

NEAR-INFRARED (0.8–2.5 MICRON) SPECTROSCOPY OF NOVA SAGITTARIUS 1998 = V4633 SAGITTARII

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ABSTRACT

The 0.8–2.4 μm spectroscopy of the moderately fast Nova Sgr 1998 = V4633 Sgr, obtained approximately 525 and 850 days after peak brightness, revealed an expanding, hydrogen-deficient shell of medium excitation level that increased with time. The strongest lines were He I and He II and the coronal line of [Si VI] 1.9641 μm . Also prominent were the lines of H I, and coronal [Ca VIII] 2.3205 μm and [Si VII] 2.4807 μm . Other lines included the [S III] lines at 0.9069 and 0.9532 μm and the coronal lines of [Al IX] 2.0444 μm and [Ti VI] 1.7155 μm . Five lines that frequently appear in novae spectra remain unidentified: 0.8926, 1.1114, 1.1900, 1.5545, and 2.1000 ± 0.005 μm . All the observed lines were roughly 1800 km s^{-1} wide (FWHM), and no asymmetries or underlying plateaus were seen. The continuum was significantly shallower than a $1/\lambda^4$ blackbody emission (approximately stellar photosphere) and steepened with age.

Key words: infrared radiation — novae, cataclysmic variables — stars: coronae — techniques: spectroscopic

1. INTRODUCTION

Near-infrared spectroscopy provides a wealth of diagnostic details about novae and the evolution of their shells because of the number and variety of lines that are available. Low-excitation hydrogen Paschen and Brackett lines provide a background against which to assess abundances, electron densities, and temperatures. They also reveal information about the shell geometry, kinematics, and optical depths (Lynch et al. 2000). The intrinsic flux ratio of the O I lines at 0.8446 and 1.1287 μm is well known, and therefore any departure from it is usually a good indicator of interstellar reddening (Rudy et al. 1991). Neutral and low ionization recombination lines of nitrogen, oxygen, carbon, phosphorus, silicon, calcium, magnesium, and iron often provide crucial abundance information that in turn can be related to the initial composition, evolutionary state, and surface mixing of the white dwarf (WD) before the outburst. As the ejecta cool and thin to reveal the hot WD, higher ionization, forbidden “coronal” lines, such as [S VIII] 0.9913 μm , [S IX] 1.2523 μm , [Al IX] 2.0444 μm , [Ca VIII] 2.3205 μm , and [Si VII] 2.4807 μm begin to appear (Greenhouse et al. 1988, 1990). By noting their relative strengths, time of emergence, and critical densities, much can be learned about the conditions in the shell. Finally, and perhaps most importantly, the extinction in the IR is much lower than in the visible, so the novae can be relatively brighter and monitored for longer periods.

We have been studying novae in the 0.8–2.5 μm region for over a decade, and two things have become clear: (1) Although there are many similarities among novae, no two are alike. Some appear to be hydrogen-poor and CNO-rich, others appear to have solar-like abundances. Some show extended emission in the line wings, others do not. Some evolve on timescales of hours near peak brightness, others can remain virtually unchanged for days or weeks. “Classical novae” is a broad term for a surprisingly inhomogeneous collection of stars and outburst phenomena. (2)

Owing to the lack of regular spectral monitoring, the episodic spectra that we observe are taken at essentially unpredictable stages in the novae’s evolution. Thus, we unavoidably miss crucial changes in the spectra. The various spectral stages outlined by Payne-Gaposchkin (1957) and Bode & Evans (1989) are indeed characteristic, but they do not describe the entire range of phenomena that we observe nowadays, especially with expanded wavelength coverage. Sometimes a nova changes so much in a few months that the new spectrum bears little resemblance to the old one. Indeed, a good case can be made for having daily or weekly spectral coverage of novae from a 3 m class telescope in order to discover and document detailed spectral changes throughout the observable life of the novae. In an effort to do this, we have been observing novae at every opportunity using the same instrument and telescope so that a homogeneous database of novae spectra is developed. In this paper, we present near IR spectra and analyses of Nova Sgr 1998 = V4633 Sgr (see Table 1).

