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The 2010 nova outburst of the symbiotic Mira V407 Cyg

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ABSTRACT

The nova outburst experienced in 2010 by the symbiotic binary Mira V407 Cyg has been extensively studied at optical and infrared wavelengths with both photometric and spectroscopic observations. This outburst, reminiscent of similar events displayed by RS Oph, can be described as a very fast He/N nova erupting while being deeply embedded in the dense wind of its cool giant companion. The hard radiation from the initial thermonuclear flash ionizes and excites the wind of the Mira over great distances (recombination is observed on a time scale of 4 d). The nova ejecta is found to progressively decelerate with time as it expands into the Mira wind. This is deduced from linewidths which change from a FWHM of 2760 km s^{-1} on day +2.3 to 200 km s^{-1} on day +196. The wind of the Mira is massive and extended enough for an outer neutral and unperturbed region to survive at all outburst phases.

Key words: stars: AGB and post-AGB – binaries: symbiotic – novae, cataclysmic variables.

1 INTRODUCTION

The symbiotic binary V407 Cyg consists of an accreting white dwarf (WD) and an O-rich Mira companion pulsating with a 745-d period. Miras with such a long pulsation period are generally OH/IR sources with a very thick dust envelope which prevents direct observation of the central star at optical wavelengths. The much thinner dust envelope in V407 Cyg is probably due to the presence of the WD companion whose orbital motion, hard radiation field in quiescence and violent mass ejection during outbursts inhibit dust formation in a large fraction of the Mira wind (Munari, Margoni & Stagni 1990, hereafter M90).

V407 Cyg was discovered by Hoffmeister (1949) as Nova Cyg 1936, just at the time when its Mira was passing through maximum brightness. No spectroscopic observations confirming it as a genuine nova outburst were however available. What actually occurred is unclear because (i) the object was discovered and remained at $B \approx 14.5$ mag for an entire Mira pulsation cycle, without declining to an expected $B \geq 19$ minimum (cf. fig. 1 in M90), but at the same time (ii) the peak brightness was much smaller than $B \sim 8$ reached by V047 Cyg during its present 2010 outburst which resembles a true nova eruption. The 1936–38 event could have been one of the usual low-amplitude, long-lasting outbursts that symbiotic binaries frequently display. Two such active phases during the 1990s were reported and discussed by Munari et al. (1994), Kolotilov et al. (1998, 2003, hereafter K98 and K03), and some earlier ones can be spotted in the historical light curves of V407 Cyg by M90 and Munari & Jurdana-Šepić (2002).

The 2010 outburst of V407 Cyg was discovered on March 10.813 UT by Nishiyama & Kabashima (2010) at $V = 7.6$ mag. This was at an unsurpassed brightness level in the star's recorded photometric history thereby underscoring the peculiarity and importance of the event. The first spectroscopic confirmation and analysis of the outburst was given by Munari, Siviero & Valisa (2010a) who described the event as a He/N nova expanding within the wind of the Mira companion. The similarity with RS Oph was also pointed out. In the following weeks and months, the outburst was intensively monitored over several wavelength regimes viz. in γ-rays (Abdo et al. 2010; Cheung et al. 2010), radio (Bower, Forster & Cheung 2010; Gawronski et al. 2010; Giroletti et al. 2010; Krauss et al. 2010; Nestoras et al. 2010; Pooley 2010), SiO maser (Deguchi et al. 2010) and IR (Joshi, Ashok & Banerjee 2010).

So far, apart from brief circulars, no comprehensive report on the photometric and spectroscopic evolution of V407 Cyg at optical and IR wavelengths is available. The aim of this Letter is thus to provide a first report; follow-up papers will present a more detailed analysis and modelling of the huge amount of data we have and are still collecting.

