Mon. Not. R. Astron. Soc. **000**, 1–10 (2002) Printed 8 May 2010 (MN LaTeX style file v2.2)

Properties, evolution and morpho-kinematical modelling of the very fast nova V2672 Oph (2009), a clone of U Sco

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Accepted 1988 December 15. Received 1988 December 14; in original form 1988 October 11

ABSTRACT

Nova Oph 2009 (V2672 Oph) reached maximum brightness V=11.35 on 2009 August 16.5. With observed t_2(V)=2.3 and t_3(V)=4.2 days decline times, it is one of the fastest known novae, being rivalled only by V1500 Cyg (1975) and V838 Her (1991) among classical novae, and U Sco among the recurrent ones. The line of sight to the nova passes within a few degrees of the Galactic centre. The reddening of Nova Oph 2009 is E_{B-V}=1.6 ±0.1, and its distance d∼19 kpc places it on the other side of the Galactic centre at a galacto-centric distance larger than the solar one. The lack of an infrared counterpart for the progenitor excludes the donor star from being a cool giant like in RS Oph or T CrB. In close similarity to U Sco, Nova Oph 2009 displayed a photometric plateau phase, a He/N spectrum classification, extreme expansion velocities and triple peaked emission line profiles during advanced decline. The full width at zero intensity of Hα was 12,000 km s^{-1} at maximum, and declined linearly in time with a slope very similar to that observed in U Sco. The properties displayed by Nova Oph 2009 leads us to infer a mass of its white dwarf close to the Chandrasekhar limit and a possible final fate as a SNIa. Morpho-kinematical modelling of the evolution of the Hα profile suggests that the overall structure of the ejecta is that of a prolate system with polar blobs and an equatorial ring. The density in the prolate system declined faster than that in the other components. Nova Oph 2009 is seen pole-on, with an inclination of 0±2° and an expansion velocity of the polar blobs of 4800±200 km s^{-1}. Given the sourthern declination, the faintness at maximum, the extremely rapid decline and its close proximity to the Ecliptic, it is quite possible that previous outbursts of Nova Oph 2009 have been missed.

Key words: stars: novae – line: profiles

1 INTRODUCTION

Nova Oph 2009 (=V2672 Oph) was discovered by K. Itagaki on August 16.515 UT at mag 10.0 on unfiltered CCD images (cf. Nakano, Yamaoka, & Kadota 2009), at position (J2000) $\alpha = 17^h38^m19^s.70$, $\delta = -26^\circ44'14''.0$. This corresponds to Galactic coordinates l=001.021, b=+02.535, thus Nova Oph 2009 lies very close to the direction to the Galactic centre.

Spectroscopic confirmation was obtained on August 17.6 UT by Ayani et al. (2009) and on August 17.8 UT by Munari et al. (2009). Both reported a very large velocity width for Hα and the paucity of other emission lines on a red and featureless continuum. Munari et al. (2009) noted the great strength of interstellar lines and diffuse interstellar bands, which indicated a large reddening and therefore accounted for the red slope of the continuum of the nova. Munari et al. (2009) also noted how the profile of the emission lines was highly structured, in the form of a broad trapezium with a sharper Gaussian on top. The trapezium had a velocity width of ∼11700 km s^{-1} at the base and ∼6900 km s^{-1} at the top, while the sharp Gaussian component had a FWHM of ∼1400 km s^{-1}. They also noted how the colours, the rapid decline, and the velocity of the ejecta suggested that Nova Oph 2009 was an outburst occourring on a massive white dwarf, not dissimilar from the U Sco type of recurrent novae, and that a search in plate archives for missed previous outbursts could pay dividends.

A report on an early X-ray detection and following evolution of Nova Oph 2009 was provided by Schwarz et al. (2009). Their August 17.948 observation with the *Swift* satellite detected the nova with both the XRT and UVOT in-

Table 1. Our BVR_CI_C photometry of Nova Oph 2009. The first column is the UT date on 2009 August. The second column gives the heliocentric Julian day − 2455000.

date	HJD	V	$B-V$	$V-R_C$	$V-I_C$	R_C-I_C
17.473	60.9727	12.466	1.777	1.619	2.737	1.137
17.801	61.3014	12.722	1.772	1.596	2.699	1.075
18.499	61.9988	13.200	1.735	1.677	2.619	0.977
18.816	62.3162	13.320	1.770	1.694	2.542	0.906
20.820	64.3196	14.417		1.652	2.445	0.864
22.834	66.3336	15.871			2.684	
23.819	67.3193	15.839		1.600	2.417	0.849
24.823	68.3231	15.923		1.421	2.215	0.819
25.816	69.3160	16.342		1.529	2.351	0.846

Table 2. Journal of the spectroscopic observations. The time in the third column is counted from maximum brightness on August 16.515 UT.

date	UT	Δt (days)	expt (sec)	disp (Å/pix)	λ range (Å)	tel.
Aug 17	19:52	+1.31	1800	0.60	5575-6805	1.22m
17	20:28	+1.34	1500	2.12	4000-8625	0.6m
18	20:31	+2.34	1200	0.60	5575-6805	1.22m
19	20:28	+3.34	2400	0.60	5590-6810	1.22m
19	20:56	+3.36	1800	2.12	4010-8650	0.6m
20	20:11	+4.33	1800	4.24	4010-8650	0.6m
21	19:52	+5.31	1800	0.60	5540-6775	1.22m
24	20:11	+8.33	3600	0.60	5525-6760	1.22m

struments. Further observations on the following days found the nova to emit at a stable X-ray flux level, while rapidly declining at ultraviolet wavelengths. Schwarz et al. (2009) suggested that the early hard X-ray emission was likely due to shocks between the fast ejecta and a pre-existing circumstellar medium (as in the recurrent nova RS Oph − e.g. Bode et al. 2006) or intra-ejecta shocks (as in the very fast classical nova V838 Her O'Brien, Lloyd, & Bode 1994). Schwarz et al. (2009) also looked for past X-ray observations in the field, and concluded that Nova Oph 2009 was not recorded as an X-ray source prior to the 2009 outburst. They also noted how the nova was not detected in gamma-rays by INTEGRAL/IBIS during Galactic bulge monitoring observations taken on 2009 August 20 and 23/24.

