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THE EVOLUTION OF THE INFRARED SPECTRA OF CLASSICAL NOVAE

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RESUMEN

Presentamos una revisión de las características de la emisión infrarroja de novas clásicas y describimos el programa del Observatorio de McDonald de monitoreo de los espectros en el infrarrojo cercano de las mismas. La banda K ($1.9 - 2.5\ \mu$m) es única en cuanto que contiene líneas de emisión fuertes de iones con un amplio intervalo de potenciales de ionización, y reviste especial importancia para la comprensión de las condiciones físicas del material gaseoso expulsado. Cinco novas fueron seguidas durante 1986-93, incluyendo Nova Cyg 1992 (V1974 Cyg). A pesar de cubrir un amplio intervalo en la velocidad de disminución y cantidad de polvo formado, todas mostraron un patrón general de evolución similar. El espectro infrarrojo de una nova está dominado inicialmente por las líneas de emisión de H I y He I, pero a medida que pasa el tiempo el grado de ionización aumenta. Eventualmente el espectro aparece dominado por líneas "coronales", las cuales requieren la ionización de especies con $PI > 100$ eV. Interpretamos este comportamiento como debido a la densidad decreciente del material expulsado y a la temperatura superficial creciente de la enana blanca que fotoioniza la envolvente de la nova.

ABSTRACT

We review the character of the infrared emission from classical novae, and describe the McDonald Observatory program of monitoring their near-infrared spectra. The K-band ($1.9-2.5\ \mu$m) is unique in containing strong emission features from ions with a wide range of ionization potentials, giving it special importance for understanding the physical conditions in the gaseous ejecta. Five novae were followed during 1986-93, including Nova Cyg 1992 (V1974 Cyg). Despite having a wide range in the speed of decline and amount of dust formed, all showed a similar overall pattern of evolution. The infrared spectrum of a nova is initially dominated by emission lines of H I and He I, but as time passes the degree of ionization increases. Eventually the spectrum becomes dominated by "coronal" lines, which require the ionization of species with $IP > 100$ eV. We intepret this behavior as being due to the declining density of the ejecta and rising surface temperature of the white dwarf which photoionizes the nova shell.

Key words: **NOVAE, CATACLYSMIC VARIABLES**

1. INTRODUCTION

The properties of the material ejected in classical nova explosions are of interest both in themselves, as tests of nucleosynthesis theory and agents of galactic chemical enrichment, and because novae provide a unique laboratory for nebular physics. The key to determining the properties and composition of nova ejecta is spectroscopy. In this review we discuss the role of infrared spectroscopy in providing valuable insights on the nature of the nova ejecta and the host binary system.

The composition of nova ejecta is determined both by the explosive nucleosynthesis event which powers the nova outburst and by the earlier evolution of the binary star. The latter includes quiescent nucleosynthesis within the star that was the precursor of the white dwarf, and the history of the binary interaction, since mass transfer is a prerequisite for a nova event (for recent general reviews, see Shara 1989; Bode & Evans 1989; Cassatella & Viotti 1991). Recent analyses show that nova ejecta contain material originating in the white dwarf interior, thus offering the opportunity to determine whether it is a C-O white dwarf, or an O-Ne-Mg white dwarf from a relatively massive progenitor (Williams *et al.* 1985; Truran & Livio 1986).

Nova ejecta are also versatile laboratories for nebular physics. They rival active galactic nuclei in displaying a very wide range in density, temperature, and degree of ionization of the gas. Furthermore, in novae the same parcel of gas evolves rapidly from one regime of physical parameters into another (*i.e.* Williams 1991). The changing emergent spectrum must be matched with the same abundances throughout this evolution, providing a uniquely rigorous test of nebular models. In addition, the conditions in nova ejecta are extreme and exotic in several ways, stretching the envelope for nebular models. For example, the highly elevated abundances of CNO, and also often of heavier nuclei such as Ne, Mg, and Al, can refrigerate the gas temperature to unusually low values, $T < 1000\ K$ (Itoh 1981; Ferland *et al.* 1984). There is also the phenomenon of the "coronal" lines that arise from extremely high ionization states of various light metals. The simultaneous presence in novae of both high expansion velocities and the extremely hard radiation field of the white dwarf lend *a priori* plausibility to either collisional ionization in shocked material or photoionization respectively as the mechanism that produces these ions (Ferland *et al.* 1986; Williams 1991). This is one of several issues that can be addressed by infrared spectroscopy (Benjamin & Dinerstein 1990; Greenhouse *et al.* 1990).