2 OBSERVATIONS

Optical photometry was recorded with several small telescopes operated by the ANS Collaboration in northern Italy, all equipped with CCDs and photometric $UBVR_CI_C$ filters. Corrections for bias, dark and flat-fields were applied in the usual manner. Photometric

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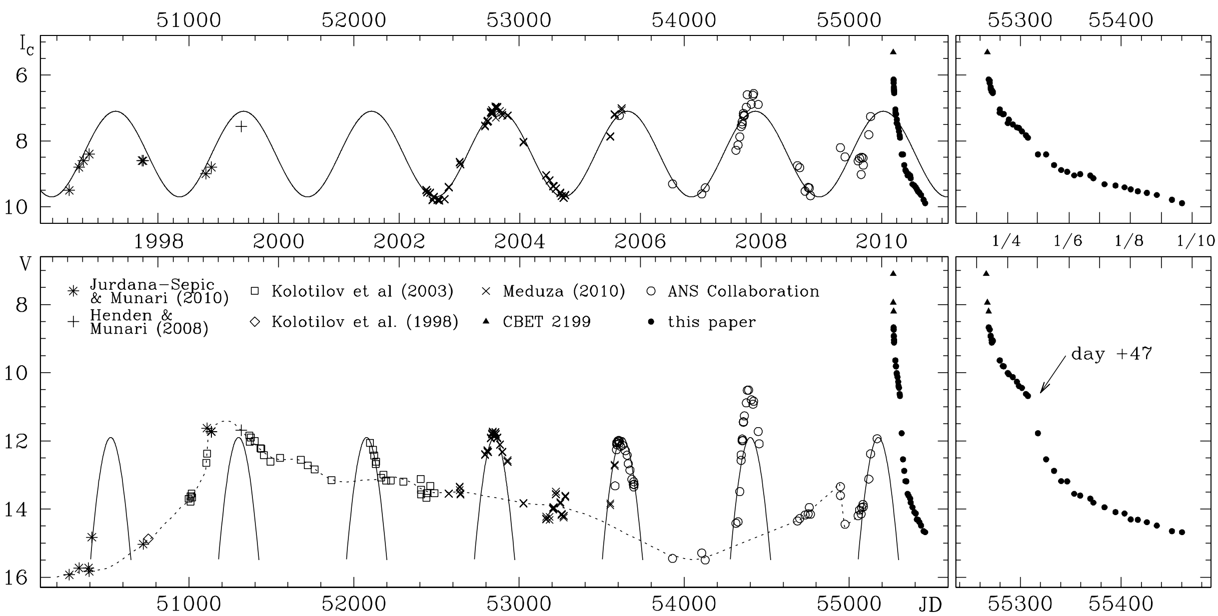

Figure 1. Photometric evolution of V407 Cyg over the last 16 yr, or seven Mira's pulsation cycles. The dashed line is hand drawn to provide a guide through the long-lasting active phase that peaked in 1998. The right-hand panels provide a zoom over the 2010 outburst.

calibration and correction for colour equations was performed for all instruments against the same $UBVR_{C}I_{C}$ sequence calibrated by Henden & Munari (2000) around V407 Cyg. Our photometry of V407 Cyg covering the 2010 outburst is presented in Table S1 and plotted in Figs 1 and 2 .

Optical spectroscopy was obtained with different telescopes: Asiago 1.82 m + Echelle spectrograph (20 000 resolving power), Asiago 1.22 m + B&C spectrograph (low-resolution mode), Varese 0.6 m + multimode spectrograph. A journal of the observations is given in Table S2. With the Varese 0.6-m telescope we obtained both low-resolution and Echelle spectra. The latter were recorded both in unbinned (resolving power 17 000, marked *ech* in Table S2) and binned mode (resolving power 10 000, marked *echB* in Table S2). All spectra (including Echelle ones) were calibrated in absolute fluxes by observations of several spectrophotometric standards during the night. Their zero-points were then checked against simultaneous BVRI photometry by integrating the band transmission profiles on the fluxed spectra.

