

Optical evolution of Nova Ophiuchi 2007 = V2615 Oph

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ABSTRACT

The moderately fast Nova Oph 2007 reached maximum brightness on March 28, 2007 at $V=8.52$, $B-V=+1.12$, $V-R_C=+0.76$, $V-I_C=+1.59$ and $R_C-I_C=+0.83$, after fast initial rise and a pre-maximum halt lasting a week. Decline times were $t_2^V=26.5$, $t_2^B=30$, $t_3^V=48.5$ and $t_3^B=56.5$ days. The distance to the nova is $d=3.7 \pm 0.2$ kpc, the height above the galactic plane $z=215$ pc, the reddening $E_{B-V}=0.90$ and the absolute magnitude at maximum $M_V^{\max}=-7.2$ and $M_B^{\max}=-7.0$. The spectrum four days before maximum resembled a F6 super-giant, in agreement with broad-band colors. It later developed into that of a standard 'FeII'-class nova. Nine days past maximum, the expansion velocity estimated from the width of H α emission component was ~ 730 km/s, and the displacement from it of the principal and diffuse enhanced absorption systems were ~ 650 and 1380 km/s, respectively. Dust probably formed and disappeared during the period from 82 to 100 days past maximum, causing (at peak dust concentration) an extinction of $\Delta B=1.8$ mag and an extra $\Delta E_{B-V}=0.44$ reddening.

Key words: stars: classical novae

1 INTRODUCTION

Nova Oph 2007 (= V2615 Oph, hereafter NOph07) was discovered by H. Nishimura at ~ 10 mag on photographic film exposed on Mar 19.81 UT (cf. Nakano 2007), and confirmed spectroscopically by Naito and Narusawa (2007). Das et al. (2007) reported infrared spectroscopy showing unusual and strong CO molecular bands in emission around optical maximum. An early report on pre-maximum spectral appearance of NOph07 in the optical was provided by Munari et al. (2007). Rudy et al. (2007) announced dust condensation occurring in NOph07 during May 2007, while Henden and Munari (2007) calibrated a BVR_CI_C photometric comparison sequence and measured an accurate astrometric position ($\alpha_{J2000} = 17\ 42\ 44.013 \pm 0''.03$, $\delta_{J2000} = -23\ 40\ 35.05 \pm 0''.07$).

2 OBSERVATIONS

The BVR_CI_C photometric evolution of NOph07 has been monitored, for seven months and over a seven magnitude decline, with three different telescopes (identified by *a, b, c* letters below and in Figures 1 and 2): (*a*) the Sonoita Research Observatory (SRO) 0.35-m Celestron C14 robotic telescope using BVR_CI_C Optec filters and an SBIG STL-1001E CCD camera, 1024×1024 array, $24\ \mu\text{m}$ pixels $\equiv 1.25''/\text{pix}$, with a

field of view of $20' \times 20'$; (*b*) the 0.30-m Meade RCX-400 f/8 Schmidt-Cassegrain telescope owned by Associazione Astrofili Valle di Cembra (Trento, Italy). The CCD is a SBIG ST-9, 512×512 array, $20\ \mu\text{m}$ pixels $\equiv 1.72''/\text{pix}$, with a field of view of $13' \times 13'$. The *B* filter is from Omega and the VRC_I_C filters from Custom Scientific; (*c*) the 0.50-m f/8 Ritchey-Cretien telescope operated on top of Mt. Zugna by Museo Civico di Rovereto (Trento, Italy) and equipped with Optec $UBVR_CI_C$ filters. The CCD is an Apogee Alta U42 2048×2048 array, $13.5\ \mu\text{m}$ pixels $\equiv 0.70''/\text{pix}$, with a field of view of $24' \times 24'$. The overall BVR_CI_C light- and color-curves are presented in Figure 1.

