1989AJ.....98.1682L

THE ASTRONOMICAL JOURNAL VOLUME 98, NUMBER 5 NOVEMBER 1989

NOVA OPHIUCHI 1988: 0.9–1.35 μm SPECTROSCOPY 6 MONTHS AFTER DISCOVERY[a)]

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Received 5 May 1989; revised 20 July 1989

ABSTRACT

Near-IR grating spectrophotometric observations ($\lambda / \Delta\lambda \simeq 400$) of Nova Ophiuchi 1988 between 0.9 and 1.35 μm on 22.2 September 1988 UT are reported. These are the first IR observations ever made of a *slow* nova. The spectrum shows a weak continuum, strong Paschen lines, and He I λ 1.083. A number of weaker lines primarily due to He I and [Fe II] may also be present. The visual extinction, distance, date of maximum brightness, and H/He abundance are calculated.

I. INTRODUCTION

Nova Ophiuchi 1988 was photographically discovered by Wakuda and Kosai (1988) on 27 March 1988 at $\alpha = 17^h08^m 50^s\!.84$, $\delta = -29°33'58.4''$ (1950) ($l^{\rm II} = 355.2$, $b^{\rm II} = +5.4$). McNaught (1988) suggested that the prenova object was a blue 20.5 mag star. Optical spectroscopy by Gilmore and Kilmartin (1988) on 24.47 April 1988 showing strong hydrogen emission and a weak continuum implied that the nova had already reached its nebular phase and thus was many weeks or months beyond maximum brightness. Further optical spectroscopy by Weller and Heathcote (1988) on 5.4 May 1988 and Jablonski *et al.* (1988) confirmed that the discovery was indeed postmaximum. Both groups reported strong Balmer lines, a weak continuum, and several Fe II emission lines.

IR observations of novae have been recently reviewed by Bode and Evans (1989) and Bode (1989), who note that only 12 novae have been observed spectroscopically in the infrared. In this paper we present the first IR spectrum of a slow nova, Nova Ophiuchi 1988.

II. OBSERVATIONS

We observed Nova Ophiuchi 1988 on 22.2 September 1988 UT (J.D. = 2447426.7) with the Lick Observatory 3 m Shane telescope using the Aerospace cooled grating spectrometer through a 7.5 arcsec aperture (Lynch *et al.* 1988). The detector was a germanium photodiode, cooled to 77 K and used in conjunction with a charge-integrating amplifier. The spectral resolution ranged from $\lambda / \Delta\lambda \simeq 350$ at 0.9 μm to $\simeq 500$ at 1.3 μm. The spectrum of the sky background was subtracted from the data, which was then divided by the spectrum of the standard star. The calibration star was 45 Ophiuchi, a nearby F5 IV star observed at the nova's airmass.

The telluric absorption features present in the spectrum of Nova Ophiuchi were removed by dividing it by the spectrum of 45 Oph. The data were reduced to relative fluxes by assuming that the continuum of 45 Oph matched a 6580 K blackbody. The data were transformed to absolute fluxes using a measurement of the monochromatic brightness of 45 Oph at 1.25 μm relative to α Lyr. Although 45 Oph is a δ Delphini variable (Jaschek and Jaschek 1987), the few hundredths of a magnitude changes displayed by such variables are small compared to the uncertainties in the actual shape of the continuum. Of more serious concern are the Paschen absorption features in this F type star. We modified the raw spectrum of 45 Oph to account for the Paschen absorption lines by interpolating the continuum surrounding each line. Because of the uncertainty in the continuum shape of 45 Oph and the large airmass at which both Nova Oph and 45 Oph were observed (4.3), the errors in the absolute line fluxes presented in Table I are probably no less than 10%.

Due to the absence of an absolute wavelength standard, the wavelength calibration was limited to using the easily identified Paschen and telluric lines, and thus no radial-velocity information can be extracted from the spectrum. Figures 1 and 2 show the nova spectrum in linear and log flux, respectively.