2. OBSERVATIONS

All observations were made with the Aerospace Corporation’s Near Infrared Imaging Spectrograph (NIRIS; Rudy, Puetter, & Mazuk 1999) on the University of California’s Lick Observatory 3 m Shane telescope at Mount Hamilton, California. The spectrograph incorporates two separate channels, separated at 1.38 μm , to provide nearly continuous coverage between 0.8 and 2.5 μm . Each channel has its own collimator, grating, camera, and HgCdTe detector array. The arrays are two-quadrant NICMOS3 devices providing 256 channels in the spectral dimension and 128 in the spatial at a scale of $1'' \text{ pixel}^{-1}$. Each channel has nearly constant spectral resolution. A $2''.7$ slit width was used, resulting in a resolution of 19 Å for the blue channel and 37 Å for the red. To facilitate background removal, spectra were acquired at two locations that were separated by (typically) $10''$ along the slit. Wavelength calibration was

TABLE 1
NOVA SGR 1998 = V4633 SGR OBSERVING CIRCUMSTANCES

Parameters	Values
Position (equatorial).....	18 2 40.47, $-27 31 38.0$ (J2000)
Position (Galactic).....	$l = +5^{\circ}13$, $b = -6^{\circ}23$
First observation (this paper)	1999 Aug 31.22 = JD 2,451,421.7
Age (days).....	≈ 525
Standard star	HR 6836: G0 V, $K = 5.18$
Second observation (this paper)...	2000 Jul 21.36 = JD 2,451,746.9
Age (days).....	≈ 850
Standard star	HR 7658: F6 V, $K = 5.40$
Date of peak brightness ^a	1998 Mar 24.5 = JD 2,450,897

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

^a Date of peak brightness judged from the AAVSO light curve (Fig. 1).

done by taking spectra of emission-line lamps.

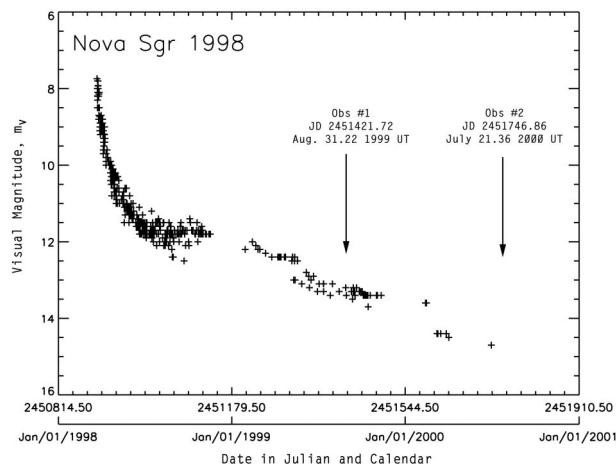
The data were reduced in the normal manner using nearby comparison stars to remove the instrumental response and most of the effects of atmospheric absorption and to estimate the absolute flux level for the nova. Because of the absence of a well-established infrared standard near in the sky to the nova, we used separate comparison stars. Spectral energy distributions for the comparison stars were taken from the models of Kurucz (1991) appropriate to their spectral types. Flux calibration was performed by normalizing these energy distributions to the K magnitudes. The latter were derived from the V magnitudes reported in the Bright Star Catalog (Hoffleit & Jaschek 1982) and the $V-K$ colors tabulated by Koornneff (1983).

3. SPECTRA AND LIGHT CURVES

V4633 Sagittarii (Nova Sagittarius 1998) was discovered by Liller (1998) on 1998 March 22.3 UT. Observations from Della Valle et al. (1998) two days after initial discovery confirmed that the nova was in its early stage. Its spectrum was dominated by Balmer series, Fe II multiplets, N II and Na I emission lines, and there was evidence of weak P Cygni profiles. With the presence of iron and expansion velocities less than 2500 km s^{-1} , Della Valle et al. suggested that this nova might belong to the Fe II class (Williams 1992). No optical polarization was detected by Ikeda, Kawabata, & Akitaya (2000) on 1998 March 25. Optical photometry by Lipkin et al. (1998) on 1998 June 7–13 suggested that the system was an eclipsing binary with a period of 0.14–0.17 days and an eclipse depth of about 0.14 mag.

Figure 1 shows the AAVSO light curve along with arrows indicating the dates of our observations. The peak apparent visual magnitude was $m_V = 7.7$ on about 1998 March 24.5 (JD 2,450,897) with $t_2 \approx 28$ days and $t_3 \approx 55$ days, which classifies it as a moderately fast nova.