2. INFRARED PHENOMENA IN NOVAE

The relatively young field of infrared astronomy has revealed or confirmed a number of surprising properties of classical novae (see reviews by Gehrz 1988, 1991). The first of these was the discovery that many novae experience an episode of dust condensation. While dust formation had been previously suggested as a possible explanation for sudden drops in the optical brightness of some novae, it took the detection of the accompanying turn-on of thermal infrared radiation from the dust to gain general acceptance for this idea (Geisel *et al.* 1970; Ney & Hatfield 1978). Over the last 20 years, dust formation has been observed in over a dozen novae. The details are anything but uniform. The dust can appear soon after visual maximum, several months later, or not at all. Nova Her 1991, which formed dust after 8 days, holds the speed record (Woodward *et al.* 1992). The dust shell can be optically thick or optically thin, and the derived dust masses range from order 10^{-9} to 10^{-5} $M_{\odot}$. Although carbon appears to be the most common dust constituent, silicates, SiO, and hydrocarbons have also been seen, and in some cases more than one kind of dust appears in the same nova (Gehrz 1991). Efforts to detect the dust at late times have been less conclusive than early monitoring, since in most cases one cannot conclusively distinguish between dust or fine-structure line emission as the origin of the broad-band infrared fluxes measured by IRAS (Dinerstein 1986; Harrison & Gehrz 1988).

It was infrared spectroscopy of Nova Cyg 1975 (Grasdalen & Joyce 1976) that called attention to the presence of emission lines from very highly-charged ions, usually seen in very hot, collisionally-ionized gases such as the solar corona. These "coronal" lines arise from species that require very high ionization energies, such as Ne VI (126 eV), Si VII (205 eV), and Al IX (285 eV). Infrared coronal lines have now been seen in quite a few novae (Greenhouse *et al.* 1990), and their appearance may be the rule rather than the exception (Benjamin & Dinerstein 1990). The emergence of coronal lines typically occurs between a few months and a couple of years after visual maximum, but this time interval varies widely. The temperatures required to produce these ions by collisional ionization are approximately $10^{5-6}\ K$. An alternative mechanism is photoionization by the white dwarf. The relative importance of these two mechanisms has been one of the major issues in understanding this phase of nova evolution. For example, if the gas is thermally ionized, its emission (predominantly in the X-rays) may control the optical light curves of novae (Ferland *et al.* 1986). If, on the other hand, the gas is photoionized, then the spectral evolution of the ejecta traces the evolution of the white dwarf.

Another phenomenon which was highlighted by infrared spectroscopy was the large enhancement of neon in some novae. Ferland & Shields (1978) suggested that a strong excess in the $8 - 13\ \mu$m band seen in Nova Cyg 1975 was due to the [Ne II] 12.8 μm line. This line was seen directly in Nova Vul 1984 No. 2 (QU Vul), where its extraordinary strength led to the coining of the term "neon nova" (Gehrz *et al.* 1985). This newly named class of novae is characterized by strong neon line emission and enhanced abundances of Ne, Mg, and other Si-group elements, as also measured in the optical and ultraviolet (Williams *et al.* 1985). These novae are believed to involve explosions on the surfaces of O-Ne-Mg white dwarfs representing the evolutionary endpoint of intermediate-mass stars (Starrfield *et al.* 1986; Livio & Truran 1986).

The definition of this new class is reshaping our ideas about novae. The typical development of a nova in the infrared has been described at length by Gehrz (1988; see especially his Figs. 2 and 6). Briefly, after n early optically thick phase that has the appearance of a warm photosphere (the "fireball" phase), optically hin free-free continuum emission and H I and He I recombination lines emerge. The lines and continuum then roceed to fade in consort. After a time interval of variable length, the coronal lines appear and their strengths row, especially relative to the H I recombination lines. Eventually all of the lines fade, at varying rates. This ehavior generally parallels the optical evolution as described by Williams (1991). The main differences are hat the near-infrared spectral region is less rich than the optical or ultraviolet in lines of species with ionization otentials of 50-150 eV and richer in lines of species with ionization potentials of 150-300 eV, and that the pectral evolution cannot be followed as long because the novae become too faint. Novae followed to very late imes in the optical sometimes show a continuing increase in the degree of ionization (*i.e.*, Krautter & Williams 989). Eventually, however, this trend must reverse as the white dwarf cools and the gas recombines. The other dditional factor in the infrared is that the dust, if it forms, contributes a thermal component with a color emperature of approximately 1000 K (the condensation temperature) to the near-infrared spectrum. In the ptical and ultraviolet, the main effect of the dust is to increase the effective extinction.

