WEBT and XMM-Newton observations of 3C 454.3 during the post-outburst phase

Detection of the little and big blue bumps

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ABSTRACT

Context. The quasar-type blazar 3C 454.3 was observed to undergo an unprecedented optical outburst in spring 2005, affecting the source brightness from the near-IR to the X-ray frequencies. This was first followed by a millimetric and then by a radio outburst, which peaked in February 2006.

Aims. In this paper we report on follow-up observations to study the multiwavelength emission in the post-outburst phase.

Methods. Radio, near-infrared, and optical monitoring was performed by the Whole Earth Blazar Telescope (WEBT) collaboration in the 2006–2007 observing season. XMM-Newton observations on July 2–3 and December 18–19, 2006 added information on the X-ray and UV states of the source.

Results. The source was in a faint state. The radio flux at the higher frequencies showed a fast decreasing trend, which represents the tail of the big radio outburst. It was followed by a quiescent state, common at all radio frequencies. In contrast, moderate activity characterized the near-IR and optical light curves, with a progressive increase of the variability amplitude with increasing wavelength. We ascribe this redder-when-brighter behaviour to the presence of a “little blue bump” due to thermal emission from the accretion disc. The X-ray spectra are well fitted with a power-law energy distribution (SED) during faint states. Moreover, the data from the XMM-Newton Optical Monitor reveal a rise of the SED in the ultraviolet, suggesting the existence of a “big blue bump” due to line emission from the broad line region, which is clearly visible in the source spectral energy distribution (SED) during faint states. Moreover, the data from the XMM-Newton Optical Monitor reveal a rise of the SED in the ultraviolet, suggesting the existence of a “big blue bump” due to thermal emission from the accretion disc. The X-ray spectra are well fitted with a power-law model with photoelectric absorption, possibly larger than the Galactic one.

Key words. galaxies: active – galaxies: quasars: general – galaxies: quasars: individual: 3C 454.3

1. Introduction

In May 2005 the flat-spectrum radio quasar 3C 454.3 was observed in an unprecedented bright optical state. This triggered observations by high-energy satellites (Chandra, see Villata et al. 2006; INTEGRAL, see Pian et al. 2006; Swift, see Giommi et al. 2006), which found an exceptionally high flux also in the X-ray band. A multiwavelength (radio-to-optical) monitoring campaign was organized by the Whole Earth Blazar Telescope (WEBT)$^1$ to follow in detail the behaviour of the low-energy emission. Past data were also collected, in order to trace it back to the Sixties. The main results were published by Villata et al. (2006): the different behaviour shown by the optical and radio historical light curves was interpreted as due to the fact that the corresponding jet emitting regions are separated and misaligned. In this picture, the inner region, which is responsible for the optical radiation, became more aligned with the line of sight during the 2004–2005 outburst. This produced an increase of the Doppler factor and a consequent enhancement of the flux. Moreover, the analysis of the colour-index behaviour during the outburst, generally redder-when-brighter, led Villata et al. (2006) to suggest the presence of a luminous accretion disc.

The WEBT continued to monitor the source also in the post-outburst period, in particular in order to detect a possible correlated event in the radio bands. Indeed, a huge mm outburst was observed to peak in June–July 2005. At the high radio frequencies (43 to ~ 22 GHz), a long-lasting outburst developed, reaching the maximum flux levels in late February 2006. The event was seen progressively delayed and fainter going towards lower frequencies, disappearing below 8 GHz. These data were presented and discussed by Villata et al. (2007). According to their interpretation, the radio peak observed in late February 2006 is
were published by Villata et al. (2006, 2007). Col. 1 reports the starting from September 2006 for the radio observers, and from observatories participating in the 2006–2007 WEBT campaign. Observations by the WEBT jet) with a di
tinsic variability mechanism (disturbances travelling down the October–November 2005. This interpretation combines an in-
tuous epochs are analysed in Sect. 4. Conclusions are drawn in

<table>
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<td>Kitt Peak (MDM), USA</td>
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not the delayed radio counterpart of the spring 2005 optical peak, but it is instead connected to a minor optical flare detected in October–November 2005. This interpretation combines an intrinsic variability mechanism (disturbances travelling down the jet) with a differential change of the emitting regions viewing angles, due to the motion of the curved jet.