All photometric measurements were carefully tied to the BVR_CI_C calibration sequence of Henden and Munari (2007). They are listed in Table 1 (available electronic only). In all, we obtained 442 independent photometric measures (115 in *V*, 106 in *B-V*, 114 in *V-R_C*, 106 in *R_C-I_C*, 107 in *V-I_C*) distributed over 67 different nights. The mean poissonian errors of the photometric points in Figure 1 is 0.004 mag in *V*, 0.006 in *B-V*, 0.006 in *V-R_C*, 0.003 in *R_C-I_C* and 0.005 in *V-I_C*. The mean r.m.s. of standard stars from the linear fit to color equations is 0.022 mag in *V*, 0.032 in *B-V*, 0.029 in *V-R_C*, 0.018 in *R_C-I_C* and 0.043 in *V-I_C*. In spite of the excellent color transformations of all three instruments to the Henden and Munari (2007) comparison sequence, the presence of strong emission

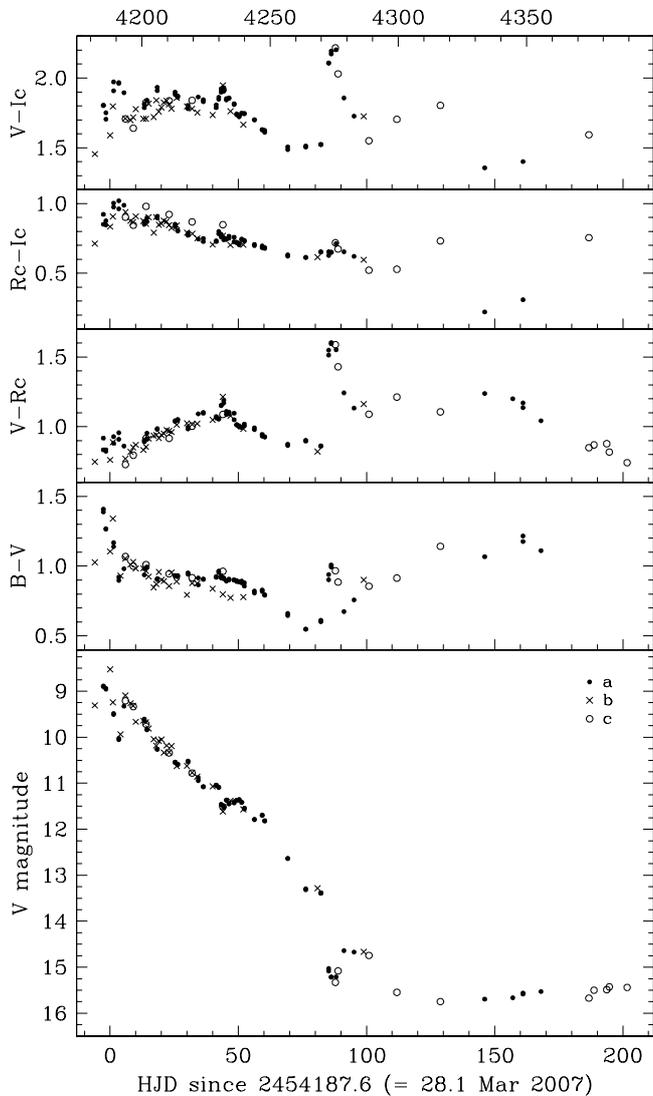


Figure 1. Light- and color-curves of Nova Oph 2007. The different symbols identify the telescopes used to collect the data which are detailed in Sect. 2. The ordinates at bottom are days from maximum brightness, those at top are heliocentric JD minus 2450000.

lines in the spectrum of NOph07 causes unavoidable differences between nova data recorded with different telescopes, at the level of a few hundreds of a magnitude as Figure 2 well illustrates.

Low and medium resolution, absolutely fluxed spectra of NOph07 were obtained on March 22.17 and 24.16 UT, 2007 with the AFOSC imager+spectrograph mounted on the 1.82m telescope operated in Asiago by INAF Astronomical Observatory of Padova. It is equipped with a Tektronix TK1024 thinned CCD, 1024×1024 array, 24 μm pixel, with a scale perpendicular to dispersion of 0.67''/pix. All observations were performed with a 1.26'' slit aligned along the parallactic angle. We adopted a 300 ln/mm grism, covering the 3500-7780 \AA interval at 4.24 $\text{\AA}/\text{pix}$ dispersion, and a 1720 ln/mm volume phase holographic grism, for the range 6400-7050 \AA at 0.64 $\text{\AA}/\text{pix}$.