3. THE MCDONALD OBSERVATORY MONITORING PROGRAM

Far more valuable to studies of novae than an isolated spectrum, taken at a single epoch on a single object, re sequences of repeated observations with the same instruments, at multiple epochs and with suitable time-ampling. This is true at any wavelength. There have recently been several concerted efforts to compile such lata sets, which enable the determination of such fundamental parameters as the composition and mass of the jecta. In the infrared, the major effort by Gehrz and his collaborators at Wyoming and Minnesota has provided nost of our knowledge about dust in novae. The same group has also been responsible for most of the work n coronal and neon line emission, through low-resolution infrared spectroscopy (see references above). In the ptical, an active monitoring program is in progress at CTIO (Williams *et al.* 1991, 1993). Other multiple-epoch ptical studies made with modern detectors are listed by Williams (1992). In the ultraviolet and radio, novae ave been monitored mainly with the IUE and VLA respectively (Starrfield & Snijders 1987; Hjellming 1991).

At McDonald Observatory, we began our program of multi-epoch observations of novae in 1986. We use medium-resolution infrared spectrometer that operates in the J, H, and K bands with selectable resolving owers of $\lambda/\Delta\lambda \approx 150, 600,$ and 1200. The detector is a 1x32-element Cincinatti Electronics InSb array; further letails on the instrument and its operation are given by Lester, Harvey, & Carr (1988). This spectrometer is sually scheduled for at least one run per month on the McDonald Observatory 2.7 m reflector. The first targets f the nova program were Nova Cyg 1986 and Her 1987; the first reported result was the detection of coronal ines in Nova Her in July 1987 (Dinerstein *et al.* 1987). A summary of the novae observed to date is given in Table 1. Prior to the appearance of the Nova Cyg 1992, most of our observations were taken with the lowest esolution ($\approx$ 200 in the K-band). Most of the observations of Nova Cyg 1992 were taken at a resolution of 600.

Our results for V1819 Cyg, V827 Her, and V2214 Oph were published in Benjamin & Dinerstein (1990). Ve observed each of these moderately bright novae ($V_{max} \approx 8$), at our lowest resolution, at 3 or 4 epochs panning a two-year period. Although this sample included both fast and slow novae, and objects with a variety f behavior regarding dust formation (Table 1), all three displayed a coronal phase during which [Si VI] 1.98 μm and [Si VII] 2.47 μm dominated the K-band spectrum. This fact, which suggests that a coronal phase is ommon if not universal in novae, was one of our primary results. The other major result was based on the atio of the lines to the continuum, which we were able to measure more accurately than previous infrared bservers because our spectral resolution was significantly higher. In the absence of thermal dust emission, the ontinuum is dominated by free-free emission. The line-to-continuum ratios set upper limits on the temperature

TABLE 1: NOVAE OBSERVED AT MCDONALD OBSERVATORY 1986-1993

Nova	Date of V_{max} ($t=0$)	V_{max}	Speed	Dust Formation	Coronal Lines Seen	# epochs observed
V1819 Cyg	09 Aug 1986	8.5	slow	none	yes	4
V827 Her	31 Jan 1987	7.6	fast	yes	yes	3
V2214 Oph	<19 Nov 1987	≈ 8	slow	?	yes	3
V838 Her	23 Mar 1991	5.3	v. fast	yes	yes	3
V1974 Cyg	24 Feb 1992	4.4	slow	none	yes	10