Krauss Hartman, Rupen, & Mioduszewski (2009) reported their detection of radio emission from Nova Oph 2009 during the first two weeks after optical maximum. The radio emission from most novae is dominated by thermal bremsstrahlung which is optically thick at early times, leading to a dependence of the flux on frequency as $F_\nu \propto \nu^{+2}$. They detected Nova Oph 2009 at 8.46 GHz with the VLA on Sept 1.13, but obtained no detection at 22.46 GHz two days later, on September 3.18. Krauss Hartman, Rupen, & Mioduszewski (2009) concluded that this was best explained by a synchrotron origin for the radio emission observed from Nova Oph 2009. To support this view, they noted that (*i*) the strong shocks in its ejecta, suggested by the hard X-ray emission, can also be the source for the relativistic electrons and strong magnetic fields needed to generate synchrotron radiation, and that (*ii*) the recurrent nova RS Oph, shows strong radio synchrotron emission within days of the outburst (Padin, Davis, & Bode 1985; Eyres et al. 2009).

The peculiarity and rarity of the phenomena displayed by Nova Oph 2009 is evident from these early preliminary accounts. In this paper we report our optical observations, that have allowed us to derive the photometric and spectroscopic evolution and the basic properties of Nova Oph 2009, which are used to perform morpho-kinematical modelling of the emission line profiles which disentangled the basic components of the expanding ejecta.

2 OBSERVATIONS

Photometric observations of Nova Oph 2009 have been obtained with two instruments in collaboration with S. Dallaporta, S. Tomaselli, A. Maitan and S. Moretti of ANS Collaboration. The first is a 0.25-m Meade LX-200 Schmidt-Cassegrain telescope located in Cembra (Trento, Italy). It is equipped with an SBIG ST-8 CCD camera, 1530×1020 array, 9 μm pixels ≡ 0.74″/pix, with a field of view of 19′×13′. The BVR_CI_C filters are from Schuler. The other one is a 0.25-m f/6 Ritchey-Chretien robotic telescope, part of the GRAS network (GRAS15, Australia). It carries an SBIG ST-10XME CCD camera 2184×1472 array, 6.8 μm pixels ≡ 0.93″/pix, with a field of view of 34′×23′. The BVR_CI_C filters are again from Schuler. The calibration of photometric zero points and colour equations have been carried out against the Landolt (1983, 1992, 2009) equatorial standards. The photometric data are presented in Table 1. The total error budget (dominated by the Poissonian noise, with only a minor contribution from the uncertainty of the transformation to the Landolt system of equatorial standards) does not exceed 0.035 mag for all points.

Spectroscopic observations of Nova Oph 2009 were obtained with two telescopes, in collaboration with P. Valisa and V. Luppi of ANS Collaboration. A journal of the observations is given in Table 2. The 0.6m telescope of the Schiaparelli observatory in Varese (Italy), is equipped with a multi-mode spectrograph (Echelle + single dispersion modes) and a SBIG ST10-XME CCD camera (2184×1472 array, 6.8 μm pixels). It was used to obtain low resolution, wide wavelength range spectra. The Asiago 1.22m telescope feeds light to a B&C spectrograph, equipped with a 1200 ln/mm grating and ANDOR iDus 440A CCD camera (EEV 42-10BU back illuminated chip, 2048×512 pixels, 13.5 μm in size). It was used to obtain the higher resolution spectra around Hα. The spectra collected with both telescopes were calibrated into absolute fluxes by observations of several spectrophotometric standards, which were observed at air-masses close to those of Nova Oph 2009. The zero points and slopes of the absolutely fluxed spectra were checked against the photometry of Table 1, by integrating the spectral flux through the BVR_C photometric bands. The error on the fluxes of our spectra turned out not to exceed 9% over the wavelength range covered.

3 PHOTOMETRIC EVOLUTION

The photometric evolution of Nova Oph 2009 is presented in Figure 1. The light- and colour-curves of Figure 1 were ob-

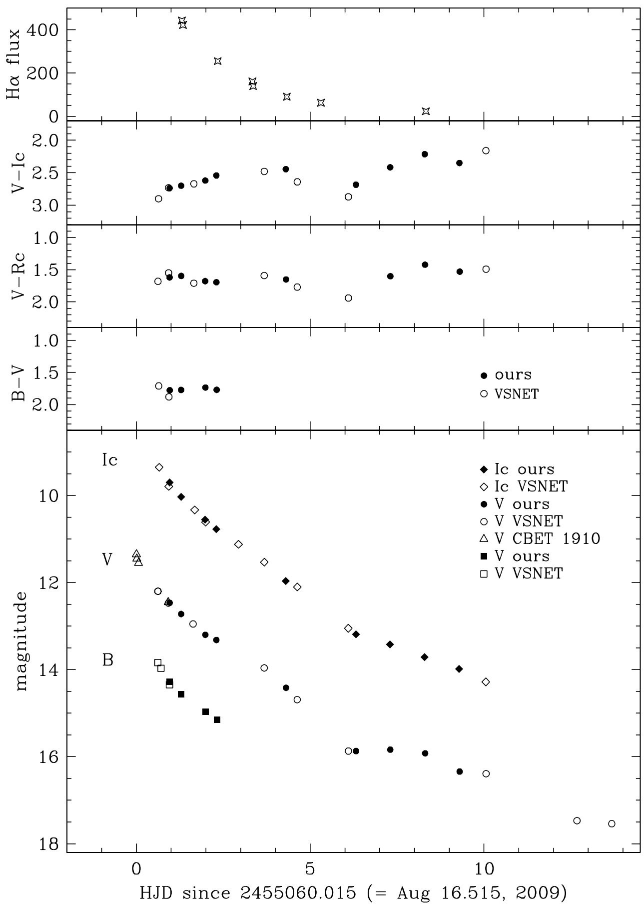

Figure 1. Photometric evolution of Nova Oph 2009. The integrated Hα flux in the top panel is in units of 10^{-13} cm^{-2} s^{-1} Å^{-1}.

tained by combining our data in Table 1 with other sources as follows.

The unfiltered CCD photometry obtained around the time of discovery by various Japanese observers and reported by Nakano, Yamaoka, & Kadota (2009), was scaled to V band by adding +1.35 magnitudes. The Japanese amateurs usually calibrate their unfiltered photometry against the R_C values of field stars taken from the USNO-B catalog. As illustrated in Table 1 and Figure 1, the $V-R_\mathrm{C}$ displayed by Nova Oph 2009 has remained fairly stable over the initial photometric evolution. Thus the application of the same shift to all data by Nakano, Yamaoka, & Kadota (2009) seems reasonable. The amount of the shift has been derived by comparison with simultaneous V band values from Table 1.

Members of the VSNET[1] Japanese amateur organisation performed some CCD filter photometry. This photometry is usually not corrected for colour equations and linked to non-specified calibration stars. Given the very red colours of Nova Oph 2009, this introduces large shifts. By comparison with the photometry in Table 1, we found the following correction to VSNET data: $B = B_\mathrm{VSNET} + 0.31$, $V = V_\mathrm{VSNET} + 0.29$, $R_\mathrm{C} = R_\mathrm{VSNET} + 0.10$, $I_\mathrm{C} = I_\mathrm{VSNET} + 0.05$. We have applied these to the VSNET data and plotted them in Figure 1.

