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THE NEON ABUNDANCE IN THE EJECTA OF QU VULPECULAE FROM LATE-EPOCH INFRARED SPECTRA

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ABSTRACT

We present ground-based SpectroCam-10 mid-infrared, MMT optical, and *Spitzer Space Telescope* IRS mid-infrared spectra taken 7.62, 18.75, and 19.38 yr, respectively, after the outburst of the old classical nova QU Vulpeculae (Nova Vul 1984#2). The spectra of the ejecta are dominated by forbidden line emission from neon and oxygen. Our analysis shows that neon was, at the first and last epochs respectively, more than 76 and 168 times overabundant by number with respect to hydrogen compared to the solar value. These high lower limits to the neon abundance confirm that QU Vul involved a thermonuclear runaway on an ONeMg white dwarf, and approach the yields predicted by models of the nucleosynthesis in such events.

Subject headings: infrared: stars — novae, cataclysmic variables — stars: individual (QU Vul, Nova Vul 1984 #2)

1. INTRODUCTION

Gehrz et al. (1985) discovered a very strong [Ne II]12.8 μm forbidden emission line in the classical nova QU Vulpeculae (Nova Vul 1984#2) 140 days after its outburst. The presence of this strong neon line and the subsequent appearance of additional infrared metallic forbidden emission lines in the spectrum as QU Vul evolved (Gehrz et al. 1986; Greenhouse et al. 1988) confirmed that there are oxygen-neon-magnesium (ONeMg) white dwarfs (WDs) in classical nova binary systems whose eruptions could significantly enrich the local interstellar medium (Gehrz 1988, 1999, 2002, 2008; Gehrz et al. 1998). Gehrz et al. (1998) argued that theoretical simulations of nova thermonuclear runaways provide evidence that ONeMg novae may, in fact, compete with supernovae as sources of some CNONeMgAl isotopes. We have pursued a long-term program to measure metal abundances in nova ejecta using infrared (IR) spectroscopy of forbidden emission lines to test this hypothesis.

Measurements of the integrated fluxes of these electron-impact (collisionally) excited, forbidden lines in nova ejecta many years after outburst are particularly valuable for evaluating abundances. In this case, the density of the expanding ejecta will have fallen well below the level where the lines are quenched by collisions, and the line fluxes are entirely due to spontaneous emission. Since coefficients of spontaneous emission are fairly well known for many important IR lines, the absolute numbers of atoms involved in these transitions can be calculated with reasonable certainty given a known distance. Because the ejected mass of hydrogen is well known from early IR and radio emission measures when most of the gas is ejected and when it is almost entirely ionized (Gehrz 1999, 2002), the ratio of the mass of an element required to produce the observed IR forbidden emission lines to the ejected hydrogen mass gives a fairly well constrained lower limit to the abundance of that element. When emission from all the lines from all ionic species and all isotopes of an element can be observed and evaluated, the lower limit converges to the actual abundance.

Several mid-IR neon forbidden emission lines in QU Vul are sufficiently strong that we have been able to observe them using SpectroCam-10 on the 5 m Hale Telescope at Mount Palomar and the Infrared Spectrograph (IRS) on the *Spitzer Space Telescope* at epochs of 7.62 and 19.38 yr after the eruption. These measurements have enabled us to determine a fairly strong lower limit to the neon abundance in this nova as reported below.

2. OBSERVATIONS AND REDUCTION

2.1. *Ground-based Mid-IR*

We observed QU Vul with the 200 inch (5 m) Hale Telescope at Mount Palomar[11] on 1992 August 9.3 UT (day 2783.9; 7.62 yr posteruption) using the SpectroCam-10 (SC-10) mid-IR camera/spectrograph (Hayward et al. 1993) in its long-slit, low-resolution spectroscopy mode with a 2″ wide slit and a resolving power of $R = \lambda/\Delta\lambda \sim 150$ at 12.81 μm. We note that the entire extent of the ejected shell was contained within the slit (see Krautter et al. 2002). A single grating setting provided a 10.6–13.2 μm spectrum that included the [Ne II] 12.81 μm line. The total on-source integration times were 160 s on QU Vul and 20 s on the standard star α Lyr. The data were reduced by extracting one-dimensional spectra from the two-dimensional spectral images, dividing the nova by the standard, then multiplying by the absolute spectral energy distribution of α Lyr (Cohen et al. 1992). The calibrated result, with 2 pixel binning for clarity, is shown in Figure 1. In Table 1, we give the total flux measured in the line.

