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NEAR-INFRARED SPECTROSCOPY OF NOVA SAGITTARIUS 1999 (V4444 SAGITTARII)

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ABSTRACT

We present 0.8–2.5 μm near-IR spectrophotometry of the very fast nova Nova Sagittarius 1999 (V4444 Sgr) taken 125 days after outburst. The emission-line spectrum of V4444 Sgr, with features ranging from C i to [Si ix] and [Si viii], exhibited perhaps the greatest spread of excitation for any single-epoch observation of a nova. However, two other novae, Nova Sagittarius 1992 No. 2 and Nova Aquila 1993, had spectra similar to V4444 Sgr between 0.8 and 1.4 μm, so such manifestations may not be uncommon. The continuum of V4444 Sgr showed a significant rise longward of 1.5 μm indicative of thermal emission from dust. The absence of any dust features in the light curve of V4444 Sgr suggests that we may have a relatively unobscured line of sight, or that some or all of the circumstellar dust was preexisting. The latter would indicate that V4444 Sgr is possibly a recurrent nova.

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

1. INTRODUCTION

Until about 20 years ago, virtually all of our knowledge about novae came from the visible part of the spectrum. With the advent of infrared detectors, better novae detection systems, and improved modeling capabilities, our understanding of novae has been greatly enriched. We now know that as a class of objects, novae are tremendously heterogeneous, as are their spectra. The 0.8–2.5 μm region provides a wealth of diagnostic detail about novae and the evolution of their shells because of the number and variety of lines that occur. Hydrogen Paschen and Brackett emission 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, 2002). The intrinsic flux ratio of the O i lines at 0.8446 μm and 1.1287 μm is well known, and therefore any departure from it is usually a good indicator of reddening (Rudy et al. 1991a, 1991b). Neutral and low ionization recombination lines of nitrogen, oxygen, carbon, phosphorus, silicon, calcium, magnesium, and iron often provide crucial abundance information, which 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] 1.2520 μm, [Al ix] 2.0445 μm, [Ca viii] 2.3205 μm, and [Si vii] 2.4807 μm, begin to appear. By noting their relative strengths, time of emergence, and critical densities, much can be learned about the conditions in the shell (Grasdalen & Joyce 1976; Greenhouse et al. 1988, 1990; Benjamin & Dinerstein 1990; Wagner & Depoy 1996; Williams 1992; Williams et al. 1991; Rudy et al. 2002). 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.

Yet the complexity of the nova explosion makes interpretation of the observed emission line strengths difficult (Lynch et al. 2002). The combination of the extreme inhomogeneity of the novae environment together with a hard ionizing spectrum produces a broad range of ionization states for any given element. Moreover, lines from different ionization states of the same element may arise in regions of very different densities and temperatures. Thus, each new nova presents us with an opportunity to observe its properties and differences from other novae and to add to the list of what is known and unknown about novae. Nova Sagittarius 1999 was one such object because of its wide range of spectral features.

Nova Sagittarius 1999 (V4444 Sgr) was discovered on 1999 April 25.731 UT by M. Yamamoto (R.A. $= 18^{\rm h}07^{\rm m}36^{\rm s}$ and decl. $= -27°20'13''$) with a visual magnitude of 8.6 (Kushida & Kushida 1999). A maximum brightness of $V_{\rm max} = 7.18$ was recorded on 1999 April 27.364 UT by Liller et al. (1999). An optical spectrum was obtained on April 27.5 UT by E. Howell and A. Soderberg (Garnavich 1999). The optical line profiles had a FWHM of 800 km s^{-1}. The observed lines included Hα with a P Cygni profile and Hβ with an absorption line with a small emission peak. Permitted Fe ii absorption lines were seen between 490.97 and 515.41 nm, as well as the strong Na i D absorption line. Howell and Soderberg (Garnavich 1999) suggest that the spectrum of V4444 Sgr at this time was of a nova near or before maximum light and could possibly be classified as a Fe ii–type nova according to Williams (1992).