of the ejecta, since hotter gas would produce a stronger continuum than is observed; we found that the ejecta are predominantly cool, $T \approx 10^4$ K, rather than $T \approx 10^{5-6}$ K. We therefore concluded that photoionization, rather than shock-heating, is the favored mechanism for producing the coronal ions. Since the [Si VI] and [Si VII] lines come from neighboring ions, they provide a quantitative measure of the degree of ionization, which in turn is related to the hardness of the radiation field. We found that the [Si VII]/[Si VI] ratio was essentially the same at two epochs separated by about a year, for both V1819 Cyg and V827 Her. This lack of ionization evolution makes it even harder to attribute the coronal lines to shock heating. If the gas density is low ($n < 10^5$ cm^{-3}), then the total volume of hot gas required to match the observed intensities of the coronal lines exceeds the volume that could have been shock heated by ejecta moving at the observed expansion velocities. On the other hand, if the density is higher, then a continuous source of mechanical heating is needed, in order to maintain the constant [Si VII]/[Si VI] ratio. Photoionization seems a more plausible mechanism for producing the apparently slow evolution of the ionization temperature, although admittedly the time-sampling was very sparse for these two novae.

Nova Her 1991 (V838 Her) was one of the fastest novae ever seen; it faded by three magnitudes in the first three days, even faster than Nova Cyg 1975 (V1500 Cyg). However, unlike V1500 Cyg and other fast novae, V838 Her was observed to form dust. The dust began condensing as early as day 8 and increased until day 22, but never radiated more than 5% of the total luminosity (Woodward *et al.* 1992). Given its rapid evolution, we were fortunate to be able to obtain observations of V838 Her at three epochs: 6 Apr 1991 (day 13), 9 May 1991 (day 49), and 20 Jun 1991 (day 91). The near-infrared continuum level dropped approximately an order of magnitude from each epoch to the next; after June 1991 the nova was too faint for us to observe. At all three epochs, the infrared continuum was dominated by the hot dust. Fitting our spectra with blackbodies, we find that the evolution of the $1 - 2.5$ μm spectrum was consistent with a dust temperature varying as $time^{-1/2}$, as expected for dust in a shell expanding at constant velocity from a constant-luminosity source, and consistent with the infrared photometry of Woodward *et al.* (1992). These authors interpret their observations in terms of carbon dust forming in optically-thick clumps. However, later-time observations by Lynch *et al.* (1992) showed the presence of an optically thin silicate emission emission feature, so perhaps Nova Cyg 1992 is yet another nova in which more than one type of dust formed.

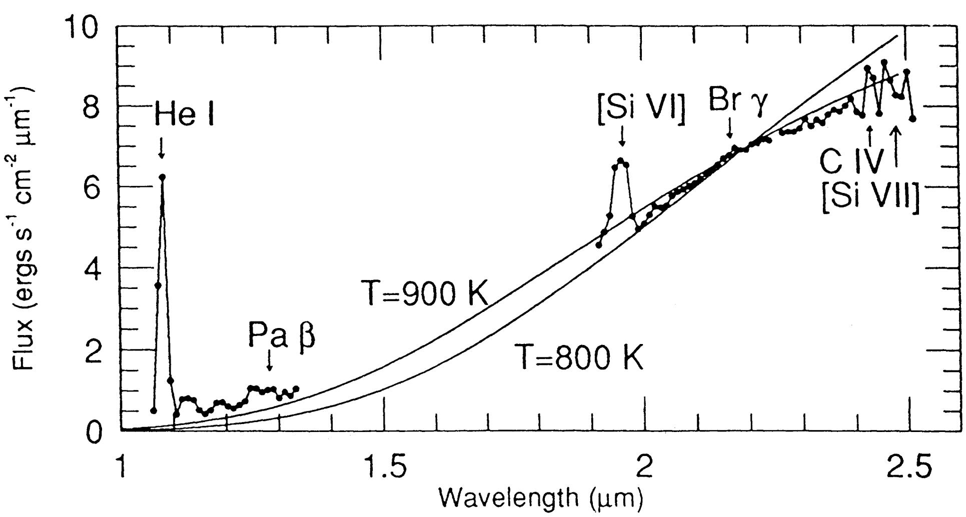

Fig 1. The spectrum of Nova Her 1991 on day 49.

Figure 1 shows our spectrum of Nova Her 1991 on day 49. In addition to the blackbody-like continuum, several strong emission lines are seen, notably He I 1.083 μm and [Si VI] 1.96 μm. The H I lines are swamped by the thermal continuum; Br γ 2.17 μm is barely detected. The simultaneous presence of dust and coronal lines supports the idea that the ejecta were clumpy or structurally complex. The [Si VII]/[Si VI] ratio was the same on days 49 and 91, and also similar to the values found for V1819 Cyg and V827 Her. Our observations

›f Nova Her 1991 will be presented and discussed more fully in Benjamin *et al.* (in preparation).

