THE ASTROPHYSICAL JOURNAL, 376:721–737, 1991 August 1

THE EVOLUTION AND CLASSIFICATION OF POSTOUTBURST NOVAE SPECTRA

R. E. WILLIAMS, M. HAMUY, M. M. PHILLIPS, S. R. HEATHCOTE, LISA WELLS,
AND M. NAVARRETE
Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatories,[1] Casilla 603, La Serena, Chile
Received 1990 December 27; accepted 1991 January 30

ABSTRACT

The first results are presented of a long-term CTIO study of the postoutburst spectra of novae, obtained with CCDs over the wavelength interval $\lambda\lambda$3200–1 μm. For certain novae the temporal coverage has been sufficiently complete that successive stages are observed in the spectral evolution, suggesting a method by which the spectra may be classified. A classification system is proposed which defines phases in evolution in terms of the characteristics of the stronger emission lines. These phases are related to physical conditions in the shell through the ionizing radiation field and mean gas density. Certain characteristics of nova spectral evolution are apparent from our limited sample, the most important of which is the necessity of invoking the presence of strong density inhomogeneities of many orders of magnitude in the envelopes in order to explain the emission spectrum. Reliable abundance determinations of nova ejecta must incorporate these condensations in the analyses. The observations also indicate that the spectral evolution of neon novae may differ from that of other novae in not developing coronal emission lines.

Subject headings: stars: novae — stars: spectral classification

1. INTRODUCTION

The spectra of novae following outburst have been studied for many decades. They are dominated by emission lines from the time of outburst onward. The specific lines vary from object to object and also show significant changes with time in any one object. Both the relative intensities and the line profiles show large variations which indicate rapid changes in the velocities and excitation conditions of the emitting gas. The myriad of different lines originating from a wide range of elements and ionization stages has made meaningful classification difficult. The fact that until recently all of the data were gathered with photographic plates, with their very limited dynamic range and inherently lower signal-to-noise ratios, has contributed to the difficulty in understanding nova spectra. In particular, the widespread belief that all novae at maximum light are characterized by absorption spectra has undoubtedly been influenced by the fact that photographic spectra are usually exposed to the point where the continuum has an optimal density, thus saturating any strong emission present. This causes the fluxes of all emission components to be underestimated, at the expense of emphasizing all absorption in the spectra. Our program has not yet been successful in obtaining spectra on the day of maximum for any object; however, we suspect from the strengths of emission components shortly after maxima that the contention that nova spectra at maximum resemble stellar absorption spectra may not be substantiated by observations with digital detectors.

Our present knowledge of nova spectra owes much to the pioneering work of Payne-Gaposchkin (1957) and McLaughlin (1960), who painstakingly gathered the data obtained for numerous novae from many sources, and characterized their spectral features as a function of time after outburst. Conceding that "the spectral development of all novae is complex, and the observations are very difficult to interpret," Payne-Gaposchkin (1957, p. 53) did not attempt an analysis of the spectra, but rather gave detailed descriptions of the spectral evolution of individual novae, concentrating on the velocity structure of the lines and their relative intensities. McLaughlin, on the other hand, did use the data to devise a complex system of classifying nova spectra which relies on the correlation of various absorption and emission features in the spectra to the outburst light curve. Rather than focusing on the general nature of the spectrum, the McLaughlin system emphasizes specific characteristics such as velocities and intensities of particular groups of lines, some evident at high dispersion. Various phases in the development of the nova spectrum are then categorized as being "premaximum," "principal," "diffuse enhanced," or "Orion," etc. However, these phases are not associated with any physical parameters of the outburst or the nova envelope and thus are purely taxonomic in nature. Any spectral classification scheme which is related to physical conditions would likely be based on entirely different criteria than those chosen by McLaughlin.

Several years ago, we initiated a program at CTIO to acquire an extensive data base of novae spectra, with good temporal and wavelength coverage. The management of such a program is made logistically difficult by the unpredictable discoveries of novae and the large differences in the time scales of their spectral evolution. At various stages in the development of different novae, significant spectral changes may occur over intervals of anywhere from a few days to a few years. The national observatory is an ideal place for such a study, since a number of telescopes are available with a resident staff to make the observations, able to adjust flexibly to the vagaries of the novae, the weather, and the variety of available instruments.

The goal of the program has been to acquire a sufficiently large sample of spectra such that some order might begin to appear in the data that would enable the development of the spectra to be understood in terms of physical parameters of the outburst. We have been successful in following some novae with regularity through the postoutburst decline so that changes have been noted progressively until they have slowed

[1] Operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

to the point where they are occurring over an interval of years. For other novae, we have succeeded only in obtaining sporadic, incomplete data. However, even these latter data are useful in elucidating the development of the spectra since one can say something about the evolution of nova envelopes from a sample of snapshots of individual novae.

2. OBSERVATIONS AND RESULTS

Spectroscopic observations were made of novae in the period following outburst, using different telescope/instrument combinations, from 1987 June through 1990 October. The observations were performed on the 1, 1.5, and 4 m telescopes, depending upon the brightness of the novae and the instruments available at the time to make the observations. Since we have undertaken a general program to follow novae spectroscopically, the scope of the observations has been too great to make an instrument change whenever an observation was desired, so the observations were normally made during nights preassigned to this program, except for novae in the month following outburst. Immediately following the outburst, the spectra evolve on a time scale of days, and therefore frequent coverage is necessary. Since Galactic novae are frequently brighter than $m_v \sim 10$ at this stage, the smaller aperture telescopes were able to be used for these observations.

The CTIO 1 m telescope is dedicated to spectroscopy with the 2D-Frutti two-dimensional photon-counting detector (S-25 photocathode), and therefore a flexible schedule of observations was possible with this system. We were interested primarily in the emission spectrum, and consequently high resolution was sacrificed in order to obtain the broadest spectral coverage permitted by the detector. Generally, a 300 lines mm^{-1} grating was employed for the observations, yielding a typical wavelength coverage of 3300–7200 Å with a resolution of 5 Å (FWHM). On some occasions a higher dispersion grating (831 lines mm^{-1}) was used, producing a wavelength coverage of 2800 Å at a resolution of 3 Å.

With the Cassegrain spectrograph of the 1.5 m telescope, a GEC CCD was employed with a fluorescent coating that extends the useful response of the detector to below the atmospheric cutoff. The widest wavelength coverage (4600 Å) was always attempted by using low dispersion gratings (158 lines mm^{-1}) providing a resolution of 16 Å. In order to achieve full coverage over the useful range of sensitivity of the CCD (3200–11000 Å), observations were taken sequentially with two different grating tilts. On the 4 m telescope we also used a coated GEC CCD together with low resolution gratings (158 lines mm^{-1}). The corresponding wavelength coverage and resolution were 3100 Å and 11 Å, respectively. A spectral coverage of 3200–9400 Å was achieved with two grating settings.

A typical sequence of observations consisted of several (two to four) narrow-slit exposures of the nova (5″ at the 1 m telescope; 3″ at the 1.5 m; and 2″ at the 4 m) in order to obtain the best spectral resolution. The observations of each nova were bracketed in time with HeAr comparison lamp exposures taken to establish the wavelength calibration. Several spectrophotometric standards (three to five) from the list of Taylor (1984) were also observed during the night with a wide slit to provide flux calibration. All of the data reduction was carried out using IRAF on SUN Workstations. Each CCD or 2D-Frutti image was divided by a normalized flat-field image obtained during daytime. Spectra for all objects were extracted and sky-subtracted, linearized in wavelength using the HeAr lamp exposures taken at the position of the object, corrected for atmospheric extinction using the mean extinction curve for CTIO given by Stone & Baldwin (1983), and then flux-calibrated using the sensitivity curve obtained for that night from the spectrophotometric standards. Although the absolute flux levels of the novae may be uncertain due to nonphotometric conditions, the relative spectrophotometry of the novae is accurate to better than 5% even under nonphotometric conditions, except shortward of 3500 Å where atmospheric refraction becomes pronounced.

The blue and red spectra of each object were generally obtained on either the same night or on two successive nights. Although the weather conditions were not always photometric, in all cases both spectra were combined. In those cases where either spectral evolution or nonphotometric weather caused flux differences between the two spectra in the overlap region (6300–6500 Å), the weaker spectrum was multiplied by an arbitrary factor to bring the continuum strength into agreement with the stronger spectrum. For most of the objects more spectra were obtained than are displayed here, inasmuch as we have limited ourselves to showing only the minimum necessary to convey the basic evolution of the lines. Ideally, in studying the evolution of nova spectra one tries to obtain data at intervals such that the changes from one spectrum to the next are always gradual. A number of factors intervene to prevent this, including (1) unpredictable time scales over which the emission-line fluxes change; (2) passage of the nova behind the Sun, requiring a hiatus of 4 months in the observations; (3) bad weather at critical times, etc. The result of all this is that it requires considerable persistence and good fortune to acquire a complete series of spectra for any one nova over the time frame covering all of the emission-line phases that novae go through after outburst, resulting from the evolution of the remnant radiation field and ejected envelope density.

Our sample of data shows regular coverage for certain objects and incomplete coverage for others, however a picture of post-outburst spectral evolution does emerge. Since the emission spectra of old resolved nova shells are characterized by low-excitation nebular lines, the evolution of nova spectra cannot be considered complete until they have arrived at a state where they display the low-excitation lines of a tenuous gas (Williams 1991). This process usually requires more than 5 yr to complete, and in some cases occurs over a much longer time scale, e.g., 25 yr. A full understanding of the evolution of an individual nova may thus require more than a decade of observations. On the other hand, spectra of a large sample of objects taken at arbitrary times are useful in revealing the different variety of conditions found in the envelopes at distinct times. Thus, we display objects for which we have a good sample of data, and also a number of novae for which only one or two spectra exist. The latter objects include the novae which have been found in outburst in the LMC, since their large distances render them too faint to be observed long after outburst.