Near-IR observations were carried out in the J, H and K bands at the Mt. Abu 1.2-m telescope during the early outburst phase. The spectra were obtained at a resolution of ∼1000 using a NICMOS3 Imager/Spectrometer. Spectra and photometry of the comparison star HR 7984 were also obtained for the spectrophotometric data reduction. Wavelength calibration was done using OH sky lines and telluric features that register with the stellar spectra. The detailed reduction of the spectral and photometric data, using IRAF tasks, follows a standard procedure that is described e.g. in Naik, Banerjee & Ashok (2009) . The journal of IR spectroscopic observations is given in Table S3, and the results of IR photometry in Table S4 and Fig. 2.

3 RESULTS

The observations presented in this paper show that the violent outburst experienced by V407 Cyg in March 2010 was a thermonuclear runaway (TNR), the same event that powers a normal nova eruption. In normal novae, the ejected material essentially expands freely into a void circumstellar medium. However, in V407 Cyg, the fast ejecta have to expand into the dense and slow wind of the Mira companion, and are thus progressively slowed down as the pre-existing circumstellar material is swept up in an expanding shell. Noteworthily, the pre-existing circumstellar material offers an ideal ionization target for the hard radiation from the initial TNR flash .

The similarity with the outburst displayed by the celebrated RS Oph is evident (Bode 1987, Evans et al. 2008, and references therein). The latter is a symbiotic binary, with an orbital period of 460 d and an M giant filling its Roche lobe (Schaefer 2009) which transfers material to a massive WD (Hachisu, Kato & Luna 2007). Similar nova eruptions have been seen also in the symbiotic binaries and recurrent novae T CrB, V745 Oph and V3890 Sgr (Schaefer 2010).

What occurred in V407 Cyg is well illustrated by the evolution of the Hα profile (Fig. 5) and its width and integrated flux (top panels of Fig. 2). At the earliest stages, the Hα profile is dominated by a sharp component superposed on a much broader one, as first noted by Munari et al. (2010a).

The sharp component, identical to that in quiescence but enormously brighter (cf. profiles for 2008 and 2009 in Fig. 5), is due to the sudden ionization of a large fraction of the Mira's wind by the flash of energetic radiation produced by the TNR event. The wind of the Mira does not as yet get perturbed kinematically, as proven by the preserved sharpness of the Hα profile that increased its emissivity by 2 orders of magnitude compared to quiescence. The flux of hard photons, however, is not large enough to ionize the whole Mira wind, as indicated by the persistence of the sharp absorption component which maintains the same heliocentric radial velocity as in quiescence (-50 km s^{-1}). The intensity of the Hα sharp component rapidly declines subsequently (cf. Fig. 2), with a recombination time-scale of 4 d, which can be written as

$$t_{\rm rec} = 0.66 \left(\frac{T_{\rm e}}{10^4\ {\rm K}}\right)^{0.8} \left(\frac{n_{\rm e}}{10^9\ {\rm cm}^{-3}}\right)^{-1} \approx 100\ {\rm h}, \qquad (1)$$

following Ferland (2003). It corresponds to a density of about 5 $\times$ 10^6 cm^{-3} for the fraction of the Mira wind ionized by the TNR