4. NOVA CYG 1992: A ROSETTA STONE

The brightest nova in nearly two decades, Nova Cyg 1992 (V1974 Cyg) inspired an unparalleled campaign ›o follow its evolution in all wavelength regions. As a result, it is the best-studied nova in history. Like V1500 Cyg and V838 Her, V1974 Cyg belongs to the class of "neon novae" believed to occur on massive, O-Ne-Mg vhite dwarfs (Hayward *et al.* 1992; Gerhz 1993; Gehrz *et al.* 1993). V1974 Cyg has two advantages over V1500 Cyg, the last naked-eye nova: a much slower light curve, and the availability of a modern suite of instruments for ›bservations beyond the optical window, from γ-rays through radio wavelengths. In addition to the favorably ›low speed of V1974 Cyg, another factor enhancing the ability of astronomers to follow its evolution has been ts failure to form dust. Dust interferes with ultraviolet observations by increasing the extinction, sometimes by ı large amount. It also interferes with infrared spectroscopy, because the strong thermal continuum decreases ›he line-to-continuum contrast for faint emission lines, as illustrated in Figure 1.

At McDonald Observatory, we initiated a sequence of observations of V1974 Cyg in June 1992, four months ıfter visual maximum. We observed it about once a month from June through December 1992, but were 'ortunate enough to be able to obtain observations at two-week intervals during the critical period late August ›o early October, when it underwent a dramatic transition from the recombination-line-dominated phase to the :oronal phase. Apart from the initial two epochs (June and July), most of the spectra were taken at a resolving ›ower of 600. This higher resolution was crucial for resolving a number of critical line pairs: in particular, 3r δ 1.945 μm/[Si VI] 1.963 μm (Figure 2), and Br γ 2.167 μm/He II 2.189 μm (Figure 3). Furthermore, the ines were somewhat spectrally resolved, so we also obtained limited information about the line profiles. At nost epochs we see a contrast between the profiles of the ionic lines, including the coronal lines, which tend to ›e asymmetric or multiply-peaked, and the H I and He I lines, which are smoother and centrally-peaked. This ;rend was also seen at at higher resolution in the mid-infrared (Hayward *et al.* 1992), and in the ultraviolet and ›ptical lines (i.e., Shore *et al.* 1993a), and provides evidence for clumping within the ejecta.

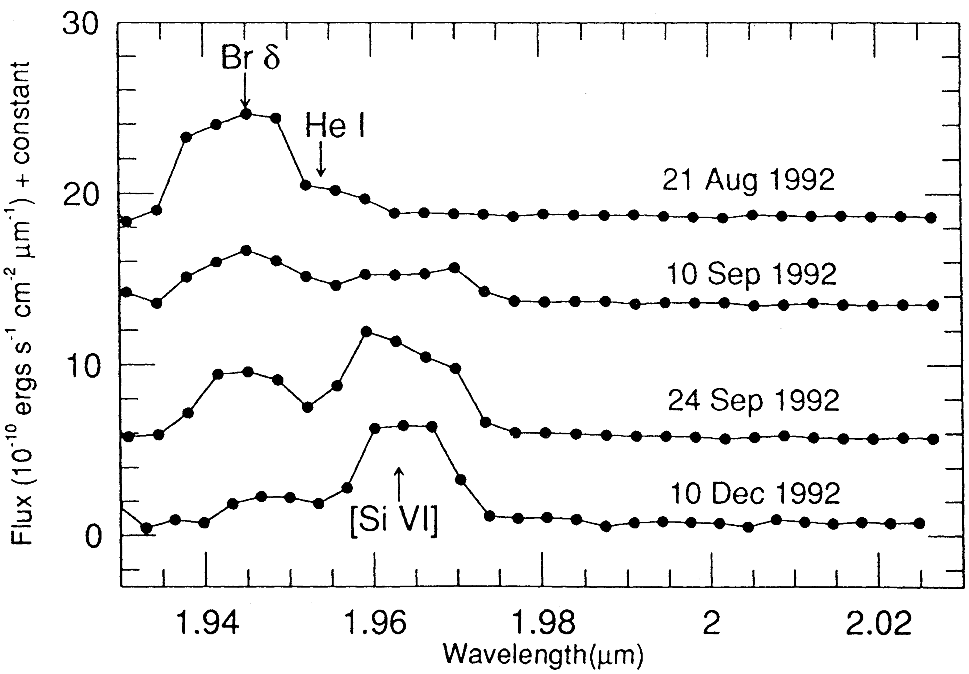

Figure 2. A sequence of spectra showing the transition of Nova Cyg 1992 to the coronal phase. At the :arliest epoch shown here, a weak line of He I is seen on the red wing of Br δ. At subsequent epochs, only Br δ ınd [Si VI] 1.963 μm are apparent.