3.1 Maximum and early decline

Nova Oph 2009 was probably discovered quite close to maximum brightness. The earliest observations given by Nakano, Yamaoka, & Kadota (2009) report the nova at V=11.35, 11.45 and 11.55 on August 16.515, 16.526 and 16.576, respectively. This corresponds to an extremely fast decline of 3.3 mag in 1 day, something that U Sco (the fastest known recurrent nova, Schaefer 2010) displays only during the first hours past true maximum, before slowing down to a decline time $t_2(V)\approx$2.0 days (Munari, Dallaporta, & Castellani 2010a). A patrol observation on August 14.142 (2.373 days before discovery, Nakano, Yamaoka, & Kadota 2009) recorded the nova fainter than V=14.0 limiting magnitude. In the rest of this paper, we will assume that the time of discovery, August 16.515, coincides with the time of maximum optical brightness.

The lightcurve of Nova Oph 2009 in Figure 1 is characterized by a smooth behaviour and decline times

$$t_2(V) = 2.3 \qquad t_3(V) = 4.2 \text{ days} \tag{1}$$

(±0.1 days) which are close to $t_2(V)$=2.0, $t_3(V)$=4.2 that are the mean values for the 1999 and 2010 outbursts of U Sco (Munari et al. 1999; Munari, Dallaporta, & Castellani 2010a). Nova Oph 2009 therefore qualifies as one of the fastest known novae. Among classical novae, similar or greater speeds have been attained only by V1500 Cyg (1975) and V838 Her (1991), while among recurrent novae, only U Sco could rival Nova Oph 2009.

After declining past $t_3(V)$, Nova Oph 2009 displayed an inflection in its light-curve, easily visible in Figure 1, and far more pronounced in V than in I_C. Around day +4.5, the nova started to decline faster than expected from smooth extrapolation of the preceding portion of the light-curve. The maximum deviation was reached around day +5.8, when Nova Oph 2009 became $\Delta V\sim$0.85 mag fainter and $\Delta V - I_\mathrm{C}\sim$0.6 mag redder than the smooth extrapolation of the light- and colour-curves of Figure 1. By day +8 the inflection was over and Nova Oph 2009 had returned to its smooth decline.

The nature of this inflection, which lasted for ∼3.5 days is unknown. The only spectroscopic observation secured during this period is an Hα profile which is of no great help, it following the line-profile evolution described later in this paper. Even if occurring around t_3, when dusty novae start to condense grains in their ejecta, the interpretation of the inflection in terms of small scale dust condensation in the ejecta of Nova Oph 2009 conflicts with (*a*) the fact that very fast classical novae and recurrent novae eject, at high speed, only minimal amounts of material, so that the density is usually lower than critical values for grains to condense, and (*b*) the grains should have condensed, grown in size and diluted at a speed much faster than observed in dusty novae, to complete their photometric life cycle in just 3.5 days.

3.2 Reddening

The very red colours of Nova Oph 2009 suggest a high reddening. This is confirmed by the intensity of the NaI D$_1$, D$_2$

[1] http://www.kusastro.kyoto-u.ac.jp/vsnet/

interstellar lines and of the 5780, 5797, 5850, 6270 and 6614 Å diffuse interstellar bands (DIBs) recorded in our spectra.

The NaI D_1, D_2 interstellar lines cannot be used because their very large equivalent width indicates they are largely over-saturated (c.f. Munari & Zwitter 1997). They must be the result of the blend of several individual components, as it is reasonable to expect given the line-of-sight passing close to the Galactic centre. Our spectra lack high enough resolution to resolve the individual components and thus to check if they are individually saturated or not.

The best measurable DIB for Nova Oph 2009 is the one at 6614 Å. It appears superimposed onto the very broad and strong Hα profile, which provides a good contrast background. The other DIBs are instead recorded onto a weak, and therefore more noisy continuum, which makes the measurement of their equivalent widths rather uncertain. The equivalent width of the 6614 Å DIB on the day +1.31 spectrum is 0.30 ±0.02 Å. By comparison with the relation E_{B-V}=5.3×E.W.(Å) calibrated by Munari (2010) between reddening and the equivalent width of the 6614 Å DIB, a reddening $E_{B-V}\sim$1.6 can be derived for Nova Oph 2009.

van den Bergh & Younger (1987) derived a mean intrinsic colour $(B-V)_\circ$=+0.23 ±0.06 for novae at maximum, and $(B-V)_\circ$=−0.02 ±0.04 for novae at t_2. Nova Oph 2009 displayed $B-V$=+1.77 at t_2, to which would correspond $E_{B-V}\sim$1.79. The flat $B-V$ evolution in Figure 1, suggests that a similar $B-V$=+1.77 could hold for Nova Oph 2009 also at maximum brightness, with a corresponding $E_{B-V}\sim$1.54.

The photometric and spectroscopic estimates of the reddening are in fair agreement, and their average value

$$E_{B-V} = 1.6 \quad \pm 0.1 \tag{2}$$

is adopted in this paper as the reddening affecting Nova Oph 2009.

3.3 Distance and peculiar location in the Galaxy

Most relations between absolute magnitude and the rate of decline take the form $M_{\rm max} = \alpha_n \log t_n + \beta_n$. The most recent calibration of this relation has been provided by Downes & Duerbeck (2000). Their relation for $t_2(V)$ gives $M(V)$=−10.40 for Nova Oph 2009, and $M(V)$=−10.41 for $t_3(V)$. Adopting the above E_{B-V}=1.6 reddening and a standard R_V=3.1 extinction law, the distance to Nova Oph 2009 would be 21 kpc. The distance remains reasonably large, even if we adopt the $M(V)$-t_2 relation calibrated by Cohen (1988) that gives 16 kpc, or the $M(V)$-t_3 relation by Schmidt (1957) that provides 17 kpc. Assigning a higher weight to the more recent calibration by Downes & Duerbeck (2000), we take the average of these determinations

$$d = 19 \quad \pm 2 \ \ \text{kpc} \tag{3}$$

as the distance to Nova Oph 2009. At Galactic coordinates l=001.021 and b=+02.535, the line-of-sight to Nova Oph 2009 passes close to the Galactic centre, crosses the whole Bulge and ends at a galacto-centric distance larger than that of the Sun. This is probably a record distance and position among known novae. The line-of-sight to Nova Oph 2009 does not cross any of the known Galactic low-extinction windows through the Bulge listed by Dutra, Santiago, & Bica (2002), as also confirmed by inspection of SDSS images showing a scarcely populated stellar field.

