The nova-like nebular optical spectrum of V404 Cygni at the beginning of the 2015 outburst decay

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ABSTRACT
We report on FORS2 optical spectroscopy of the black hole X-ray binary V404 Cygni, performed at the very beginning of its 2015 outburst decay, complemented by quasi-simultaneous Swift X-ray and ultra-violet as well as REM near-infrared observations. Its peculiar spectrum is dominated by a wealth of emission signatures of H\textsc{i}, He\textsc{i}, and higher ionisation species, in particular Fe\textsc{ii}. The spectral features are divided between broad red-shifted and narrow stationary varieties, the latter being emitted in the outer regions. Continuum and line variability at short time scale is high and we find Baldwin effect-like anti-correlations between the full-widths at half-maximum and equivalent widths of the broad lines with their local continua. The Balmer decrement H\alpha/H\beta is also abnormally large at 4.61 ± 0.62. We argue that these properties hint at the broad lines being optically thick and arising within a circumbinary component in which shocks between faster optically thick and slower optically thin regions may occur. We associate it to a nova-like nebula formed by the cooling remnant of strong accretion disc winds that turned off when the mass-accretion rate dropped following the last major flare. The Fe\textsc{ii} lines likely arise from the overlap region between this nebula and the companion star winds, whereas we favour the shocks within the nebula as responsible for the optical continuum via self-absorbed optically thin bremsstrahlung. The presence of a near-infrared excess also points towards the contribution of a strongly variable compact jet or a dusty component.

Key words: binaries: close – X-rays: binaries – Optical: stars – accretion, accretion discs – Stars: individual: V404 Cygni – ISM: jets and outflows

1 INTRODUCTION
On 2015 June 15, the Burst Alert Telescope instrument (BAT, Barthelmy et al. 2005) mounted on the Swift satellite (Gehrels et al. 2004) detected the Galactic black hole (BH) X-ray binary (XRB) V404 Cygni after 26 years of quiescence (Barthelmy et al. 2015). The rarity of such an event triggered a collaborative multiwavelength observational campaign of unprecedented scale and despite its brevity, the extreme behaviour exhibited by the source has puzzled the community. Indeed, unlike most of other microquasars whose outbursts can be well-described by hysteresis-like (or q-shape) hardness intensity diagrams tracing spectral transitions between corona-dominated hard states and disc-dominated soft states (Fender et al. 2004), V404 Cygni underwent several hard X-ray flares with up to 10-fold flux variations within a few hours. Whether it transitioned between different spectral states is not clear, several authors having claimed that it was always caught in the hard state (see e.g., Rodriguez et al. 2015; Natalucci et al. 2015; Jenke et al. 2016), while Radhika et al. (2016) argue that it went through several transitions within each flare. The ori-
gin of these flaring events has not been clarified yet, but several studies point towards hard X-ray spectra stemming from Compton scattering of relatively hot photons, maybe from the jets (Natalucci et al. 2015; Jenke et al. 2016), while Chandra and GTC/OSIRIS spectroscopic observations hint at the likely presence of a strong quasi-spherical accretion disc wind (ADW) detected via narrow soft X-ray emission lines (King et al. 2015) as well as optical P-Cygni profiles (Muñoz-Darias et al. 2016). Finally, this extreme variability pattern was not restricted to the X-ray domain and was observed in all bands, including fast radio flares from transient jets (Mooley et al. 2015; Tetarenko et al. 2015a), as well as second-optical photometric flickering associated with optically-thin synchrotron from compact jets (Gandhi et al. 2016).

As one of the brightest microquasars at optical wavebands, both in outburst and quiescence, V404 Cygni has been extensively studied in this spectral domain. During the 1989 outburst, several authors reported very rich optical spectra dominated by strong emission signatures from Hα and He i as well as higher ionisation elements (see e.g. Casares et al. 1991; Gotthelf et al. 1992). The continuum and lines were found to be strongly variable, and various morphologies were observed, including single to triple-peaked features as well as transient P-Cygni profiles; some of these characteristics were again observed during the 2015 outburst (see e.g. Muñoz-Darias et al. 2016). The system’s properties are also relatively well-constrained, and V404 Cygni consists of a K0-3IV star orbiting a BH with a 6.08 ± 0.06 $M_\odot$ mass function in 6.471 ± 0.001 days, the secondary-to-primary mass ratio being $q = 0.600^{+0.004}_{-0.005}$ (Casares et al. 1992; Casares & Charles 1994; Khargharia et al. 2010). Its distance was also assessed via accurate radio parallax measurements at 2.39 ± 0.14 kpc (Miller-Jones et al. 2009), but the inclination of the system remains relatively unknown, with values from 50° to 70°, which leads to a poorly constrained BH mass in the range 8–15 $M_\odot$ (Shahbaz et al. 1994; Khargharia et al. 2010).

In this paper, we report on medium-resolution optical spectroscopy of V404 Cygni – complemented by X-ray, ultraviolet, and near-infrared data – performed right after the last major flare, at the very beginning of its decay to quiescence (see Figure 1). Section 2 details the data reduction procedure, whereas Section 3 is dedicated to the spectral analysis. We discuss the outcomes and their implications in Section 4 and conclude in Section 5.