In this paper, we present near-IR spectroscopic observations of V4444 Sgr taken on 1999 August 31.19 UT. Section 3 will compare the spectrum with those of previous novae. Section 4 will focus on interpreting the light curve, discussion of the reddening and the distance, and the possibility that V4444 Sgr is a recurrent nova.

2. OBSERVATIONS

All observations were made with the Aerospace Corporation's Near Infrared Imaging Spectrograph (Rudy, Puetter, & Mazuk 1999) on the University of California's Lick Observatory 3 m Shane Telescope. The spectrograph incorporates two separate channels, divided at 1.38 μm, to provide nearly continuous coverage between 0.8 and 2.5 μm. Each channel has separate collimators, gratings, cameras, and HgCdTe detector arrays. The arrays are two-quadrant NICMOS3 devices, providing 256 channels in the spectral dimension and 128 in the spatial at a scale of 1″ pixel^{-1}. Each channel has nearly constant spectral resolution. A 2″.7 slit width was used, resulting in a resolution of 16 Å for the blue channel and 37 Å for the red. To remove the background, spectra were acquired at two locations along the slit with a separation of about 10″. Wavelength calibration was achieved by using features from helium and argon emission-line lamps, telluric absorption features, and OH lines from the night sky.

The observations were reduced by dividing the spectrum by that of a nearby comparison star, HR 6836, to remove instrument response and the effects of atmospheric absorption. HR 6836 is a star of spectral type G0 V and has a derived *K* magnitude of 5.18. We computed *K* based on Koornneef's (1983) calculations of $V-K$ and the visual magnitude, *V*, of HR 6836. Flux calibration was performed by taking the spectral shape of Kurucz (1991) appropriate for a G0 V star and setting the level based on the derived *K* magnitude.

3. NEAR-IR SPECTRA

The spectrum of V4444 Sgr is shown in Figure 1. The emission lines are identified in Table 1. Figures 2 and 3 show the blue (0.8–1.4 μm) and red (1.4–2.5 μm) region of the spectrum with the major emission lines identified. Our observation was taken about 125 days after peak brightness. From the light curve and the measured values of t_2 and t_3 (see § 4), V4444 Sgr is classified as a very fast nova (Payne-Gaposchkin 1957). The *J*, *H*, and *K* magnitudes were 12.4, 12.0, and 10.0, respectively. The *J*, *H*, and *K* magnitudes were obtained by multiplying the observed nova spectrum by a representative atmospheric transmission curve for Lick Observatory during the summer months. The resulting product was then convolved with the *J*, *H*, and *K* filter profiles. An identical procedure was applied to the spectrum of an AO star normalized to zero magnitude. The ratio of the nova spectrum to the AO star produced the given *J*, *H*, and *K* magnitudes. The continuum of V4444 Sgr was relatively flat until a rise in the region longward of 1.5 μm. The rise was most likely because of thermal emission of dust around the nova.

Overall, the spectrum contained narrow, blended emission lines with a very large range of excitation. The lines had a FWHM of approximately 2000 km s^{-1}. Low excitation emission lines were present, such as Lyβ fluorescent O I at 0.8446 and 1.1287 μm. In addition, C I and N I lines were