Another peculiarity of Nova Oph 2009 and its position is the z=0.8 kpc height above the galactic plane. della Valle & Livio (1998) found that He/N novae, such as Nova Oph 2009 (see Section 4), belong to the disk population of the Galaxy and are located at small heights above the Galactic plane. While Nova Oph 2009 is undoubtedly away from the Bulge, its height above the Galactic plane is difficult to reconcile with the $z\leqslant$100-200 pc found by della Valle & Livio (1998) for He/N novae. The proportion of He/N novae characterised by high z is becoming uncomfortably large in comparison with the della Valle & Livio (1998) scale height − other recent high-z examples being V2491 Cyg (= Nova Cyg 2008 N.2) at z=1.1 kpc (Munari et al. 2010b), and V477 Sct (= Nova Sct 2005 N2), located at z=0.6 kpc (Munari et al. 2006).

3.4 The plateau phase and comparison with U Sco

The light-curves of Nova Oph 2009 and U Sco (its 2010 outburst) are compared in Figure 2. The match is remarkable, with the exception of the inflection displayed by Nova Oph 2009 around day +5.8 and described in sect. 3.1 above, which has no counterpart in U Sco.

The strict similarity extends also to later phases, when U Sco displayed a plateau phase. Hachisu et al. (2000, 2002) and Hachisu, Kato, & Schaefer (2003) have postulated that a plateau is characteristic of recurrent novae, and in particular of the U Sco subclass of recurrent novae, a position shared by Schaefer (2010). Their idea is that the plateau is caused by the combination of a slightly irradiated companion star and a fully irradiated flared disk with a radius 1.4 times the Roche lobe size. At the time of the plateau, the outbursting white dwarf is experiencing stable nuclear burning and supersoft X-ray emission. The irradiation of the disk and the companion by a stable central engine leads to a fairly constant flux added to that steadily declining from the expanding ejecta. This leads to a flattening of the light curve (the plateau), which lasts until the time when the nuclear burning turns off.

The plateau phase of Nova Oph 2009 is well seen in the $I_{\rm C}$ light-curve of Figure 2. Unfortunately, the observations in the V band stopped due to the faintness of the nova right at the time when it was entering the plateau phase. There are just two observations defining the plateau of Nova Oph 2009, but they support a close similarity with the plateau of U Sco that lasted from day +12 to day +19. During that period U Sco was found to be - as predicted - a bright supersoft X-ray source (Schlegel et al. 2010; Osborne et al. 2010).

The plateau for Nova Oph 2009 is $\Delta I_{\rm C}$=0.6 mag brighter than in U Sco as illustrated by Figure 2, while the V-band panel seems to support instead a similar brighness level. We do not attach much significance to the $\Delta I_{\rm C}$ offset. It could be connected to differences in the irradiated disks and secondaries between Nova Oph 2009 and U Sco.

The mass of the white dwarf of U Sco is believed to be very close to the Chandrasekhar limit (Kato & Hachisu 1989; Hachisu et al. 2000; Thoroughgood et al. 2001), and thus, if net mass is being added over time to the white dwarf, is a prime candidate for explosion as a Type Ia supernova. The great similarity of all observational parameters between U

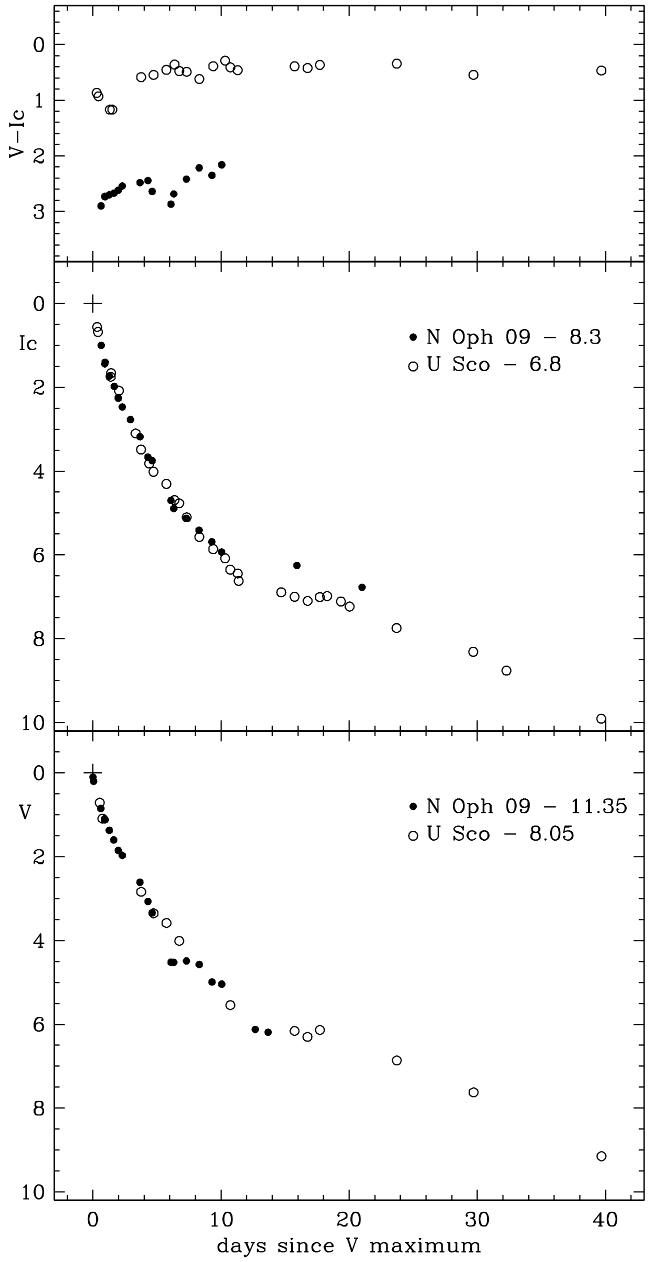

Figure 2. Comparison between the photometric evolutions of Nova Oph 2009 and U Sco during its 2010 outburst (from Munari, Dallaporta, & Castellani (2010a). The V and I_C light-curves are scaled by the given quantities to coincide at their optical maxima (see text for details), marked by the cross point at (0,0).

Sco and Nova Oph 2009 leads us to infer an equally massive white dwarf also in the latter, and an additional candidate for a future Galactic SNIa.

3.5 The progenitor

The progenitor of Nova Oph 2009 had no recorded optical or infrared counterpart in 2MASS and SDSS surveys. If the donor star is an M0 giant as in the recurrent nova RS Oph, and the parent population of Nova Oph 2009 is the Galactic disk, then its observed infrared magnitude and colour should be $K_s\sim12.3$ and $J-K_s$=1.8, or $K_s\sim10.3$ and $J-K_s$=2.0 if the donor star is an M5 giant as in the other recurrent nova T CrB.