### 2 OBSERVATIONS AND DATA REDUCTION

The data set consists of quasi-simultaneous observations obtained on 2015 June 27, with (1) the FOCal Reducer/Low disperser Spectrograph 2 (Obs. ID 095.D-0459, PI Rahoui; FORS2, Appenzeller et al. 1998) mounted on the UT1 Cassegrain focus at the European Southern Observatory (ESO) Very Large Telescope (VLT) at Cerro Paranal; (2) the X-Ray Telescope (XRT, Burrows et al. 2005) and Ultra-Violet/Optical Telescope (UVOT, Roming et al. 2005) on board the Swift(Gehrels et al. 2004) satellite (Obs. ID 00031403061, Public; Obs. ID 00033861002, PI Altamiro); (3) the Joint European X-ray Monitor (JEM-X, Lund et al. 2003) and Imager On board INTEGRAL Satellite (IBIS, Ubertini et al. 2003) mounted on the INTEGRAL Gamma-Ray Astrophysics Laboratory (INTEGRAL, Winkler et al. 2003) satellite (Science Window ID 155700300010, 155700320010, and 155700340010); and (4) the Rapid Eye Mount IR (Obs. ID 29023, PI Casella; REMIR, Calzolotti et al. 2005) installed on the Rapid Eye Mountain (REM) telescope at Cerro La Silla. For the sake of building a radio to X-ray spectral energy distribution (SED), we also use quasi-simultaneous radio data obtained with the RATAN-600 radio telescope at 2.3, 4.6, 8.2, 11.2, and 21.7 GHz (Trushkin et al. 2015) between MJD 57199.9 and MJD 57200.7, as well as 97.5 GHz and 140.5 GHz flux densities from the NOrthern Extended Millimeter Array (NOEMA) and integrated between MJD 57199.3 and MJD 57200.1 (Tetarenko et al. 2015b).

#### 2.1 FORS2 observations

On 2015 June 27, we performed FORS2 medium-resolution spectroscopy of V404 Cygni (see Figure 1) with the 600V (hereafter V) and 600I (hereafter I) grisms combined with the GC345 and OG590 filters, respectively, for a total 4500 – 9300 Å spectral coverage. In both cases, we used the standard resolution (SR) collimator and the slit-width was set to 1′′ with a rotation angle always close to the parallactic angle. Atmospheric conditions were medium-to-good, with a thin sky transparency and a 1.91 airmass. The exposure time of each individual frame was set to 30 s and a total of 20 and 19 exposures were taken in both V and I, respectively, which, accounting for overheads, gives a 67 s effective time resolution for variability study. The A0V spectro-

| Table 1. Summary of V404 Cygni observations and archival data we made use of in this study. The orbital phase $\phi$ of the BH was estimate using the ephemeris given in Casares & Charles (1994). |
|---|---|---|---|---|---|
| Facilities | ID | Instrumental configuration | Start date (MJD) | Exp. Time (second) | $\phi$ |
| ESO VLT | 095.D-0459 | FORS2/GC345+600V, OG590+600I | 57200.2661 | 600, 570 | 0.05–0.06 |
| INTEGRAL | 155700300010 | JEMX-1, JEMX-2, ISGRI | 57200.1179 | 2620, 2597, 2075 | 0.03–0.04 |
| " | 155700320010 | " | 57200.1904 | 2570, 2551, 2046 | 0.04–0.05 |
| " | 155700340010 | " | 57200.2629 | 2587, 2584, 2064 | 0.05–0.06 |
| Swift | 00031403061 | XRT, UVOT/W1 | 57200.1388 | 58, 73 | 0.03 |
| " | 00033861002 | XRT, UVOT/U | 57200.3925 | 1475, 1494 | 0.07–0.08 |
| ESO REM | 29023 (AOT29) | REMIR/J, H, Ks | 57200.2899 | 50, 50, 50 | 0.06 |
| AAVSO | V, I | − | 57200.2638 | − | 0.05–0.06 |
| IRAM | − | NOEMA/97.5 GHz, 140.5 GHz | 57199.3000 | 5400, 9000 | 0.86–0.97 |
| RATAN-600 | − | 2.3 GHz, 4.6 GHz, 8.2 GHz, 11.2 GHz, 21.7 GHz | 57199.9000 | − | 0.97–0.09 |
Optical spectroscopy of V404 Cygni

photometric standard star LTT 7379 was observed in similar conditions for flux-calibration.

We reduced the data using the dedicated pipeline (v. 5.3.5) implemented in the ESO data reduction environment Reflex v. 2.6 (Freudling et al. 2013), which follows the standard steps for optical spectroscopy reduction and produces cleaned and background subtracted 2D spectroscopic images. The wavelength-calibration was achieved by deriving a dispersion solution using Helium, Argon, and Mercury/Cadmium arc observations. We then used the routines apall, standard, sensfunc, and calibrate implemented in IRAF v. 2.16 to optimally extract the source, sky, and spectro-photometric standard star 1D spectra, compute the sensitivity function, and apply it to V404 Cygni V and I spectra for flux calibration. The accuracy of the dispersion solution was finally assessed by measuring the centroids of the brightest OH emission lines present in the sky spectra. We found systematic +0.6 to +0.8 Å offsets, likely due to the five-hour time gap between the science and arc observations. A −0.8 Å correction was thus applied to all line centroid measurements listed in this study. When applicable, we also corrected all listed radial velocity shifts for a 13 km s$^{-1}$ barycentric-heliocentric velocity as estimated at the epoch of the observations.

The flux-calibrated spectra were corrected for slit-losses, which we estimated assuming the slit transmission factor used by ESO for its exposure time calculators. It consists in an error function erf that depends on the slit-width and the image quality at the focal plane of the telescope. We slightly modified it to include potential slit-centring offsets implied by the wavelength-dependent atmospheric differential refraction for a given airmass and rotation angle, as formulated in Filippenko (1982). The wavelength-dependence of the image quality along the slit was modeled using the expression given in Martinez et al. (2010), which takes into account the combined effects of the airmass and the outer scale of the turbulences. The reference image quality was directly measured on each individual 2D spectroscopic frame at 5015 Å and 7065 Å in V and I, respectively, through Gaussian fitting of the spatial profiles, and we find values in the range 0″6-0″8. We stress here that our observations were seeing-limited and the spectral resolution was thus better than the one expected when a source fully fills the slit. Through the fit to the full-widths at half-maximum (FWHMs) of the arc lines, we measure the slit-limited resolution between $R \sim 1100 - 1500$ and $R \sim 1400 - 1900$ in V and I, respectively. The seeing-limited resolution being roughly equal to the slit-limited one divided by the image quality, we consequently reached