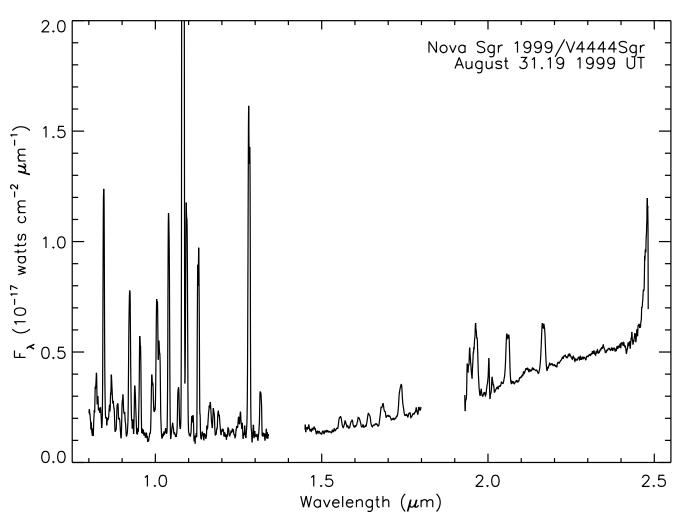

FIG. 1.—Near-IR spectra (0.8–2.5 μm) from 1999 August 31.19 UT of V4444 Sgr.

TABLE 1

V4444 Sagittarii Line List from 1999 August 31.19 UT

Lab Wavelength[a] (μm)	ID	F/F(Paβ)
0.8237, 0.8242	He II + N I	0.30
0.8446	O I	0.49
0.8680, 0.8750	N I + H I Pa12	0.24
0.8863	H I Pa11	0.069
0.8913	[b]	0.036
0.9015	H I Pa10	0.10
0.9069	[S III]	0.053
0.9229	H I Pa9 + ?	0.34
0.9393, 0.9345	N I + He II	0.056
0.9532, 0.9545, 0.9603	[S III] + H I Pae + C I	0.23
0.9913	[S VIII]	0.19
1.0049	H I Paδ	0.41
1.0124	He II	0.26
1.0400	[N I]	0.53
1.0520	N I	0.029
1.0684	C I	0.094
1.0830	He I	6.21
1.0938	H I Paγ	0.69
1.1114	[b]	0.053
1.1287	O I	0.52
1.1626, 1.1660, 1.1673	He II + C I	0.12
1.1748	C I	0.074
1.1900, 1.1901, 1.1969	[b] + C I + He I	0.073
1.2528, 1.2517, 1.2549, 1.2562, 1.2569	He I + [Si IX]? + C I	0.11
1.2785, 1.2790, 1.2818	H I Paβ + He I	1.00
1.3164	O I	0.11
1.5545	[b]	0.044
1.5701	H I Br15	0.017
1.5881	H I Br14	0.020
1.6109	H I Br13	0.034
1.6407	H I Br12	0.051
1.6807, 1.6918	H I Br11 + He II	0.14
1.7002	He I	0.041
1.7362, 1.7356	H I Br10 + [P VIII]?	0.17
1.9446	H I Br8	0.19
1.9641	[Si VI]	0.39
2.0581	He I	0.29
2.1655	H I Brγ	0.24
2.4807	[Si VII]	0.66

NOTES.—The flux for F(Paβ) is 1.06×10^{-19} W cm^{-2}. Note that F(Paβ) includes a contribution from He I.

[a] All wavelengths are laboratory wavelengths as measured in air.

[b] Unidentified line—seen in other novae.

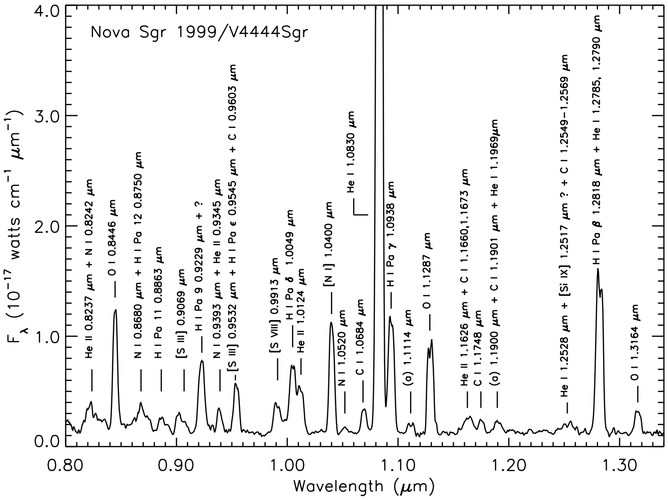

FIG. 2.—The 0.8–1.4 μm region of V4444 Sgr spectrum with line identifications. Here, "(a)" designates unidentified lines seen in other nova.