Low and medium resolution, absolutely fluxed spectra

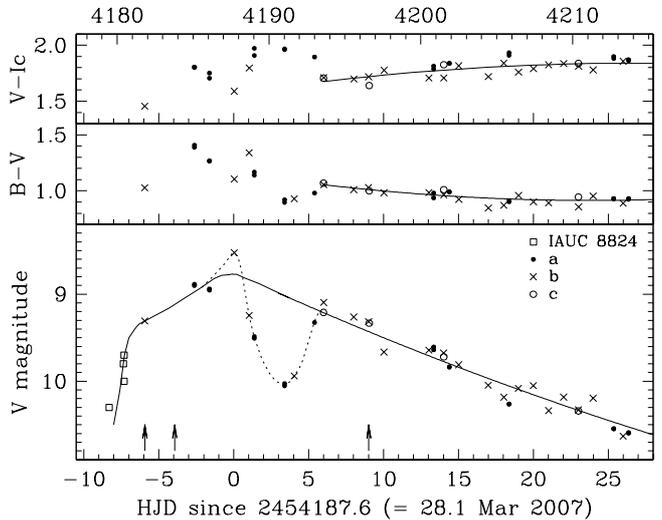


Figure 2. Enlargement of the early portion of Nova Oph 2007 photometric evolution. The meaning of the solid and dashed lines is outlined in Sect. 3.1. Symbols and ordinates as in Figure 1. The arrows point to times when we recorded optical spectra.

of NOph07 were obtained on April 6, 2007 also with the 0.6-m telescope of Osservatorio Astronomico G. Schiaparelli (Varese, Italy), equipped with a grating spectrograph and SBIG ST-10XME CCD, 2184×1472 array, 6.8 μm pixel. The slit width was 2.0''. A 600 ln/mm grating was used to cover the 3900-7100 \AA range at 1.76 $\text{\AA}/\text{pix}$, and a 1800 ln/mm grating for the 6200-6900 \AA range at 0.32 $\text{\AA}/\text{pix}$.

3 PROPERTIES OF NOVA OPH 2007

3.1 Rise, maximum brightness and early decline

The early phase of NOph07 photometric evolution is shown in greater detail in Figure 2. The solid line in the V -band panel represents a smoothed interpolation of the observed behavior, whose declining branch is given by the parabolic expression $V=8.75 + 0.079 \times t - 0.00045 \times t^2$ where t is the time in days from maximum brightness. This expression well fits the observed decline between $t=+6$ and $t=+65$ ($B=9.78 + 0.075 \times t - 0.00043 \times t^2$ would equally well fit the B -band light-curve over the same period). On top of this smooth behavior, around maximum brightness NOph07 displayed an oscillation (indicated by the dashed line in Figure 2) that took ~ 8 days to complete, and reached a peak-to-valley amplitude $\Delta V \approx 1.3$ mag.

The V -band maximum of NOph07 occurred around March 28.1, 2007 UT ($=2454187.6$), when the nova was measured at $V=8.52$, $B - V=+1.12$, $V - R_C=+0.76$, $V - I_C=+1.59$ and $R_C - I_C=+0.83$. Decline times were $t_2^V=26.5$, $t_3^B=30$, $t_3^V=48.5$ and $t_3^B=56.5$ days. They correspond to a moderately fast speed class.

The color changes of NOph07 around maximum brightness have been quite large and poorly correlated among the various bands (cf Figure 2), amounting to $\Delta(B - V)=0.51$, $\Delta(V - R_C)=0.20$, $\Delta(V - I_C)=0.38$, $\Delta(R_C - I_C)=0.19$ mag. Once the oscillation noted around maximum quenched down, the evolution of colors settled onto a smooth behaviour similarly to that of V -band lightcurve.