Monitoring of the source by the WEBT continued and was complemented, in July and December 2006, by two pointings of the XMM-Newton satellite to study the high-energy emission in the post-outburst phase. In this paper we present the results of this new observing effort on 3C 454.3. A third XMM-Newton pointing was performed in May 2007 and its results will be reported in a further paper, where the multifrequency historical behaviour of the source will be reconstructed and analysed.

This paper is organised as follows: the radio-to-optical observations by the WEBT are presented in Sect. 2, while Sect. 3 reports on the results of the XMM-Newton pointings. The broadband spectral energy distributions (SEDs) of the source at various epochs are analysed in Sect. 4. Conclusions are drawn in Sect. 5.

2. Observations by the WEBT

Table 1 contains the list of the radio, near-infrared, and optical observatories participating in the 2006–2007 WEBT campaign (starting from September 2006 for the radio observers, and from May 2006 for the near-infrared and optical ones). Earlier data were published by Villata et al. (2006, 2007). Col. 1 reports the name of the observatory and the country where it is located, Col. 2 gives the telescope size, and Col. 3 the observing bands. Notice that for each group (radio, near-infrared, and optical), the observatories are listed in order of longitude; indeed, one of the WEBT characteristics is the spread in longitude of its members, which in principle allows continuous 24 hour monitoring.

Light curves in Johnson-Cousins UBVRI bands are plotted in Fig. 1. The largest contributions (more than 30 observing nights) came from the Mt. Maidanak, Roque (KVA), Crimean, Osaka Kyoku, and Skinakas observatories. The source magnitude has been calibrated according to Angione (1971) in the U band, to Raiteri et al. (1998) in the BVR bands, and to González-Pérez et al. (2001) in the I band. A cleaning process was applied to minimize data scattering due to photometric uncertainties, as described by e.g. Villata et al. (2002) and Raiteri et al. (2005). The total number of data points in Fig. 1 is 3201, ~ 63% of which are in the R band.

Figure 1 shows the source in a rather faint state, but with significant magnitude variations: the difference between the minimum and maximum brightness levels is 0.72, 0.91, 1.04, 1.28, and 1.38 mag in the U, B, V, R, and I band, respectively. Notwithstanding the different sampling of the light curves, a progressive increasing of the variability amplitude with wavelength is clearly recognizable.

The R-band light curve is compared to the near-IR ones in Fig. 2. The latter are less sampled than the optical ones, since only the 110 cm telescope at Campo Imperatore was monitoring the source at these frequencies. The JHK fluxes have a maximum at JD = 2453979, in correspondence to one of the brightest optical peaks. We can see that the variability amplitude continues to increase with wavelength (1.43, 1.80, and 1.86 mag in J, H, and K bands, respectively). This trend seems to be another indication in favour of the existence of a luminous accretion disc, which was suggested to be responsible for the redder-when-brighter behaviour found by Villata et al. (2006). We will come back to this point in the following section.

The behaviour of the radio emission at different frequencies is shown in Fig. 3, where the first panel reports the optical light curve in the R band for a comparison. We also included data from the VLA/VLBA Polarization Calibration Database.

In contrast with the optical light curves, showing some activity, the radio flux displays only a smooth decreasing trend, which is mainly recognizable at the higher frequencies, where we see the tail of the big radio outburst peaking in late February 2006 that was analysed by Villata et al. (2007). Indeed, we notice that at the beginning of the period considered in Fig. 3, the radio spectrum is still inverted, as during the outburst, suggesting that the flux enhancement comes from the inner radio emitting region. Then, as the high-frequency flux decays, the radio spectrum becomes softer and softer, and the flux density increases with increasing wavelength. This behaviour is highlighted in Fig. 3 by reporting the 37 GHz (20-day binned) cubic spline interpolation in the various radio panels for a comparison between frequencies. As expected, the 37 GHz spline matches the 43 GHz data fairly well, while lower-frequencies light curves intersect the spline at some time, when the corresponding spectral index changes sign and the spectrum is no longer inverted.

3. Observations by XMM-Newton

The X-ray Multi-Mirror Mission (XMM) - Newton satellite observed 3C 454.3 twice during the period considered in this pa-
per (PI: C. M. Raiteri). The first time was during revolution number 1202, from July 2, 2006 at 21:25:07 UT to July 3 at 01:58:37 UT (JD = 2453919.39244–2453919.58237). The second observation took place during revolution number 1287, from December 18, 2006 at 20:07:27 UT to December 19 at 00:25:14 (JD = 2454088.33851–2454088.51752).