1 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

2 https://www.eso.org/observing/etc/doc/formulabook/node18.html

Figure 1. V404 outburst as seen through I band photometry. The red vertical bars mark the time range of our FORS2 observations, and the inset displays a zoom-in centred on the FORS2 epoch.
Figure 2. Flux-calibrated time-averaged FORS2 spectrum of V404 Cygni (magenta) compared to that of a K0III giant star suffering from the same ISM extinction and scaled to V404 Cygni companion star’s optical magnitudes (green). All the detected emission lines and DIBs are marked.

\[ R \sim 1200 - 1900 \text{ and } R \sim 2200 - 2900 \text{ in } V \text{ and } I, \text{ respectively.} \]

Finally, based on the continuum level gap between \( V \) and \( I \) in the overlap region, we estimate that the flux calibration is accurate at 3\%, although the statistical noise is a lot lower. Moreover, we derive \( V = 15.72 \pm 0.03 \) and \( I = 12.90 \pm 0.03 \) through the convolution of the average flux-calibrated spectrum with Johnson and Cousins filters, whereas the average simultaneous AAVSO magnitudes during our observations are \( V = 15.67 \pm 0.05 \) and \( I = 12.95 \pm 0.01 \).

2.2 Swift observations

We reduced the XRT data with HEASOFT v. 6.17 and the 2016 January 20 calibration data base (CALDB) version. We used xrtpipeline v. 0.13.1 to collect events in Windowed Timing (WT) mode to avoid pile-up. For Obs. ID 00031403061, the source and background spectra were extracted with xselect v. 2.4c using 40-pixel square boxes in the 0.4–10 keV energy range. We generated the ancillary response file (ARF) with xrtmkarf and used the latest version (v. 015) of the response matrices provided by the Swift team. We rebinned the spectrum to obtain a minimum of 50 counts per channel, and restricted the effective energy range to 0.4–5 keV as the source is not detected beyond.

In contrast, the XRT data for Obs. ID 00033861002 appeared clearly extended towards the South-West direction without the clear presence of a point source.

This is likely due to the formation of the X-ray dust scattered rings reported in Beardmore et al. (2015); Vasilopoulos & Petropoulou (2016). For this reason, no spectrum was extracted and we decided not to use these data for this study.

The UVOT photometry was obtained in two filters, W1 for Obs. ID 00031403061 and U for Obs. ID 00033861002. We produced an image in each of them with uvsimsum. We then used uvotsource to extract the source in a 5’’ region and the background counts in a 15’’ source-free circular aperture, respectively. The derived V404 Cygni flux densities are \((7.89 \pm 0.89) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}\) and \((1.79 \pm 0.09) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}\) in W1 and U, respectively.

2.3 INTEGRAL observations

The data were reduced with the jemx_science_analysis and ibis_science_analysis routines implemented in the Off-Line Scientific Analysis (OSA) v10.2 suite using the most recent calibration files. Images were first generated in 16 bands between 3.04 and 34.88 keV for the two JEM-X instruments whereas 4 bands were used for the IBIS Soft Gamma-Ray Imager (ISGRI, Lebrun et al. 2003), covering the range 20 to 200 keV. A careful analysis of all produced images showed that V404 Cygni was detected in all JEM-X and ISGRI bands during the first two science windows but only with JEM-X below 16 keV during the third one, which
is simultaneous to our FORS2 observations. We then extracted JEM-X and ISGRI spectra at V404 Cygni Chandra position and generated redistribution matrix files (RMF) re-binned to the spectral ranges of interest.

2.4 REM observations
The REM data were taken on June 27 2015 with REMIR in J, H and $K_s$ and consist in a sequence of three images per filter, each image being constituted of five frames that were dithered using a prism wedge. The reduction process, done automatically by the robotic Automatic Quick Analysis pipeline ($\text{AQuA}$, Testa et al. 2004), consisted in first obtaining an empty sky image from a median stack of the five dithered frames and subtracting it from each of them. Following the application of a flat-field image, the images were re-aligned and stacked to obtain a final image with a S/N equivalent to the total exposure time of the five-image sequence. Photometry was then performed using the PSF-fitting software DAOPHOT (Stetson 1987) and the fluxes were calibrated using some secondary standard stars in the field against the 2MASS catalogue (Skrutskie et al. 2006). We measure the following magnitudes: 11.40 ± 0.06, 11.35 ± 0.05, and 11.37 ± 0.05 in $J$, 10.72 ± 0.08, 10.80 ± 0.08, 10.85 ± 0.08 in $H$, as well as 10.25 ± 0.09, 10.24 ± 0.07, and 10.33 ± 0.08 in $K_s$.

3 RESULTS
Figure 2 displays the 4500–9300 Å slit-loss corrected average spectrum of V404 Cygni. The expected contribution from its companion star, modelled by a K0III spectrum scaled to the disc contribution-corrected magnitudes derived in Casares et al. (1993) when the source was in quiescence and reddened to the ISM extinction along the line-of-sight of the source (see below), is also displayed. The detected lines, the measurements of which are listed in Table 2, are also marked. We give their measured wavelength $\lambda_l$ and laboratory wavelength $\lambda_i$ in Å, radial velocity shifts $\Delta V$ in km s$^{-1}$ if any, equivalent widths $W$ in Å, FWHMs in km s$^{-1}$, quadratically corrected from the instrumental FWHMs, as well as their intrinsic fluxes in erg cm$^{-2}$ s$^{-1}$. Note that their underlying continuum was locally assessed with a first-order polynomial. The latter being the primary source of inaccuracy, each measurement was repeated several times with different continuum placements within the same wavelength range to obtain a set of values that eventually averaged out. The uncertainties listed in Table 2 are therefore the scatter to the mean rather than the statistical errors for any one fit, which are much smaller.

3.1 The optical spectroscopic content
V404 Cygni optical spectrum is very rich, with a wealth of $H\alpha$ ($H_\beta$, $H_\beta$, the Paschen series), $He\alpha$ and $He\beta$ emission lines. We report a weak $C_{III}+N_{III}$ fluorescence complex (also called the Bowen Blend, BB) around 4640 Å that likely originates from the irradiated accretion disc as our observations took place at $\phi \approx 0.05$ (see Table 1), i.e. when the emission from the irradiated hemisphere of the companion star is not visible to the observer. We moreover detect several less common emission features, most of which we associate with $Fe\ II$ along with some signatures of $Si\ II$, $O_1$, $O_1$, $O_III$, and $N_II$, which were not present at the beginning of the outburst (Bernardini et al. 2016). A unidentified complex, which might as well be an instrumental feature as a blend of $He\ I$ and $He\ II$ lines, is also present around 8223 Å.