Figure 1 shows the presence of Paschen emission lines β, γ, δ, ϵ, ζ, η, He I λ 1.083 μm, and a very weak continuum, all consistent with a postmaximum nebular phase. Figure 2 shows a number of possible weak lines, including [Fe II] and He I as well as an unidentified feature at 1.01 μm in the far red wing of Paδ. Table I lists the lines. The line-to-continuum ratio for He I λ 1.083 is about 300. The emission lines are resolved in the stronger features (Paδ, Paζ, Paβ, and He I λ 1.083) and show a mean FWHM of 900 ± 150 km/s.

TABLE I. Line list of Nova Ophiuchi 1988 (0.9–1.35 μm).

λ(μm)	SPECIES	TRANSITION	FLUX (W cm^{-2})
0.902	H I	Pa$_\eta$	1.6×10^{-19}
0.923	H I	Pa$_\zeta$	2.1×10^{-19}
0.955	H I	Pa$_\epsilon$	3.7×10^{-19}
1.005	H I	Pa$_\delta$	4.4×10^{-19}
1.012	?		
1.083	He I	2^3S - 2^3P	2.2×10^{-17}
1.094	H I	Pa$_\gamma$	6.5×10^{-19}
1.1969	He I		
1.2528 [1.2567]	He I + [Fe II]		
1.2785	He I		
1.282	H I	Pa$_\beta$	1.47×10^{-18}

[a)] This work was supported in the Space Sciences Laboratory by the Aerospace Sponsored Research Program.

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0004-6256/89/051682-04$00.90

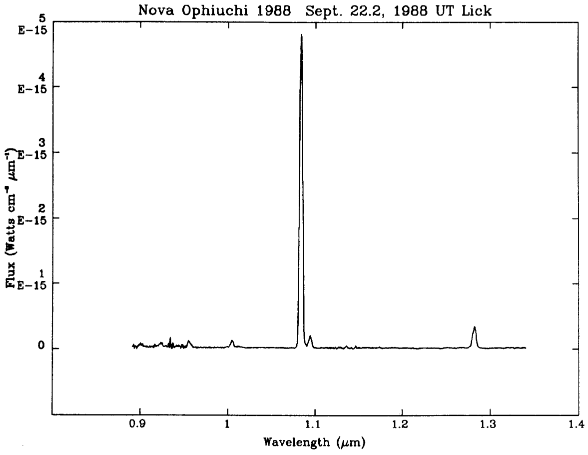

FIG. 1. Spectrum of Nova Ophiuchi 1988 on 22.2 September 1988.

III. DISCUSSION

The interstellar reddening to the nova can be calculated from the Paschen line ratios for β, γ, and δ, the others being blended with atmospheric features or too noisy for a reliable reddening analysis. Using the case B values computed by Brocklehurst (1971) and tabulated by Osterbrock (1974), and correcting the spectrum for the weak Paschen absorption lines in 45 Ophiuchi's spectrum, we obtain $A_V = 2.6 \pm 1.0$ using Paδ, Paζ, and Paβ. The relatively large uncertainty in A_V is due to scatter in A_V calculated from the various Paschen line ratios. We believe this is due to the poor S/N ratio of the weaker lines and not to any departure of the nova from case B recombination conditions. A similar analysis of Weller and Heathcote's Balmer lines gives $A_V = 1.9 \pm 0.6$. We shall adopt the mean of $A_V = 2.25$. Taking Olson's (1975) relation for color excess for the nova's $\sim 10^4$ K temperature ($R = 3.3$), and $E(B - V) = 0.4$ mag/kpc from Lucke's (1978) analysis of reddening in the nova's vicinity, we find 1.4 mag/kpc of visual extinction. Using our value of A_V, we find the distance $D = 1.6 \pm 0.8$ kpc.

