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Optical evolution of Nova Ophiuchi 2007 = V2615 Oph

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ABSTRACT

The moderately fast Nova Oph 2007 reached maximum brightness on 2007 March 28 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 $t_3^B = 56.5$ d. The distance to the nova is $d = 3.7 \pm 0.2$ kpc, the height above the Galactic plane is $z = 215$ pc, the reddening is $E(B - V) = 0.90$ and the absolute magnitude at maximum is $M_V^{max} = -7.2$ and $M_B^{max} = -7.0$. The spectrum four days before maximum resembled a F6 supergiant, in an agreement with broad-band colours. It later developed into that of a standard 'Fe II'-class nova. Nine days past maximum, the expansion velocity estimated from the width of Hα emission component was ~730 km s^{-1}, and the displacement from it of the principal and diffuse-enhanced absorption systems was ~650 and 1380 km s^{-1}, respectively. Dust probably formed and disappeared during the period from 82 to 100 d 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: novae, cataclysmic variables.

1 INTRODUCTION

Nova Oph 2007 (= V2615 Oph, hereafter NOph07) was discovered by H. Nishimura at ~10 mag on photographic film exposed on March 19.81 UT (cf. Nakano 2007), and confirmed spectroscopically by Naito & Narusawa (2007). Das, Ashok & Banerjee (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 2007 May, while Henden & Munari (2007) calibrated a $BV\ R_C\ I_C$ 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 7 mag decline, with three different telescopes (identified by a, b and c letters below and in Figs 1 and 2): (a) the Sonoita Research Observatory (SRO) 0.35-m Celestron C14 robotic telescope using $BV\ R_C\ I_C$ Optec filters and an SBIG STL-1001E CCD camera, 1024 × 1024 array, 24 μm pixels ≡ 1.25 arcsec pixel^{-1}, with a field of view of 20 × 20 arcmin^2, (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 μm pixels ≡ 1.72 arcsec^2 pixel^{-1}, with a field of view of 13 × 13 arcmin^2. The B filter is from Omega and the $VR_C\ I_C$ filters are from Custom Scientific and (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 $UBV\ R_C\ I_C$ filters. The CCD is an Apogee Alta U42 2048 × 2048 array, 13.5 μm pixels ≡ 0.70 arcsec^2 pixel^{-1}, with a field of view of 24 × 24 arcmin^2. The overall BVR_CI_C light and colour curves are presented in Fig. 1.

All photometric measurements were carefully tied to the $BV\ R_C\ I_C$ calibration sequence of Henden & Munari (2007). They are listed in Table 1. In all, we obtained 442 independent photometric measures (115 in V, 106 in $B - V$, 114 in $V - R_C$, 106 in $R_C - I_C$ and 107 in $V - I_C$) distributed over 67 different nights. The mean poissonian errors of the photometric points in Fig. 1 are 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 rms of standard stars from the linear fit to colour 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 colour transformations of all three instruments to the Henden & Munari (2007) comparison sequence, the presence of

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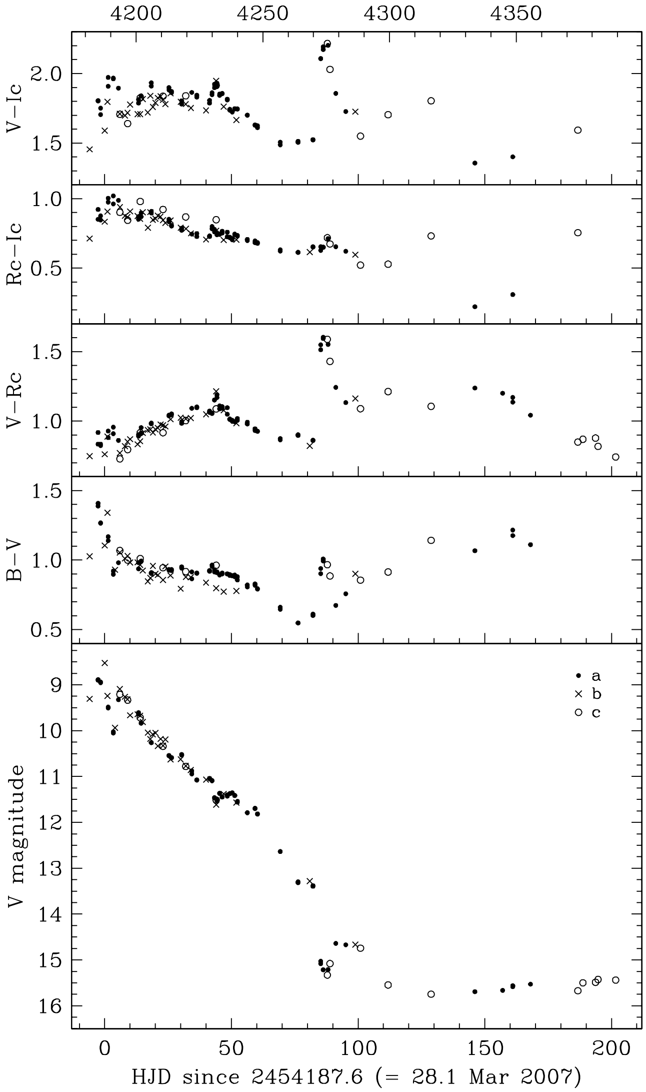