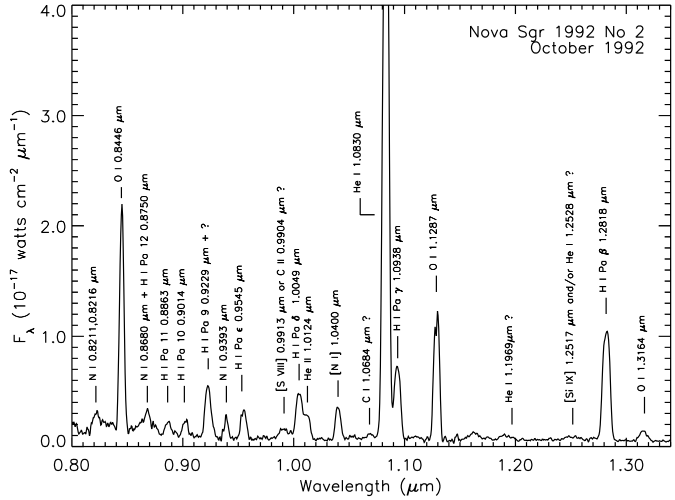

FIG. 4.—Near-IR spectra (0.8–1.4 μm) of Nova Sgr 1992 No. 2 (Rossano et al. 1994). This nova exhibited similar emission lines to V4444 Sgr (see Fig. 3), including [S VIII] at 0.9913 μm, [Si IX] at 1.2517 μm, and [N I] at 1.0400 μm.

observed, including [N I] at 1.0400 μm, as well as He I at 1.0830 μm and hydrogen Paschen and Bracket lines. The presence of carbon, nitrogen, and oxygen lines in the spectrum indicate that the underlying WD was probably a carbon-oxygen–type star (Bode & Evans 1989). With these lower excitation lines, there also were higher excitation lines or "coronal" lines. These included [S VIII] at 0.9913 μm, [Si VI] at 1.9641 μm, and [Si VII] at 2.4807 μm. It is also possible that [P VIII] at 1.7356 μm was present and blended with H I Br 10 at 1.7362 μm, as well as [Si XI] at 1.2517 μm with He I at 1.2528 μm and C I at 1.2549–1.2569 μm.

As mentioned in § 1, earlier novae have been observed that exhibit a diverse spread of emission-line excitation. In particular are two novae: Nova Sagittarius 1992 No. 2 (Rossano et al. 1994) and Nova Aquilae 1993 (Lynch et al. 1995). These two novae had similar characteristics in their spectra to V4444 Sgr. The spectrum of each nova was taken 90 days or longer from peak brightness, and the novae were considered fast to very fast nova. The spectra for Nova Sagittarius 1992 No. 2 and Nova Aquilae 1993, together with line identifications, are shown in Figures 4 and 5, respectively. Upon comparing the blue (0.8–1.4 μm) region of the three novae, it was evident that they exhibited similar characteristics. However, the presence of coronal lines in both novae was ambiguous. For example, the line 1.2520 μm can be identified as either [S IX] at 1.2517 μm, He I at 1.2528 μm, or C I from 1.2549 to 1.2614 μm. Similarly, [S VIII] at 0.9913 μm could instead have been C II at 0.9904 μm. While there was no way to absolutely exclude its presence in Nova Sgr 1992 No. 2 and Nova Aql 1993, C II at 0.9904 μm can be ruled out in V4444 Sgr. This is because the broader wavelength coverage of the object includes the region where the C II lines at 1.7834, 1.7853, and 1.7855 μm would be. These are among the strongest C II features in the near-infrared, and they are absent from the spectrum of V4444 Sgr. Given the other similarities of the two older novae with V4444 Sgr, it seems