There are only three 2MASS sources within 13 arcsec of the astrometric position of Nova Oph 2009. 2MASS 17382110-2644114 lies 5.6 arcsec away and has K_s=12.1 and $J-K_s$=1.67; 2MASS 17382076-2644079 is 5.5 arcsec away with K_s=10.3 and $J-K_s$=1.69; 2MASS 17382052-2644184 lies at a distance of 5.2 arcsec and has K_s=13.2 and $J-K_s$=1.39. While the third source appears too blue, the first two could broadly agree with an M giant at the distance and reddening of Nova Oph 2009. Their positions, however, are not reconciliable with Nova Oph 2009. Nakano, Yamaoka, & Kadota (2009) lists five independent and accurate measurements for the astrometric position of the nova. If σ is the r.m.s. of these five measurements, then all these three 2MASS sources are more distant than 10σ from the mean astrometric position of the nova.

Hanes (1985) derived a G0V spectral type for the donor star in U Sco, shining in quiescence at K=16.45, $J-K$=0.43. Closely similar values were later measured by the 2MASS survey. Such a donor star for Nova Oph 2009 would put it far below the detection thresholds of both 2MASS and SDSS surveys.

We may thus conclude that the donor star in Nova Oph 2009 is *not* a cool giant as in RS Oph and T CrB, but much more likely a dwarf as in recurrent novae of the U Sco type and in most classical novae. Its orbital period should therefore be less than two days, and not months or years.

4 SPECTRAL EVOLUTION

Only few spectral lines are usually recorgnizable on spectra of novae characterized by very large expansion velocities. This is caused by the large blending of individual lines that wash them out into the underlying continuum energy distribution. Nova Oph 2009 is no exception to this rule as illustrated by its spectral evolution presented in Figure 3. Only Hα and OI 8446 Å stand out prominently, all other lines emerging only weakly from the underlying continuum. Table 3 reports the absolute fluxes of the emission lines that it was possible to recorgnize and measure with confidence.

The spectra of Nova Oph 2009 classify it among He/N novae, as usual for fast examples. The general appearance of Nova Oph 2009 spectra is very similar to those of U Sco, once the reddenings of the two objects are matched, as the comparison of Figures 3 and 4 indicate.

The top panel of Figure 1 compares the evolution of the integrated flux of Hα to the photometric one. The decline rate is identical to that of the V-band flux, while it is slower than for I_C. This agrees with the $V-I_C$ evolution, which is directed toward bluer $V-I_C$ colours. The Hα contributes less than 10% to the V-band flux (as proved by integration of the photometric transmission profile on the spectra as observed and with Hα clipped), and this prevents the equality of V-band and Hα decline rates from turning into a circular argument. The HeI/Hα intensity ratio doubled from day +1.34 to day +4.33, as expected for an excitation increasing during decline from maximum. The Hα/Hβ flux ratio kept constant at 35 between these two dates, a very high value to which contributes the large reddening affecting Nova Oph 2009.

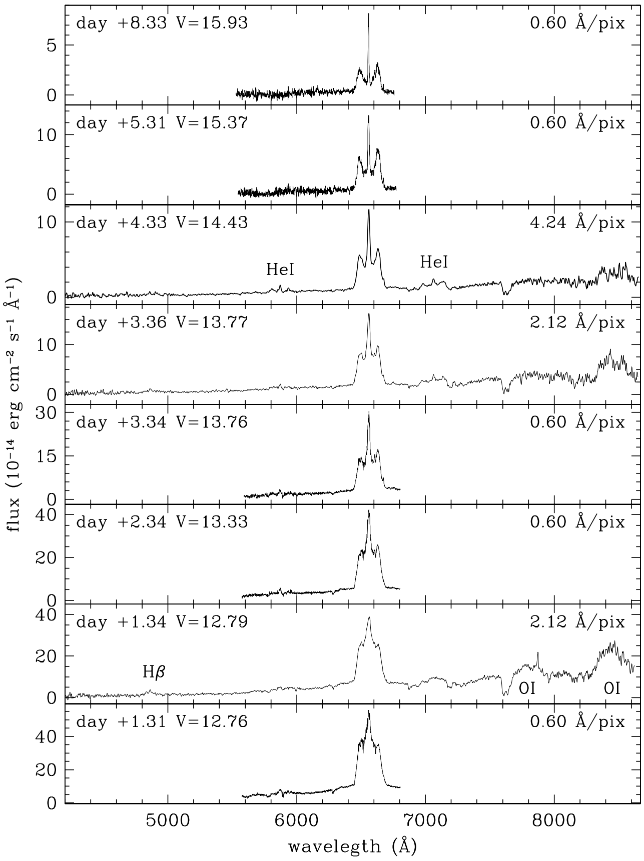

Figure 3. Spectroscopic evolution of Nova Oph 2009.

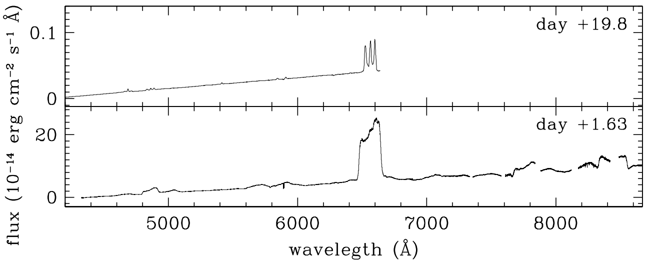

Figure 4. Sample spectra from the 1999 outburst of U Sco to highlight the similarities with the spectroscopic evolution of Nova Oph 2009 in Figure 3. The U Sco spectra are from Munari et al. (1999), and their reddening has been set equal to E_{B-V}=1.6 of Nova Oph 2009.

The intensity of the OI 8446 Å emission line under normal recombination, optically thin conditions should be appreciably weaker than the OI 7772 line, 0.6× its flux. On day +1.34 the reddening-corrected ratio was 1.63. The inversion in intensity between the two OI lines is usually associated with fluorescence pumped by absorption of hydrogen Lyman-β photons, as first pointed out by Bowen (1947). For the Lyman-β fluorescence to be effective, the optical depth in Hα should be large, presumably owing to the population of the $n = 2$ level by trapped Lyman-α photons. The large optical depth in Hα is confirmed also by the $F_{8446}/F_{H\alpha}$ flux ratio that under optically thin, low ionization conditions and typical nova chemical abundances should be quite low,

Table 3. Integrated fluxes of emission lines (in units of 10^{-13} cm^{-2} s^{-1} Å^{-1}).

day	Hγ	Hβ	NII 5675	HeI 5876	Hα	HeI 7065	OI 7774	OI 8446
+1.31					443			
+1.34	1.83	12.2	6.05	11.2	422	21.7	80	186
+2.34					255			
+3.34					161			
+3.36		3.75		5.45	140	15.0		80
+4.33		2.53		4.32	91	13.0		32
+5.31					63			
+8.33					24			

of the order of $\sim 10^{-3}$ (Strittmatter et al. 1977). The reddening corrected ratios for days +1.34, +3.36 and +4.33 are respectively 0.14, 0.18 and 0.11, indicating a persisting large optical depth in Hα during the pre-plateau evolution of Nova Oph 2009.