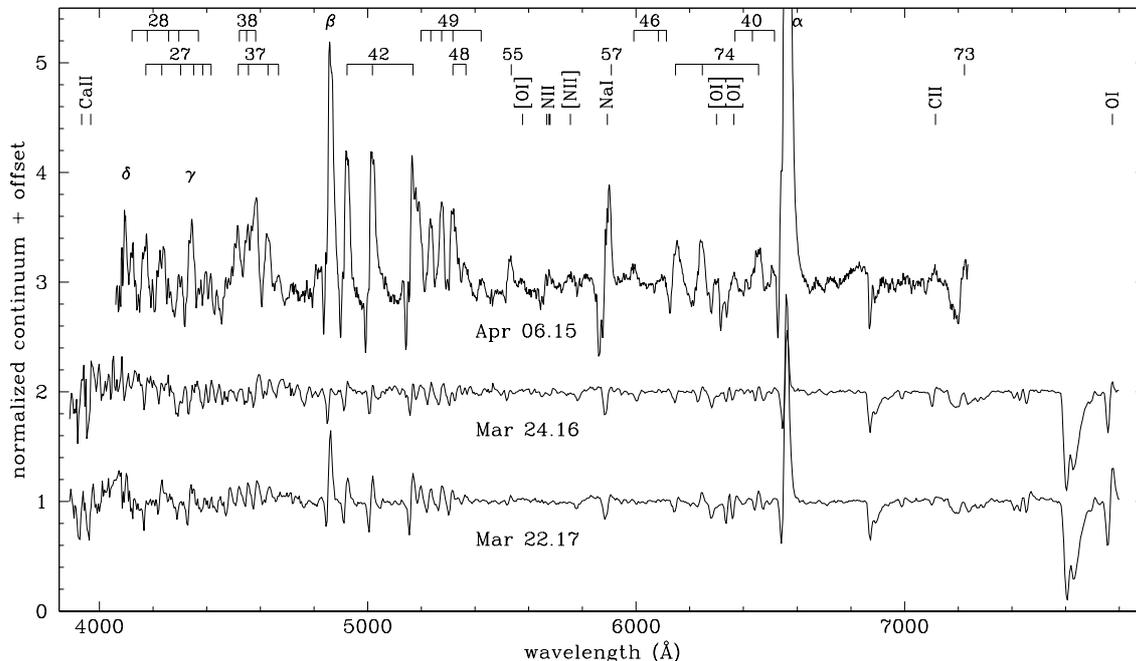


Figure 3. Spectral appearance of Nova Oph 2007 on 6 and 4 days before maximum and 9 days past it. The ordinate scale is the same for all spectra, which are continuum normalized and off-set for better visibility.

The parabolic fits given as solid lines in Figure 2 corresponds to $B - V = 1.165 - 0.0211 \times t + 0.00044 \times t^2$ and $V - I_C = 1.566 + 0.0205 \times t - 0.00038 \times t^2$ (between $t=+6$ and $t=+65$).

The initial rise of NOph07 to maximum was fast. Nakamura (2007) reports that nothing was visible at nova position down to 13.0 mag at $t=-10.3$ days, and down to 11.3 mag at $t=-9.3$ days according to Tago (2007). Combining with discovery magnitude estimates reported in IAUC 8824 (cf Figure 2), this corresponds to a rising rate *faster* than 1.2 mag day^{-1} . At $t=-6.5$, when the nova was $\Delta V \sim 0.9$ mag below maximum, it slowed its rising rate, entered a pre-maximum halt phase and completed the rise to maximum at a more leisurely $0.14 \text{ mag day}^{-1}$ rate.

3.2 Reddening

van den Bergh and Younger (1987) derived a mean intrinsic color $(B - V)_o = +0.23 \pm 0.06$ for novae at maximum, and $(B - V)_o = -0.02 \pm 0.04$ for novae at t_2 . We measured for NOph07 $B - V = +1.12$ at maximum and $B - V = +0.89$ at t_2 , which correspond respectively to $E_{B-V} = 0.89$ and $E_{B-V} = 0.91$. In the rest of this paper we will adopt $E_{B-V} = 0.90$ for NOph07 (corresponding to $A_V = 2.85$ and $A_B = 3.78$ for a standard $R_V = 3.1$ extinction law), which is in good agreement with a preliminary $E_{B-V} = 1.0$ reddening estimate from infrared OI emission lines by Rudy et al. (2007). The large reddening affecting NOph07 is confirmed by the large equivalent width of interstellar NaI D lines that are easily visible on our low resolution spectra superimposed on the emission component of NaI D P-Cyg profile of the nova (but not visible at the compressed scale of Figure 3). The resolution of these spectra is however too low to give a reliable measure of the equivalent width of NaI D from which to derive E_{B-V} via the Munari and Zwitter (1997)

calibration. From these interstellar NaI D lines, we can only place a $E_{B-V} > 0.7$ lower limit to the reddening.