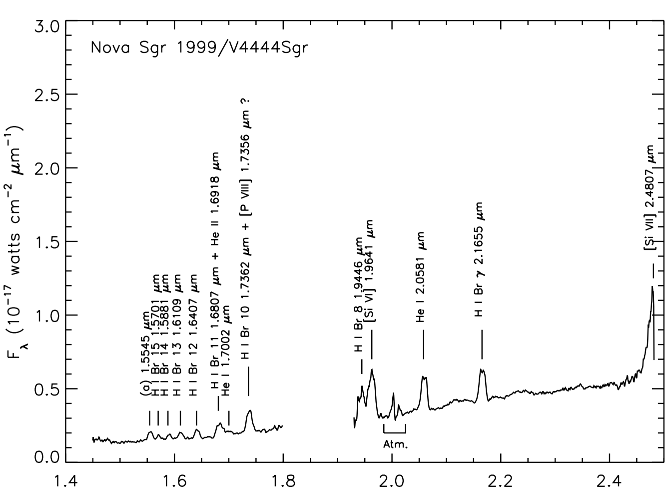

FIG. 3.—Same as Fig. 2, but for the 1.4–2.5 μm region

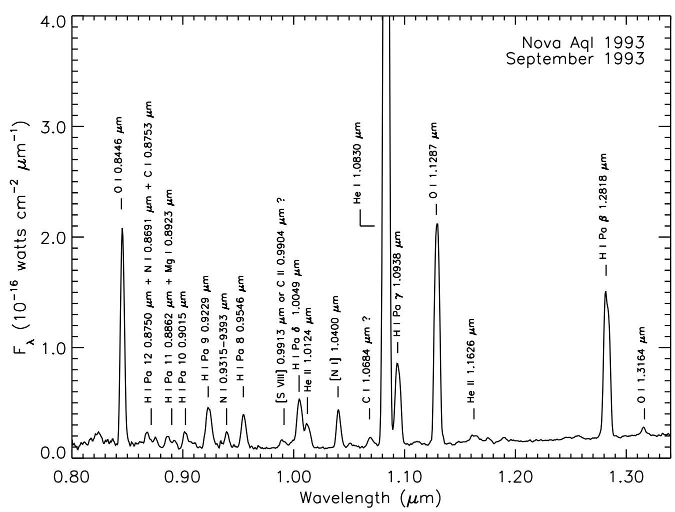

FIG. 5.—Near-IR spectra (0.8–1.4 μm) of Nova Aql 1993 (Lynch et al. 1995). This is another nova with similar emission lines to V4444 Sgr (see Fig. 3) and Nova Sgr 1992 No. 2 (see Fig. 4). Some comparable lines include [S VIII] at 0.9913 μm and [N I] at 1.0400 μm.

probable that [S VIII] at 0.9913 μm was the proper identification, and that both novae had entered the coronal phase.

Qualitatively, the diverse emission lines in the spectrum of V4444 Sgr, and also in Nova Sagittarius 1992 No. 2 and Nova Aquilae 1993, could be attributed to the nonhomogeneous environment of the novae. This includes the varying range of UV flux from the WD and shell, which is surrounded by regions of dense and diffuse gas. As a whole, these dense optically thick regions and more diffuse optically thin regions provide the necessary condition to produce low- and high-excitation emission lines.

4. LIGHT CURVE, REDDENING, AND DISTANCE

The visual brightness of V4444 Sgr declined rapidly as seen in the light curve (Fig. 6). The date for peak brightness was adopted from the light curve in Figure 6 as 1999 April 28.4 UT or JD 2,451,296.8431. The peak apparent visual magnitude on this date was $V = 7.60 \pm 0.50$. From the visual light curve, the time taken for the nova to diminish by 2 mag, t_2, was 3 days, and the time for the nova to diminish by 3 mag, t_3, was 23 days. Thus, V4444 Sgr can be classified as a very fast nova (Payne-Gaposchkin 1957). A very fast nova is classified as having a t_2 of less than 10 days and a rate of decline during that time greater than 0.20 mag day^{-1} (Bode & Evans 1989; Payne-Gaposchkin 1957). The light curve showed a smooth decline with no obvious fading indicative of a dust formation event.