This spectroscopic content is consistent with that reported in some previous studies of the 1989 outburst (Casares et al. 1991; Wagner et al. 1991; Gotthelf et al. 1992). Yet, despite having a similar continuum flux level, $H_\alpha$ and $H_\beta$ are 50 and 20 times brighter, respectively, than during 1989 July 1–4 observations presented in Gotthelf et al. (1992). This explains why their equivalent widths are so much larger than those previously reported, with $W_{H\alpha} \approx 1130 \AA$ and $W_{H_\beta} \approx 241 \AA$ in the FORS2 spectrum compared with about -110 Å and -12 Å, respectively, in 1989 July 1–4. $H_\alpha$ also has very broad wings of ±2000 km s$^{-1}$. Complex and variable line profiles were previously reported, including double and triple-peaked emissions as well as P-Cygni profiles (Muñoz-Darias et al. 2016). In our case, although the 1100 to 1900 average resolution of the FORS2 spectra prevents a detailed analysis, it is very likely that all the features are single-peaked. $H_\beta$ 18865, $\lambda$0015, and $\lambda$0229 profiles do show two local maxima, but we do not believe those are physical.

Based on their radial velocities, the features are separated between stationary and red-shifted, pointing towards at least two components responsible for V404 Cygni optical emission. Most of the higher ionisation species, in particular $Fe\ II$ and $Si\ II$, as well as $Pa\ (17-3)$ to $Pa\ (11-3)$, do not exhibit any velocity shift, although we stress that the uncertainties on the centroid measurements are sometimes quite large and we cannot rule out that some of them are actually displaced. $Pa\ (10-3)$ and $Pa\ (9-3)$ centroids do show +20 to +30 km s$^{-1}$ shifts but they are likely not physical. In contrast, $H_3$, $He\ I$ 5876, $H_\alpha$, $He\ I$ 6678, $He\ I$ 7065, $He\ I$ 7281, and $O_1$ 7774 are unambiguously red-shifted, with radial displacements ranging between about +70 to +120 km s$^{-1}$.

Finally, besides features intrinsic to V404 Cygni, we searched for diffuse interstellar bands (DIBs) and we report two centred at 5780 Å and 6284 Å. Herbig (1975) showed that DIBs were strongly correlated to the ISM extinction along the line-of-sight of the sources in which they are detected and derived several relationships between their equivalent widths and $E(B-V)$. Here, we nonetheless rely on DIB5780 only as DIB6284 is likely contaminated with some atmospheric absorption troughs. Jenniskens & Desert (1994) obtained $W_{5779} = (0.647 \pm 0.053) \times E(B-V)$. We measure $W_{5779} = 0.798 \pm 0.027$ Å which leads to $E(B-V) = 1.233 \pm 0.116$. For an average total-to-selective extinction ratio $R_V = 3.1$, we thus derive $A_V = 3.82 \pm 0.36$, in line with previous estimates (see e.g. Hynes et al. 2009). We note that this $A_V$ value is consistent with a distance in the range 2.4–2.8 kpc as derived using the 3D extinction map given in Marshall et al. (2006), which is similar to the 2.39 ± 0.14 kpc distance measured through radio parallax and reported in Miller-Jones et al. (2009).
3.2 The optical spectroscopic variability

During this outburst, V404 Cygni emission has been highly erratic and extreme multi-wavelength variations were reported by several authors (Tetarenko et al. 2015a; Rodriguez et al. 2015; King et al. 2015; Kimura et al. 2016; Martí et al. 2016; Rana et al. 2016). A strong variability pattern with FORS2 is therefore expected, and the fact that both \( V \) and \( I \) observations consist of 20 and 19 sub-exposures of 30 s each, respectively, allows us to investigate changes in the spectral continuum as well as the centroids, intrinsic fluxes, equivalent widths, and FWHMs of the spectral lines on a 67 s time scale, taking into account observing overheads. Figure 3 displays the evolution of the simultaneous AAVSO \( V \) and \( I \) pre-validated magnitudes compared with that of the synthetic magnitudes derived through the convolution of Johnson and Cousins filters with the sub-spectra. It is clear that despite some small discrepancies, the match in \( V \) is quite good, which confirms the reality