Chronological series of spectral scans are presented in Figures 1–9 for those classical novae for which we have obtained useful data. Emission-line identifications are given for all but the weakest lines, and in cases where the proper identification is uncertain, we have made the assignment on the basis of those candidate transitions that should be present given the other lines observed and the physical conditions in the envelope. In the figures, each line identification is given only on the initial appearance of that line in the spectrum, and it remains valid for the feature at that wavelength for all later spectra until a subsequent identification is given. For example, the Balmer line Hϵ λ3970 appears early in the evolution of most novae but is frequently superceded in strength by the forbidden line [Ne III] λ3968 later in the evolution. Each spectral scan is identified by the date on which it was obtained, and the date of maximum visual brightness of the nova appears at the top right of each series. Each of the spectra are also assigned a spectral phase which appears at the left edge of the scan, according to the classification system which is defined and discussed in § 3. Comments on the individual novae are as follows:

2.1. *V394 Coronae Austrinae*

This recurrent nova underwent its first recorded outburst in 1949 and was characterized by a very rapid decline. A second outburst was discovered by W. Liller on 1987 August 2 (IAU Circ., No. 4428), although prediscovery patrol photographs by both Liller and R. H. McNaught established that 1987 July 29 was the date of maximum brightness in the visible, at $m_v \approx 7.2$. We were able to obtain spectra only within the first month of decline, during which time only permitted lines were present, as seen in Figure 1. Initially, very broad Balmer lines and nitrogen transitions were prominent, the latter almost certainly due to continuum fluorescence from the postoutburst white dwarf radiation. By August 18, the lines had sharpened considerably and He II λ4686 was quite strong, with only H and He lines present. A more extended record of the spectral development has also been given by Sekiguchi et al. (1989), who found that the line spectrum eventually faded into the continuum without ever displaying any forbidden lines. In this sense, the spectral evolution was very similar to that of another recurrent nova, U Sco (Barlow et al. 1981; Sekiguchi et al. 1988).

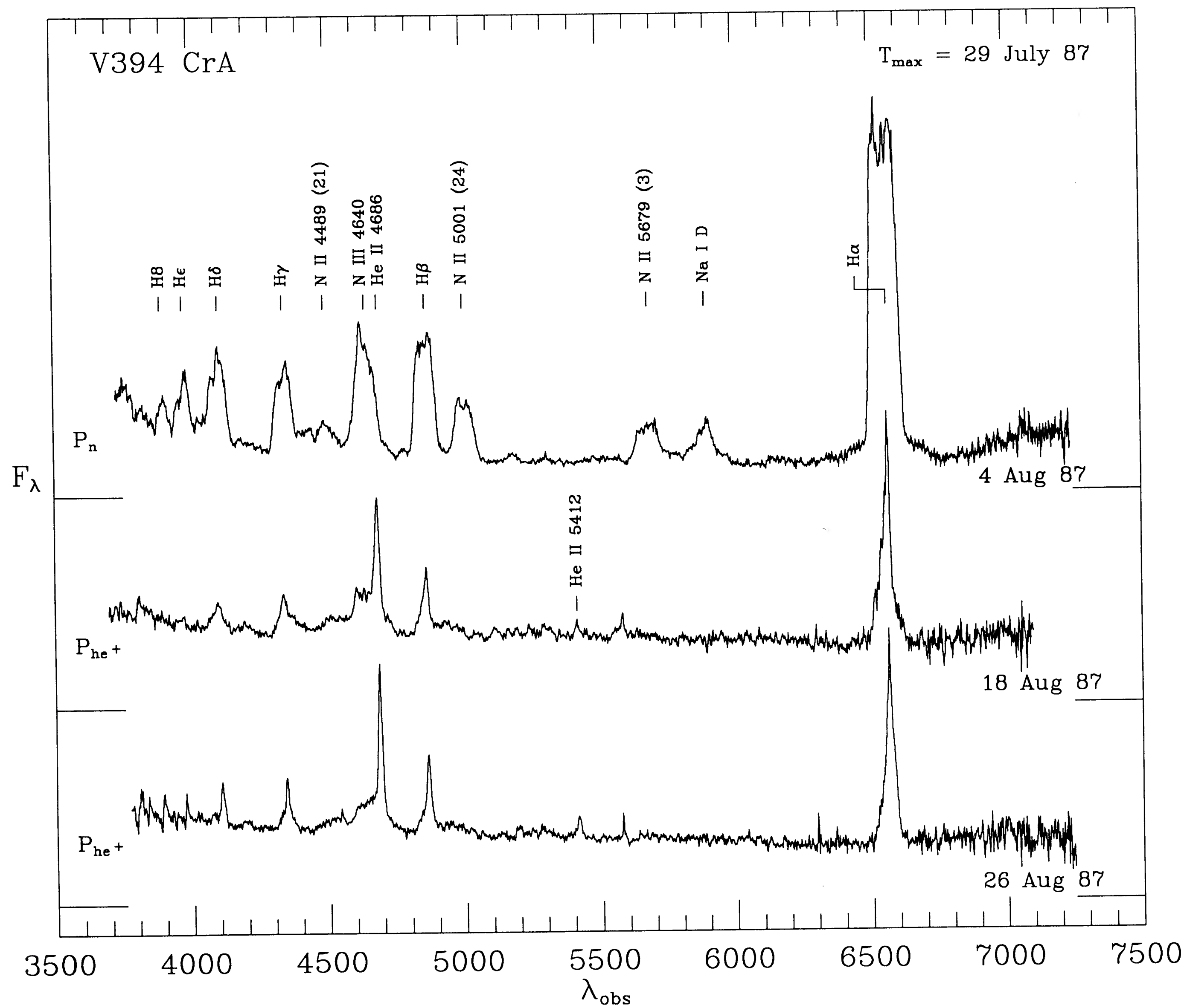

FIG. 1.—Spectral scans of the recurrent nova V394 CrA following its 1987 July outburst

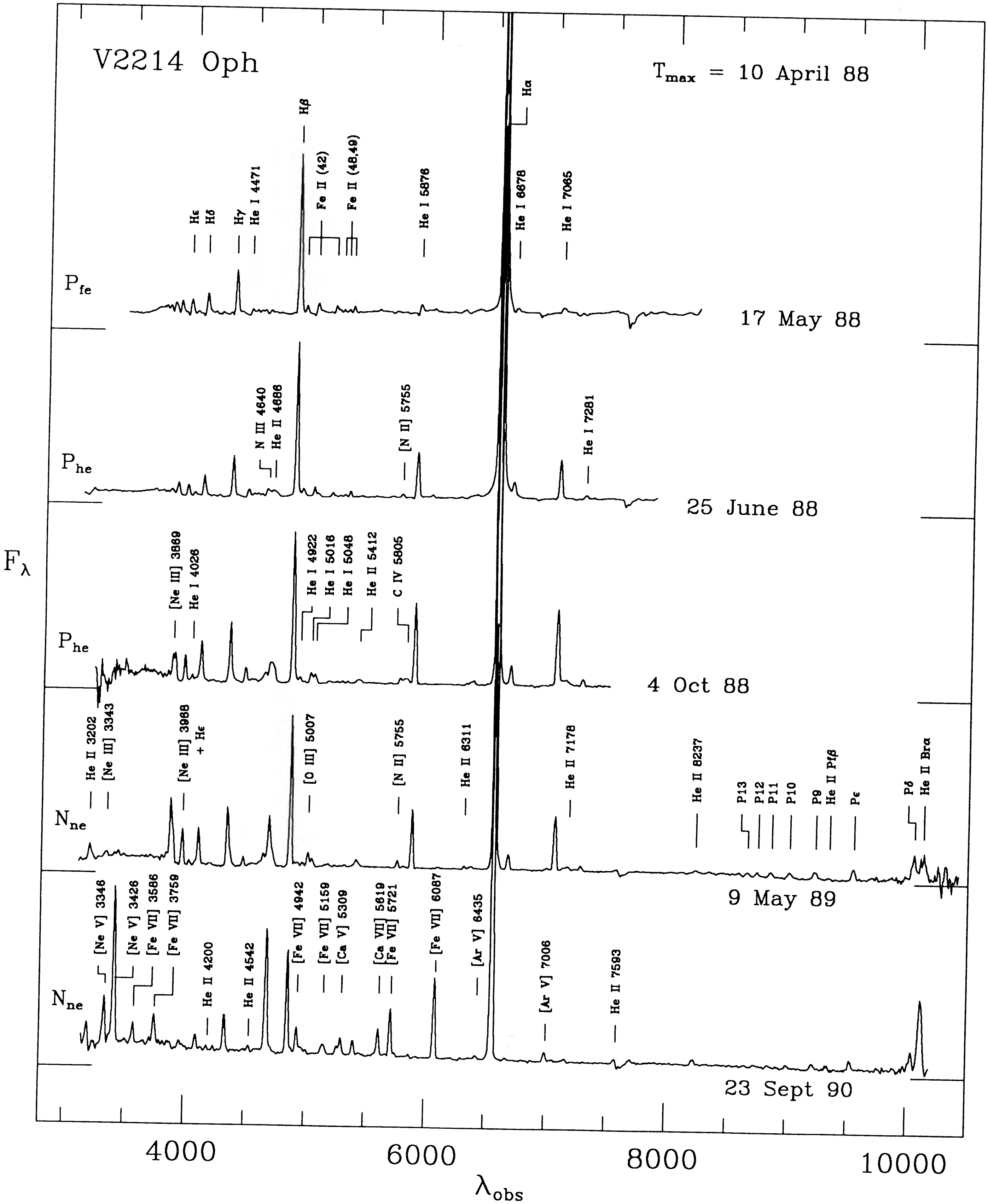

FIG. 2.—Spectral scans of the nova V2214 Oph (Nova Ophiuchi 1988) following its 1988 April outburst

2.2. *Nova Ophiuchi 1988 (V2214 Oph)*

The belated announcement of the discovery of this nova by Wakudu was made 3 weeks after it was first observed to be in outburst, at about the time it achieved maximum brightness, on 1988 April 10 at $m_v \sim 8.5$ (IAU Circ., Nos. 4581, 4582). The initial spectra we obtained are typical of many nova immediately after outburst, so little spectral evoution may have preceded our first observations on May 6. The early spectra show strong Balmer lines and Fe II, with the Balmer lines having weak P Cygni absorption components in the blue (Fig. 2). Within a month He I lines strengthen, and after 2 months He II and [N II] λ5755 appear, while the Balmer absorption becomes weak.