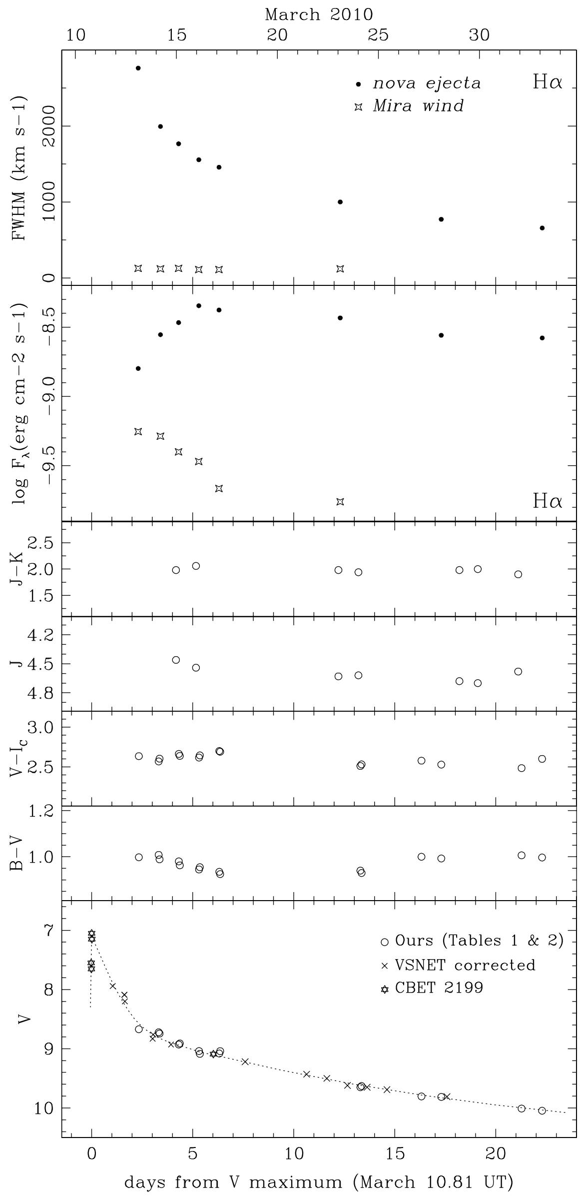

Figure 2. Lower panels: early optical and IR photometric evolution of V407 Cyg during the 2010 outburst. The dashed line is hand drawn for guidance. Upper panels: evolution in width and integrated flux of the Hα emission line. 'Nova ejecta' refers to the broad component (cf. sect. 3), 'Mira wind' to the superimposed narrow one (see Fig. 5).

initial flash. The point at day +12.3 in Fig. 2, e.g. the last epoch at which a narrow component could still be resolved in the Hα profiles of Fig. 5, deviates from the $t_{\rm rec}$ = 4 d of earlier points. By this time, the nova ejecta has begun to turn optically thin and the hard radiation field of the central star (presumably still burning hydrogen at its surface during the constant luminosity phase) is hot and intense enough to produce coronal emission lines, as reported by Munari et al. (2010b). The same radiation field, leaking through the optically thin ejecta, is also responsible for sustaining the ionization of the circumstellar gas not yet reached by the expanding shell.

The broad component of the V407 Cyg Hα profiles in Fig. 5 originates instead in the material ejected at high velocity, as in any normal nova. The broad spectrum nicely matches that of a normal 'He/N' nova (Williams 1992) as illustrated by the low-resolution optical and IR spectra for days +2.3 and +4.2 in Figs 3 and 4, respectively. A He/N spectrum is typical of fast novae and of RS Oph too. The nova ejecta is rapidly decelerated while trying to expand through the surrounding Mira wind and the distinction between a sharp and a broad component to the emission lines is then progressively attenuated, disappearing two weeks past optical maximum. As more material is swept by the expanding shell, the velocity continues to decrease. Fig. 2 illustrates the temporal evolution of the FWHM (in km s^{-1}) of the broad component of Hα, which is accurately fitted by the expression

$$\mathrm{FWHM} = 4320 - 5440 \log t + 2635(\log t)^2 - 460(\log t)^3, \qquad (2)$$

including later phases characterized by 400, 280 and 200 km s^{-1} on days +48.2, +105 and +196, respectively. The same trend is shared also by the hydrogen lines dominating the IR spectra of Fig. 4. For comparison the FWHM of Hα in quiescence was stable at ∼120 km s^{-1} (cf. profiles for 2008 and 2009 in Fig. 5). Fig. 5 shows the emergence of [N II] 6548, 6584 Å doublet two months past optical maximum. It did not originate in the expanding material, but instead in the outer wind of the Mira, external to the expanding shell. This is proved since its profile FWHM of ∼110 km s^{-1} is much sharper than that of the adjacent Hα and identical to the width in quiescence. The existence of an outer region of the Mira wind not yet reached on day +196 by the already greatly slowed down ejecta (cf. the sharp absorption component at −50 km s^{-1} in Fig. 5) leads us to speculate that some part of the ejecta could remain bound to the binary system and could be re-accreted at later times by the WD.