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
\text{Element} & \lambda^a & \lambda^b & \Delta \lambda^c & W^d & \text{FWHM}^e & \text{Fline}\text{f}^g \\
\hline
\text{He}\text{II} & 4583.8 & 4583.8 & - & * & * & * \\
\text{Fe}\text{II} & 4632.0 & 4630.8 & - & * & * & * \\
\text{Fe}\text{II} & 4866.4 & 4865.9 & - & * & * & * \\
\text{Fe}\text{II} & 4714.0 & 4713.1 & - & * & * & * \\
\text{H}\alpha & 6564.6 & 6562.7 & 76 & -1129 & 0.4 & 1056 & 13 \\
\text{He}\text{I} & 6608.9 & 6678.2 & 108 & -390 & 0.4 & 950 & 31 \\
\text{He}\text{I} & 7065.2 & 7065.2 & 85 & -40.7 & 1.5 & 920 & 41 \\
\text{He}\text{I} & 7283.4 & 7281.3 & 74 & -8.2 & 1.1 & 809 & 111 \\
\hline
\text{I band} & & & & & & \\
\text{He}\text{I} & 7065.2 & 106 & -41.8 & 1.2 & 906 & 26 & 256.8 & 8.0 \\
\text{He}\text{I} & 7281.3 & 86 & -8.7 & 0.8 & 8033 & 88 & 60.7 & 5.6 \\
\text{He}\text{I} & 7773.4 & 110 & -10.6 & 1.0 & 546 & 48 & 106.1 & 6.2 \\
\text{He}\text{I} & 7875.8 & 6.1 & 7873.5 & - & * & * & * \\
\text{He}\text{I} & 7894.6 & - & 7894.6 & - & * & * & * \\
\text{Pa} (17-3) & 8467.2 & 8.8 & 8467.3 & - & -3.5 & 1.1 & 462 & 60 \\
\text{Pa} (16-3) & 8501.2 & 0.9 & 8502.5 & - & -24.8 & 2.5 & 465 & 25 \\
\text{Pa} (15-3) & 8544.6 & 0.8 & 8545.4 & - & -45.2 & 4.4 & 574 & 32 \\
\text{Pa} (14-3) & 8598.8 & 0.5 & 8598.4 & - & -20.7 & 2.2 & 585 & 30 \\
\text{Pa} (13-3) & 8665.6 & 0.6 & 8665.0 & - & -48.5 & 4.0 & 621 & 34 \\
\text{Pa} (12-3) & 8751.2 & 0.5 & 8750.5 & - & -30.1 & 2.1 & 632 & 35 \\
\text{Pa} (11-3) & 8863.5 & 0.5 & 8862.8 & - & -44.6 & 3.1 & 676 & 24 \\
\text{Pa} (10-3) & 9015.9 & 0.5 & 9014.9 & 20 & -60.2 & 3.0 & 702 & 30 \\
\text{Pa} (9-3) & 9230.4 & 0.8 & 9229.0 & 33 & -85.8 & 4.6 & 927 & 101 \\
\hline
^a& Measured wavelength in Å \\
^b& Air laboratory wavelength in Å \\
^c& Radial velocity shift in km s\(^{-1}\), corrected for a 13 km s\(^{-1}\) heliocentric-barycentric velocity \\
^d& Equivalent widths in Å \\
^e& Full-width at half-maximum in km s\(^{-1}\), quadratically corrected for instrumental broadening \\
^f& Intrinsic line flux in units of 10\(^{-15}\) erg cm\(^{-2}\) s\(^{-1}\) \\
\end{array}
\]

Table 2. Optical lines in V404 Cygni FORS2 spectrum. “I” marks the features have a complex continuum making the measurements difficult; “a” means that the lines are detected but measurements would be unreliable.
of the spectral variability and points towards the flux calibration of each \( V \) sub-spectrum to be accurate at about 10\%. However, differences are larger in \( I \), and while the evolutions of both the AAVSO pre-validated and FORS2 synthetic magnitudes are similar, flux discrepancies are wider. We did a similar comparison with the simultaneous \( I \) magnitudes presented in Kimura et al. (2016) and find the same discrepancies. Large losses are likely mostly due to sky transparency variations, in particular thin clouds passing. However, it is not clear why some of our synthetic magnitudes are significantly smaller, i.e. we find large flux excesses. No problem was reported during the observations and we are not aware of any extra light entering the slit and/or the detector. The spectro-photometric standard star was moreover observed in similar conditions in both \( V \) and \( I \) and its flux-calibration is very good. Even if the flux level of the average \( I \) spectrum is accurate, it is clear that the flux-calibration of each individual \( I \) sub-spectrum was likely compromised, with mild to severe differences with photometric measurements. Although we believe that this does not affect the relevance of the variability pattern, we decided not to investigate the flux variability of the lines present in the \( I \) sub-spectra. Nonetheless, their equivalent widths and FWHMs being independent on the accuracy of their local continuum, we still trace the changes in these two quantities, although we only consider the \( I \) sub-spectra for which the difference between the AAVSO and synthetic magnitudes is lower than 0.2 in absolute value.

We thus selected the brightest \( \text{H} \text{i} \) and \( \text{He} \text{i} \) as well as four \( \text{Fe} \text{II} \) features and the way we measured the line parameters differs from that used for the average spectrum. Indeed, to ensure that the choice of continuum had the smallest effect as possible, a given line was fitted, in all the sub-spectra, within the exact same window with a single Gaussian and its base continuum was extrapolated with a first-order polynomial from the exact same wavelengths. Likewise, uncertainties were measured from the real errors as given after the extraction process. The first result is that none of the lines, including the red-shifted ones, exhibit detectable centroid variations. Second, there is an obvious correlation between the intrinsic fluxes and local continua (Figure 4), which clearly hints at a common origin for the continuum and line variability. While this could also be interpreted as an evidence that all the features come from the same component, the evolution of their respective equivalent widths hints at two different behaviours (Figure 5). Indeed, those of \( \text{He} \text{i} \lambda 5876 \), as well as \( \text{Fe} \text{II} \lambda 5169 \) and \( \lambda 5317 \) are unambiguously anti-correlated with their underlying continua, whereas the others show little changes. Likewise, the FWHMs of the first three lines plus those of \( \text{He} \text{i} \lambda 6678 \) and \( \text{He} \text{i} \lambda 7065 \) (in both \( V \) and \( I \)), show a similar anti-correlation (Figure 6), whereas the four \( \text{Fe} \text{II} \) lines have constant FWHMs.

### 3.3 The X-ray emission

As shown in Table 1, only the last \( \text{INTEGRAL} \) pointing is strictly simultaneous with the FORS2 observations. However, V404 Cygni is barely detected by \( \text{INTEGRAL} \) at this epoch and we can only make use of a 3.6-16 keV JEM-X spectrum. While this is enough to perform a phenomenological spectral fit, it cannot allow us to get a better view of the X-ray properties of the source. This is the reason why we also use the remaining X-ray spectra, which were obtained 0.5 and 2.2 hours before. Concerning the non-simultaneity of the X-ray spectra, we stress that we are not interested in performing a very detailed spectral analysis and that our aim here is only to obtain a rough estimate of the nature of the high-energy emission from V404 Cygni.