3.1. Results from EPIC

The European Photon Imaging Camera (EPIC) includes three detectors: MOS1, MOS2 (Turner et al. 2001), and pn (Strüder et al. 2001). Since a bright state of the source could not be excluded, a medium-filter/small-window configuration was chosen in order to avoid possible contamination by lower-energy photons as well as photon pile-up.

Data were reduced with the Science Analysis System (SAS) software, version 7.0. Only the good time intervals were selected, i.e. the periods which are free of high-background flares. This temporal filtering, which was performed according to standard prescriptions, reduced the available integration time for MOS1, MOS2, and pn by ~ 4%, 5%, and 30%, respectively in July. For the December data these numbers became ~ 25%, 27%, and 40%, because of a very high background at the beginning of the exposure.

Both the source and background spectra were extracted by setting (FLAG==0) and (PATTERN<=4) in the selection expression for all the three EPIC detectors. The first string rejects artifacts as well as events next to both CCD edges and bad pixels, which may have incorrect energies; the second string selects only single and double pixel events, which have the best energy calibration. Source spectra were extracted from circular regions with ~ 35 and ~ 40 arcsec radii for MOS and pn, respectively; background spectra were selected as the largest source-free circles that can be arranged on the same CCD: ~ 20 and ~ 40 arcsec radius regions for MOS and pn, respectively.

By means of the grppha task of the FTOOLS package, each source spectrum was grouped with the corresponding response matrix file, ancillary response file, and background spectrum, as well as binned to have a minimum of 25 counts in each bin. The grouped spectra were then analysed with the Xspec package, version 11.3.2. Only energy channels between 0.3 and 12 keV were considered.

The same model spectrum was applied to the MOS1, MOS2, and pn data simultaneously to increase the statistics. We first applied a single power law with Galactic absorption modelled according to the Wilms et al. (2000) prescriptions and $N_H = 0.724 \times 10^{21}$ cm$^{-2}$, from the Leiden/Argentine/Bonn (LAB) Survey (see Kalberla et al. 2005). The results are shown...
in Table 2, where Col.2 reports the column density, Col.3 the photon spectral index $\Gamma$, Col.4 the unabsorbed flux density at 1 keV, Col.5 the 2–10 keV observed flux, and Col.6 the value of $\chi^2/\nu$ (with the number of degrees of freedom $\nu$).

The three EPIC spectra fitted with the above model are displayed in the top panels of Fig. 4 (July 2–3) and Fig. 5 (December 18–19), while the bottom panels show the ratio between the data and the folded model. Assuming a flat cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_M = 0.27$, the luminosity of the source in the 2–10 keV rest frame energy range is $1.90 \times 10^{46}$ erg s$^{-1}$ in July, and $2.46 \times 10^{46}$ erg s$^{-1}$ in December.

We notice that fitting previous X-ray spectra of 3C 454.3 often required extra absorption. Villata et al. (2006) reported a value of $N_H = (1.34 \pm 0.05) \times 10^{21}$ cm$^{-2}$ for the Chandra observation of May 2005, during the outburst phase\footnote{Notice that there was a misprint in the Villata et al. (2006) paper, because of which 1.34 became 13.4.}. In that case the unabsorbed 1 keV flux density was $\sim 14$ times higher, but the power-law slope was very similar: $\Gamma = 1.477 \pm 0.017$. An even higher hydrogen column density was found by Giommi et al. (2006) when fitting the April–May 2005 data taken by the XRT instrument onboard Swift ($N_H \sim 2–3 \times 10^{21}$ cm$^{-2}$) and when re-analysing the BeppoSAX data of June 2000. In this last case, the brightness level of the source was rather low, and comparable to what we find for the XMM-Newton observations. By looking at Fig. 5, we see that the model slightly overestimates the data at the low-energy end of the plot. This could be an indication that some extra absorption is needed also in this case. To check this point, we reanalysed the XMM-Newton data letting $N_H$ to vary freely, and obtained $N_H = (0.87 \pm 0.06) \times 10^{21}$ cm$^{-2}$ for July, and $(1.01 \pm 0.06) \times 10^{21}$ cm$^{-2}$ for December (see Table 2). The F-test probability in the two cases is $5.2 \times 10^{-6}$ and $4.6 \times 10^{-17}$, respectively, indicating that from a statistical point of view the hypothesis of extra absorption is reasonable.
Table 2. Results of fitting the EPIC data with a power-law model with photoelectric absorption.