Figure 2¹ is from NIRIS data taken on 1998 August 31.22 UT, approximately 525 days after peak brightness. Based on the strong [Si VI] 1.9629 μm and the presence of [Ca VIII] 2.3202 μm , the nova was in the early stages of its coronal phase. He II 1.0124 μm was about 2.5 times as strong as Paschen δ , about half the value it would ultimately be expected to reach as the excitation increases. Lines of



Peak Magnitude on JD 2450897 or March 24.5 1998 UT

FIG. 1.—Light curve of Nova Sgr 1998. Note the monotonic decline until about JD 2,451,000, when it appears to level off for about 100 days and then continues a decline at about 1.5 mag yr^{-1} . There is no precipitous decrease in brightness indicative of dust formation, and the spectra show no long wavelength upturn that would be a sign of thermal emission from dust.

[N I] and [S III] are weak but present, indicating some regions with densities in the range 10^6 – 10^7 cm^{-3} . J , H , and K_s magnitudes determined from the spectrum are 13.3, 13.2, and 12.7, respectively. Our observations showed no evidence of dust formation at either observation epoch. Based on the shape of the continuum, the spectrum does not exhibit the large degree of reddening expected from the object's galactic coordinates ($l = 5^{\circ}13$, $b = -6^{\circ}23$).

Figure 3 shows the spectrum taken on 2000 July 21.36 UT, approximately 850 days after peak brightness. In the 11 month interval since our first measurement, the nova had faded by more than a magnitude at J (J , H , and K magnitudes were 14.8, 14.4, and 13.8, respectively). As expected, He I 1.0830 μm weakened considerably, and the He II 1.0124 μm line fluxes exceeded those of He I 1.0830 μm , indicating

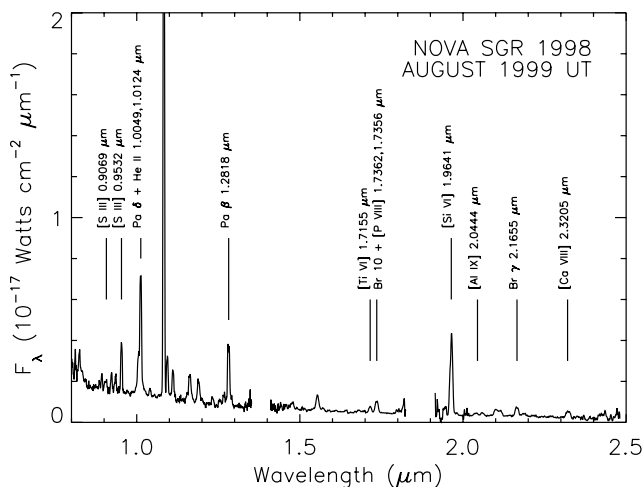


FIG. 2.—Spectrum of 1999 August 31.22. The spectrum showed a weak, underlying continuum with many emission lines. The most prominent lines were those of He I 1.0830 μm , He II 1.0124 μm , and the [Si VI] 1.9641 μm coronal line. The slope of the continuum was approximately $1/\lambda^2$, indicating that the continuum was, at least in part, nonstellar in origin.

¹ The data shown in Figs. 2 and 3 are available electronically as ASCII files from the authors.

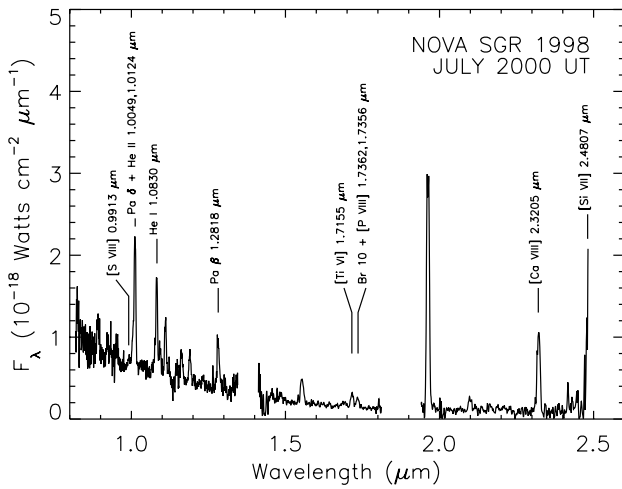


FIG. 3.—Spectrum of 2000 July 21.36. The spectrum had faded considerably, and the lines had weakened. Note, however, the appearance of the [Si VII], and [S VIII] coronal lines. The slope of the continuum was approximately $1/\lambda^3$, significantly steeper than before (Fig. 2).

that most of the helium had become doubly ionized. The strongest features in the spectrum were the coronal lines of [Si VI] 1.9641 μm and [Ca VIII] 2.3205 μm . [Si VII] 2.4807 μm and [S VIII] 0.9913 μm appeared since our previous observation.