A very interesting event occurs over a short period in July, when a sharp absorption component suddenly develops in the Balmer lines on July 8, as shown in Figure 3. Within a day the absorption has weakened, and although daily spectra were not obtained after this date, the feature has virtually disappeared by July 20. The same feature is evident, albeit very weakly, in the He I λ4471 and λ5016 lines. The abrupt change appears only in the absorption component and is too rapid to ascribe to some general change in the entire expanding envelope. It is almost certainly due to an individual absorbing cloud which, through a component of random motion superposed on the outwardly directed velocity field, happens to pass in front of part of the Balmer-line–emitting gas. This event demonstrates that the envelopes of novae must be highly inhomogeneous, consisting of discrete emitting and absorbing clouds which have small filling and covering factors.

By 1988 October forbidden lines such as [Ne III] and [N II] λ5755 appear and become stronger with time. The ionization steadily increases until in 1990 the [Ne V] lines are far stronger

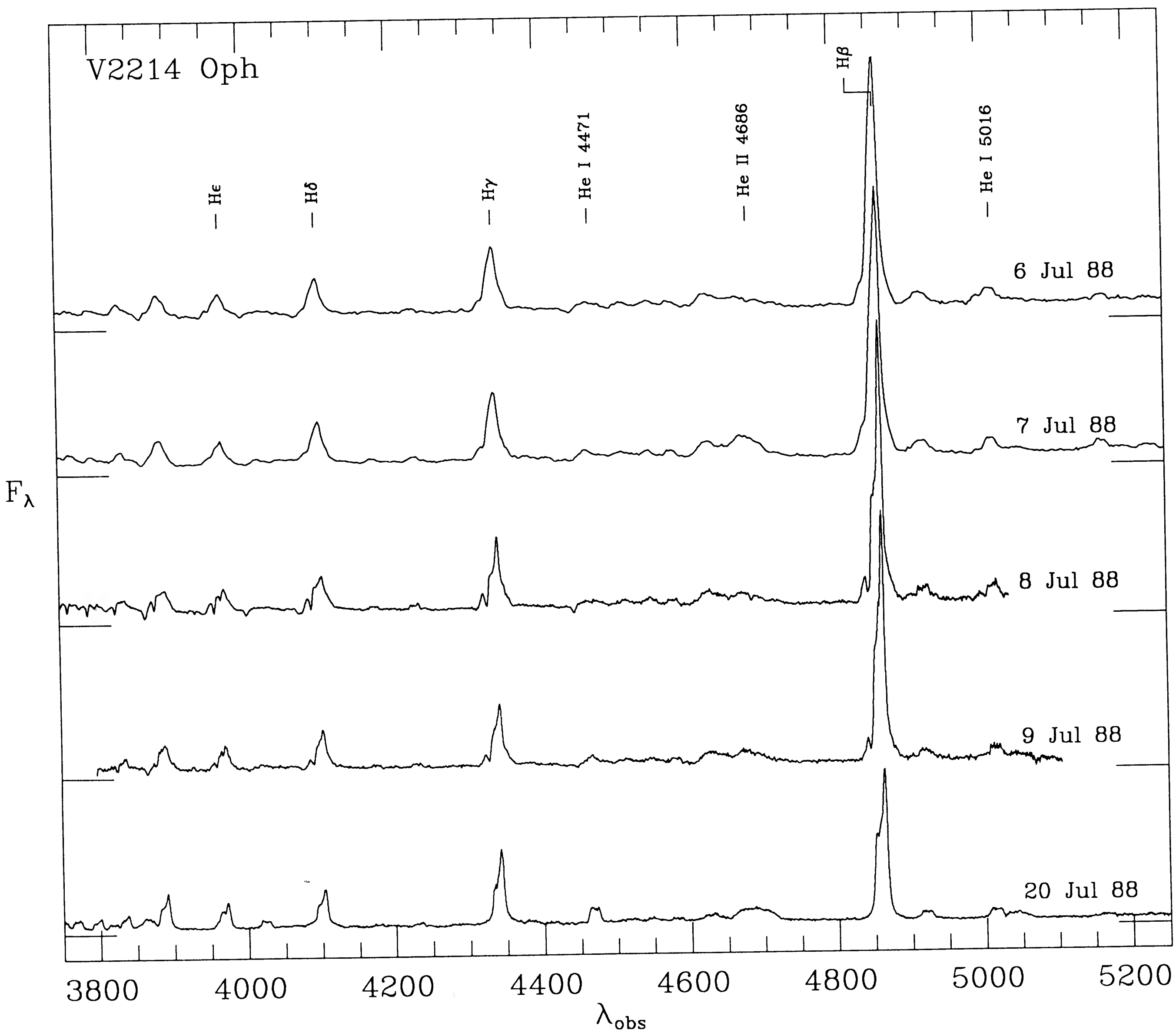

FIG. 3.—Higher resolution spectra of V2214 Oph in 1988 July, showing the sudden appearance and disappearance of a narrow absorption feature in the blue wings of the Balmer lines.

than [Ne III], and the spectrum is rich with [Fe VII] lines. Although a detailed study of this nova has not yet been made, the relative strengths of [Ne III] λ3869/[O III] λ5007 almost certainly qualify V2214 Oph as a "neon" nova.

2.3. *V745 Scorpii*

V745 Sco was discovered in outburst by W. Liller on 1989 July 30 (IAU Circ., No. 4820), although maximum light apparently occurred between July 28 and 30 at $m_v \sim 9.7$ (IAU Circ., No. 4821). The same system had previously undergone outburst in 1937, and therefore this object entered the class of recurrent novae. Our earliest spectrum, obtained on August 1, shows strong, broad Balmer lines, with very strong He I λ5876 and He II and Fe II lines also present (Fig. 4). The nova experiences a rapid spectral evolution, presumably due in part to a rapidly decreasing envelope density. On August 5, He II λ4686 is moderately strong, and the coronal [Fe X] λ6375 emission line is detectable. During the next 2 weeks, the [Fe X] strengthens, and [Fe VII] and [Fe XI] lines appear, while the Fe II multiplets become weaker. He II λ4686 does not increase in strength in this interval, and the first evidence of a late-type companion appears in the red. By September a significant change in line strengths occurs once again, with the ionization level dropping considerably, such that [O I] λ6300 and [O II] λ7325 become two of the stronger lines in the spectrum. Relative to the declining nova, the secondary companion becomes dominant in the red, and based upon the TiO and VO features between λ7000 and 8000 Å a spectral type of M8 III can be assigned to it (Turnshek et al. 1985).

No spectra were obtained of V745 Sco between 1989 September and 1990 May. By the latter date, the [N II] and [O II] auroral transitions were still strong, and the line widths had decreased to the point where [N II] λ6584 could be resolved from Hα. In addition, a rich array of Fe forbidden lines had appeared. At this time, the spectrum was changing very slowly with time.

2.4. *Nova Scorpii 1989 No. 2 (V977 Scorpii)*

Nova Sco 1989 No. 2 was discovered on 1989 August 17 near maximum light by W. Liller (IAU Circ., No. 4836) during a lunar eclipse. Prediscovery photographs by both Liller and McNaught (IAU Circ., No. 4838) confirm that maximum light occurred on August 18 at $m_v \sim 9.5$. Specra taken several days after outburst reveal low-excitation permitted lines, including Fe II, O I, and Ca II (Fig. 5). The wavelengths longward of Hα contain a wealth of heavy element lines, including Mg II multiplets which are probably excited by resonance fluorescence of Lyβ. One month later, the auroral transitions of [N II] and [O II] are present, but the excitation is still so low that He I lines are only marginally detectable. Early in 1989 October, the auroral transitions have become stronger, and the ionization level is higher, as evidence by the definite appearance of He I lines. By 1990 February, nebular lines and He II λ4686 are becoming strong, and the increasing level of ionization continues into 1990 June, as the higher ionization [Fe VII] λ6087 line also becomes increasingly stronger. During this period, O I λ8446 slowly decreases in strength, declining from the strongest emission line in the spectrum.

2.5. *Nova Scuti 1989 (V443 Scuti)*

The initial observation of Nova Scuti was made by P. Wild on 1989 September 20 at a brightness of $m_p = 10.5$ (IAU Circ., No. 4861), although a subsequent search of photographs by McNaught (IAU Circ., No. 4862) and by Wenzel (IAU Circ., No. 4868) revealed that visual maximum probably occurred on 1989 September 18 at $m_p \sim 9.5$, or perhaps even a few days earlier. The data which we have indicate that the nova's spectral evolution was very similar to that of Nova Sco 1989 No. 2. The initial spectrum is shown in Figure 6, 2 weeks after maximum, featuring strong Balmer and Fe II lines, in addition to Na I D with a P Cygni profile. In the near-IR, strong O I λ7773 and λ8446, together with other permitted lines of Ca II, N I, and C I occur, in addition to the same Mg II multiplets that were observed in Nova Sco 1989 No. 2, which are populated by cascading from $Mg^+ 5p\,^2P^o$, which itself is connected to the ground state by a strong resonance line at λ1026. In November, 2 months after outburst, strong forbidden lines have appeared, including the auroral lines [N II] λ5755 and [O II] λ7325, whose unusual strengths are attributable to high densities which collisionally deexcite the nebular lines. After a 5 month haitus in data, the spectrum in 1990 April shows many more nebular lines emerging, although the auroral transitions of [O II], [N II], and [O III] remain unusually strong. The spectrum remains essentially unchanged through our last observations at the end of 1990, with the exception of the emergence of the [S III] $\lambda\lambda$9072, 9535 lines.