Figure 1. Light and colour curves of NOph07. The different symbols identify the telescopes used to collect the data which are detailed in Section 2. The ordinates at bottom are days from maximum brightness, those at top are heliocentric JD minus 245 0000.

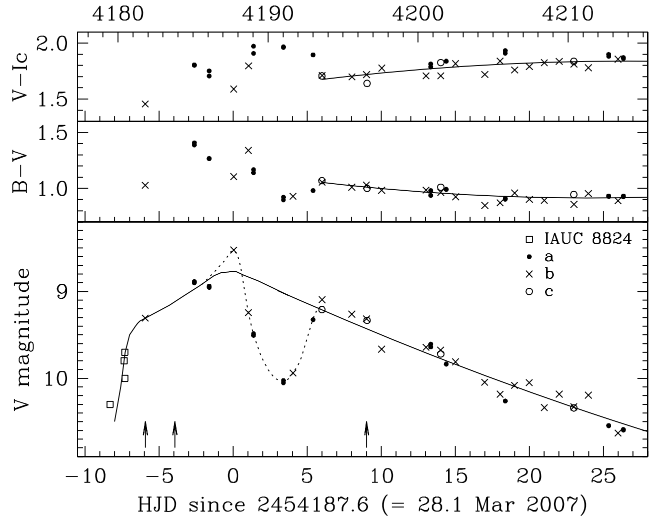

Figure 2. Enlargement of the early portion of NOph07 photometric evolution. The meaning of the solid and dashed lines is outlined in Section 3.1. Symbols and ordinates as in Fig. 1. The arrows point to times when we recorded optical spectra.

strong emission 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 Fig. 2 well illustrates.

Low and medium resolutions, absolutely fluxed spectra of NOph07, were obtained on 2007 March 22.17 and 24.16 UT with the AFOSC imager+spectrograph mounted on the 1.82-m 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 arcsec^2 pixel^{-1}. All observations were performed with a 1.26 arcsec^2 slit aligned along the parallactic angle. We adopted a 300 ln/mm grism, covering the 3500–7780 Å interval at 4.24 Å pixel^{-1} dispersion, and a 1720 ln/mm volume phase holographic grism, for the range 6400–7050 Å at 0.64 Å pixel^{-1}.

Low and medium resolutions, absolutely fluxed spectra of NOph07, were obtained on 2007 April 6 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 arcsec^2.

Table 1. Sample of photometric measurements. The full table is available as Supplementary Material in the online version of this article.

HJD	V	$B-V$	$V-R_{\mathrm{C}}$	$I_{\mathrm{C}}-R_{\mathrm{C}}$	$V-I_{\mathrm{C}}$	Obs
2454201.6103	9.674	0.965	0.855	0.855	1.708	b
2454201.6232	9.720	1.011	0.916	0.980	1.826	c
2454201.9883	9.937	1.093	0.953	0.870	1.839	a
2454201.9920	9.935	1.090	0.914	0.897	1.839	a

A 600 ln/mm grating was used to cover the 3900–7100 Å range at 1.76 Å pixel^{-1} and a 1800 ln/mm grating for the 6200–6900 Å range at 0.32 Å pixel^{-1}.

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 Fig. 2. The solid line in the V-band panel represents a smoothed interpolation of the observed behaviour, whose declining branch is given by the parabolic expression $V = 8.75 + 0.079 \times t - 0.000\,45 \times t^2$ where t is the time in days from maximum brightness. This expression well fits the observed decline between $t = +6$ and $+65$ ($B = 9.78 + 0.075 \times t - 0.000\,43 \times t^2$ would equally well fit the B-band light curve over the same period). On top of this smooth behaviour, around maximum brightness NOph07 displayed an oscillation (indicated by the dashed line in Fig. 2) that took ∼8 d to complete and reached a peak-to-valley amplitude $\Delta V \approx 1.3$ mag.