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[11] Observations at the Palomar Observatory were made as part of a continuing collaborative agreement between the California Institute of Technology and Cornell University.

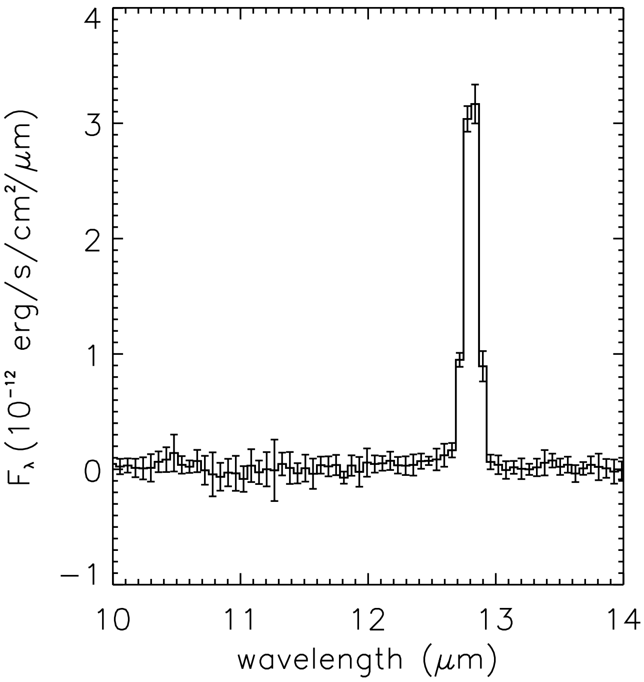

FIG. 1.—SpectroCam-10 spectrum of QU Vul taken on 1992 August 9.3 UT. The [Ne II] line at 12.81 μm has an integrated flux of 6.84×10^{-12} erg s^{-1} cm^{-2}.

2.2. *Ground-based Optical*

An optical spectrum of QU Vul was obtained with the 6.5 m Multiple Mirror Telescope and Blue Channel Spectrograph (Schmidt et al. 1989) on 2003 September 13.31 UT (day 6836; 18.72 yr posteruption) in generally photometric conditions and 1″ FWHM seeing. Three 600 s integrations of the nova were obtained through a $1'' \times 180''$ entrance slit oriented along the parallactic angle to avoid loss of light at the slit from differential atmospheric refraction and to improve the relative photometric accuracy. A 300 lines mm^{-1} grating centered at 6400 Å was utilized that covered the entire optical region on the detector; however, a long-pass order separation filter blocked all light shortward of ∼3800 Å and yielded calibrated spectra covering the region 3800–8000 Å at a resolution of about 7 Å FWHM. The spectrophotometric standard star BD +28 4211 was observed at a similar air mass as QU Vul, using a wider $5'' \times 180''$ entrance slit to enable accurate flux calibration. The spectra of HeNeAr and a quartz-halogen lamp were obtained to facilitate accurate wavelength calibration and flat-fielding respectively. The spectra were reduced using standard IRAF packages[12] and spectral extraction techniques. The optical spectrum is presented in Figure 2.

2.3. *Spitzer IRS*

We observed QU Vul on 2004 May 11.7 UT (day 7077.6; 19.38 yr posteruption) with the IRS (Houck et al. 2004) on the *Spitzer Space Telescope* (*Spitzer*; Werner et al. 2004; Gehrz et al. 2007) as part of the Gehrz Guaranteed Time Observing Program (GGTOP), program identification number (PID) 124. The observations were conducted using the short-wavelength (5.2–14.5 μm) low-resolution module (SL), the short-wavelength (9.9–19.6 μm) high-resolution module (SH), and the long-wavelength (18.7–37.2 μm) high-resolution module (LH). The resolving power for SL is $R = \lambda/\Delta\lambda \sim 60$–120, while $R \sim 600$ for SH and LH. Emission lines observed with the latter modules are marginally resolved. All observations utilized visual Pointing Calibration and Reference Sensor (PCRS) peakup on nearby isolated stars to ensure proper placement of the target in the narrow IRS slits. The spectroscopic astronomical observation request (AOR) key 0005044992 (0005044992), consisted of 5 cycles of 6 s ramps in SL (30 s on source), and 6 cycles of 6 s ramps in SH and LH (36 s on source each).