The absolute visual magnitude was calculated to be $M_v = -8.97 \pm 0.04$ from the M_v-t_2 relation by Della Velle & Livio (1995). The absolute blue magnitude was calculated to be $M_b = -8.22 \pm 0.62$ using the M_b-t_3 relation by Pfau (1976). This gives us a $(B-V) = +1.51 \pm 0.44$, which is indicative of large reddening. For reference, van den Bergh & Younger (1987) found that the intrinsic color of novae 2 mag below visual maximum brightness is $\langle B-V \rangle_0 = -0.02 \pm 0.04$. Using the observed O I flux ratios for lines 0.8446, 1.1287, and 1.3164 μm in Table 1, the color excess was $E(B-V) = 1.07 \pm 0.10$ (Rudy et al. 1991a, 1991b). This color excess calculation assumes Lyβ fluorescence as the main contributor of the O I lines, particularly 0.8446 and 1.1287 μm, which contribute equal number of photons. The intrinsic flux ratio of 1.1287 to 0.8446 μm because of Lyβ fluorescence is 0.75. A correction for continuum fluorescence is also included assuming flux ratios between the lines 0.8446, 1.1287, and 1.3164 μm. The intrinsic flux ratios due to continuum fluorescence are 3.11 for the ratio of 0.8446 to 1.3164 μm and 0.066 for the ratio of 1.1287 to 1.3164 μm. A color excess value was also calculated from the observed hydrogen lines using the method of Rudy et al. (1999). Here, the reddening of V4444 Sgr was measured by comparing the observed ratios of the hydrogen lines to Paβ with their case B values from Storey & Hummer (1995) for a $N_e = 10^8$ cm^{-3} and $T_e = 10^4$ K gas. The calculation also assumed the extinction properties of the dust were described by the reddening curve of Draine (1989). As shown in Figure 7, the reddening was obtained from a least-squares fit to a plot of the observed line ratios divided by the case B values as a function of extinction at the wavelength of the respective line. The best-fit value was $E(B-V) = 0.48 \pm 0.15$. This value is substantially lower than the calculated color excess using the O I lines and is probably due to the fact that the hydrogen lines deviated from the case B conditions. To calculate the visual extinction, we used the color excess value of 1.07, thus $A_v = 3.32 \pm 0.31$ with a calculated distance of $d = 4.48 \pm 0.44$ kpc. For comparison, Kawabata et al. (2000) found the following results: $t_2 = 3.2$ days, $M_v = -9.0 \pm 0.2$, $E(B-V) = 0.75 \pm 0.04$, $A_v = 2.8 \pm 0.3$, and $d = 4.7 \pm 0.7$ kpc.

The continuum of V4444 Sgr showed a rise in the red (1.4–2.5 μm) region, suggestive of thermal emission from dust. Many classical novae do not produce dust until well after their initial outburst, and those that do are generally fast nova (Gehrz 1988). Nova Herculis 1991 (V838 Her) is an example of a very fast nova that showed dust formation only days after the initial outburst (Harrison & Stringfellow 1994). Generally, dust formation is seen in the visual light curves as a sharp drop in brightness as the dust obscures the bright central regions. Even though the near-IR spectrum of V4444 Sgr indicates dust was present around the nova, the