From 24 April 1987 to 22 September 1987 ($\simeq 150$ days), the four reported spectra revealed substantially the same content: strong hydrogen lines and weak permitted lines of [Fe II] and He I. Notably absent were absorption lines and forbidden lines, the latter of which normally appear after the nova has faded by 2–3 magnitudes. The relatively long duration of the spectrum of permitted lines during a period when the nova is expected to fade by ~ 3 magnitudes suggests that the light curve's slope is of order 3 mag/ 150 days ~ 0.02 mag/day. Figure 3 shows the light curve of the nova along with a linear fit whose slope is 0.01375 mag/day and which shows no tendency to flatten out. Such a slope and the persistently unchanging spectrum imply that Nova Ophiuchi is a "slow" nova (McLaughlin 1960) and that from April to September 1987 it was in its early postmaximum decline. The absence of any forbidden lines (which are expected to develop in late 1989) means that the shell's density was too high to show emission characteristic of the "diffuse enhanced" spectrum or the "Orion" spectrum.

The date of maximum brightness and absolute magnitude can be roughly estimated based on other novae. The mean absolute magnitude of galactic novae at peak brightness is correlated with rate of decline (McLaughlin 1960; Schmidt 1957) via $M_V(\max) = -11.5 + 2.5 \log t_3$, where t_3 is the time in days taken to decline from peak brightness by 3 visual magnitudes. Our least-squares fit with a slope of 0.01375 mag/day leads to $t_3 = 3/0.01375 = 218$ days, and $M_V(\max) = -5.7$. A similar analysis using Cohen's (1985) relation between $M_V(\max)$ and t_2 [Cohen's Eq. (1)] gives exactly the same answer for $M_V(\max)$. Using $A_V = 2.25$, $D = 1.6$ kpc, and $M_V = -5.7$, we find $m_v(\max) = 8$. Extrapolating the fit in Fig. 3 backwards in time to $m_v = 8$, we estimate the earliest date of maximum brightness on about 16 November 1987 or J.D. = 2447115. This date is viewed as the earliest possible date of maximum, because the slopes of most light curves decrease with time (although at this time Nova Ophiuchi's light curve shows no such tendency). These estimates are subject to considerable uncertainty.

If McNaught's identification of the prenova object as a 20.5 mag star is correct, then our postulated peak brightness

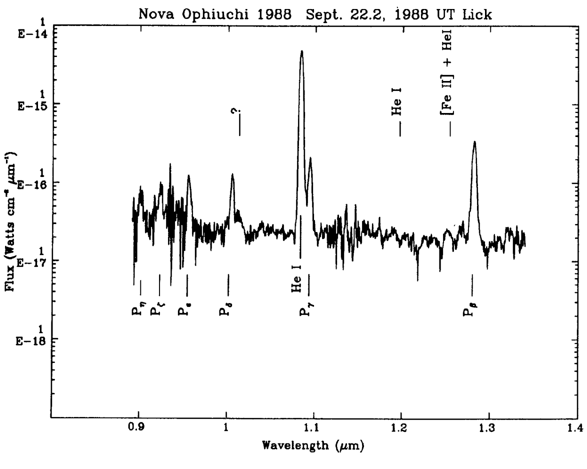

FIG. 2. Same as Fig. 1, with intensity plotted logarithmically.

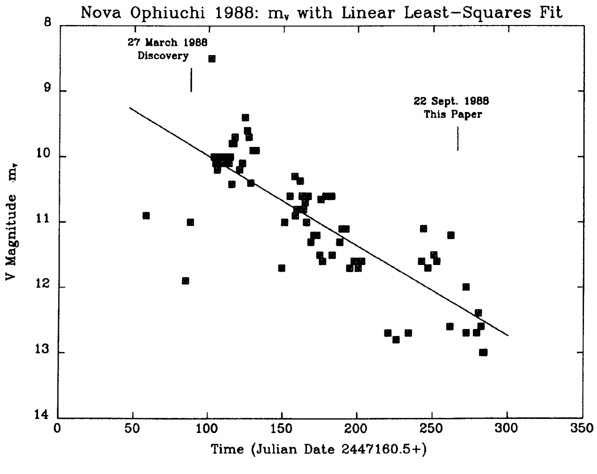

FIG. 3. Light curve of Nova Ophiuchi 1988 with least-squares linear curve fit (based on IAU Circulars).

of $m_v = 8$ leads to a range of 12.5 mag. This is a surprisingly large value for such a slow nova, especially in view of Bertaud's relation between range and t_3 which gives $\Delta m = 14.74 - 2.8 \log t_3 = 8.2$ mag for $t_3 = 218$ days. On the other hand, the peak brightness based on McNaught and Bertaud (1948) is $20.5 - 8.2 = 12.3$, which is clearly incorrect since at the nova's discovery it was more than 2 mag brighter than this.