On both dates, the lines appeared symmetric and unstructured with FWHMs of 1800 km s^{-1} . There was no evidence of underlying plateaus like those shown by Nova Oph 1998 (Lynch et al. 2000) or P Cygni profiles.

The hydrogen lines were relatively weak compared with those of the heavier elements. While this is to be expected for high-excitation objects, our impression was that the shell was hydrogen-deficient. We also observed several prominent unidentified emission lines at 0.8926, 1.1114, 1.1900, 1.5545, and $2.1000 \pm 0.005 \mu\text{m}$ (Table 2) Some or all of these lines are usually present in other nova spectra regardless of excitation condition. As Table 2 shows, the lines grow in strength relative to the hydrogen lines as the excitation increases, indicating that they may originate from

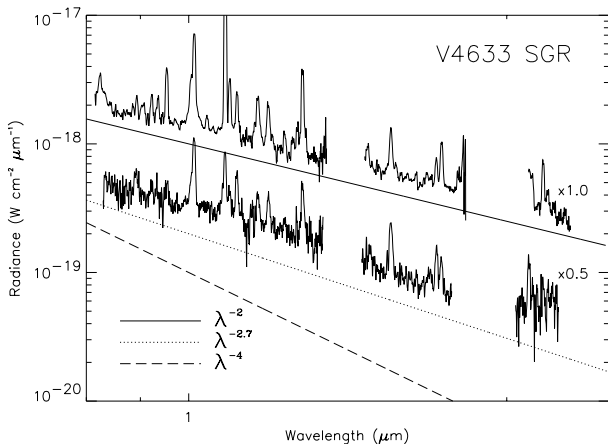


FIG. 4.—Slope of the continuum ($d \log F / d \log \lambda$). It increased from about -2 to -2.7 between 1999 August and 2000 July, but in neither case approached the value of -4 expected from a stellar photosphere.

TABLE 2
NOVA SGR 1998 LINE LIST

Lab Wavelength (μm)	ID	$F/F(\text{Pa}\beta)$ 1999 August	$F/F(\text{Pa}\beta)$ 2000 July
0.8237	He II	0.16	...
0.8863	Pa 11	0.07	...
0.8926	a,b	0.15	0.74
0.9015	Pa 10	0.08	...
0.9069	[S III]	0.10	...
0.9229	Pa 9	0.20	0.28
0.9345	He II	0.19	...
0.9532	[S III]	0.25	...
0.9545	Pa ϵ	0.36	0.42
0.9913	[S VIII]	...	0.06
1.0049	Pa δ	0.49	0.43
1.0124	He II	1.75	1.96
1.0400	[N I]	0.07	...
1.0830	He I	6.68	1.39
1.0938	Pa γ	0.54	0.39
1.1114	a,b	0.38	0.85
1.1626	He II	0.42	0.46
1.1673	He II	0.08	0.15
1.1900	a,b	0.42	0.56
1.1969	He I	0.07	...
1.2330	[Fe VI] ^a	0.13	0.18
1.2528	He I	0.13	...
1.2674	[Fe VI] ^a	0.23	...
1.2785, 1.2790	He I	0.18	...
1.2818	Pa β	1.00	1.00
1.2889	[Fe VI] ^a	0.12	...
1.4760	He II	0.14	...
1.5545	b	0.34	0.65
1.5701, 1.5719	Br 15 + He II	0.05	...
1.6109	Br 13	0.23	...
1.6407	Br 12	0.40	...
1.6806	Br 11	0.05	...
1.7155	[Ti VI]	0.14	0.34
1.7362, 1.7356	Br 10 + [P VIII]	0.29	0.23
1.9446	Br 8	0.23	...
1.9641	[Si VI]	1.60	...
2.0373	He II	0.04	...
2.0444	[Al IX]	0.05	...
2.0581	He I	0.07	...
2.1000	b	0.17	0.39
2.1120, 2.1132	He I	0.13	...
2.1655	Br γ	0.23	0.13
2.1882	He II	0.08	...
2.3205	[Ca VIII]	0.24	2.18
2.4807	[Si VII]	...	1.30