The V-band maximum of NOph07 occurred around 2007 March 28.1 UT (=2454 187.6), when the nova was measured at $V = 8.52$, $B - V = +1.12$, $V - R_{\mathrm{C}} = +0.76$, $V - I_{\mathrm{C}} = +1.59$ and $R_{\mathrm{C}} - I_{\mathrm{C}} = +0.83$. Decline times were $t_2^V = 26.5$, $t_2^B = 30$, $t_3^V = 48.5$ and $t_3^B = 56.5$ d. They correspond to a moderately fast speed class.

The colour changes of NOph07 around maximum brightness have been quite large and poorly correlated among the various bands (cf.

Fig. 2), amounting to $\Delta(B-V)=0.51$, $\Delta(V-R_C)=0.20$, $\Delta(V-I_C)=0.38$ and $\Delta(R_C-I_C)=0.19$ mag. Once the oscillation noted around maximum quenched down, the evolution of colours settled on to a smooth behaviour similarly to that of *V*-band light curve. The parabolic fits given as solid lines in Fig. 2 correspond to $B-V=1.165-0.0211\times t+0.000\,44\times t^2$ and $V-I_C=1.566+0.0205\times t-0.000\,38\times t^2$ (between $t=+6$ and 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 $t=-10.3$ d and 11.3 mag at $t=-9.3$ d according to Tago (2007). Combining with discovery magnitude estimates reported in IAUC 8824 (cf. Fig. 2), this corresponds to a rising rate *faster* than 1.2 mag d^{-1}. At $t=-6.5$, when the nova was $\Delta V\sim0.9$ 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 mag d^{-1} rate.

3.2 Reddening

van den Bergh & Younger (1987) derived a mean intrinsic colour $(B-V)_o=+0.23\pm0.06$ for novae at maximum and $(B-V)_o=-0.02\pm0.04$ 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 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 O I emission lines by Rudy et al. (2007). The large reddening affecting NOph07 is confirmed by the large equivalent width of interstellar Na I D lines that are easily visible on our low-resolution spectra superimposed on the emission component of Na I D P-Cyg profile of the nova (but not visible at the compressed scale of Fig. 3). The resolution of these spectra is, however, too low to give a reliable measure of the equivalent width of Na I D from which to derive $E(B-V)$ via the Munari & Zwitter (1997) calibration. From these interstellar Na I 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 d past maximum are calibrated tools to estimate distances to novae.

Published relations between absolute magnitude and rate of decline generally take the form $M_{\max}=\alpha_n\log t_n+\beta_n$. Cohen (1988) M_V–t_2^V and Schmidt (1957) M_V–t_3^V relations provide $M_V=-7.27$ and -7.29 for NOph07, respectively. Capaccioli et al. (1989) and Schmidt-Kaler (1965, cf. Duerbeck 1981) M_B–t_2^B relations give $M_B=-7.24$ and 7.46, respectively. de Vaucouleurs (1978) and Pfau (1976) M_B–t_3^B relations lead to $M_B=-7.10$ and -7.52, respectively, while della Valle & Livio (1995) *s*-shaped relation calibrated on novae in Large Magellanic Cloud and M31 provides $M_V=-7.56$. Buscombe & de Vaucouleurs (1955) suggested that all novae have the same absolute magnitude 15 d after maximum light. Different calibrations of their relation are available from Buscombe & de Vaucouleurs (1955), Schmidt (1957), Pfau (1976), de Vaucouleurs (1978), Cohen (1985), van den Bergh & Younger (1987), van den Bergh (1988), Capaccioli et al. (1989) and Downes & Duerbeck (2000). The brightness of NOph07 15 d after maximum light, derived from the parabolic fits in Fig. 2, was $V_{15}=9.83$ and $B_{15}=10.81(\pm0.015)$.

The mean value for all these distance estimates (and its error of the mean) is $d=3.7\pm0.2$ kpc. At such distance, the absolute magnitudes of NOph07 at maximum would have been $M_V^{\max}=-7.2$ and $M_B^{\max}=-7.0$, and the height above the Galactic plane is $z=215$ pc, which is within the vertical scaleheight of the Galactic thin disc.