3.3 Distance

The rate of decline from maximum and the observed magnitude 15 days past maximum are calibrated tools to estimate distances to novae.

Published relations between absolute magnitude and rate of decline generally take the form $M_{\text{max}} = \alpha_n \log t_n + \beta_n$. Cohen (1988) $M_V - t_2^V$ and Schmidt (1957) $M_V - t_3^V$ relations provide $M_V = -7.27$ and $M_V = -7.29$ for NOph07, respectively. Capaccioli et al. (1989) and Schmidt-Kaler (1965, cf Duerbeck 1981) $M_B - t_2^B$ relation give $M_B = -7.24$ and $M_B = -7.46$, respectively. de Vaucouleurs (1978) and Pfau (1976) $M_B - t_3^B$ relations lead to $M_B = -7.10$ and $M_B = -7.52$, respectively, while della Valle and Livio (1995) *s*-shaped relation calibrated on novae in LMC and M31 provides $M_V = -7.56$. Buscombe and de Vaucouleurs (1955) suggested that all novae have the same absolute magnitude 15 days after maximum light. Different calibrations of their relation are available from Buscombe and de Vaucouleurs (1955), Schmidt (1957), Pfau (1976), de Vaucouleurs (1978), Cohen (1985), van den Bergh and Younger (1987), van den Bergh (1988), Capaccioli et al. (1989) and Downes and Duerbeck (2000). The brightness of NOph07 15 days after maximum light, derived from the parabolic fits in Figure 2, was $V_{15} = 9.83$ and $B_{15} = 10.81 (\pm 0.015)$.

The mean value for all these distance estimates (and its error of the mean) is $d = 3.7 \pm 0.2 \text{ kpc}$. At such distance the absolute magnitudes of NOph07 at maximum would have been $M_V^{\text{max}} = -7.2$ and $M_B^{\text{max}} = -7.0$, and the height above the galactic plane is $z = 215 \text{ pc}$, which is within the vertical scale height of the galactic Thin Disk.

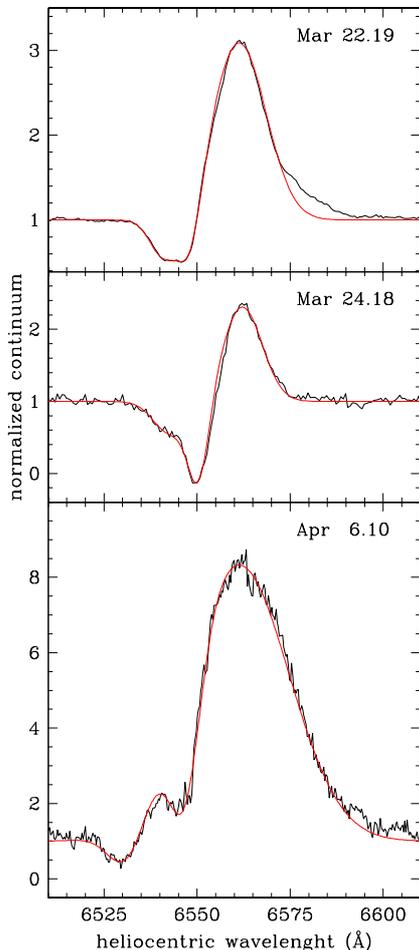


Figure 4. Continuum normalized H α profile of Nova Oph 2007 on 6 and 4 days before maximum and 9 days past it, at the same time of the low-res spectra of Figure 3. The fit with the emission and absorption components detailed in Table 2 is overlotted.

3.4 Dust formation ?

Rudy et al. (2007) reported dust formation occurring in NOph07 during May 2007, when their infrared spectra of the nova were characterized by persisting low ionization conditions, being dominated by FeII, NI, OI and CI emission lines. According to Rudy et al., the dust was absent on their May 7 ($t=+50$ days) observations and was instead substantially present on May 31 ($t=+74$) when they estimated from OI emission lines the reddening affecting the nova to have increased from $E_{B-V}=1.0$ to 1.3.