2.6. *V3890 Sagittarii*

The nova V3890 Sgr had already been considered as a classical nova due to a recorded outburst in 1962 (Duerbeck 1987). Like V745 Sco, which became a recurrent nova when Liller recorded a second outburst in 1989, V3890 Sgr was independently discovered by A. Jones (IAU Circ., No. 5002) and by Liller (IAU Circ., No. 5010) to be in another outburst in 1990 April, at a maximum brightness of $m_v \sim 8.5$ on April 27 (IAU Circ., Nos. 5002, 5004). We did not begin to obtain spectra during this outburst until late May, as seen in Figure 7, although previous spectra have been reported by other investigators in both northern and southern hemispheres (IAU Circ., Nos. 5006, 5007, 5015, 5019, and 5021). It evolved very quickly after maximum, from having predominantly permitted lines to showing high-ionization forbidden lines. In this sense, its spectrum developed very similarly to that of the recurrent nova V745 Sco. Our first spectrum shows strong coronal lines of [Fe X] λ6375 and [Fe XI] λ7891, in addition to very strong O I λ8446. At this time He I lines and He II λ4686 are also prominent, and there is a hint of a component of red continuum from a late-type secondary companion in the nova system. The latter becomes increasingly prominent in succeeding weeks as the continuum from the nova envelope fades. On June 7 the [Fe X] is still strong, and other forbidden lines are increasing in strength, notably the auroral lines [N II] λ5755 and [O III] λ4363, and also nebular lines such as [O III] λ5007 and [Ne V] λ3426. During the next month, the spectrum undergoes a significant change: the previously strong [Fe X], [Fe XI], and O I λ8446 lines all disappear. At the same time, all the other low-to-moderate ionization forbidden nebular and auroral lines, such as [Ne V], [O III], [Fe VII], and [N II] continue to increase relative to the permitted lines. The unusual strengths of [N II] λ5755, [O III] λ4363, and [Fe VII] λ6087 with respect to Hβ are particularly noteworthy in this regard. Also worth mentioning is the emergence in V3890 Sgr of the same [Fe II] to [Fe VII] forbidden line spectrum that appeared in V745 Sco, also a classical nova with short recurrence time and a luminous red companion. Based on the atlas of Turnshek et al. (1985), the V3890 Sgr secondary is also of spectral type M8 III.

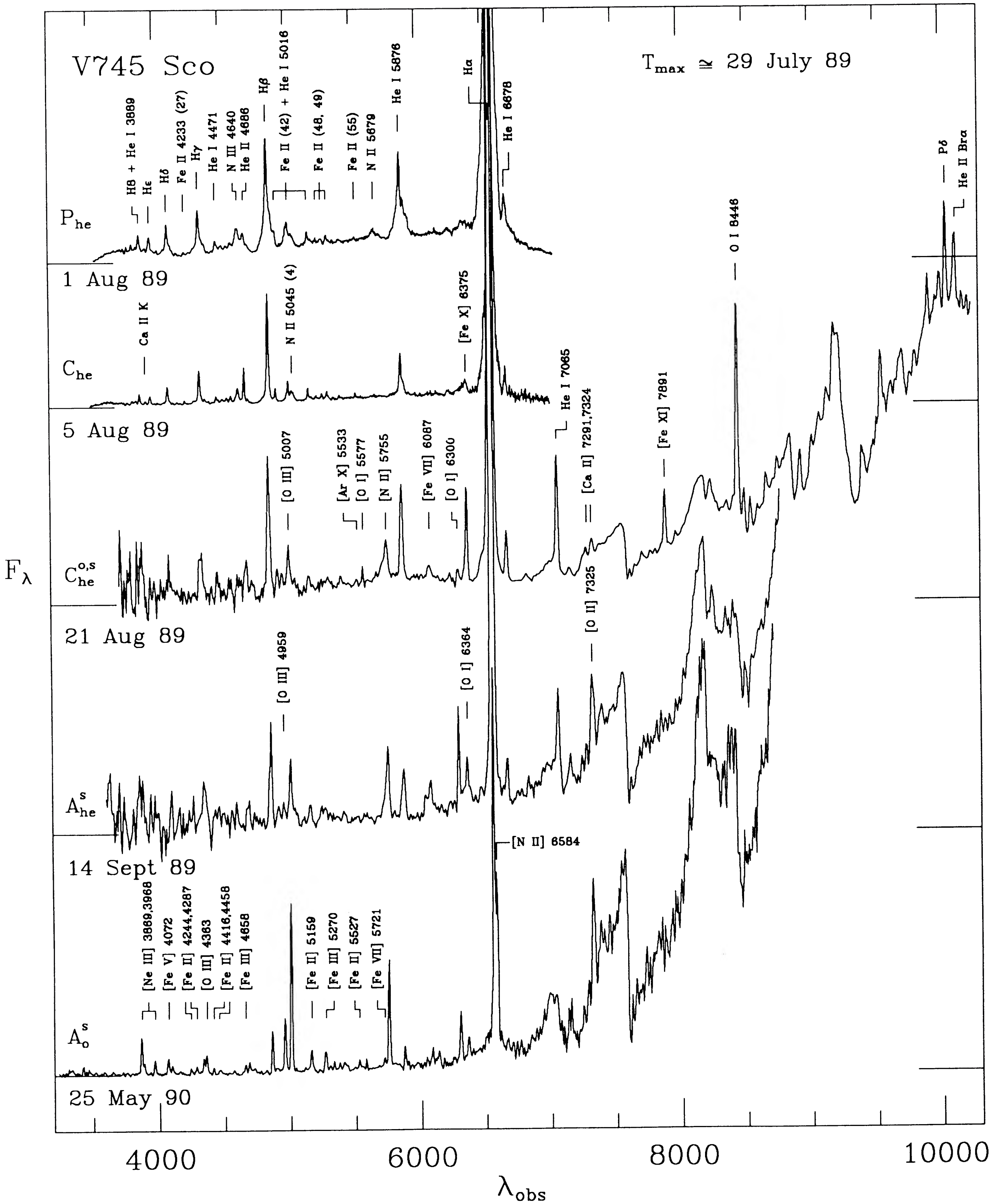

FIG. 4.—Spectral scans of the recurrent nova V745 Sco after its outburst in 1989 July

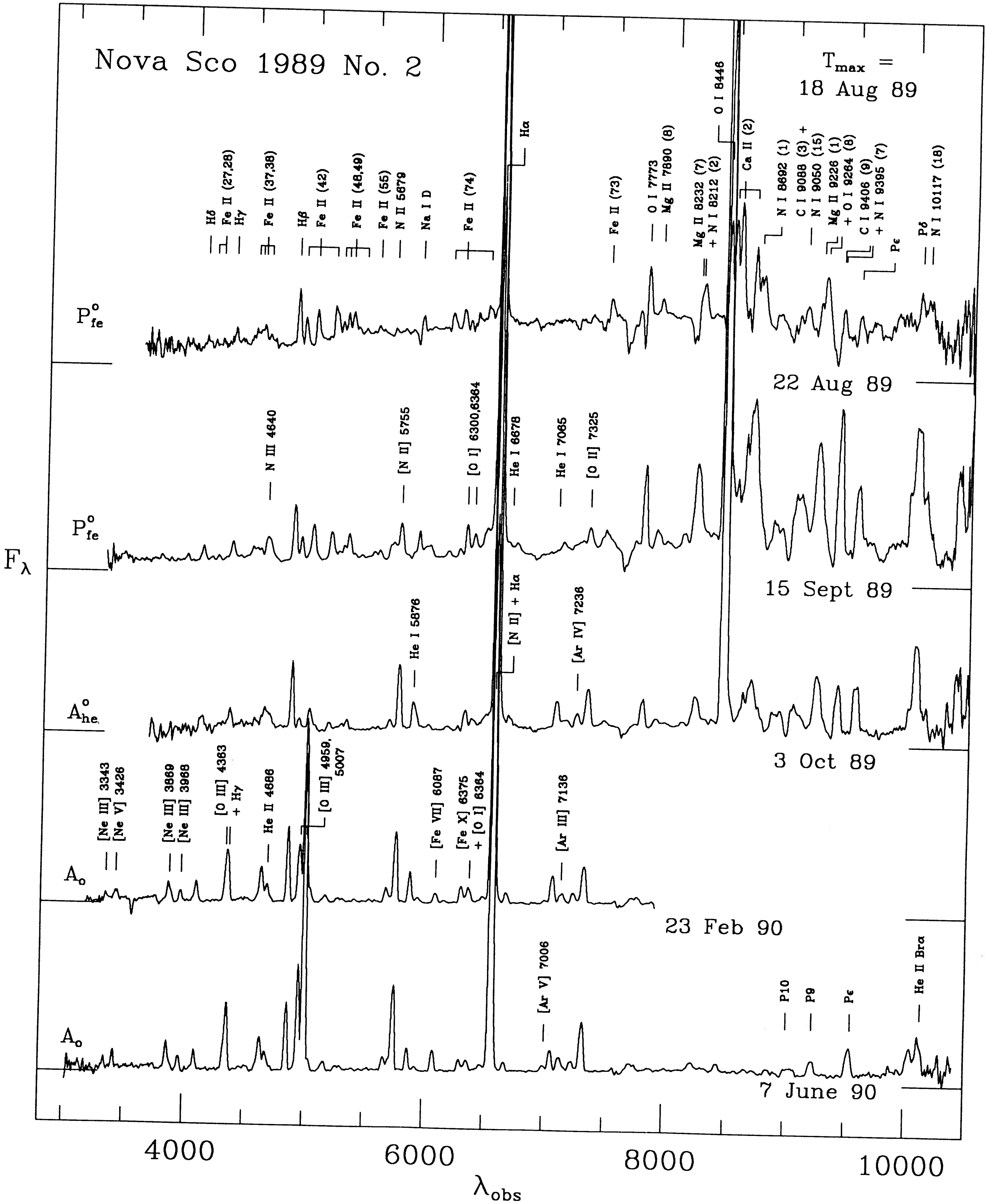

FIG. 5.—Spectral scans of V977 Scorpii (Nova Scorpii 1989 No. 2) following its 1989 August outburst