3.4 Dust formation?

Rudy et al. (2007) reported dust formation occurring in NOph07 during 2007 May, when their infrared spectra of the nova were characterized by persisting low-ionization conditions, being dominated by Fe II, N I, O I and C I emission lines. According to Rudy et al., the dust was absent on their May 7 ($t=+50$ d) observations and was instead substantially present on May 31 ($t=+74$) when they

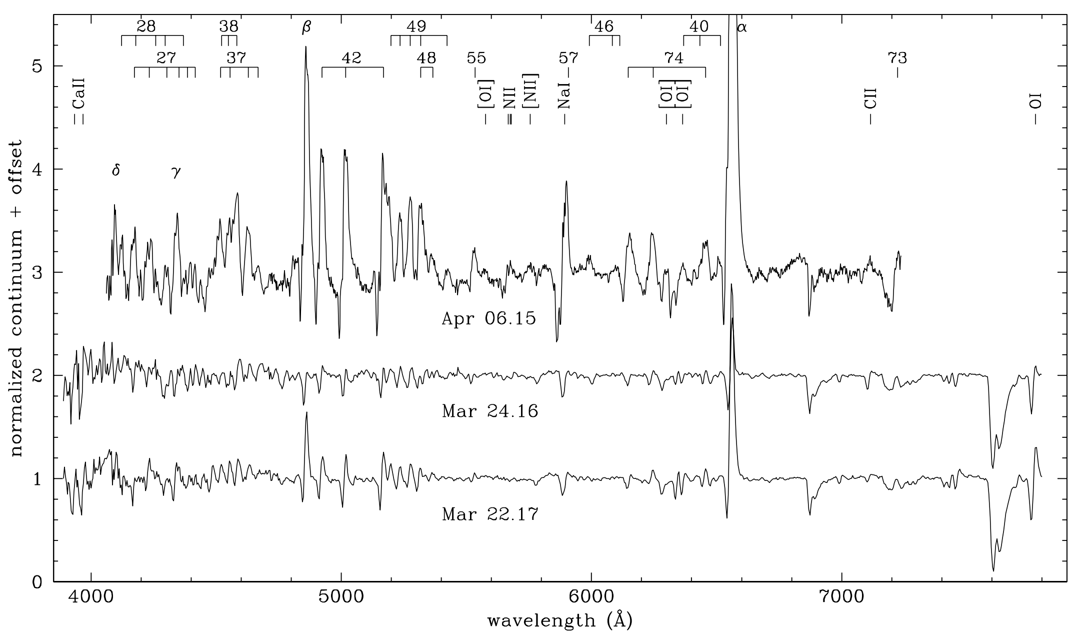

Figure 3. Spectral appearance of NOph07 on 6 and 4 d before maximum and 9 d past it. The ordinate scale is the same for all spectra which are continuum normalized and off-set for better visibility.

estimated from O I 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 & 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 light curve of Fig. 1, where all colours 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 colour evolution, the nova displayed between $t \approx +82$ and $+100$ a fading and recovery in brightness, paralleled by first reddening and then a return to normal optical colours. The event well documented by Fig. 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 $R_V = 3.1$ extiction 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 colours, nevertheless the observed $\Delta(V-R_C)$ and $\Delta(R_C-I_C)$ require an explanation. To this aim, it is sufficient that a fraction of flux in the Hα + [N II]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 Hα + [N II] blend was contributing 80 per cent 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 per cent of the Hα + [N II]6458 − 84 Å flux was not affected by the extinction. This could be easily the case because [N II] 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 NOph07, 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 Fig. 3, where all significant emission lines are identified. We obtained the first spectrum at $t = -6$. It is characterized by low-ionization conditions and weak emission lines of mainly Fe II, Balmer and O I, flanked by P-Cyg absorption profiles. The overall intensity of absorption lines, in particular, of CH 4310 Å, Ca II H and K, Na I D and Hγ supports 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 $B-V = +1.0$ colour 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 Hα, [O I] 7772 Å and Fe II 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 suggests 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 (Na I D and Ca II H and K) appear on the continuum of Fig. 3. The spectrum for $t = +9$ and $\Delta V = 0.9$ mag down from maximum is that of a classical Fe II-class nova, with all relevant Fe II multiplets in emission, Balmer and Na I lines also in strong emission, and feeble traces of [O I], C II, [N II] and N II just beginning to emerge.