IRS Basic Calibrated Data (BCD) products were calibrated and processed with the *Spitzer* Science Center (SSC) IRS pipeline version 13.2. Details of the calibration and raw data processing are specified in the IRS Pipeline Description Document, v1.0.[13] Bad pixels were interpolated over in individual BCDs using bad pixel masks provided by the SSC. Multiple data collection events were obtained at two different positions on the slit using *Spitzer*'s nod functionality. Sky subtraction was only possible for the SL observations, as no dedicated sky observations were performed for the SH and the LH mode observations. Sky subtraction was performed by differencing the two-dimensional SL BCDs to remove the background flux contribution. Spectra were then extracted from the background-corrected SL data and the SH and LH BCDs with SPICE (version 1.3-beta1) using the default point source extraction widths. The extracted spectra were then combined using a weighted linear mean into a single-output data file. The high-resolution IRS data were not defringed. At the time of reduction, the errors generated by the SSC pipeline were not reliable and therefore errors were estimated from the standard deviation of the flux at each wavelength bin. The continuum was not detected over much of the spectral range of our data (absolute flux calibration of the IRS modules is $\lesssim$10%) and no emission was detected in the second-order SL spectra. A good fit to the spectral lines was obtained using a nonlinear least-squares Gaussian routine (the Marquardt method; Bevington & Robinson 1992) that fit the line center, line amplitude, line width, continuum amplitude, and the slope of the continuum. The spectra are shown in Figures 3–5.

Given that the [Ne II]12.81 μm line is accessible from the ground, we have investigated the possibility of continuing to monitor it in QU Vul using today's very large ground-based telescopes. During the interval between our SC-10 measurement of QU Vul (7.62 yr after outburst) and our *Spitzer* measurement (19.32 yr after outburst), we attempted unsuccessfully several times to detect this line in QU Vul using the long wavelength spectrometer LWS (Jones & Puetter 1993) on the Keck I 10 m telescope. More advanced mid-IR spectrometers are now available. One example is the Very Large Telescope Imager and Spectrometer for mid-IR (VISIR) at ESO Paranal. We have used the VISIR Exposure Time Estimator[14] to calculate that VISIR on the ESO Paranal UT3 8.2 m telescope would require about 15 hr of integration time to achieve the same signal-to-noise ratio (20/1) on this line as we reached with *Spitzer* IRS SL in 30 s. We conclude that further ground-based monitoring of the [Ne II]12.81 μm line in QU Vul is untenable.

3. DETERMINATION OF ABUNDANCES

Lower limits to the abundance of an element in the ejecta of a nova can be determined by dividing the number of atoms required to produce the lines of the element that are observed by the total number of hydrogen atoms in the ejecta. The lower limit so determined converges to the actual abundance when all lines of

[12] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[13] See http://ssc.spitzer.caltech.edu/irs/dh/pdd.pdf.

[14] See http://www.eso.org/observing/etc.

TABLE 1

Physical Parameters for Neon Emission Lines Observed in QU Vulpeculae

Observatory (1)	Date (UT) (2)	Day (3)	Emission Line (μm) (4)	Integrated Flux (10^{-12} erg s^{-1} cm^{-2}) (5)	log T_e (K) (6)	Υ_{ij} (7)	n_e (10^5 cm^{-3}) (8)	$n_{\rm crit}$ (10^5 cm^{-3}) (9)	N_i (10^{50}) (10)	N_j (10^{49}) (11)	$(Z/H)_{\rm QUVul}/(Z/H)_{\odot}$[a] (12)
WIRO	1985 May 15.4	141.3	[Ne II] 12.81	220 ± 20	4.0	0.283	332	7.03	4.5	19.5	$\gtrsim$20
WIRO	1985 Aug 23.4	241.3	[Ne II] 12.81	97 ± 10	4.0	0.283	67	7.03	2.1	8.6	$\gtrsim$9.4
IRTF	1986 Jul 30.0	581.9	[Ne II] 12.81	71.9 ± 3.4	4.0	0.283	4.8	7.03	3.5	6.4	$\gtrsim$13
IRTF	1986 Jul 30.0	581.9	[Ne VI] 7.64	247 ± 19	4.0	2.720	4.8	3.44	0.58	5.5	$\gtrsim$3.6
WIRO	1986 Aug 11.0	593.0	[Ne VI] 7.64	249 ± 25	4.0	2.720	4.8	3.44	0.58	5.6	$\gtrsim$3.6
Hale	1992 Aug 9.3	2783.9	[Ne II] 12.81	6.84 ± 1.09	3.0	0.272	0.04	2.31	24.1	0.61	$\gtrsim$76
Spitzer	2004 May 11.7	7077.6	[Ne II] 12.81	0.475 ± 0.032[b]	3.0	0.272	0.0026	2.31	23.1	0.04	$\gtrsim$73
Spitzer	2004 May 11.7	7077.6	[Ne III] 15.56	1.09 ± 0.028	3.0	0.596	0.0026	1.08	30.1	0.17	$\gtrsim$95
Spitzer	2004 May 11.7	7077.6	Total Neon	...	...	...	...	...	...	...	$\gtrsim$168
Spitzer	2004 May 11.7	7077.6	[O IV] 25.91	0.304 ± 0.012	3.0	1.641	0.0026	0.02	4.9	0.001	$\gtrsim$2.3