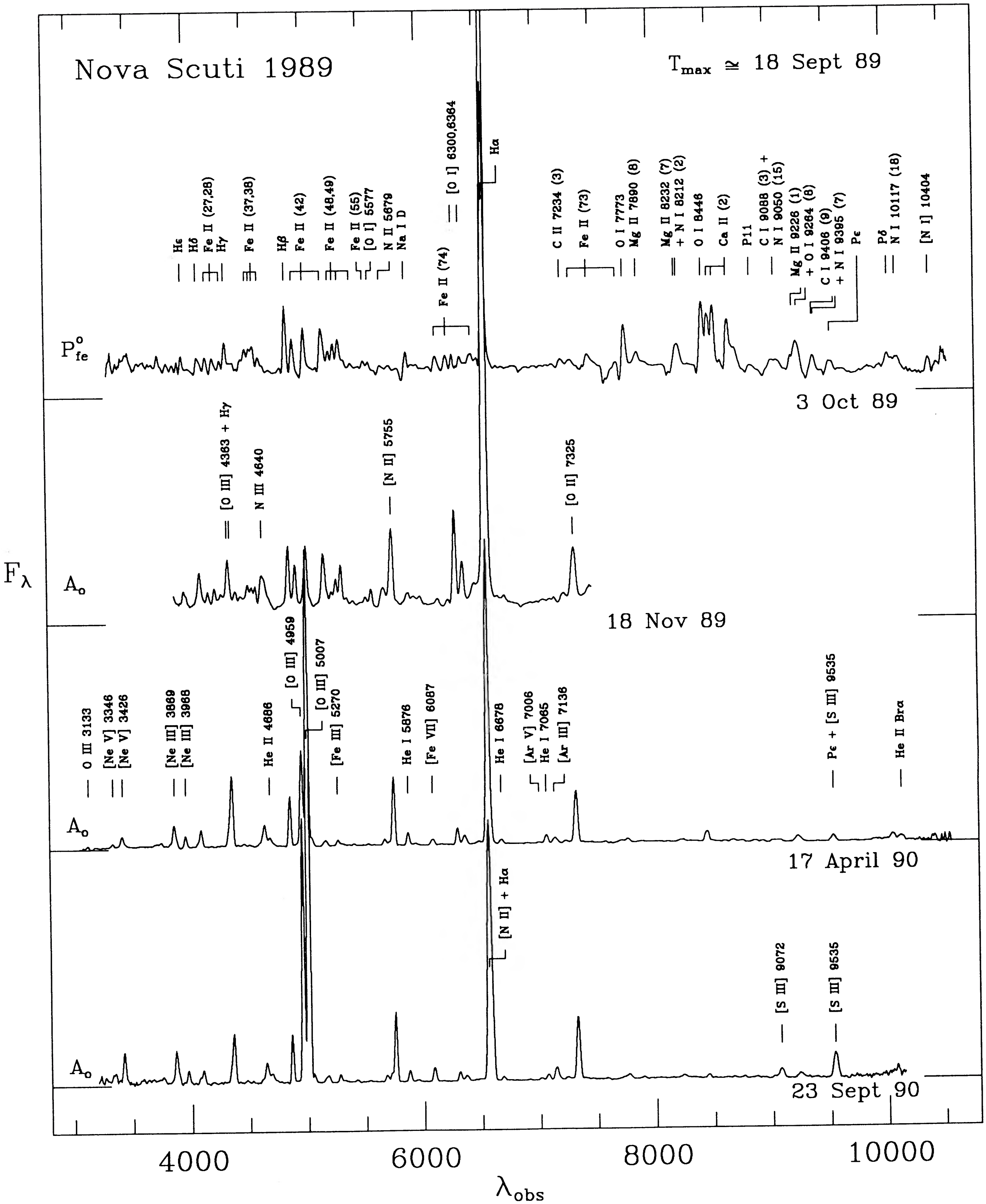

FIG. 6.—Spectral scans of V443 Scuti (Nova Scuti 1989) after its outburst in 1989 September

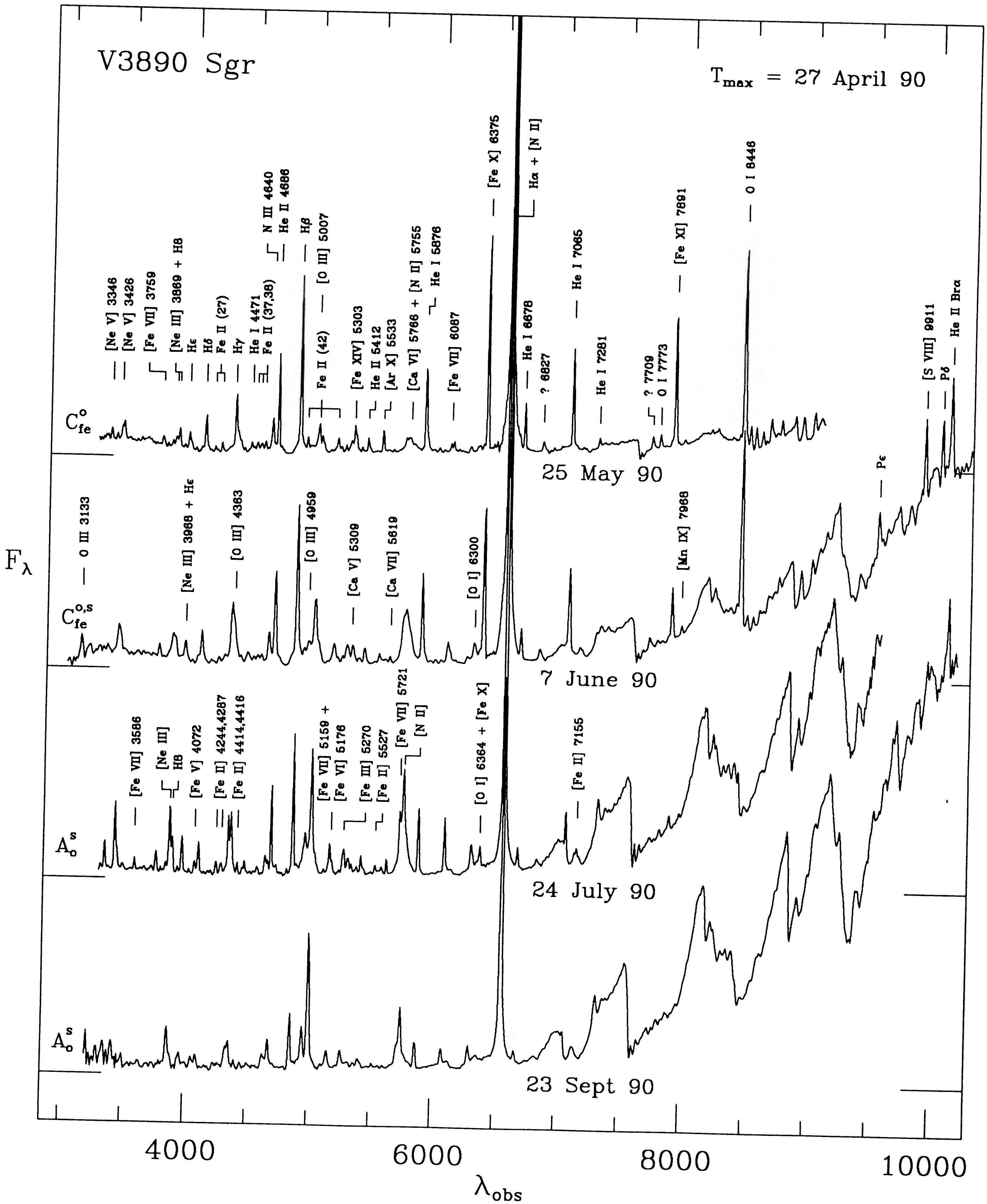

FIG. 7.—Spectral scans of the recurrent nova V3890 Sgr after its 1990 April outburst

2.7. *LMC Novae*

Due to their greater distance than Galactic novae, novae in the LMC are more than 3–4 mag fainter on average than the brighter novae observed in the Galaxy. Because they are fainter, the study of LMC novae requires larger telescopes, and thus our coverage of these novae has been rather sketchy. During the past several years we have obtained spectral scans of four LMC novae (Figs. 8 and 9), and although the coverage is incomplete the data are useful in establishing their emission spectra characteristics near visual maximum. The novae are as follows:

2.7.1. *Nova LMC 1988 No. 1*

This nova was discovered by G. Garradd in March and achieved a maximum brightness of $m_v \sim 11.2$ on 1988 March 23 (IAU Circ., Nos. 4568, 4569). We obtained spectra during the first month following outburst, as shown in Figure 8, during which time the spectrum did not evolve in a dramatic fashion. As is typial of many novae near maximum, the Balmer lines dominate the spectrum in the visible, accompanied by low-ionization lines of Fe II, Na I, O I, and the Ca II infrared triplet. A number of these lines have blue absorption components. By April 22, the O I $\lambda 8446$ and Fe II lines have increased in strength relative to Hβ, and the forbidden lines [O I] $\lambda 6300$, [O I] $\lambda 5577$, and [N II] $\lambda 5755$ have appeared above the continuum. Presumably the strong Hα feature observed consists of an unresolved, perhaps dominant, [N II] $\lambda 6584$ component. Unfortunately, no further data were obtained for this nova to document the strengthening of the forbidden lines, due to its poor location in the sky after April and its faintness after the LMC once again became favorably placed for observation.

2.7.3. *Nova LMC 1988 No. 2*

Also discovered by Garradd, this nova was found at maximum on 1988 October 13 with $m_v \sim 10.5$ (IAU Circ., Nos. 4663, 4664, 4666). Our spectral scans show it to have been dominated initially by broad Balmer lines with narrow, blueward absorption components, and Fe II emission (Fig. 8). As is frequently the case, Na I *D* is also present with a P Cygni profile. Two weeks after maximum N II multiplets 3, 21, and 24, which may be excited from resonance fluorescence of the $3d\,^3P^o$ state via scattering of $\lambda 529$ radiation, become stronger, and remain so until our final spectrum in mid-November. This is one of the few novae we have observed in which the line profiles become more flat-topped with time. In spite of the high expansion velocities of the envelope ($\sim 10{,}000$ km s^{-1}), no forbidden lines appear within the first month after outburst.

2.7.3. *Nova LMC 1990 No. 1*

This nova was discovered by G. Garradd on 1990 January 16 on a patrol photograph at an apparent brightness of $m_p \approx 11.5$ (IAU Circ., No. 4946), where no object had been apparent on January 3. Subsequently, W. Liller found from searching his own PROBLICOM exposures that the nova was already in outburst at this brightness on January 14 (IAU Circ., No. 4961), thus having achieved maximum on this date, or earlier. In Figure 9, our first scans show the spectrum to be very similar to that of LMC 1988 No. 2, in having very broad Balmer lines with N III $\lambda 4640$ and N II $\lambda 5001$. However, unlike LMC 1988 No. 2, this nova evolved very rapidly, developing strong forbidden lines within 2 weeks of discovery. In particular, both [Ne III] $\lambda 3869$ and [Ne V] $\lambda 3426$ are strong on January 26 and have become stronger than Hβ by February 6. The fact that [O III] $\lambda 5007$ is weak in comparison to the strong [Ne III] line almost certainly indicates that the neon abundance is very high. Thus, "neon" novae are not just peculiar to our Galaxy, but also exist in the LMC.