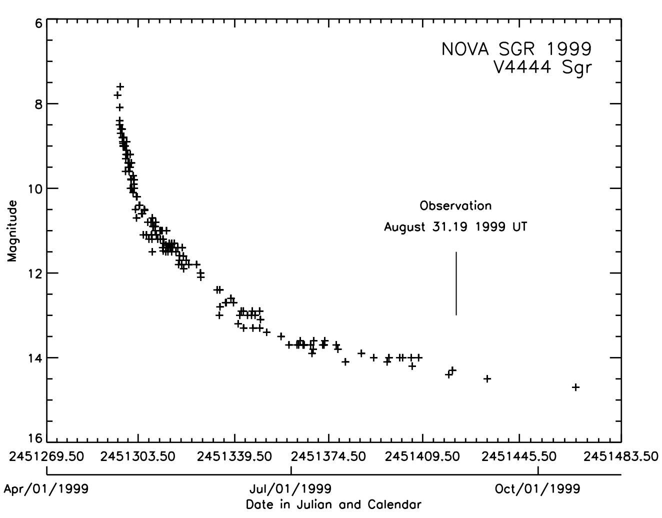

FIG. 6.—Visual light curve for V4444 Sgr. Data provided by the AAVSO. The light curve has a relatively smooth decline with an absence of a brightness drop indicating dust formation.

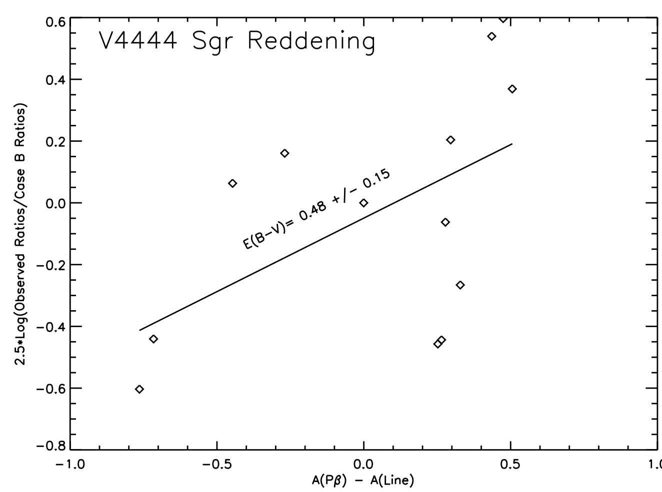

FIG. 7.—Reddening of V4444 Sgr using the hydrogen lines. Shown on this plot is the differential extinction between Paβ and the other hydrogen lines vs. the observed flux ratio of a given line to Paβ, divided by the case B values for the same ratio. Thus, the reddening value is equal to the slope of a linear fit to the data points. For V4444 Sgr, the value is $E(B-V) = 0.48 \pm 0.15$.

visual light curve does not show a sudden drop in visual magnitude. The presence of thermal emission and the absence of a dust formation signature in the light curve suggest, we may have had a relatively unobscured line of sight. Alternatively, the thermal emission and lack of a dust formation signature may be because of preexisting dust that was warmed by the current outburst. Optical spectropolarimetry of V4444 Sgr by Kawabata et al. (2000) showed evidence of preexisting small grains located around the WD. They concluded that the dust cloud was located less than 50 AU from the central star. This dust cloud is not necessarily the cause of the thermal emission feature seen in our spectrum. This also suggests that V4444 Sgr could be a recurrent nova (Webbink, Livio, & Truran 1987).

5. SUMMARY AND CONCLUSION

In this paper, we presented near-IR spectra of V4444 Sagittarii taken in 1999 August UT. V4444 Sgr was a very fast nova that we observed 125 days after peak brightness. The spectrum of V4444 Sgr exhibited a remarkable spread of emission lines, ranging from features of C I and N I to high excitation coronal lines such as [S VIII] and [Si VII]. Two earlier novae, Nova Sagittarius 1992 No. 2 and Nova Aquilae 1993, which were observed only between 0.8 and 1.4 μm, showed very similar spectra to V4444 Sgr in that region. This suggests that the behavior manifested by V4444 Sgr may not be uncommon. The continuum had a significant rise in the red (1.4–2.5 μm) region of the spectrum, indicating the presence of warm dust. If dust was present before the outburst, it may suggest that V4444 Sgr is a recurrent nova.

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