[a] Col. (12) represents the abundance by number of the given emission line.
[b] The IRS 12.81 μm values are the weighted mean of measurements from the SL and SH modules.

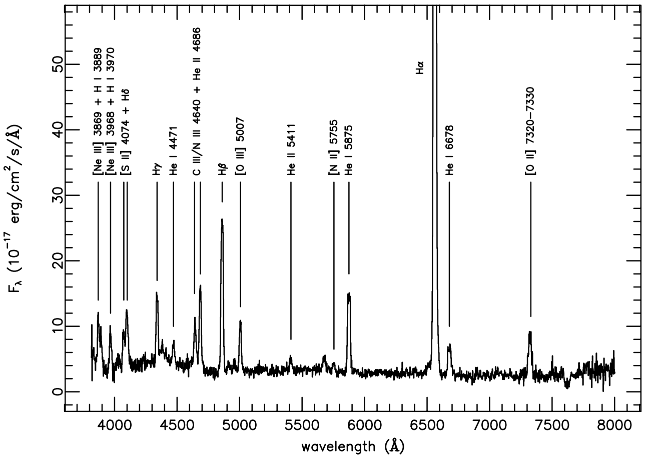

FIG. 2.—MMT Blue Channel optical spectrum of QU Vul taken on 2003 September 13.31 UT. Prominent recombination lines of H and He are evident. The [Ne III] lines near 3869 and 3968 Å are weak and blended with adjacent hydrogen lines at the spectral resolution of the instrument.

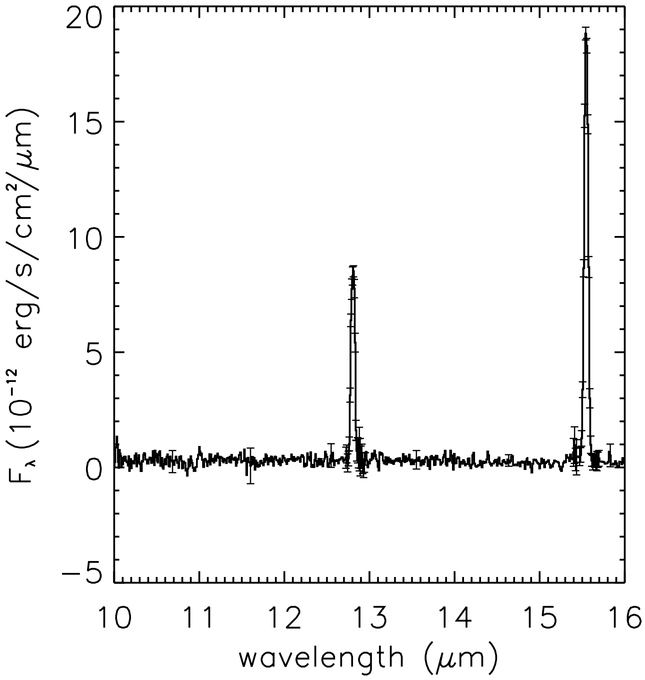

FIG. 4.—*Spitzer* SH spectrum of QU Vul taken on 2004 May 11.7 UT. No sky subtraction was performed. The [Ne II] line at 12.81 μm has an integrated line flux of 4.34×10^{-13} erg s^{-1} cm^{-2}. Also evident is the [Ne III] line at 15.56 μm with an integrated line flux of 1.09×10^{-12} erg s^{-1} cm^{-2}. For clarity, a representative subset of continuum errors is plotted.

all ions and isotopes can be evaluated. At very late epochs, hydrogen emission lines and the free-free continuum are no longer observed in the IR, so that the number of hydrogen atoms must be determined from the mass known to have been ejected in the eruption. We note that the majority of the mass is expelled within the first few hours of the outburst and very little thereafter, so that the number of hydrogen atoms is well constrained by early IR measurements and radio continuum observations (Gehrz 1988, 1999, 2002, 2008; Gehrz et al. 1998).