2.7.4. *Nova LMC 1990 No. 2*

This recurrent nova was discovered by W. Liller on 1990 February 14 in outburst with $m_p \approx 11.2$, and based on positional coincidence is very likely to be the same nova that was observed in outburst in the LMC in 1968 (IAU Circ., No. 4964). We succeeded in obtaining a spectrum in the visible on 23 February, as seen in Fig. 9, which featured prominent Balmer lines and a very strong He II $\lambda 4686$ line. The lines have narrow cores with broad wings. This is our only spectrum, although UV data were obtained by Shore et al. (1991) using the *IUE*.

3. CLASSIFICATION OF SPECTRA

The study of the evolving spectra of novae provides an excellent opportunity to understand conditions in the ejecta and the nature of the central remnant. An important aspect of novae is the fact that one can directly observe spectral changes while physical conditions vary over orders of magnitude. The range of ionization parameters and densities found in some individual novae exceeds that found in all QSOs and active galactic nuclei combined. It is therefore of value to systematically study novae and understand their different characteristics. In order to do so, it would be beneficial to have a system whereby the spectra can be categorized. At the moment there is no way of describing the important characteristics of the spectrum of a nova at a particular epoch, other than to display a plot of it. It follows that there is no convenient way of describing the evolution of spectra except to show a series of plots at different epochs. A system of classifying the variety of emission-line spectra is needed. Since there is little value in classification for its own sake, any system should be based on characteristics which are tied to physical parameters that determine the spectrum, such as the ionization parameter. Given the variety of spectra, there are many different ways in which one might proceed, but because there are more than just two parameters that dictate the appearance of the spectra, a simple scheme like the MKK spectral classification of stellar absorption spectra, based on effective temperature and luminosity, is not feasible.

A general framework for understanding the basic evolution of post-outburst spectra has been suggested by Williams (1991), in which the changing line emission is interpreted in terms of photoionization of the expanding shell by an evolving radiation source associated with the central remnant. The radiation source maintains the Eddington luminosity for a period following the eruption during which time it has an effective photospheric radius that decreases via mass loss until it approaches the white dwarf surface. Independently, the surface outburst reactions terminate, and the luminosity of the source declines below $L_{\rm edd}$. Jointly, these two effects act to cause the effective temperature of the radiation to first increase and then decrease, with the time scale determined by the outburst, varying from as little as weeks to as much as decades for different novae. The evolution of $T_{\rm rad}$, coupled with the constantly decreasing shell density, dictates the nature of the line spectrum. The high densities immediately after outburst restrict the emission lines to permitted transitions. As the density falls, auoral transitions and then nebular forbidden lines emerge

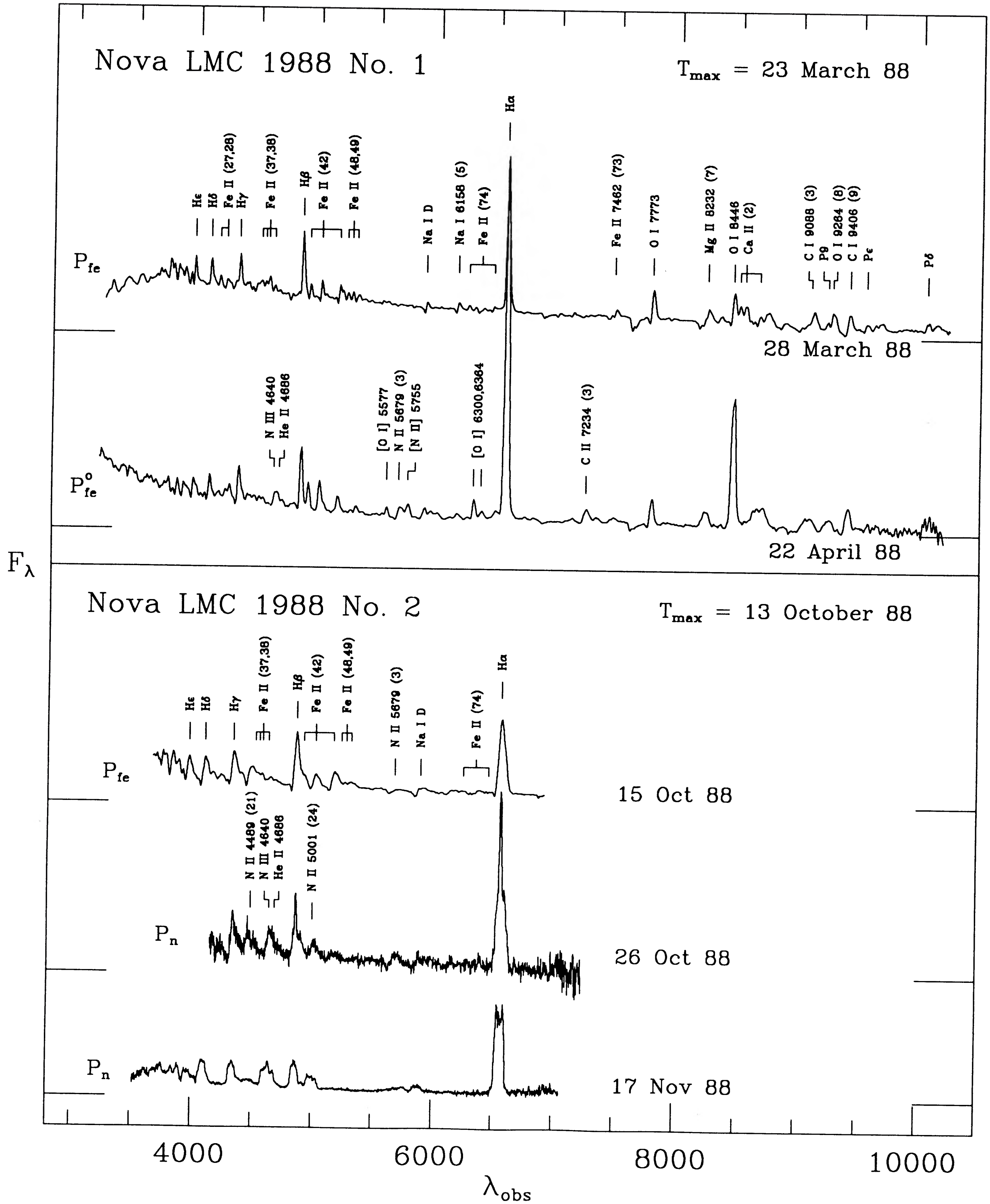

FIG. 8.—Spectral scan of two 1988 novae in the LMC: Nova LMC 1988 No. 1 and Nova LMC 1988 No. 2

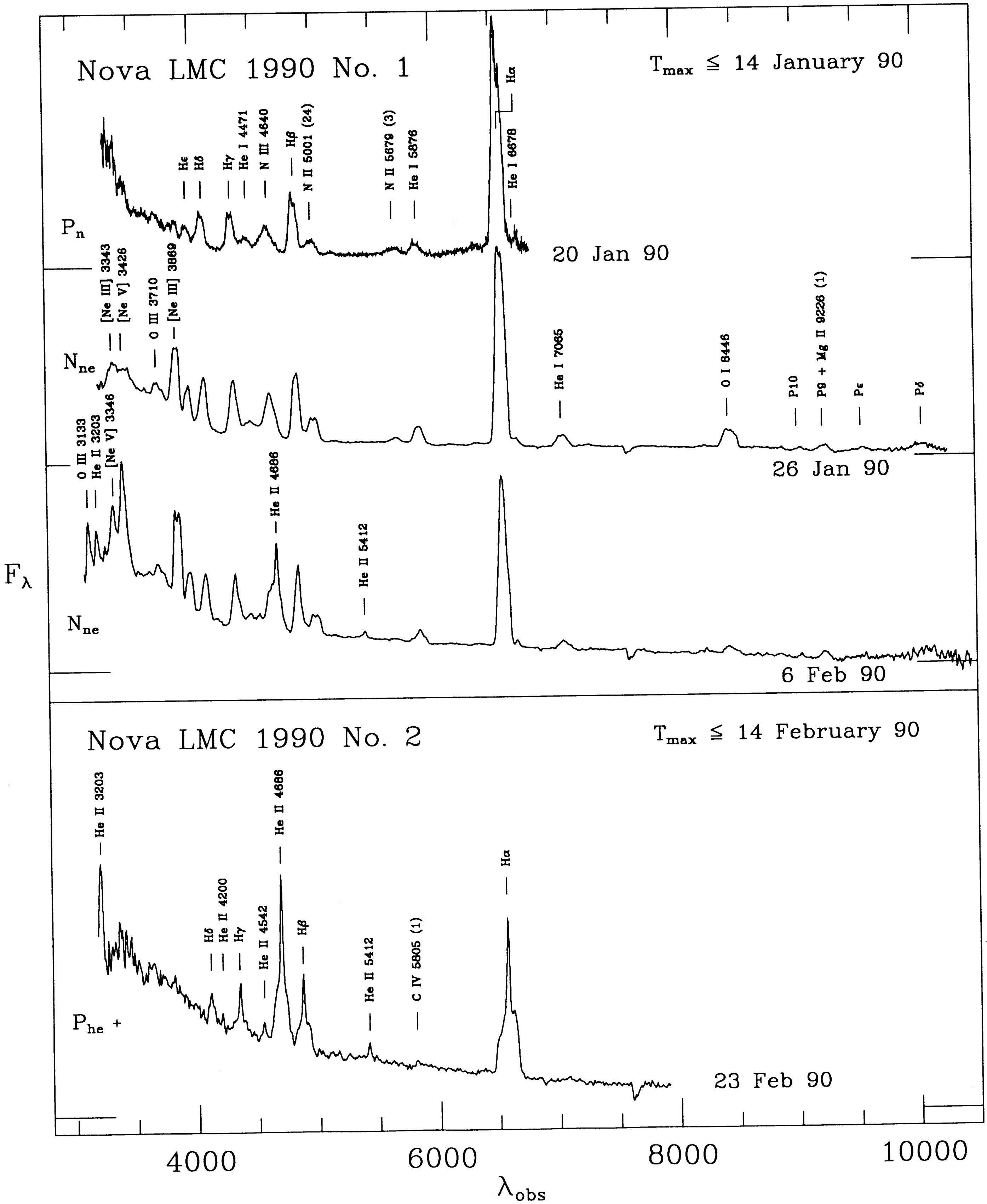

FIG. 9.—Spectral scans of two 1990 LMC novae: Nova LMC 1990 No. 1, which underwent outburst in 1990 January, and the first known extragalactic recurrent nova, Nova LMC 1990 No. 2, which underwent outburst in 1990 February.

from the shell, initially with increasing ionization and then with decreasing ionization.