The light curve of V407 Cyg over the last 15 yr is presented in Fig. 1. It is characterized by three main components: (1) the 745-d pulsation of the Mira (sinusoid drawn as a solid line), which dominates the light curve at reddest wavelengths; (2) the presence of a limited amplitude, slow evolution active phase (dashed line in the *V*-band panel) that peaked in intensity in 1998/99 (described in detail by K98 and K03) when it rivalled in *V* the brightness of the Mira but went unnoticeable in $I_{\rm C}$. This corresponds to the typical, non-TNR outbursts that essentially all symbiotic stars have experienced several times in their recorded photometric history and (3) the violent, rapid and bright TNR outburst of 2010. The latter overwhelmed the brightness of the Mira at optical wavelengths, but only equalled it in the *K* band (cf. data in Table S4 with the long term *JHK* light curve of the Mira presented by K98 and K03). Fig. 2 presents a zoomed view on the earliest evolution of the 2010 outburst in the $BVR_{\rm C}I_{\rm C}JHK$ bands. The optical maximum was reached at *V* = 7.1 on March 10.8 UT, and the subsequent decline was very fast and characterized by t_2^V = 5.9 and t_3^V = 24 d. The decline was similarly fast in T CrB, V745 Sco, RS Oph and V3890 Sgr that showed t_2 = 4, 5, 7 and 9 d, respectively. The *V*-band light curve in Fig. 1 shows a distinct knee at day +47. By analogy with RS Oph (cf. Hachisu et al. 2006), it could mark the end of the stable H burning on the WD.

The outburst evolution seen in the $I_{\rm C}$ panel in Fig. 1 could appear in conflict with the expected underlying pulsation cycle of the Mira. Indeed, the pulsation of the latter is known to be highly variable from cycle to cycle (K98; Munari & Jurdana-Šepić 2002), with puzzling sharp minima occurring at various pulsation phases (Kiziloglu & Kiziloglu 2010; some of them are visible also in the light curve of Fig. 1 in 2007 and 2009), and that could be related to the unusual nature of the Mira in V407 Cyg. In fact, Miras of such a long pulsation period are usually the central stars of OH/IR sources and their thick dust cocoon prevent them from being visible in the optical. As remarked by M90, the presence of the hot and outbursting WD companion could disturb the formation of the