The neon and oxygen emission lines observed in the spectra of QU Vul are forbidden transitions excited by electron impact. The total number of ions required to produce the observed line strengths, assuming a uniform temperature distribution and density along the line of sight in a homogeneous medium, can be determined following detailed balancing arguments described by Osterbrock (1989). The [Ne II], [Ne VI], and [O IV] lines can be treated as arising from two-level atoms. [Ne III] has a ^3P ground term giving rise to emission lines at 15.56 and 36.02 μm. Our spectra do not extend to long enough wavelengths to measure

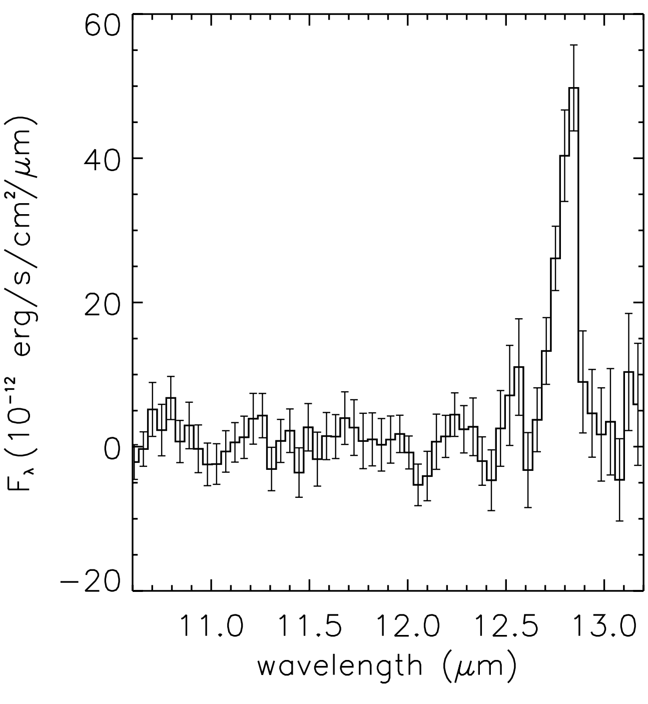

FIG. 3.—*Spitzer* background-subtracted SL spectrum of QU Vul taken on 2004 May 11.7 UT. The [Ne II] line at 12.81 μm has an integrated line flux of 4.96×10^{-13} erg s^{-1} cm^{-2}.

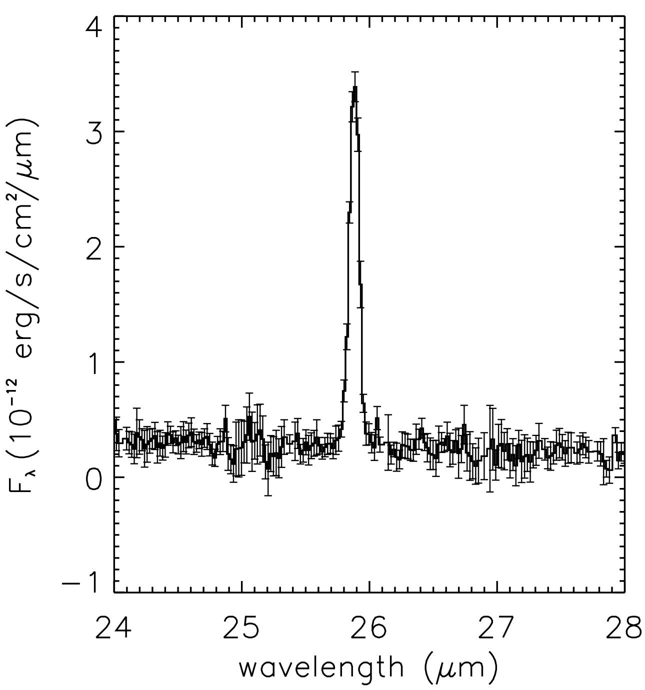

FIG. 5.—*Spitzer* long high 1 (LH1) spectrum of QU Vul taken on 2004 May 11.7 UT. No sky subtraction was performed. The [O IV] line at 25.91 μm has an integrated line flux of 3.04×10^{-13} erg s^{-1} cm^{-2}. The absolute flux calibration of the flux near the line is uncertain by less than 10%.