Dust generally forms in novae during the transition from stellar to nebular spectra, right when the high ionization rapidly sweeps through the ejecta (Gehrz et al. 1998, Shore and Gehrz 2004). Thus, the Rudy et al. (2007) announcement of dust forming in NOph07 during persistent, low ionization conditions would correspond to an unusual behaviour for a nova. The event also has no counterpart on the optical lightcurve of Figure 1, where all colors on May 31 are appreciably *bluer* than on May 7, contrary to the reported increase by 0.3 in E_{B-V} .

Dust could have formed later, three months and $\Delta V=5.5$ mag past maximum, peaking on June 22. Superimposed on a smooth light- and color-evolution, the nova

Table 2. Heliocentric velocity, velocity span at half maximum, equivalent width and integrated absolute flux (in $\text{erg cm}^{-2} \text{sec}^{-1}$) of the emission and absorption components of the H α profiles shown in Figure 4.

	RV_{\odot} (km/s)	VHM (km/s)	e.w. (Å)	Flux
<i>2007, March 22.19</i>				
<i>emission</i>	-44	780	-38.0	3.24×10^{-11}
<i>absorptions</i>	-642	332	5.4	-4.60×10^{-12}
	-969	387	4.1	-3.49×10^{-12}
<i>2007, March 24.18</i>				
<i>emission</i>	-4	571	-8.7	9.41×10^{-12}
<i>absorptions</i>	-541	301	3.9	-4.22×10^{-12}
	-886	484	2.5	-2.70×10^{-12}
<i>2007, April 6.10</i>				
<i>emission</i>	-44	1455	-248.6	2.32×10^{-10}
<i>absorptions</i>	-697	430	32.0	-3.00×10^{-11}
	-1425	506	12.5	-1.16×10^{-11}

displayed between $t \approx +82$ and $t \approx +100$ a fading and recovery in brightness, paralleled by first reddening and then a return to normal optical colors. The event well documented by Figure 1, amounted to $\Delta B=1.8$ mag, $\Delta(B-V)=0.4$ and $\Delta(V-I_C)=0.6$, which nicely correspond to an increase in the reddening by $\Delta E_{B-V}=0.44$.

For a normal $R_V=3.1$ extinction law, a $\Delta E_{B-V}=0.44$ dust condensation event should produce $\Delta(V-R_C)=0.28$ and $\Delta(R_C-I_C)=0.35$ reddenings. We have instead observed $\Delta(V-R_C)=0.5$ and $\Delta(R_C-I_C)=0.1$, that would correspond to $\Delta E_{B-V}=0.80$ and 0.12, respectively. Even if the mean value would well agree with $\Delta E_{B-V}=0.44$ derived from B , V and I_C colors, nevertheless the observed $\Delta(V-R_C)$ and $\Delta(R_C-I_C)$ requires an explanation. To this aim, it is sufficient that a fraction of flux in the H α + [NII] 6458-84 Å emission blend originates from gas external to the region where dust condensed. This emission blend usually accounts for the vast majority of the flux in the R_C -band of novae during advanced decline. For sake of discussion, if we assume that in NOph07 at the time of the $\Delta E_{B-V}=0.44$ dust condensation event the H α + [NII] blend was contributing 80% of the collected R_C -band flux, to account for the observed $\Delta(V-R_C)=0.5$ and $\Delta(R_C-I_C)=0.1$ it is enough that 10% of the H α + [NII] 6458-84 Å flux was not affected by the extinction. This could be easily the case because [NII] originates in the most external parts of the ejecta, where the gas density is possibly too low to support fast and efficient dust grain formation.

To be properly addressed, the issue as to whether dust actually formed in Nova Oph 2007, when and how much, and its radial location within the expanding ejecta, will have to wait for the publication of all available information, especially infrared and spectroscopic data.