The overall evolution of the infrared spectrum of V1974 Cyg followed the familiar pattern seen in earlier novae. From June to August 1992, the brightest lines in the J, H, and K bands were recombination lines of H I and He I. Also apparent were several He II lines, particularly at 1.163 μm and 2.189 μm, which we had not seen in previous novae, probably due to a combination of faintness and line-blending. The lines and continuum faded slowly, by only a factor of two between mid June and early September. The real action began on September 9, when we discovered that, within a period of merely two weeks, the [Si VI] 1.963 μm line (which requires ionizations of 167 eV), had changed from being undetectable to rivaling the adjacent H I Br δ line in strength. By September 23, it was stronger than Br δ. This sequence is illustrated in Figure 2, and shows the *time-scale, as well as the epoch,* of the transition to a coronal phase. Other coronal lines that also appeared during this transition were [Ca VIII] 2.32 μm (147 eV) and [Si VII] 2.47 μm (206 eV).

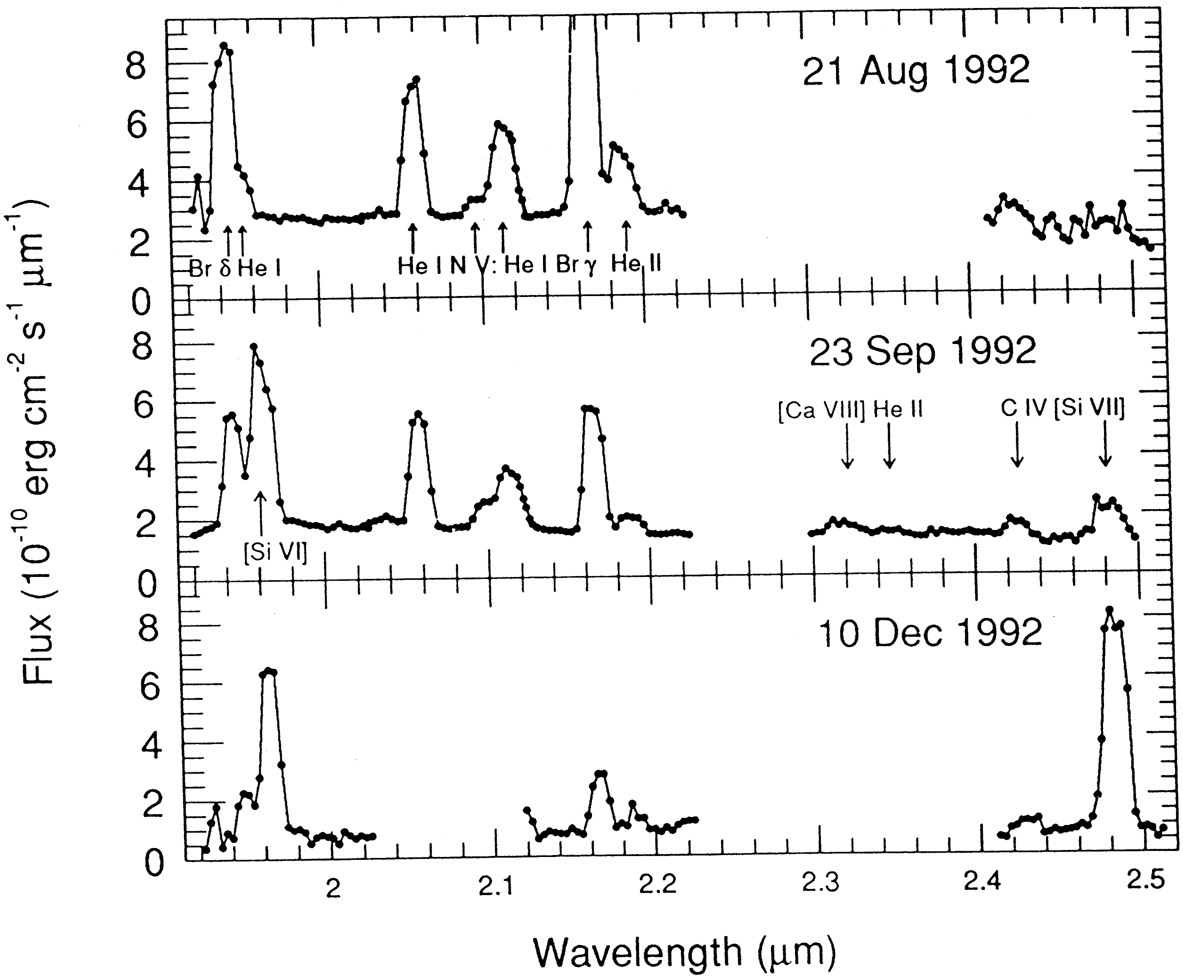

Figure 3. A montage of K-band spectra of Nova Cyg 1992, taken at a resolution of 600. At the first epoc *(top panel)* the only strong lines in the spectrum were due to H I, He I, and He II. The second epoch show *(center)* is shortly after the coronal lines had appeared, and by the third epoch *(bottom panel)* the degree c ionization had increased further, as shown by the strength of [Si VII] 2.48 μm.

The subsequent evolution has consisted mainly of a trend towards ever-increasing ionization of the ejecta Figure 3 gives a graphical overview of the evolution through December 1993. Between days 253 and 29(the [Si VII] line increased in strength by a factor of three, while [Si VI] decreased slightly. At the sam time, the ratio of the continuum to the H I and He I lines increased, consistent with an increase in electron temperature, as would be expected if the ejecta were photoionized by a radiation field of increasing hardness. This interpretation is also consistent with the evolution of the UV and X-ray fluxes (Starrfield 1992; Shore *et al.* 1993b; Stringfellow & Bowyer 1993). As of spring 1993, infrared coronal lines of even higher ionization have appeared, *e.g.* [Al IX] 2.04 μm (285 eV) and [S IX] 1.25 μm (328 eV) (Woodward & Greenhouse 1993; Dinerstein *et al.* 1993). Species of very high ionization have also appeared in the optical (Garnavich 1993). The McDonald Observatory results through December 1992 were presented by Dinerstein *et al.* (1992); a more complete description and analysis is in preparation.