the strength of the 36.02 μm line. In this case, we must treat the 15.56 μm line as coming from a two-level atom, an approximation that gives us a lower limit to the number of [Ne III] atoms in the ejecta.

The level populations (total number of ions), N_i and N_j, in the lower (i) and upper (j) energy states can be computed from the line luminosity, $L_c = 4\pi D^2 F$, where D (cm) is the distance to the nova and F (erg s^{-1} cm^{-2}) is the integrated apparent intensity of the line. For QU Vul, we take D to be 3.14 kpc (Krautter et al. 2002). We regard this distance estimate as being superior to others given in the literature because the shell was well resolved by the *Hubble Space Telescope* (*HST*) NICMOS imager allowing a well-constrained expansion parallax to be derived. The total number of ions in the state N_i is

$$N_i = \frac{L_c}{n_e h\nu_{ji}} \frac{[1 + (n_e/n_{\rm crit})]}{q_{ij}}, \tag{1}$$

where n_e (cm^{-3}) is the electron number density, $n_{\rm crit}$ is the critical density of the transition, h is the Planck constant, and ν_{ji} (Hz) is the frequency of the transition. The parameter q_{ij} (cm^3 s^{-1}) is the excitation rate coefficient, which is a function of temperature, and is expressed as

$$q_{ij} = \frac{8.63\times10^{-6}}{\omega_i T_e^{1/2}} \Upsilon_{ij} \exp\left(\frac{-h\nu_{ij}}{kT_e}\right), \tag{2}$$

where ω_i is the statistical weight of the lower state, k is the Boltzmann constant, T_e (K) is the electron temperature, and Υ_{ij} is the dimensionless thermally averaged effective collision strength (Hummer et al. 1993). Values of Υ_{ij}, which is temperature dependent, were taken from Pradhan (1995), Saraph & Tully (1994), McLaughlin & Bell (2000), and Blum & Pradhan (1992) for [Ne VI] ($^2P_{3/2} \to {}^2P_{1/2}$), [Ne II] ($^2P_{1/2} \to {}^2P_{3/2}$), [Ne III] ($^3P_1 \to {}^3P_2$), and [O IV] ($^2P_{3/2} \to {}^2P_{1/2}$), respectively.

The critical density, $n_{\rm crit}$ (cm^{-3}), for a given transition is computed from the ratio of A_{ij} to q_{ji} (Osterbrock 1989), where A_{ij} (s^{-1}) is the radiative transition probability and q_{ji} (cm^3 s^{-1}) is the temperature-dependent, de-excitation rate coefficient defined as

$$q_{ji} = \frac{8.63\times10^{-6}}{\omega_j T_e^{1/2}} \Upsilon_{ij}, \tag{3}$$

where $\omega_j = (2J+1)$ is the statistical weight of the upper state and J is the total angular momentum quantum number of the upper state.

When $n_e \ll n_{\rm crit}$, collisional de-excitation of the ion in state (j) is not significant compared with radiative decay. As can be seen from Table 1 (cols. [8] and [9]), this was the case for the ejecta of QU Vul when the *Spitzer* observations were made in 2004. A_{ji} values obtained from the NIST database[15] are 2.02×10^{-2} s^{-1} ($\pm$10%) for [Ne VI], 8.59×10^{-3} s^{-1} ($\pm$10%) for [Ne II], and 5.19×10^{-4} s^{-1} ($\pm$3%) for [O IV]. For [Ne III], we adopt $A_{ji} = 5.84\times10^{-3}$ s^{-1} ($\pm$10%) from Kramida & Nave (2006).