A striking feature of Nova Oph 2009, and once again a matter of close similarity with U Sco, is the very large width of its emission lines and how it evolved with time. The temporal dependence of the full width at zero intensity (FWZI) of the Hα emission in Nova Oph 2009 is shown in Figure 5, where the equivalent data for U Sco are taken from Munari et al. (1999). The temporal behaviour for the two novae is identical, with a linear decline of $\sim$250 km s^{-1} per day, and a starting value of 12,000 km s^{-1} for Nova Oph 2009, about 2,000 km s^{-1} larger than in U Sco and 2,000 km s^{-1} larger than in RS Oph (Munari et al. 2007). The FWZI depends mainly on the outermost ejecta, those ejected with the largest velocity. Compared with inner ejecta, the outer ones experience a more rapid decline in electron density and a large dilution of the ionizing radiation from the central source. Consequently the emission of the faster moving ejecta declines faster than that of the inner ejecta, which results in a progressive reduction in the width of the emission lines.

5 ON THE PROBABLE NATURE OF NOVA OPH 2009 AS A RECURRENT NOVA

Such a strict photometric and spectroscopic similarity with U Sco leads us to speculate that Nova Oph 2009 is itself a recurrent nova. However, only one outburst has been recorded from Nova Oph 2009, but it is highly probable that several others have been missed for the following reasons: (1) Nova Oph 2009 lies less than 4° away from the ecliptic, and thus suffers from periods of long seasonal invisibility due to conjunction with the Sun. Every lunation it also suffers from the proximity to the Moon; (2) its $\delta = -26°44'$ southern declination means that it is observable only for a brief fraction of the year by northern latitudes where observers have been historically concentrated; (3) the faint peak brightness attained by Nova Oph 2009 ($V\sim$11.35, $B\sim$13.1) means that it would have remained outside the range of detection by patrol surveys until very recently, when the introduction of large format CCDs allows coverage of significant areas of the sky with short focal length telescopes. In fact, Nova Oph 2009 was discovered by K. Itagaki using a 0.21-m f/3 reflec-

Table 4. Results of Gaussian fitting to observed spectra. Shown are the observation dates, including time since outburst, and individual components FWHM and radial velocity displacement in km s^{-1}. Components N. 1 and 4 relate to the polar blobs, N. 2 to the equatorial ring and N. 3 to the prolate structure described in sect 6.2

day	Component 1		Component 2		Component 3		Component 4	
	FWHM	Radial	FWHM	Radial	FWHM	Radial	FWHM	Radial
+2.34	2128	-3428	982	-183	3791	-183	2258	3245
+3.34	2152	-3474	844	-228	3717	-228	2172	3108
+5.31	2310	-3428	528	-228	3083	-228	2319	3063
+8.33	2283	-3383	333	-274	3598	-274	2314	2971

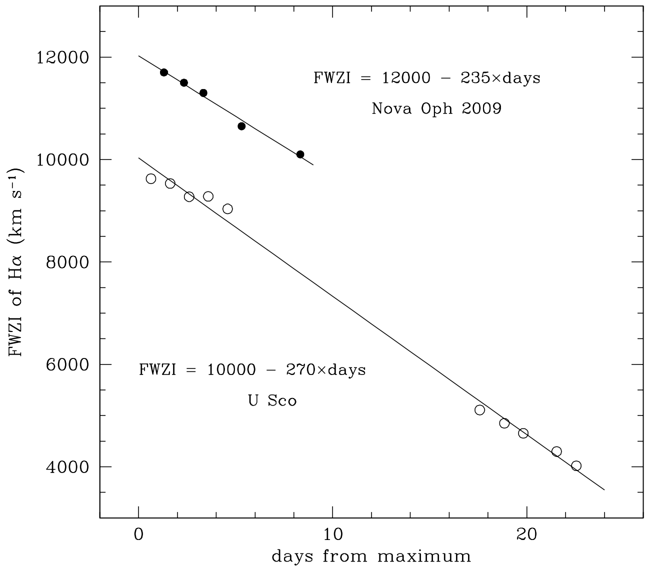

Figure 5. Comparison between the decline with time of the FWZI of Hα for Nova Oph 2009 and U Sco.

tor, a light-collector far more sensitive that the usual digital SLR cameras used by Japanene amateurs to discover Galactic novae; and (4) a decline time $t_2(V)$=2.3 days means that nova would have returned below the threshold for discovery (V~14) in just three days.

Given all these restrictions, its indeed surprising that at least this outburst of Nova Oph 2009 has been discovered. The central region of the Galaxy has been imaged many times especially by amateurs looking for impressive pictures. It is quite possible that other outbursts of Nova Oph 2009 lie undetected on such archive images, especially those imaging into red wavelengths. A devoted search is highly encouraged. It is less probable that an outburst could be discovered by inspection of historical plate archives. In fact, the B~13.1 mag attained at maximum, places Nova Oph 2009 below the limiting magnitude of most of the patrol plates collected worldwide in the past.

6 MORPHO-KINEMATICAL MODELLING OF THE Hα PROFILE

Using the morpho-kinematical code *Shape*[2] (Version 3.56, Steffen et al. 2010) we have analysed and disentangled the three-dimensional geometry and kinematic structure of the early outburst spectra of Nova Oph 2009. *Shape* was originally developed to model the complex structures of planetary nebulae and is based on computationally efficient mathematical representations of the visual world which allows for the construction of objects placed at any orientation in a cubic volume. *Shape* has been developed as an optically thin model therefore, when dealing with optically thick lines one must make the assumption that for what is observed the optical depth is low and that absorption has not altered greatly the shape of the profile.

The adopted model is based on previous studies of classical novae, which explored the structures of classical novae from resolved optical imaging and hydrodynamical modelling (e.g. Slavin, O'Brien, & Dunlop 1995; Lloyd, O'Brien, & Bode 1997).

6.1 Initial information

We performed Gaussian fitting using the IRAF task `SPECFIT` on days +2.34 through +8.33 after outburst. These allow us to decompose different Gaussian components of the Hα line and retrieve information like the FWHM of the components and their radial velocity displacements (Table 4).

The values derived in Table 4 are used to find the displacement of the system from the rest wavelength of the Hα line to be about -232 km s^{-1} and to determine the size of the remnant using the values for the FWHM and radial velocity displacement of component 1.