The absence of certain spectral lines from the spectrum provides some information about the temperature and density of the line-emitting region. High densities are suggested by the lack of detectable forbidden lines, notably those of [S II] λ 1.0287, λ 1.0320, λ 1.0336, and λ 1.0370, and [S III] λ 0.9069 and λ 0.9532. If we assume $T_e = 10^4$ K, then the absence of these features suggests that n_e exceeds 10^6 cm^{-3}. The absence of the He II lines at 1.0124 and 1.1630 μm, which are prominent in nebulae like NGC 7027 (Treffers *et al.* 1976), indicates $T_e < 20\,000$ K.

The strength of the He I λ 1.083 μm line relative to the hydrogen lines provides additional information about the nebula density and temperature, as well as information about the He/H abundance. Following the general analysis of Osterbrock (1974), the ratio of the intensities of λ 1.083 to Paγ, which is insensitive to reddening, is

$$\frac{I(1.083)}{I(\mathrm{Pa}\gamma)} = \frac{(n_e n_{\mathrm{He}^+} + \alpha_{1.083} + n_e n_{2^3S} q_{2^3S,2^3P})}{n_e n_{\mathrm{H}^+} \alpha_{\mathrm{Pa}\gamma}} \left(\frac{1.0938}{1.0830}\right), \qquad (1)$$

where $\alpha_{1.083}$ and $\alpha_{\mathrm{Pa}\gamma}$ are the case B recombination coefficients and $q_{2^3S,2^3P}$ is the collisional excitation coefficient. The population density of the 2^3S level is given by the equilibrium expression

$$n_e n_{\mathrm{He}^+} \alpha_t = n_{2^3S}(A_{2^3S,1^1S} + n_e q_{\mathrm{tot}}), \qquad (2)$$

where α_t is the recombination coefficient to all the triplet levels and q_{tot} denotes the collisional rates to the singlets and to the continuum (Clegg 1987). Expressions (1) and (2) can be used to solve for the abundance ratio of helium to hydrogen in terms of the measured ratio of the two lines:

$$\frac{n_{\mathrm{He}^+}}{n_{\mathrm{H}^+}} = \left(\frac{\alpha_{\mathrm{Pa}\gamma}}{\alpha_{1.083} + [(\alpha_t n_e q_{2^3S,2^3P})/(A_{2^3S,1^1S} + n_e q_{\mathrm{tot}})]}\right) \times \left(\frac{1.0830}{1.0938}\right)\left(\frac{\mathrm{I}(1.083)}{\mathrm{I}(\mathrm{Pa}\gamma)}\right). \qquad (3)$$

Because of the dependence of λ 1.083 strength on density, a wide range of abundances are possible for the observed ratio of the lines. In addition, the recombination coefficients have a weak dependence on density and both the recombination coefficients and the collisional rates are dependent on temperature as well. Nevertheless, some conclusions are possible. The λ 1.083 line is at least a factor of 200 greater than He I λ 1.1969. Since recombination alone would result in a value of ~ 100 (Robbins 1968), significant collisional production of λ 1.083 does occur. This argues for temperatures $> 10^4$ and electron densities $> 10^3$.