The total number of ions in state N_j is expressed as

$$N_j = \frac{L_c}{A_{ji} h\nu_{ji}}. \tag{4}$$

The electron number density, n_e, of the ejecta at the epoch commensurate with the given neon line observation was inferred by adopting a free-expansion model for the ejected shell. Assuming spherical symmetry and a uniform shell with a filling factor of unity,

$$n_e = \frac{3}{4\pi}\frac{M_{ej}}{R_s^3}\frac{1}{m_p} = \frac{3}{4\pi}\frac{M_{ej}}{(V_o\Delta t)^3}\frac{1}{m_p}, \tag{5}$$

where $M_{ej} = 3.6\times10^{-4}\ M_\odot$ (Taylor et al. 1988) is the mass of the ejected shell of radius R_s (cm), V_o is the outflow velocity in cm s^{-1} taken to be 1190 km s^{-1} (Krautter et al. 2002; Rosino et al. 1992), Δt is the time since maximum light (day 0 = 1984 December 25.1 UT = JD 2, 446, 059.6) in seconds, and m_p is the mass of the proton. The slow velocity chosen here is consistent with the line widths, which are marginally resolved by IRS SH and SC-10. We emphasize that this is the mean electron density inferred from the unity filling factor and that there is some evidence for structure in the ejecta from the asymmetry in the [Ne II] and [O IV] lines.

Thus, a lower limit to the abundance of neon in QU Vul with respect to the solar value given by the strength of a given neon forbidden line alone is

$$\frac{({\rm Ne/H})_{\rm QUVul}}{({\rm Ne/H})_\odot} \geq \frac{(N_i + N_j)/N_{\rm H}}{7.413\times10^{-5}}, \tag{6}$$

where the solar abundance of neon by number $({\rm Ne/H})_\odot = 7.413\times10^{-5}$ (Lodders 2003), and the total number of hydrogen atoms in the nova shell is taken as $(M_{ej}/m_p) = 4.3\times10^{53}$. On dates when more than one neon forbidden line was observed, the individual abundances derived from equation (6) are summed to provide an estimate of the total neon abundance. We stress that the total mass of neon in the ejecta of QU Vul, derived by the method described above, is a lower limit. The oxygen abundance is calculated in a similar fashion, where the solar abundance of oxygen is $({\rm O/H})_\odot = 4.898\times10^{-4}$ (Lodders 2003).

The observed neon line flux densities, $\log(T_e)$, n_e, level populations, and derived neon abundances are summarized in Table 1. An initial value of $\log(T_e) = 4.0$ was adopted for the abundance calculation for the first few hundred days. Later, a value of $\log(T_e) = 3.0$ was adopted based on the continuum-subtracted hydrogen Brackett-γ to Paschen-α emission line ratio derived from the *HST* narrowband observations of the ejecta obtained by Krautter et al. (2002) on day 2783.9 (=JD 2,448,843.5). Assuming case B conditions and the hydrogen recombination line emissivities tabulated by Storey & Hummer (1995), the *HST* [H I(7–4)/H I(4–3)] $= (7.27\pm0.46)\times10^{-2}$ ratio suggests that $\log(T_e) = 3.0$ for a $n_e = 1.0\times10^3$ cm^{-3}. The latter n_e is of the order expected from equation (5).

Examination of the line profiles in the optical spectrum (Fig. 2) that we obtained $\approx$242 days prior to the *Spitzer* observations lead us to conclude that the Balmer, He I, and He II lines probably come from both the low-temperature ejecta and from the hot accretion disk in the binary system. Given the resolution of our spectrum, it is impossible to deconvolve the different components, and an analysis of the hydrogen line ratios yields an upper limit to the electron density in the ejecta. Dereddened [assuming $E(B-V) = 0.6$; Andrea et al. 1994; Saizar et al. 1992] flux ratios derived from Gaussian fits to the prominent H recombination lines in the day 6836 (=JD 2,452,895.8) spectrum yield $({\rm H}\beta/{\rm H}\alpha) \simeq 0.29\pm0.05$ and $({\rm H}\gamma/{\rm H}\alpha) \simeq 0.14\pm0.03$. Assuming case B conditions and the hydrogen recombination line emissivities tabulated by Storey & Hummer (1995), the optical line ratios are consistent with $\log(T_e) = 3.0$ and $n_e \sim$ 200–1,000 cm^{-3}. Again, this range

[15] See http://www.physics.nist.gov.

of values for n_e is consistent with the value we derive by applying equation (5).