6.2 Modelling

We used information in Table 4 to constrain a physical size for the remnant. The derivation of the proposed structure of the system was aided from work being undertaken by the authors for V2491 Cygni (Ribeiro et al. 2010, in preparation). Here we explore a combination of structures with polar blobs and equatorial ring, prolate structure with equatorial rings, prolate structure with tropical rings and a structure similar to RS Ophiuchi as suggested by Ribeiro et al. (2009). The parameter space is sampled for inclinations from 0 to 90°, and velocities from 100 to 8000 km s^{-1}. Our models of V2491 Cyg produced synthetic spectra for various combinations of parameters and this allowed us to compare the spectra observed here to initially place constraints on the overall structure.

We note that there is evidence of significant Hα optical depth at early time as derived in Section 4 above. The modelling of the Nova Oph 2009 spectra thus initially focused

[2] Available from http://bufadora.astrosen.unam.mx/shape/

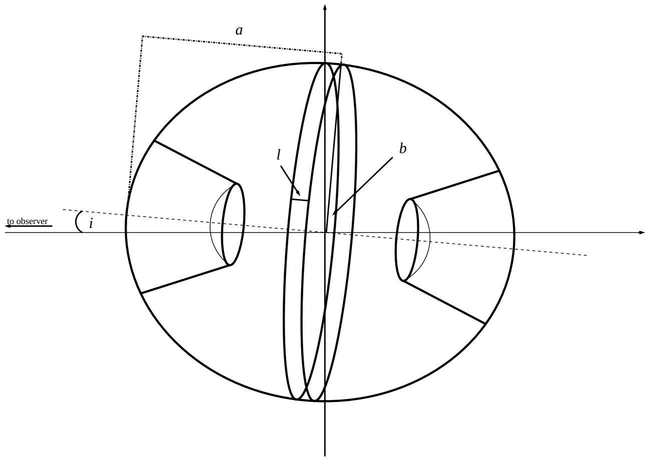

Figure 6. Two-dimensional representation of the three-dimensional expanding structure of the Nova Oph 2009 remnant. The overall structure is that of a prolate system with polar blobs and an equatorial ring. The semi-major axis (a) is larger than the semi-minor axis (b) by 15%. The width of the ring is designated w. The inclination of the system (i) is defined as the angle between the line of sight to the observer and the semi-major axis.

on day +8.33 after outburst because at this time we assume that the Hα line is least optically thick. The assumed physical size of the object was taken only from component 1 in Table 4 because it is assumed that the blue side of the line suffers less self-absorption than the red.

Work by Slavin, O'Brien, & Dunlop (1995), and later updated in Bode (2002), of several novae suggested that the remnants could be classified into two broad groups defined by the speed class of the nova. Slavin, O'Brien, & Dunlop (1995) demonstrated that slow novae tend to produce structured remnants which could be described as having polar blobs and/or equatorial ring morphology in contrast to the faster novae which produced inhomogeneous approximately spherical, shells with discrete randomly distributed knots. They then went on to show that the axial ratio (the ratio of the lengths of the major and minor axes of the nova shell) and the speed class (t_3 time) were correlated. It was shown that novae with fast decline from maximum light demonstrate a lower degree of remnant shaping than slow novae and therefore we account for this when considering the overall geometry of our system. A ratio of 1.15 for the semi-major axes versus semi-minor axis was taken as an estimate from the nova's speed class.

The suggested structure for the remnant was that of polar blobs and an equatorial ring with a low density prolate structure surrounding these two. The low density prolate structure is used to account for some of the lower velocities observed in the spectra. We sample the whole of parameter space for the inclination of the system from 0 to 90° (in 1° steps), where an inclination of 0° is for the material expanding along the semi-major axis being in the line of sight (Figure 6). We also explored the velocity range available for nova explosions from 100 to 8000 km s^{-1} (in 100 km s^{-1} steps).

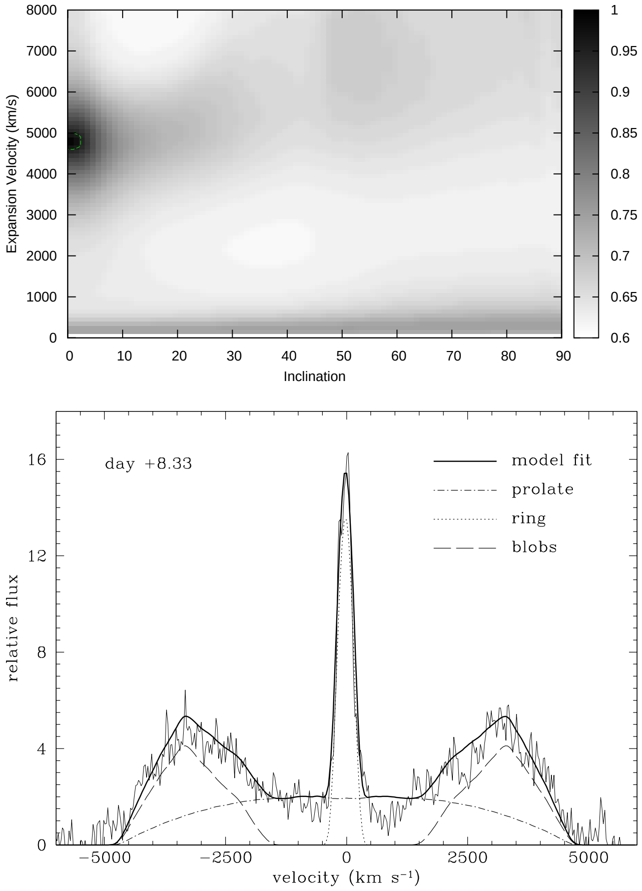

Figure 7. Top – image displaying results of a $\mathcal{X}^2$ fit comparing the observed spectrum with the model spectrum for different inclinations and velocities. The grey scale represents the probability that the observed $\mathcal{X}^2$ value is correct. Also shown is the 2σ level contour in green. Bottom – the observed spectrum for day +8.33 and the best fit model spectrum. The components of the model fit (prolate region, polar blobs and equatorial ring) are also shown.

6.3 Results

The observed spectrum and the model spectra for each of the inclinations and velocities were compared to find the best fit via a $\mathcal{X}^2$ test (Figure 7, top). We derive the best fit inclination and maximum expansion velocity (at the poles) as $0\pm2°$and 4800 ± 200 km s^{-1} respectively (2σ confidence intervals).

Figure 7 also shows the best fit model spectra and the contribution of each individual component to the overall model spectrum. Just taking a model with polar blobs and an equatorial ring did not match the overall line profile. Even adjusting the densities in each component the model spectrum would not fully replicate the observed spectrum. We therefore introduced a filled shell prolate structure as an additional component (see Figure 6). This would be associated with material ejected more isotropically than that in the ring or blobs.