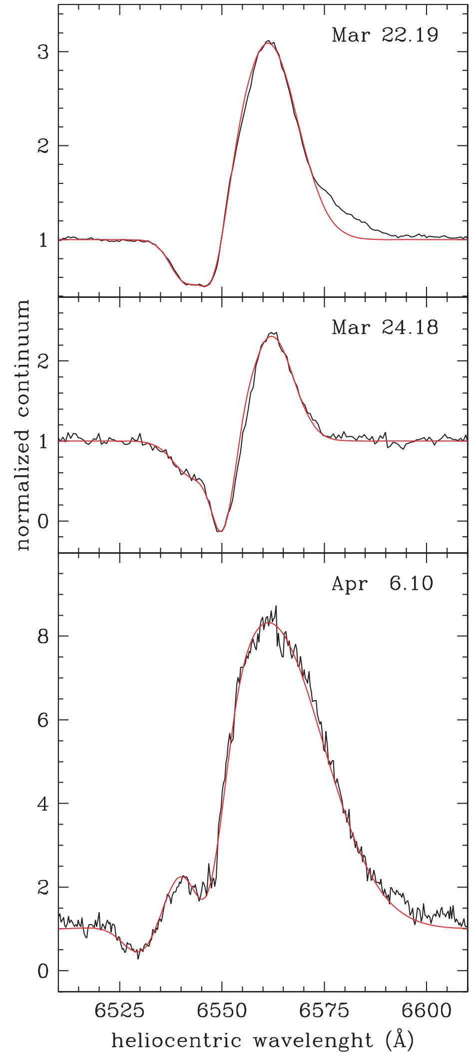

Figure 4. Continuum normalized Hα profile of NOph07 on 6 and 4 d before maximum and 9 d past it, at the same time of the low-resolution spectra of Fig. 3. The fit with the emission and absorption components detailed in Table 2 is overplotted.

Fig. 4 presents the evolution of the Hα profile from high-resolution observations obtained on the same dates of the low-resolution spectra of Fig. 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 Fig. 4, and their radial velocity, full width at half-maximum (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 Hα

Table 2. Heliocentric velocity, velocity span at half maximum (VHM), equivalent width and integrated absolute flux (in erg cm^{-2} sec^{-1}) of the emission and absorption components of the Hα profiles shown in Fig. 4.

	RV$_\odot$ (km s^{-1})	VHM (km s^{-1})	Equivalent width (Å)	Flux
		2007 March 22.19		
Emission	−44	780	−38.0	3.24×10^{-11}
Absorptions	−642	332	5.4	-4.60×10^{-12}
	−969	387	4.1	-3.49×10^{-12}
		2007 March 24.18		
Emission	−4	571	−8.7	9.41×10^{-12}
Absorptions	−541	301	3.9	-4.22×10^{-12}
	−886	484	2.5	-2.70×10^{-12}
		2007 April 6.10		
Emission	−44	1455	−248.6	2.32×10^{-10}
Absorptions	−697	430	32.0	-3.00×10^{-11}
	−1425	506	12.5	-1.16×10^{-11}

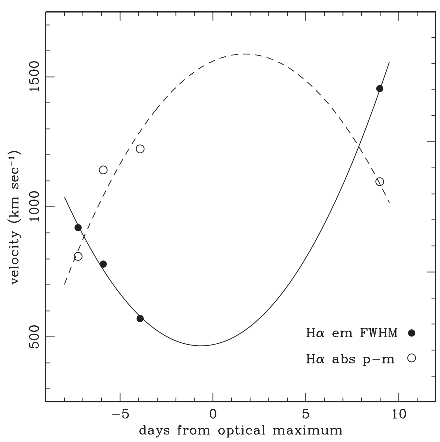

Figure 5. Evolution around maximum brightness of the FWHM of the emission component of Hα profile (ordinate scale at left-hand side) and the velocity of the pre-maximum absorption system (ordinate scale at right-hand side). Data from Table 2 and Naito & Narusawa (2007) for $t = -7.3$. The fits are explained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

emission component) of 730 km s^{-1}, and the presence of the principal and diffuse-enhanced absorption systems, whose displacement from the emission component is ∼650 and 1380 km s^{-1}, respectively. 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^{-1}, pretty close to observed values.

Fig. 5 illustrates the evolution with time of the FWHM of the Hα emission component and the radial velocity of the principal absorption system, combining data in table 2 with Naito & 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 Fig. 5 of the FWHM of the Hα emission component is given by FWHM $= 470 + 13.8 \times t + 10.6 \times t^2$, and that for the velocity of the principal absorption system is RadVel $= -190 + 32 \times t - 9.4 \times t^2$.

3.6 Late photometric evolution

The photometric evolution presented in Fig. 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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SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article.

Table 1. Photometric measurements.

This material is available as part of the online paper from http://www.blackwell-synergy.com/doi/abs/10.1111/j.1365-2966.2008.13238.x (this link will take you to the article abstract).

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