For comparison, we have recalculated the neon abundances that can be inferred from the data taken on 1985 May 15.4 UT (Gehrz et al. 1985), 1985 August 23.4 UT (Gehrz et al. 1986), and 1986 July 30.0 UT and August 11.0 UT (Greenhouse et al. 1988) based on a more recent understanding of the expansion velocity and density development of the ejecta as described above, as well as the new values for the excitation and emission constants associated with the observed neon transitions. As is evident from the data in Table 1, the early epochs clearly fail the criterion that $n_e \ll n_{crit}$, suggesting that the dramatic difference in abundance estimates for the early epoch relative to the later epochs likely is due to strong collisional damping of the emission lines. Also, it is not obvious that the relative locations of line formation within the expanding ejecta have remained the same over time.

The large neon overabundances (at least 76 times solar on day 2783.9 and 168 times solar on day 7077.6) derived from our most recent observations (Table 1, col. [13]) are even larger than the value of 21.7 ± 1.7 reported by Schwarz (2002; hereafter S02) based on detailed photoionization models constrained by multiwavelength line fluxes obtained much earlier in the development of the ejecta. Closer examination of the assumptions made in the current analysis reveals that the discrepancies between the current analysis and that made by S02 can be easily resolved. The best-fit Cloudy model parameters reported by S02 suggest a distance estimate of 2.4 kpc compared to our adopted value of 3.14 kpc. From equations (1) and (4), and the relationship between flux and luminosity, the abundance estimates scale as D^2. If we adopt instead a distance of 2.4 kpc, our calculated abundances drop by a factor of $\approx$1.7. Further, in our analysis, we have made the elementary assumption that the ejecta uniformly fills a spherical volume with $R = V_0 \Delta t$. If instead we assume a spherically symmetric shell with a total volume half that of the sphere approximation, the electron number density would go up by a factor of 2, consequently reducing our abundance estimates by a corresponding factor of 2, bringing them into close agreement with estimates made by S02. On the other hand, we note that S02 used a solar neon abundance 1.59 higher than the more current value given by Lodders (2003). Correcting S02's values upward by this factor brings them in line with our results given the distance and the volume estimates discussed above. We also stress that the abundance values for neon given by us are inferred from the total mass of hydrogen in the ejecta as determined from radio continuum measurements (Taylor et al. 1988) and not from hydrogen recombination line strengths.

Other estimates of the neon abundance by number in QU Vul using ionization correction factor (ICF) techniques and Cloudy modeling have ranged from 60 to 254 times solar. The weaknesses in the ICF method and other Cloudy models are discussed in detail by S02. The reader should be aware that Livio & Truran (1994) have pointed out that the uncertainties in the various methods of determining abundances in novae can lead to discrepancies of factors of $\approx$2–4 under some circumstances. Our results (Table 1), taken in context alongside rigorous photoionization modeling, suggest a significant overabundance of neon in the ejecta of QU Vul.

The neon that we have detected in our spectra is most likely ^{20}Ne dredged up from the WD outer layers at some time during the thermonuclear runaway. In addition, a fraction could be ^{22}Ne which is produced from the decay of ^{22}Na ($\tau_{1/2} = 2.6$ yr) and which is predicted to be produced by thermonuclear runaways on ONeMg WDs (Starrfield et al. 1992). Moreover, the formation and ejection of low levels of ^{22}Na, decaying into ^{22}Ne, can account for the production of some of the ^{22}Ne (Neon E) anomalies found in meteorites (Black 1972).

4. CONCLUSIONS

Given the data summarized in Table 1, we conclude that neon in this nova was at least 76 and 168 times overabundant with respect to the solar value at epochs of 7.62 and 19.38 yr past outburst. While this indicates that individual novae such as QU Vul might be important local sources for enriching the interstellar medium with neon, they likely contribute no more than a few percent of the total Galactic abundance of neon. However, a fraction of the ejected neon could be ^{22}Ne produced by the decay of ^{22}Na which may be produced during the outburst and could contribute to the ^{22}Ne (Neon $-$ E) anomalies found in meteorites. However, the most significant implication of the high level of neon enrichment observed in QU Vul—since its source must certainly be dredge-up of matter from the underlying degenerate core—is that it provides unambiguous evidence for the occurrence of ONeMg white dwarfs among cataclysmic variable systems. The level of enrichment seen here is consistent with the high values predicted by the theoretical models of thermonuclear runaways on ONeMg white dwarfs presented by Iliadis et al. (2002).

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