The series of spectra we have obtained do show the general behavior described above. For example, the spectra of all of the novae consist initially of permitted lines only, usually of lower ionization. With increasing time, the level of ionization always increases, and forbidden lines begin to appear. The He I and He II lines usually strengthen in the early decline, although they are occasionally prominent from the outset. The earliest forbidden transitions are usually the higher excitation "auroral" transitions, i.e., [N II] λ5755, [O III] λ4363, and [O II] λλ7319, 7330, which have higher critical densities than their lower excitation "nebular" counterparts, and so suffer less collisional deexcitation at higher densities. As the densities in the expanding shell decrease, the familiar nebular lines then emerge, e.g., [O III] λ5007, [N II] λ6584, [Ne III] λ3869, and [Fe VII] λ6087. The maximum level of ionization achieved in the nova envelopes is almost always greater than that found in Galactic planetary nebulae and H II regions. Eventually, after sufficient time, the ionization level drops and the lines from the envelope weaken such that they blend into the continuum of the quiescent system.

The behavior of the spectra of postoutburst novae described above leads naturally to a system of classification which we have formulated, based on the prominent lines in the spectrum. Basically, we catalog nova spectra in terms of the types of transitions that are strong in the visible spectrum, excepting the Balmer lines because they are always prominent at all stages of postoutburst novae. We distinguish four distinct types of lines: permitted (P), auroral (A), nebular (N), and coronal (C). At any given time, each nova spectrum is assigned a phase depending upon the presence of certain lines, and a subclass is also assigned to the phase depending upon the relative strengths of selected non-Balmer lines. The fundamental classification scheme is based entirely on emission lines within the interval 3400–7500 Å, because of the accessibility of CCD detectors to this region of the spectrum, and it is defined as explained in the following section.

3.1. *Tololo Nova Spectal Classification System*

I. Every spectrum is classified as belonging to either phase C, P, A, or N depending upon the following criteria:

(a). Phase C. If [Fe X] λ6375 emission is clearly present and stronger than [Fe VII] λ6087, the nova spectrum is considered to be in the coronal phase, regardless of any other line strengths.

(b). Phase P. If not in phase C, the spectrum is considered to be in the permitted-line phase when the strongest non-Balmer line is a permitted transition.

(c). Phase A. If not in phase C, the spectrum is considered to be in the auroral line phase whenever any forbidden auroral transition has a flux greater than that of the strongest non-Balmer permitted line, regardless of any nebular line strengths.

(d). Phase N. If not in phases C or A, the spectrum is considered to be in the nebular-line phase when the strongest non-Balmer line is a forbidden nebular transition.

II. Each of the four spectral phases is assigned a subclass, depending upon the stronger non-Balmer line fluxes, and this subclass is denoted by a subscript to the spectral phase, representing the line or ion of the strongest of the candidate lines. The subclasses are different for each of the spectral phases, and are as follows:

(a). Phase C Subclasses: The subclass is assigned from the strongest non-Balmer line in the spectrum, and is one of the following:

1. a = auroral transition: [N II] λ5755; [O I] λ5577; [O II] λ7319, λ7330; [O III] λ4363
2. he = He I λ5876, λ7065
3. he$^+$ = He II λ4686
4. n = N III λ4640; N II λ5679; [N II] λ6584
5. o = [O III] λ5007
6. ne = [Ne III] λ3869; [Ne V] λ3426
7. fe = [Fe X] λ6375; [Fe XIV] λ5303

(b). Phase P Subclasses: The subclass is assigned from the strongest non-Balmer line in the spectrum:

1. he = He I λ5876, λ7065
2. he$^+$ = He II λ4686
3. c = C IV λ5805; C II λ7234
4. n = N II λ5679, λ5001; N III λ4640; N V λ4605
5. fe = Fe II λ5018, λ5169, λ5317
6. na = Na I λ5892
7. ca = Ca II H and K

(c). Phase A Subclasses: The subclass is assigned from the strongest non-Balmer and nonauroral line in the spectrum:

1. he = He I λ5876, λ7065
2. he$^+$ = He II λ4686
3. n = [N II] λ6584; N III λ4640; N II λ5679, λ5001
4. o = [O III] λ5007; [O I] λ6300
5. ne = [Ne III] λ3869; [Ne V] λ3426
6. fe = [Fe VII] λ6087; Fe II λ5018, λ5169

(d). Phase N Subclasses: The subclass is assigned from the strongest nebular line in the spectrum:

1. n = [N II] λ6584
2. o = [O I] λ6300; [O III] λ5007
3. ne = [Ne III] λ3869; [Ne V] λ3426
4. fe = [Fe II] λ4244, λ5159; [Fe III] λ4658, λ5270; [Fe V] λ4072; [Fe VI] λ5176; [Fe VII] λ6087

III. In addition to the phases and subclasses assigned to each spectrum, our experience with observing a number of novae over an extended wavelength range into the near-IR has demonstrated that two optional, independent subclass assignments might yield useful information. In some novae, the near-IR can at times be dominated by a very strong O I λ8446 line, and/or by the red continuum of a late-type secondary companion in the binary system. Therefore, when the extended spectral coverage permits it, we suggest that a superscript be attached to the spectral phase when either of the following conditions occurs:

(a). o = flux of O I λ8446 exceeds that of Hβ

(b). s = the clear presence of a component of red continuum from a late-type secondary companion.

This classification system has been formulated over the time that we have been observing novae, and since we have studied only a limited number of objects, the scheme will undoubtedly benefit from revision in the future, as other novae are observed. We have attempted to define a system that is succinct and informative in providing pertinent information related to conditions in the envelope, without being too complicated. Further experience will dictate how the system might be improved by modifications.

Several explanatory comments should be made to clarify certain aspects of the classification scheme. First, unless [N II] λ6584 is clearly resolved separately from Hα, the Hα + [N II] emission feature is always considered *for classification purposes* to be due entirely to Hα alone. A similar situation applies to

[O III] λ4363, which is usually blended with Hγ. Unless clearly resolved from Hγ, the [O III] line flux should be considered to be that component of the Hγ + [O III] feature which exceeds the geometrical mean of Hβ and Hδ. Second, consistent with the assignment of the subclasses for phases C, P, and N, one might consider assigning the phase A subclass on the basis of the strongest auroral line. This, however, has turned out so consistently to be [N II] λ5755 that we felt little information was conveyed by such an assignment. Therefore, we have excluded the auroral line strengths from consideration in the definition of the auroral phase subclass.

The definition of the main spectral phases is based on relative intensities of non-Balmer lines because, from our experience with postoutburst spectral evolution, appreciable changes frequently occur in the spectra from the appearance and disappearance of lines which never achieve the strength of Hβ, the obvious candidate for a flux benchmark. Consequently, any classification scheme that is based on the strength of lines relative to Hβ would be too insensitive to fundamental changes in the nature of the spectrum. Since the Balmer lines are always prominent at all times in the spectra, it is sensible to devise a scheme based on the strengths of lines which show larger variations in intensities than the Balmer lines at different times during postoutburst decline.

Finally, it is our experience that valid provisional spectral phases can be assigned to novae in the period before they develop forbidden lines from spectral scans that have restricted wavelength coverage, as long as they cover the region from Hγ to Hα. Any strong lines falling outside this interval are likely to be nebular forbidden lines, so if spectra in the period following outburst do not fully extend between 3400 and 7500 Å, a tentative spectral phase may be assigned on the basis of line strengths in the interval between Hγ and Hα.

4. SPECTRAL EVOLUTIONARY SEQUENCES

The fact that a basic description of the emission-line spectrum at a particular time can be given in terms of a phase and subclass means that one can describe the time evolution of a spectrum by giving the sequence of phases through which each nova passes after outburst. Such a record may be incomplete for many novae for which the temporal coverage is not complete; nevertheless, it does provide a simple method of categorizing the evolution of the most salient features of their spectra.

We propose defining the evolutionary sequence of each nova spectrum by taking all of the different phases in which it has been observed, together with the subclasses observed for each phase, and writing them in order of their appearance. Beginning with the initial phase, all of the different subclasses observed for that phase are given in order, as subscripts to that phase. The next spectral phase is then written immediately following the first, until the evolution has terminated. Although we have a limited sample of novae, it appears that all of them pass first through the permitted phase and should eventually end up in the nebular phase. The designation of the sequence for a given nova should therefore be considered incomplete if it has not been observed within the first several days after visual maximum light or if the first spectra are not of phase P. Any novae which have not been followed sufficiently regularly and for which it appears that a spectral phase probably has occurred that was not observed, have that missing phase denoted in the sequence by a dash. In addition, in defining the spectral sequences, the optional subclasses denoting the presence of O I λ8446 and a late-type secondary companion should be denoted only once for each nova, corresponding to that phase during which each condition was first observed.

We have assigned spectral phases to all of the spectral scans that appear in Figures 1–9. Taking V977 Sco as an example, the following distinct phases were assigned to its individual spectra: P^{o}_{fe}, A^{o}_{he}, and A_{o}. Its spectral evolution sequence would therefore be designated: $P^{o}_{fe}\,A_{he,o}$. Since we have been following nova spectra for only 3 yr, most of the ones we have studied are still evolving. Up to the last observations we have made, presented in Figures 1–9, the spectral evolution sequences of the novae are the following:

Nova Spectral Evolution Sequences

V394 CrA	P_{n,he^+}
V2214 Oph	$P_{fe,he}\,N_{ne}$
V745 Sco	$P_{he}\,C^{o,s}_{he}\,A_{he,o}$
Nova Sco 1989 No. 2	$P^{o}_{fe}\,A_{he,o}$
Nova Scuti 1989	$P^{o}_{fe}\,A_{o}$
V3890 Sgr	$-C^{o,s}_{fe}\,A_{o}$
Nova LMC 1988 No. 1	P^{o}_{fe}
Nova LMC 1988 No. 2	$P_{fe,n}$
Nova LMC 1990 No. 1	$P_{n}N_{ne}$
Nova LMC 1990 No. 2	P_{he^+}

It is clear from the study of old, spatially extended nova shells that they all eventually evolve to a low density, low-to-moderate ionization state over a time scale of decades, and thus most of the nova spectra presented here are still changing. The usefulness of the classification scheme is that it enables one to quickly define important aspects of each nova's spectral evolution without having to review the entire series of spectra for each object. Because of the complexity of nova spectra, the classification does not convey detailed information about the spectrum of each nova; nevertheless, there are some interesting characteristics that are revealed by the above sequences. For example:

1. Immediately after outburst, the emission lines are first produced in conditions in which they are all permitted transitions. Forbidden lines appear later within a time scale of a few days to months.