We then evolved the overall structure fitted on day +8.33 to earlier times assuming a linear expansion and keeping the inclination and expansion velocity constant. As demonstrated in Figure 8, and Table 4, the observed spectrum shows the central component has higher velocities at

Table 5. Evolution of the implied density ratios for the different model components.

day	Blob/Prolate	Blob/Ring	Prolate/Ring
+2.34	0.80	0.89	1.11
+3.34	2.36	1.60	0.69
+5.31	4.00	1.08	0.27
+8.33	6.40	0.84	0.13

earlier times, implying that some deceleration has occurred in this direction as the ejecta expanded.

We then modelled the earlier epoch data (Figure 8) so that we keep the polar blobs and prolate structure expanding linearly but the ring width (w) was derived from the values in Table 4 for component 2 (with the ratio of the semi-major to semi-minor axis kept always as 1.15). The results are shown in Figure 8.

The assumption of a decelerating ring replicates the spectra well (Figure 8). The fact that the ring shows a smooth flat top structure compared to the observed spectra is because we do not include small scale structure in the model. There is also some higher velocity material associated with the wings of the central component that is not reproduced. Furthermore, to better replicate the line profiles it was required that we change the density ratios of the components with time (Table 5). What is evident from the ratio of the densities is that the prolate structure reduces in density compared with the other structures while the blobs initially increase in density compared with the ring then this ratio reduces again at a later time.

6.4 Discussion

We have constrained an overall structure, inclination and expansion velocity for the nebular remnant in Nova Oph 2009 from modelling the Hα. The inclination and maximum expansion velocity have been derived as 0±2°and 4800±200 km s^{-1} respectively. The velocity derived is consistent with the FWZI at this time (Figure 5). A structure with polar blobs and an equatorial ring sitting within a prolate morphology replicates the spectra well. In classical nova systems however, a structure with polar blobs and an equatorial ring originates in systems with low ejecta expansion velocity associated with slow speed class (e.g., Lloyd, O'Brien, & Bode 1997).

The density variations in Table 5 indicate that the prolate structure quickly reduces in relative density. While for example, the blobs initially have lower density than the ring, this ratio then increases, possibly due to the interaction of the ring material with any pre-existing equatorial material, only to decrease again later.

Our conclusions are; (a) if Nova Oph 2009 is a recurrent nova the shaping mechanism may be different from that of classical novae. For example, Ribeiro et al. (2009) find RS Oph to have an axial ratio of 3.85 and compared to its fast decline from maximum, the relationship originally found by Slavin, O'Brien, & Dunlop (1995) breaks down. The same could be happening here, except that Nova Oph 2009 has a main-sequence or subgiant secondary so ejecta/wind interactions such as in RS Oph may not be important, (b) at this

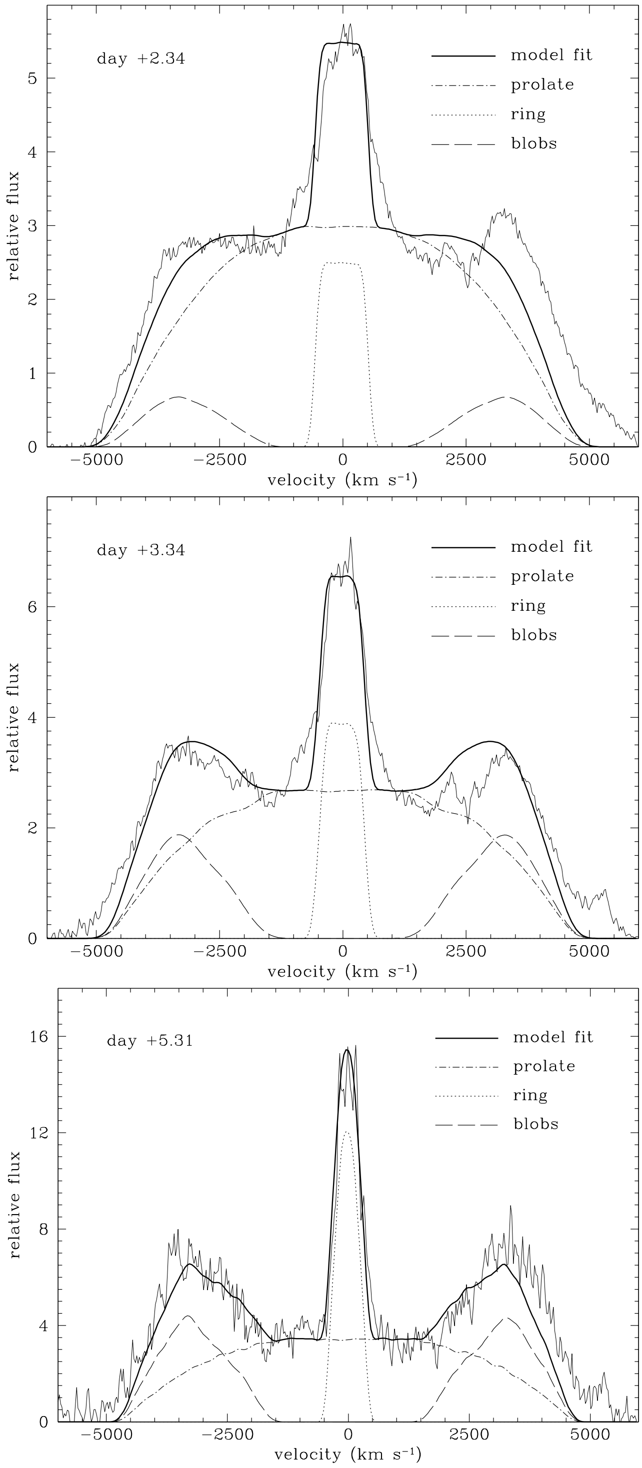

Figure 8. Early evolution of the Hα profile and fitting by model spectra see Figure 7 for further information.

early time the formation of the remnant may still be taking place and at later times the remnant could appear more spherical. We note however that most of the shaping occurs in the first few hours in classical novae (Lloyd, O'Brien, & Bode 1997). This points to the need for better modelling of the evolution of classical novae and recurrent novae from the early to late times. Such work is however greatly aided if we can ultimately spatially resolve them.

ACKNOWLEDGMENTS

The authors would like to thank W. Steffen and N. Koning for valuable discussions on the use of *Shape* and adding special features to the code. We would like also to thank M. Darnley for useful discussion and the ANS Collaboration observers S. Dallaporta, S. Moretti, A. Maitan, S. Tomaselli, P. Valisa and V. Luppi for providing part of the data discussed in this paper. VARMR is funded by an STFC studentship.

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