NOTE.—The $F(\text{Pa}\beta)$ for 1999 August is $2.25 \times 10^{-20} \text{ W cm}^{-2}$. The $F(\text{Pa}\beta)$ for 2000 July is $5.40 \times 10^{-21} \text{ W cm}^{-2}$.

^a See Rudy et al. 2001.

^b Unidentified line—common in novae.

multiply ionized species and may be as yet unidentified coronal lines.

The nova's continuum shows significant changes as well. In our first observation the slope of the continuum was about λ^{-2} ($d \log F / d \log \lambda$). The next observations showed that it had steepened to around $\lambda^{-2.7}$. In either case, it was considerably shallower than what would be expected for a Rayleigh-Jeans emitter, i.e., λ^{-4} (Fig. 4). The steepening of the continuum is just the opposite of what was observed in Nova Oph 1998 (Lynch et al. 2000). Its continuum flattened very rapidly after peak brightness and then displayed a

fixed slope for many months. We do not yet fully understand the behavior of the continua in novae.

4. DISCUSSION AND ANALYSIS

The reddening and thus distance to V4633 Sgr are very uncertain. The general shape of the spectrum does not show a drop off in the blue indicative of significant reddening. To quantify the reddening, we used the H I and He II lines and assumed that the intrinsic line ratios matched those of case B recombination theory. The last assumption is questionable, especially for the hydrogen lines, but there is no evidence for distinctively non-case B such as with Nova Oph 1998 (Lynch et al. 2000). The absence of fluorescently excited O I lines and the presence of He II and forbidden lines in our earliest spectrum indicates that the ejecta have already thinned considerably. Moreover, uncertainties in the reddening are dominated by errors in the measured line strengths because of blending, complex line profiles, and the signal-to-noise ratio of the measurements. These same effects also dominate the small variations in the case B values because of density and temperature; therefore, we adopt values of 10^4 K and 10^4 cm⁻³ for the electron temperature and density, respectively. The hydrogen lines measured from the 1999 August data indicate $E(B - V) = 0.28 \pm 0.13$. The He II lines yield values that range from 0.13 to 0.49, depending whether $0.8237 \mu\text{m}$ (whose value is very uncertain) is included in the fit. A fit to the few hydrogen lines that could be extracted from the 2000 July data gives a slightly negative value with a large formal error. Our best estimate from combining these measurements is $E(B - V) = 0.3 \pm 0.2$. Taking $R = 3.1$ (Mathis 2000), we find $A_V = 0.9 \pm 0.6$.

Taking an average value for the interstellar extinction of 1.0 mag kpc^{-1} (typical) and $A_V = 0.9$ from above, we find a distance of roughly 0.9 kpc, which seems unreasonably small. On the other hand, the object's distance can be estimated by using the empirical relations between speed class

and absolute visual magnitude (Della Valle & Livio 1995), and we find a distance of 11 kpc. In view of the object's galactic coordinates ($5^\circ.1$, $-6^\circ.2$), this is a surprising, perhaps unreasonably large, distance. With such disparate derived distances, we are unable to narrow the rather large range of possible distances found by Ikeda et al. (2000) of 2–10 kpc.

5. SUMMARY AND CONCLUSIONS

Nova Sgr 1998 = V4633 Sgr was a moderately fast nova, whose light curve flattened considerably after about 100 days and thus remained brighter than other novae in this speed class. This allowed us to monitor it much later than is usually possible. The spectrum showed significant evolution between the epochs of observation, most notable being the strengthening and, in some cases, the emergence of coronal lines. The changes in the spectrum seen relatively late in the object's life (+850 days) demonstrates the value of observing novae long after their outbursts. Although the spectrum is not in and of itself peculiar, the derived reddening and distance determinations appear to be questionable. The frequent recurrence of several strong unidentified lines is just one of the many riddles about novae that further spectroscopy should be able to solve.

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