2. Within 1 month of the outburst, recurrent novae (one should say, those classical novae with shortest recurrence times) enter a high ionization phase, marked either by strong coronal [Fe X] emission (V745 Sco, V3890 Sgr) or very strong He II (V394 CrA, LMC 1990 No. 2).

3. The presence of coronal lines is frequently accompanied by low ionization lines, e.g., O I λ8446, Fe II, or N II.

4. The so-called neon novae, which all have strong [Ne III] or [Ne V] lines and therefore pass through the phase N_{ne}, appear to evolve directly from the permitted to the nebular phase, without passing through a coronal or auroral phase. The absence of a coronal stage for neon novae is interesting in view of the fact that these systems are believed to contain massive O-Ne-Mg white dwarfs. Assuming that they achieve the Eddington luminosity after outburst, the smaller radii of the massive degenerate primaries in these novae should result in the very high radiation temperatures which produce the coronal phase. On the other hand, if the photospheric radius were to remain much greater than the white dwarf radius, say through continuing mass loss, until after the luminosity dropped substantially below L_{edd}, the coronal phase would

then be by-passed. The fact that neon novae either tend to pass through an auroral stage does suggest that the ejected shell differs in some way in these systems, either in terms of the density, mass, or importance of inhomogeneities. Whatever the cause, the observations indicate that the spectral evolution of neon novae differs from that of other novae, and this should be exploited to provide essential information on the neon nova phenomenon.

The above characteristics are based upon a small sample of objects, and therefore some of these points may in fact not remain valid after we have acquired spectra for a larger group of novae. They do illustrate, however, that examination of the spectra of novae as they evolve might reveal important properties and tendencies of these systems.

There are a number of other facts that become evident from an inspection of the spectral scans. For example, the emission lines tend to become narrower with time, and measurements of the line widths show that Hβ is usually among the narrowest of the lines. Those novae whose spectra show very broad asymmetric or "ragged" profiles immediately following outburst usually evolve rapidly and develop a He II λ4686 line which is stronger than Hβ. Curiously, however, the very high ionization coronal phase in novae is usually *not* accompanied by strong He II emission. Since helium should be doubly ionized under these conditions, a solar He/H abundance should produce a He II λ4686 flux equal to that of Hβ. This is not the case, and a low He/H abundance is unlikely to be the cause since it would require the helium abundance to be less than solar. Nor can one appeal to high densities affecting the λ4686/Hβ ratio in the coronal line region, since it is the source of forbidden [Fe x] emission, which has a critial density of $N_e^c \sim 10^7$ cm^{-3}. It must be that the coronal region in nova envelopes co-exists with a higher density component of gas whose filling factor is smaller but whose emission measure exceeds that of the coronal gas. The He II, He I, and Balmer lines are produced in this denser component, and the fact that the He ionization is not complete in this zone must be due to its significantly higher density, which leads to incomplete ionization of helium.

There are several other characteristics of the emisson spectra which indicate that the envelopes of novae must be very inhomogeneous. First, the sudden absorption feature that appeared in the Balmer and He I lines of V2214 Oph in early 1988 July, 3 months after maximum, is unlikely to have been the result of a sudden change in conditions in the entire envelope. Much more likely, it was produced by the passage of an individual small cloud of high density and optical depth in front of the central continuum source. The fact that the absorption came and went in a week, with the transverse velocity of the cloud probably of the order of 10% of the outward expansion velocity, would indicate that the cloud radius was of the order of 10^{-2} the radius of the entire envelope. Second, the simultaneous presence of lines of Fe II, O I λ8446, and [Fe x] λ6375 or [Ar x] λ5535, as observed in V745 Sco, V977 Sco, V3890 Sgr, and V443 Sct is quite likely due to strong density inhomogeneities. An alternative explanation is that the envelope is ionization bounded, with an inner high-ionization zone producing the coronal lines, and an outer neutral zone where the lower ionization species originate. However, this is very unlikely since nova envelopes having a density sufficiently low to produce forbidden lines must be very density-bounded (Williams 1991), thereby lacking any outer lower ionization zones. Almost certainly, the wide range of ionization seen in the emission lines of novae must be due to inhomogeneities with large differences in densities, for which the level of ionization is inversely related to the gas density. This should produce high ionization forbidden lines from low density gas, together with low ionization permitted lines from high density cloudlets, in accordance with what is observed. Although lower ionization forbidden lines are also observed, such as [N II] and [O III], these frequently are strong auroral transitions which may be formed at relatively high densities.

A final argument in favor of the existence of a wide range of densities in nova envelopes is provided by the relative intensities of the He I and forbidden lines. Almog & Netzer (1989) have computed He I line intensities for a wide range of conditions, and their results demonstrate that whenever $F(\lambda5876) > 4F(\lambda4471)$ these lines must be formed at a density of $N_e \sim 10^{10}$ cm^{-3}. On the other hand, the critical densities of most nebula forbidden transitions are of the order of $N_e^c \lesssim 10^7$ cm^{-3}, and thus these latter lines tend to be formed at lower densities. Without detailed models one cannot rule out the possibility that lines such as [Ne III] λ3869, [O III] λ5007, and [Fe x] λ6375 are formed at higher densities; however, it is more likely that they are produced at densities $N_e \lesssim 10^7$ cm^{-3}. In a number of novae, we have observed these forbidden lines to be present while measuring $F_{\lambda5876} > 4F_{\lambda4471}$, even allowing for uncertain reddening corrections, viz., in V2214 Oph, V745 Sco, V977 Sco, V443 Sct, and V3890 Sgr. We take this as clear evidence for the existence of distinct emitting regions in nova envelopes with a range of densities extending over many orders of magnitude.

The realization that the spectra of novae are the product of emission from different components of the envelope, having distinctly different densities has important implications for the analysis of the emission lines. Any determination of element abundances or physical conditions must take this fact into account so as to ensure that any comparison of line strengths involves lines coming from the same emitting volume. In particular, any calculation of heavy element abundances with respect to hydrogen which involves a comparison of forbidden lines with Balmer lines must consider the effect of condensations. The same is true of the He lines, which arise preferentially from the highest densities in the envelope, thus being affected by both collisional and optical depth effects. Any determination of the He/H abundance in novae is best made after radiative recombination has been established as the formation mechanism, i.e., after the unreddened line ratios have evolved to the values $F_{\lambda5876}/F_{\lambda4471} \simeq 3.5$, $F_{\lambda7065}/F_{\lambda6678} \simeq 1.5$, and $F_{\lambda5876}/F_{\lambda7065} \simeq 2.8$ (Almog & Netzer 1989). Since the effects of condensations are observed to diminish as the envelopes expand, the most secure abundance determinations are those made for spatially resolved shells, decades after the outburst. The least secure results derive from analyses made shortly after maximum light, e.g., during the permitted spectral phase.

Our current understanding of nova envelopes in the period following outburst is still rudimentary, since it depends on the analysis of the spectra at different epochs when they are undergoing significant change. The fact that one can actually observe spectral changes occurring is valuable in arriving at an understanding of how the expanding shells evolve. In this sense, they may be very useful in the analysis of emission-line spectra of objects such as active galactic nuclei and quasars, whose evolution occurs over time scales much longer and which therefore can be studied only via snapshots at a fixed epoch for each object. The novae we have observed still need to be followed for additional years, until some of them develop resolved shells, since their spectra are still evolving. In addition, a larger sample of objects augmented by new discoveries, will help in the characterization of the different types of novae. The fact that the emission spectra of novae pass through phases in which they, at different times, appear similar to the spectra of QSOs, active nuclei, and Galactic nebulae means that their analyses may eventually contribute in an essential way to the understanding of these diverse objects. More directly, they will eventually yield information on the nature of nova outbursts and the structure of accreting white dwarfs.

We are happy to acknowledge the important contributions of the many people, and especially Bill Liller here in Chile, who are actively engaged in projects to discover new novae. We have also benefited from the professionalism of the CTIO mountain observer support crew who have provided many instrument set-ups for us on short notice.

REFERENCES

Almog, Y., & Netzer, H. 1989, MNRAS, 238, 57
Barlow, M. J., et al. 1981, MNRAS, 195, 61
Duerbeck, H. W. 1987, Space Sci. Rev., 45, 1
McLaughlin, D. B. 1960, in Stars and Stellar Systems, Vol. 6, Stellar Atmospheres, ed. J. L. Greenstein (Chicago: Univ. of Chicago Press), 585
Payne-Gaposchkin, C. 1957, The Galactic Novae (Amsterdam: North-Holland)
Sekiguchi, K., et al. 1989, MNRAS, 236, 611
Sekiguchi, K., Feast, M. W., Whitelock, P. A., Overbeek, M. D., Wargau, W., & Spencer Jones, J. 1988, MNRAS, 234, 281
Shore, S. N., Sonneborn, G., Starrfield, S. G., Hamuy, M., Williams, R. E., Cassatella, A., & Drechsel, H. 1991, ApJ, 370, 193
Stone, R. P. S., & Baldwin, J. A. 1983, MNRAS, 204, 347
Taylor, B. J. 1984, ApJS, 54, 259
Turnshek, D. E., Turnshek, D. A., Craine, E. R., & Boeshaar, P. C. 1985, An Atlas of Digital Spectra of Cool Stars (Tucson: Western Research)
Williams, R. E. 1991, in IAU Colloquium 122, Physics of Classical Novae, ed. A. Cassatella & R. Viotti (Berlin: Springer), 215