We first combined the \textit{Swift}/XRT (#00031403061) and \textit{INTEGRAL}/JEM-X+ISGRI (#155700300010) data sets to build a 0.5–150 keV spectrum (hereafter Spec1) and fit it, using \texttt{xspec} v. 12.9.0, with a model consisting of a viscous disc (\texttt{ezdiskbb}, Zimmerman et al. 2005) and a spherical Comptonisation component (\texttt{comppt}, Titarchuk 1994). Both were modified by the ISM extinction, modelled with \texttt{TBABS} for the abundances and cross-sections given in Wilms et al. (2000) and Verner et al. (1996), respectively, and multiplicative constants were introduced to take calibration discrepancies into account. We restricted the XRT spectrum to the 0.5–3.2 keV energy range, as including data points up to 5 keV resulted in an abnormally low XRT multiplicative constant.

![Figure 3](image-url) Variations at 67 s time scale of the \( V \) (left) and \( I \) (right) synthetic magnitudes derived from the convolution of V404 Cygni sub-spectra with Johnson and Cousins photometric filters (green). We compare them to the simultaneous pre-validated AAVSO \( V \) and \( I \) magnitudes (grey).

![Figure 4](image-url) Table 1

| Component  | Tbabs | Halpha | Hebeta | Hdelta |
|------------|-------|--------|--------|--------|
| log(N/H)   |       |        |        |        |
| E(1/2) keV |       |        |        |        |
| E(1/4) keV |       |        |        |        |

![Figure 5](image-url) The X-ray emission of V404 Cygni. This is the reason why we also use the remaining X-ray spectra, which were obtained 0.5 and 2.2 hours before.
During the fitting process, the seed photon temperature $kT_0$ of COMPTT was more over tied to the maximum accretion disc temperature $kT_{	ext{max}}$. The best-fit parameters are listed in the first column of Table 3 and the best-fit model is displayed in the middle panel of Figure 7. The fit is satisfactory, with a reduced $\chi^2$ of 1.02, and points towards a relatively cold accretion disc: $(kT_{\text{max}} = 0.28 \pm 0.03$ keV) dominating the soft X-rays below 3 keV whereas a warm and thick Compton component $(kT_0 = 39^{+23}_{-21}$ keV and $\tau = 3.46^{+0.66}_{-1.19}$) is responsible for the bulk of the emission beyond 4 keV. The inferred inner radius $R_{\text{in}}$ for $f \sim 1.7$ (Shimura & Takahara 1995), $i \sim 67^\circ$, and $M_{\text{BH}} \sim 9 M_\odot$ as given in Khargharia et al. (2010) ranges between 3 and 6 $R_\odot$, i.e. we do not see evidence for significant truncation of the inner accretion disc, although we stress that a $f = 1.7$ value may not be fully appropriate when the hard X-ray continuum dominates the emission (see, e.g. Reynolds & Miller 2013). We also note that the derived column density $N_H = 0.85^{+1.03}_{-0.98} \times 10^{22}$ cm$^{-2}$, is consistent with an ISM extinction $A_V$ between 3.4 and 4.3 once converted with the relationship given in Güver & Özel (2009), i.e. a similar value than that derived via optical spectroscopy.

We used the same model to fit the second INTEGRAL/JEM-X/ISGRI 3.6–150 keV spectrum (#155700329010, hereafter Spec2) but the lack of soft X-ray data prevented us from constraining the accretion disc parameters. We therefore kept COMPTT only and fixed $kT_0$ to the value derived for Spec1, assuming that the accretion disc had not significantly cooled down or heated up. We derive similar parameters (see Table 3, second column, and Figure 7, middle panel, for the best-fit parameters and best-fit model, respectively), and the fit is good, with a reduced $\chi^2$ of 1.12. The only difference with Spec1 is that the 4–150 keV flux is three times higher, $3.37 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ vs $1.13 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$, hinting at an X-ray variability driven by the Compton component.

Our third 3.6–16 keV JEM-X spectrum, simultaneous with our FORS2 observations (#155700340010, hereafter Spec3), was fit with an absorbed power law, the column density being fixed to that found for Spec1. The best-fit parameters are listed in the third column of Table 3 and the best-fit model is displayed in the right panel of Figure 7. We find that Spec3 is quite soft, with a photon index $\Gamma = 3.31^{+0.26}_{-0.24}$ and a lot fainter than Spec1 and Spec2, with a 4–15 keV flux of about $0.3 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ against $2.4 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ and $5.7 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$, respectively. For comparison, we also fit the 3.6–16 keV parts of Spec1 and Spec2 with absorbed power laws and find that both spectra are harder than Spec3, with 1.5–2 photon indices. This softening is likely the reason why V404 Cygni is not detected by IBIS, and assuming that Spec3 also stems from Comptonisation, a possible explanation for such a phenomenon is a change in the physical properties of the Comp-
ton component. In particular, a steepening of the power law may, for instance, result from a drastic cooling at constant optical thickness or alternatively a drop in opacity at constant temperature. This behaviour may indicate that the source has entered a hard to soft transition following a substantial temperature. In particular, a steepening of the power law may, for instance, result from a drastic cooling at constant optical thickness or alternatively a drop in opacity at constant temperature. This behaviour may indicate that the source has entered a hard to soft transition following a substantial flux decrease between Spec2 and Spec3. These types of transitions have been observed in some persistent microquasars which are predominantly found in the hard state, such as GRS 1758−258 (see, e.g., Smith et al. 2001).
4 DISCUSSION

