_\odot$ for all models. The steep changes in the curves of radiation pressure as a function of depth result from the presence of ionization zones (or regions of molecule formation in the cool model). These regions produce large changes in the opacity, $\chi$, and corresponding changes in $a_{\text{rad}}=\int \chi H_\lambda \ d\lambda$, although the flux, $H_\lambda$, is varying much more slowly.

We note that the region of radiation pressure driving is smallest in the cool model and it is possible that at this time radiative driving is insufficient to produce a wind. We emphasize, however, that the nova has cooled from higher temperatures at which radiative driving extended throughout the entire outer layers. Therefore, just before discovery there was sufficient radiative driving, and a few days after discovery there was again sufficient driving, to produce a wind.

The rate of mass loss is a derived quantity for our atmospheres, $\dot{M}=4\pi r^2 v$. Note that the rate of mass loss scales directly with $v$, so reducing the velocity reduces the rate of mass loss. We find for the cool model that $\dot{M}=2.5\times10^{-3} M_\odot \ yr^{-1}$. $T_{\text{eff}}$ increases as $\dot{M}$ decreases so that by the time $T_{\text{eff}}=16000$ K, the rate of mass loss has decreased to $2.5\times10^{-4} M_\odot \ yr^{-1}$ and at $T_{\text{eff}}=23000$ K,
The nova spent a few days at the lowest effective temperatures when it should have ejected a significant fraction of its accreted envelope.

5. SUMMARY

In this paper we have discussed the early evolution of Nova Cas 1993. The light curve and the time evolution of its UV spectra indicate that Nova Cas 1993 is a slow nova of the DQ Her type. Based on this similarity we predicted that Cas93 would form dust (Shore et al. 1993a; Shore & Starrfield 1994) and this prediction was confirmed by observations of the nova in mid-February 1994. Our NLTE, spherical, expanding, atmosphere models of the nova shell indicate that hydrogen is depleted by about a factor of two in the ejecta compared with solar, and that carbon and oxygen are possibly enhanced by factors as large as 100, however, the latter result has to be confirmed by a more detailed analysis of the spectra.

Our fits to the spectral energy distribution show that the effective temperature of the shell increased slowly from 8000 K (1993 Dec 13) to about 24 000 K (1994 Jan 28) and that the ejecta had the shallow density profile of a nova in the optically thin "wind" stage. In contrast to V1974 Cyg, no fireball stage was observed in Nova Cas 1993 and it must have occurred prior to the announcement of discovery. The expansion velocities of the shell decreased from 2000 to about 1300 km s\(^{-1}\) and the models are consistent with either a "wind" velocity law or a homologous (linear) velocity law.

The models indicate that, during most of the outburst, the acceleration of the material by the radiation pressure gradient was much larger than the gravitational deceleration caused by the central star. The radiative acceleration exceeded the gravitational deceleration in the hotter models by factors of order 1000. Therefore, the material could reach the high velocities observed in novae by radiation pressure alone. Only the very coolest model showed a small layer where the radiative acceleration was insufficient to drive mass loss. However, the ejected material must have already reached a very high velocity by this time. It thus appears that radiation pressure is sufficient to drive mass loss in the DQ Her-type slow novae, and that mechanical driving is not a prerequisite for mass ejection, although it likely adds to the forces producing mass loss.

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