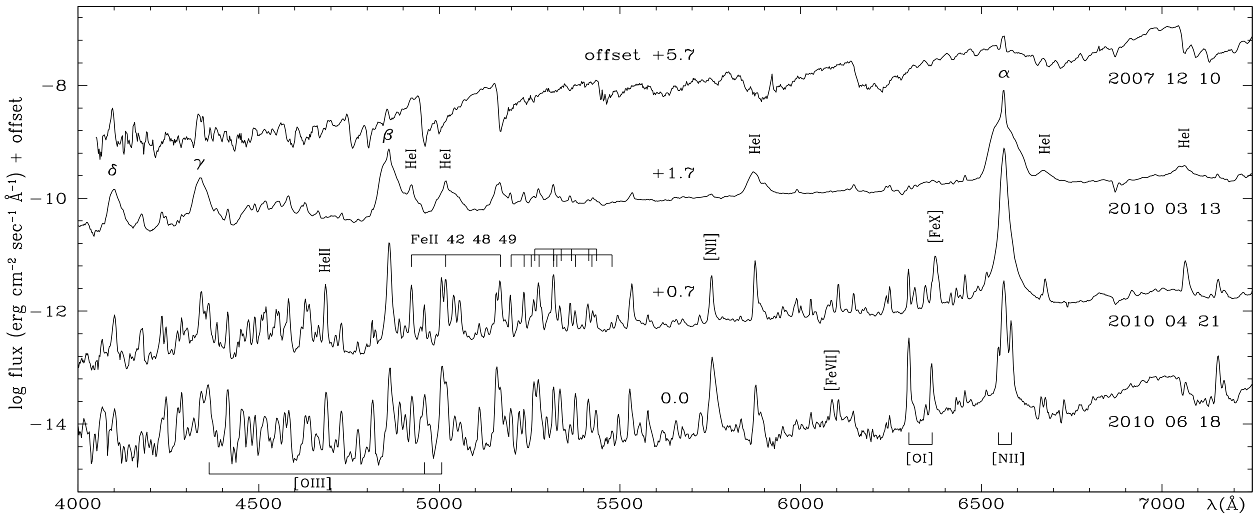

Figure 3. A sample of the absolutely fluxed, optical spectra of V407 Cyg that we collected during the 2010 outburst. The 2007 December 10 spectrum shows the quiescence spectrum at the time of Mira brightness maximum. Only some of the emission lines are identified.

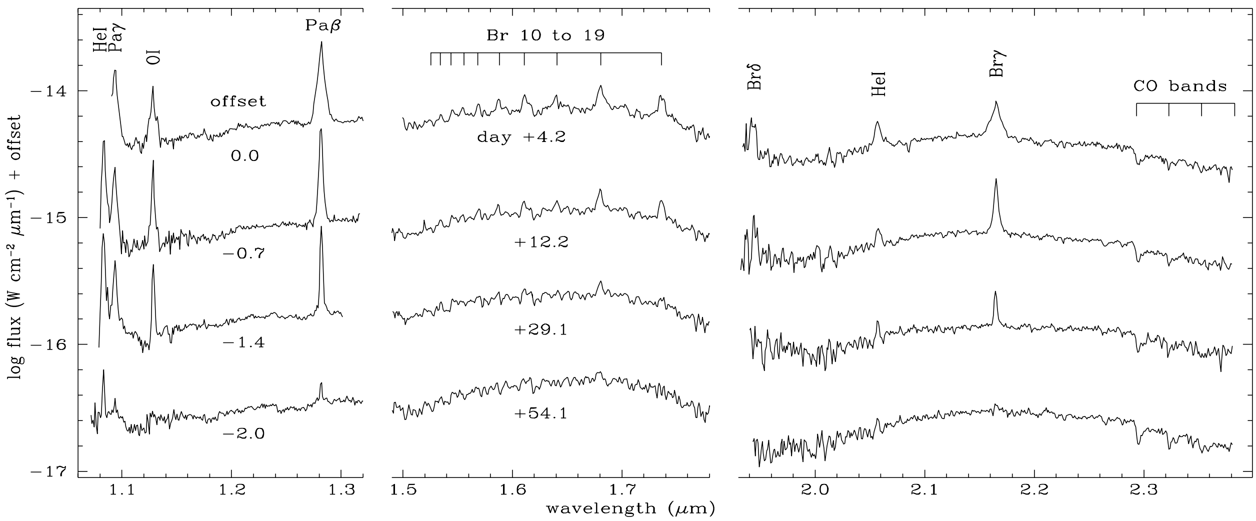

Figure 4. A sample of our absolutely fluxed IR spectra of V407 Cyg for the 2010 outburst. Major emission lines are identified.

dust cocoon and thus make the Mira in V407 Cyg visible at optical wavelengths.