The wealth of H\textsc{i}, He\textsc{i}, and higher ionisation lines in V404 Cygni optical spectrum, the strength of the Balmer emission signatures, and the variability pattern at short time scale are exceptional and confirm the peculiarity of the V404 Cygni outburst with respect to more classical BH XRBs. In the following sections, we investigate the origin of the spectroscopic content and draw a possible scenario to explain this behaviour.
where $i$ is the system’s inclination. Although V404 Cygni’s outer radius is unknown, its derived orbital parameters are accurate enough to estimate the typical Keplerian velocities $V_L$ and $V_C$ at the Roche lobe and circularisation radii $R_L$ and $R_C$, respectively, the former being larger and the latter smaller than $R_{\text{out}}$. Using the expressions given in Eggleton (1983) and Frank et al. (2002) as well as the Kepler’s third law, we derive:

$$V_L \sin i = 4.07 \times 10^5 \left(\frac{2\pi G f}{P}\right)^{\frac{1}{2}} \sqrt{(1 + q)(0.7 + q^{\frac{2}{3}} \ln(1 + q^{-\frac{1}{3}}))}$$

and

$$V_C \sin i = 2.85 \times 10^5 \left(\frac{2\pi G f}{P}\right)^{\frac{1}{2}} (0.5 - 0.227 \log q)^{-2}$$

in km s$^{-1}$. Here $q$ is the secondary-to-primary mass ratio, $P$ is the orbital period in days, and $f$ is the orbital mass function of the BH in $M_\odot$. For V404 Cygni parameters as given in Casares & Charles (1994) and using Equation 1, we can thus conservatively expect typical FWHMs between 400 km s$^{-1}$ and 700 km s$^{-1}$ for optical emission lines originating anywhere between the Roche lobe and circularisation radii (not necessarily the disc), and this is the case for most of the detected features listed in Table 2.

However, Hα, Hβ, HeI λ5876, HeI λ6678, and HeI λ7065 are all broader, with FWHMs≥ 900 km s$^{-1}$, i.e. three to four times closer to the BH if we associate this broadening to a Keplerian rotation. Taking into account that these five H and HeI lines also are the only ones exhibiting significant radial velocity red-shifts and anti-correlations between their local continua and both their equivalent widths and FWHMs, we can speculate that they originate from a different emitting region than the outer system. For Hα and Hβ this statement is further strengthened by the average Balmer decrement Hα/Hβ= 4.61 ± 0.62, measured from the line fluxes corrected for the ISM extinction $A_V = 3.82 \pm 0.36$ as derived in Section 3.1. This value is larger than and inconsistent with the ≈3.2 value found just before the outburst initial rise (Bernardini et al. 2016) and the canonical 2.86 for case B recombination of an ionised 10000 K nebula (Baker & Menzel 1938). It is also very different from

### 4.1 Where do the emission lines come from?

In outbursting microquasars, optical emission lines are thought to stem from the irradiated chromosphere of the outer accretion disc. In this case and assuming that they are principally rotationally broadened, we have the following relationship between the Keplerian velocity $V_{\text{out}}$ at the outer radius $R_{\text{out}}$ and their FWHMs (see, e.g., Casares 2016):

$$V_{\text{out}} \sin i = \sqrt{\frac{GM_{\odot}}{R_{\text{out}}}} \sin i \leq \frac{FWHM}{2} \text{ km s}^{-1}$$

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unity, which is expected from optically thick irradiated accretion discs found in cataclysmic variables (Williams 1980; Williams & Shipman 1988; Tomsick et al. 2016) and some outbursting microquasars (see e.g. Rahoui et al. 2014). As shown in Drake & Ulrich (1980), a possible explanation for such a large Balmer decrement is the combined effects of high optical depths in the Balmer lines and the relative importance of collisional excitation compared to radiative or recombination processes. This could also explain the anti-correlation between their equivalent widths and local optical continua. Indeed, if the lines are optically thick, any increase of the ionising radiation enhances their optical depths further, as shown in Ferland & Netzer (1979), and the higher the ionising field, the flatter their flux evolution. Assuming an optically thin continuum emitting region, which is reasonable considering the broad Hα wings, this phenomenon effectively results in the aforementioned anti-correlation. Incidentally, if optical depth effects really are important, we expect the Hα/Hβ decrement to be anti-correlated to the Hβ local continuum, as Hα optical depth increases at a faster pace, and this is exactly the case (see top-left panel of Figure 8). In contrast, the variations of the three He/Hβ decrements in function of Hβ continuum rather show a clear upwards evolution (see the remaining three panels of Figure 8), which strengthens the hypothesis of a rapid optical depth increase in Hβ. Likewise, He i 5876/He i 6678 and He i 5876/He i 7065 decrements point towards a similar enhancement for He i 5876 optical depth, as they evolve upwards too (see Figure 9).

Nonetheless, He i 6678/He i 7065 decrement is constant, hinting at the lack of significant optical depth variations, which may explain why the two lines do not exhibit the same unambiguous equivalent width/local continuum anti-correlation.

4.2 A classical nova-like nebula in V404 Cygni?

The same decrement analyses for all the narrow H1 and He I lines (FWHM ~ 400 – 600 km s⁻¹), which we argue likely stem from the outer regions, do not show any peculiarity and remain constant. Based on their equivalent widths, large radial velocity red-shifts and/or the evolu-

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**Figure 8.** Hα (top left), He i 5876 (top right), He i 6678 (bottom left), and He i 7065 (bottom right) over Hβ flux ratios variations in function of Hβ underlying continuum.

**Figure 9.** He i 5876/He i 6678 (left), He i 5876/He i 7065 (middle), and He i 6678/He i 7065 (right) flux ratios variations in function of the denominator underlying continuum.
tion of their decrements, it is therefore tempting to associate \Healpha, \Hbeta, \Hei\lambda 5876, \Hei\lambda 6678, and \Hei\lambda 7065 to an expanding broad line region (BLR) in which collisional processes may be important, lines are optically thick, and the continuum optically thin. But what could this BLR be and how does this relate to the FWHM/local optical continuum anti-correlation? A first explanation is that these FWHM variations trace the irradiation-induced expansion or contraction of the BLR, i.e. a decrease or an increase of its Keplerian velocity, similarly to what we would expect from the inflated base of a Compton-heated accretion disc wind (ADW, Begelman et al. 1983). In this case, the maximum FWHM changes for the lines in V, i.e. when the optical continuum is increasing, imply an expansion of the emitting zones of about 20% and 40%, respectively. In contrast, the \Hei\lambda 7065 FWHM increase in I, i.e. when the optical continuum is decreasing, gives a contraction of about 40%. We note that King et al. (2015) reported the X-ray detection of blue-shifted emission lines and that P-Cygni profiles were observed in the optical domain (Muñoz-Darias et al. 2016), which favours the ADW base hypothesis. It is however not clear to which extent we really could follow Keplerian velocity variations at such a short time scale. Moreover, without any better knowledge of the simultaneous X-ray properties of the source, it is difficult to say whether a 20-40% radius increase in less than half an hour is realistic. Another possibility is that FWHM variations are thermally driven, i.e. the narrowing is due to cooling and the broadening to heating. Such an explanation may seem counter-intuitive as cooling and heating would be accompanied by an optical continuum increase and decrease, respectively, but this apparent paradox can be solved if we consider that the emission lines and the continuum arise from the same component and that the emission stems from optically thin bremsstrahlung or synchrotron.