5. FUTURE PROSPECTS

The story of Nova Cyg 1992 is far from complete, but already the coordinated effort to study it is answering many fundamental questions about novae. So far, the observations support the picture that the ionization of the ejecta is dominated by the white dwarf radiation field, but it is still possible that other mechanisms (such as shocks) contribute to the evolution of the spectrum. It is to be hoped that the success of the multi-wavelength campaign on Nova Cyg 1992 will inspire future efforts on bright novae. A major difficulty with this type of observational program, however, is the logistical difficulty in arranging for the observing time at facilities where the schedule is determined many months in advance. The availability of more sensitive instrumentation does not by itself alleviate this problem.

Flexible scheduling procedures that allow for assignment of partial nights and quick response to targets of opportunity are a key ingredient for the success of studies of time-variable phenomena such as novae. Building in the kind of flexibility needed for the many important scientific projects that require such observing strategies should be considered in the planning of the next generation of astronomical facilities. An example of a ground-based facility that will allow for flexible scheduling, including the capability to modify the priorities and observing plan at short notice, is the Spectroscopic Survey Telescope. To be built at the site of McDonald Observatory in west Texas as a collaboration between the Pennsylvania State University and the University of Texas and several additional participating institutions, it will be operated as a queue-scheduled facility. Similar considerations are also important in the realms of X-ray, UV, and infrared astronomy. The fact that it was possible to point the IUE satellite at Nova Cyg 1992 on very short notice, for example, enabled astronomers to catch its dramatic early evolution in the ultraviolet (Starrfield 1992; Shore *et al.* 1993a). An analogous effort was the deployment of the Kuiper Airborne Observatory to the southern hemisphere to obtain observations of SN 1987A. The ability of existing and future facilities to react promptly to accomodate unanticipated but time-critical observations should be an important criterion in evaluating their overall effectiveness.

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