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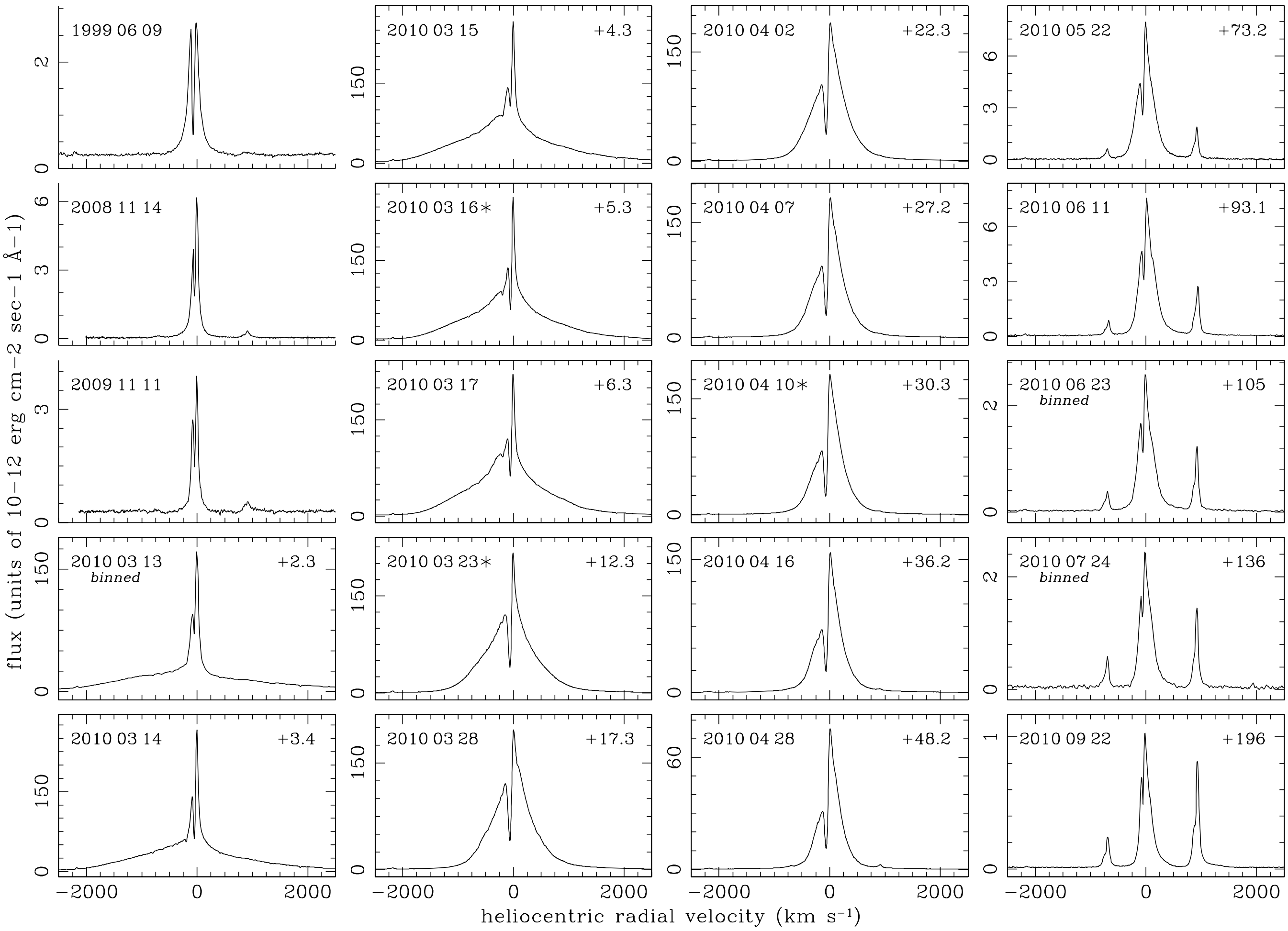

Figure 5. Evolution of the Hα profile of V407 Cyg during the 2010 outburst. Older profiles are given for reference purposes, and pertain to the brightness peak during the 1997–2006 active phase (1999), and to quiescence at the time of a Mira minimum (2008) and maximum (2009). The three spectra marked with ∗ are courtesy of Christian Buil and fluxed by us against our low-resolution spectra.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:[1]

Table S1. Our optical photometry of V407 Cyg during the 2010 outburst.

Table S2. Journal of our optical spectroscopic observations of V407 Cyg during the 2010 outburst and a few earlier epochs.

Table S3. Journal of our IR spectroscopic observations of V407 Cyg during the 2010 outburst. The integration times in brackets are for the J, H and K bands, respectively.

Table S4. Our *JHK* photometry of V407 Cyg during the 2010 outburst.

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[1] Tables S1–S4 available in electronic form only.

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