3.5 Spectral evolution

The evolution of low-resolution spectra of NOph07 around maximum brightness is presented in Figure 3, where all significant emission lines are identified. We obtained the first

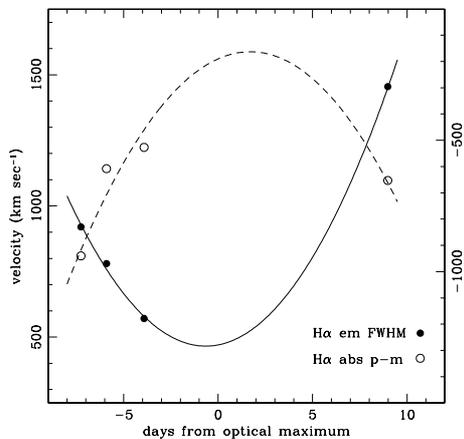


Figure 5. Evolution around maximum brightness of the FWHM of the emission component of $H\alpha$ profile (ordinate scale at left) and of the velocity of the pre-maximum absorption system (ordinate scale at right). Data from Table 2 and Naito and Narusawa (2007) for $t=-7.3$. The fits are explained in Sect. 3.5.

spectrum at $t=-6$. It is characterized by low ionization conditions and weak emission lines of mainly FeII, Balmer and OI, flanked by P-Cyg absorption profiles. The overall intensity of absorption lines, in particular of CH 4310 Å, CaII H and K, NaI D and $H\gamma$ support a classification as an F2-3 supergiant (allowing for a slight overabundance of Carbon in the ejecta, as typical of novae). This matches the observed $B-V=+1.0$ color on the same UT date. Two days later and 0.2 mag closer to maximum brightness on $t=-4$, all emission lines had weakened considerably, with only $H\alpha$, [OI] 7772 Å and FeII 4923, 5018 Å lines still displaying a detectable emission component. At the same time the underlying absorption spectrum increased, following a pattern quite typical for novae (cf McLaughlin 1960, hereafter M60) that sees a decrease in the ionization conditions and cooling of the spectral continuum along the rise to maximum brightness, and a reversed pattern during the decline from it. The intensity of the absorption lines suggest an F5 supergiant to be the closest spectral classification. Remarkably strong diffuse interstellar bands (in particular 4430, 5780, 6284 and 6614 Å) and interstellar lines (NaI D and CaII H and K) rise above the continuum of Figure 3. The spectrum for $t=+9$ and $\Delta V=0.9$ mag down from maximum is that of a classical FeII-class nova, with all relevant FeII multiplets in emission, Balmer and NaI lines also in strong emission, and feeble traces of [OI], CII, [NII] and NII just beginning to emerge.

Figure 4 presents the evolution of the $H\alpha$ profile from high resolution observations obtained on the same dates of the low resolution spectra of Figure 3. All three profiles clearly indicate the presence of two absorption components in addition to the emission one. A fitting with three gaussian components is overplotted to the observed profiles in Figure 4, and their radial velocity, FWHM, equivalent width and absolute flux are listed in Table 2. The post maximum spectrum on $t=+9$ is characterized by an expansion velocity of the ejecta (estimated from the $H\alpha$ emission component) of 730 km sec^{-1} , and the presence of the principal and diffuse enhanced absorption systems, whose displacement from the emission component are ~ 650 and 1380 km/s , respec-

tively. The statistical relations by M60 would predict for the t_2, t_3 decline rates of NOph07 a velocity for these absorption systems of 700 and 1350 km/s , pretty close to observed values.

Figure 5 illustrates the evolution with time of the FWHM of the $H\alpha$ emission component and of the radial velocity of the principal absorption system, combining data in Table 2 with Naito and Narusawa (2007) earlier measurement for $t=-7.3$. Both suggest an evolution that reaches minimum values around the time of maximum brightness, as observed in other novae (cf. M60). For sake of documentation and without attaching to them excessive significance given the limited number of observational points they rest upon, the parabolic fitting in Figure 5 of the FWHM of the $H\alpha$ emission component is given by $\text{FWHM}=470 + 13.8 \times t + 10.6 \times t^2$, and that for the velocity of the principal absorption system is $\text{RadVel} = -190 + 32 \times t - 9.4 \times t^2$.

3.6 Late photometric evolution

The photometric evolution presented in Figure 1 is characterized by a marked flattening, settling in around $t=+130$, that interrupted the normal decline when the nova was $\Delta V=7.0$ mag fainter than maximum. The effect is real because (i) it is present in data collected independently with different instruments, and (ii) there is no evidence for an optical faint companion neither in our images, nor in DSS, 2MASS or DENIS survey data down to $V \approx 20$ mag, which could have perturbed the measurement of NOph07. The approaching conjunction with the Sun stopped our monitoring at $t=+200$ and with it the possibility to further follow this interesting photometric phase.

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