If we once again assume $\mathrm{T_e} = 10^4$, and employ the collision coefficients of Berrington *et al.* (1982) and Clegg (1987), the recombination coefficients listed in Osterbrock (1974), and the A value for the transition from 2^3S to the ground state given by Hatta and Grant (1981), we can compute the $n_{\mathrm{He}^+}/n_{\mathrm{H}^+}$ abundance directly from Eq. (3). For $n_e > 10^4$ the abundance is consistent with the solar value. We find $n_{\mathrm{He}^+}/n_{\mathrm{H}^+} = 0.14$, 0.12, and 0.11 for $n_e = 10^4$, 10^5, and 10^6, respectively. For lower temperatures, collisional excitation of λ 1.083 is not adequate to account for the strong line observed indicating an abundance greater than solar. However, if the abundance exceeded the solar value by a factor of 3 or more, it is probable that we would have detected λ 1.1969. The fact that the He abundance showed no gross enhancements is consistent with the notion that slow novae exhibit smaller enhancements in nuclear-burning products than do fast novae (e.g., Starrfield 1989). Implicit in this argument is the assumption that the H II and He II regions are coincident, however. If the nebula were low excitation, the He II region would be smaller than its hydrogen counterpart and even larger values for the $(n_{\mathrm{He}^+}/n_{\mathrm{H}^+})$ ratio would be possible.

IV. CONCLUSIONS

The discovery of Nova Ophiuchi 1988 (27 March 1988) occurred several months after peak brightness (no earlier than 16 November 1987), with $m_V(\max) \simeq 8$. It suffers visual extinction of $A_V = 2.6 \pm 1$ mag and is located at a distance of 1.6 ± 0.8 kpc. Based on the Paschen lines and He I λ 1.083, we derive a H/He ratio that is near the solar value.

We would like to thank the referee for positive and constructive suggestions, as well as John Morey for his expertise in telescope operation. This project was supported in part by The Aerospace Sponsored Research Program.

REFERENCES

Berrington, K. A., Fon, W. C., and Kingston, A. E. (1982). Mon. Not. R. Astron. Soc. **200**, 347.

Bertaud, C. (1948). Ann. Astrophys. **11**, 1.

Bode, M. (1989). In *Proceedings of the 22nd ESLAB Symposium on Infrared Spectroscopy in Astronomy*, edited by M. Kessler, SP-290 (ESLAB, Paris) (in press).

Bode, M., and Evans, A. (1989). In *Classical Novae*, edited by M. Bode and A. Evans (Wiley, London).

Brocklehurst, M. (1971). Mon. Not. R. Astron. Soc. **157**, 211.

Clegg, R. E. S. (1987). Mon. Not. R. Astron. Soc. **229**, 31.

Cohen, J. G. (1985). Astrophys. J. **292**, 90.

Gilmore, A. C., and Kilmartin, P.M. (1988). IAU Circ. No. 4586.

Hatta, J., and Grant, I. P. (1981). J. Phys. B **14**, 2111.

Jablonski, F. J., Kirhakos, S. D., Diaz, M. P., and Batista, R. (1988). IAU Circ. No. 4619.

Jaschek, C., and Jaschek, M. (1987). *The Classification of Stars* (Cambridge University, Cambridge), p. 226.

Lucke, P. B. (1978). Astron. Astrophys. **64**, 367.

Lynch, D. K., Rudy, R. J., Rossano, G. S., and Puetter, R. C. (1988). IAU Circ. No. 4663.
McLaughlin, D. B. (1960). In *Stellar Atmospheres*, edited by J. Greenstein (University of Chicago, Chicago), p. 585.
McNaught, R. H. (1988). IAU Circ. No. 4582.
Olson, B. I. (1975). Publ. Astron. Soc. Pac. **87**, 349.
Osterbrock, D. E. (1974). *Astrophysics of Gaseous Nebulae* (Freeman, New York).
Robbins, R. R. (1968). Astrophys. J. **151**, 497.
Schmidt, T. (1957). Z. Astrophys. **41**, 181.
Starrfield, S. (1989). In *Classical Novae*, edited by M. Bode and A. Evans (Wiley, London), p. 39.
Treffers, R. R., Fink, U., Larson, H. P., and Gautier, T. N. (1976). Astrophys. J. **209**, 793.
Wakuda, M., and Kosai, H. (1988). IAU Circ. Nos. 4581, 4582.
Weller, W. G., and Heathcote, S. R. (1988). IAU Circ. No. 4594.