A third alternative, which would reconcile the two aforementioned scenarios, is the presence of a quasi-spherical optically thin nebula surrounding V404 Cygni, which was also proposed by Muñoz-Darias et al. (2016). Indeed, the optical spectrum strongly resembles that of Fe II-type classical novae in their post-outburst nebular phase (see, Shore 2008, for a review). This phase is thought to occur once fast and optically thick ADWs stop being fuelled and massively ejected following a significant drop in mass-accretion rate and X-ray ionising emission. Their outer shell, previously formed, then starts growing and cooling down, becoming optically thin in the process and effectively turning into a nebula, while remnant inner optically thick ADWs keep expanding for some time. Moreover, large Balmer decrements and equivalent width/continuum anti-correlations are also seen and explained in a similar way as we do for V404 Cygni, and a narrowing with time of the broad emission lines is also observed. This narrowing is mainly thought to stem from shocks occurring between the nebulae and much slower stellar winds. In the V404 Cygni case, we can expect slow winds from its cool sub-giant companion star, and the presence of many narrow Fe II emission lines, which behave differently from both the broad features and the other \Halpha and \Hei

Figure 10. V404 Cygni SED modelled with a self-absorbed optically thin bremsstrahlung in the optical and near-infrared domain. A $-0.62$ spectral index power law, consistent with optically thin synchrotron, is superimposed on the RATAN-600 AND NOEMA radio and sub-millimetre contemporaneous data. The inset displays a zoom-in centred on the REMIR, FORS2, and UVOT data.
signatures, hints at the existence of a stellar winds/nebula front, as suggested in Williams (2012) for classical novae. However, it is important to remember that our data not only suggest a narrowing when the continuum is increasing, but also a broadening when it is decreasing. The spectroscopic content is also divided between narrow stationary features and broad red-shifted ones. Thus, another explanation that could account for both could be that the broad lines actually originate from deeper in the nebula, in a region, which could be the remnant ADW, moving faster than the outer optically thin shell and eventually colliding with it. The collision leads to the temporary narrowing of the thick emission lines, which re-broaden once the interaction is over because we see deeper in the nebula again.

4.3 The origin of optical continuum

In the soft state, the optical continuum of outbursting low-mass XRBs is usually dominated by the viscous or reprocessed emission of the accretion disc, to which synchrotron radiation from the compact jets is added in the hard state. The companion star contribution may also be detectable but only when the source is close to quiescence. In the $\nu$ vs $E_\nu$ plan, this leads to a blue continuum from the disc, with a spectral index between roughly 0.3 and 2, and a potential red excess when jets are present (see e.g., Rahoui et al. 2012, 2015, in the case of GX 339-4 and Swift J1753.5-0127).

Figure 10 displays the extinction-corrected average continuum of V404 Cygni during our observations, corrected for the companion star emission, and it is clear that it does not correspond to the previous description. Indeed, it is characterised by a red increase and a blue exponential decay with rough spectral indices of $+2$ and $-1.5$, respectively, the turnover being located around $3.6 \times 10^{14}$ Hz, and a peak around $3.6 \times 10^{14}$ Hz. We there-}

5 SUMMARY AND CONCLUSION

We have presented a comprehensive study of the V404 Cygni optical spectrum at the very beginning of its 2015 outburst decay. The high S/N of each individual spectrum as well as the short exposure time has allowed us to perform a thorough analysis of the continuum and spectral variability pattern and to investigate the origin of the existing correlations. We find that the spectral features may originate in three different regions: (1) a fast-moving optically thick plasma, likely an ADW remnant, within a classical nova-like nebula for the broadest (FWHM $\sim 900 - 1000$ km s$^{-1}$) and redshifted ($\Delta V \sim 70 - 120$ km s$^{-1}$) emission lines; (2) the slow-moving or stationary optically thin outer shell of the aforementioned nebula for the narrow high ionisation emission lines (FWHM $\sim 400 - 600$ km s$^{-1}$); and (3) the outer accretion disc for the remaining narrow H$\alpha$ and He$\alpha$ features. This geometry assumes the existence of a massive, almost discrete optically thick ADW that was turned-off prior to the decay and was detected via X-ray emission lines and optical P-Cygni profiles. We further argue that the optical continuum is unlike any observed in other BH XRBs and likely arises from the aforementioned shocks, perhaps through optically thin bremsstrahlung cooling.

Our results confirm the uniqueness of this V404 Cygni outburst in the microquasar family and point towards the dominant role played by massive ADW ejecta in the source properties. It is not clear if these ejecta can be held responsible for part of the extreme flaring activity the source exhibited during its outburst, or if they are only a consequence of the strong flares irradiating the accretion disc. In either case, the reasons behind this behaviour are unknown, but
it is noteworthy that V404 Cygni, like the other extreme microquasar GRS 1915+105, is characterised by a long orbital period and a very large accretion disc, which, according to Kimura et al. (2016), could prevent sustained accretion in the inner regions and induce large disc instabilities. Whether or not this is the case, we note that V404 Cygni behaviour, including the various observed anti-correlations, is not only seen in the classical novae from which we draw a parallel, but also in some AGN and Seyfert galaxies (see, e.g. Lee et al. 2013) with the well-known Baldwin effect (Baldwin 1977). This may point towards the importance of the universal presence of broad line regions in accreting systems spanning whole compact objects mass scale.

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