<table>
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<tr>
<th>Date</th>
<th>$N_H$ [10$^{21}$ cm$^{-2}$]</th>
<th>$\Gamma$</th>
<th>$F_{1keV}$ [\mu Jy]</th>
<th>$F_{2-10keV}$ [erg cm$^{-2}$ s$^{-1}$]</th>
<th>$\chi^2$/\nu (\nu)</th>
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<td>July 2–3</td>
<td>0.724</td>
<td>1.52 ± 0.01</td>
<td>0.86 ± 0.01</td>
<td>7.09 × 10$^{-12}$</td>
<td>0.857 (1093)</td>
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<tr>
<td>Dec. 18–19</td>
<td>0.724</td>
<td>1.57 ± 0.01</td>
<td>1.18 ± 0.01</td>
<td>8.86 × 10$^{-12}$</td>
<td>1.051 (1074)</td>
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<td>Free absorption</td>
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<td></td>
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<tr>
<td>July 2–3</td>
<td>0.87 ± 0.06</td>
<td>1.55 ± 0.02</td>
<td>0.90 ± 0.02</td>
<td>6.96 × 10$^{-12}$</td>
<td>0.842 (1092)</td>
</tr>
<tr>
<td>Dec. 18–19</td>
<td>1.01 ± 0.06</td>
<td>1.65 ± 0.02</td>
<td>1.29 ± 0.02</td>
<td>8.53 × 10$^{-12}$</td>
<td>0.985 (1073)</td>
</tr>
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</table>

Fig. 2. R-band (top panel) and JHK light curves of 3C 454.3 from May 2006 to January 2007. All near-infrared data are from Campo Imperatore. Maximum and minimum (red lines) as well as average (green lines) brightness levels are indicated. Arrows mark the times of the XMM-Newton pointings of July and December 2006.

Another possibility is that the need of extra absorption hides the fact that the intrinsic spectrum of the source is not a power law, but presents some curvature in the soft X-ray range. We investigated this hypothesis by fitting the XMM-Newton data with both a broken and a double power-law model, but the results do not imply any significant curvature of the source spectrum, and do not improve the goodness of fit.

3.2. Results from OM

Besides the X-ray detectors, XMM-Newton also carries a co-aligned 30 cm optical–UV telescope (Mason et al. 2001), the Optical Monitor (OM). The instrument is equipped with optical $VBU$ filters, ultraviolet UVW1, UVM2, UVW2 filters, as well as optical and UV grisms. In both the July and December pointings, we chose to use a $B$, $U$, UVW1, UVM2 sequence, as a compromise between a good spectral coverage and the limited duration of the observation. Exposure times for each filter are given inCols. 5 and 8 of Table 3 for the July and December observations, respectively.

Fig. 4. EPIC spectrum of 3C 454.3 on July 2–3, 2006; black squares, red triangles, and green diamonds represent MOS1, MOS2, and pn data, respectively. The bottom panel shows the ratio between the data and the folded model, a power law with Galactic absorption.

Fig. 5. EPIC spectrum of 3C 454.3 on December 18–19, 2006; black squares, red triangles, and green diamonds represent MOS1, MOS2, and pn data, respectively. The bottom panel shows the ratio between the data and the folded model, a power law with Galactic absorption.
The OM data were reduced with the omichain task of SAS version 7.0, and the results were analysed with omsource. Source magnitudes are reported inCols. 6 and 9 of Table 3. The error on the source magnitude also takes into account the dispersion of the results obtained by varying the parameters of the aperture photometry, in particular the location and size of the regions from which the background is extracted.

We noticed that the $U$ and $B$ magnitudes of the brightest stars in the field are in fair agreement with the ground-based calibrations in the $U$ band by Angione (1971) and in the $B$ band by Raiteri et al. (1998), which we have adopted for the WEBT data (see Sect. 2).

We derived the Galactic extinction (mag) in the various bands (Col. 2 of Table 3) by adopting the $B$-band value of Schlegel et al. (1998) and then applying the equations by Cardelli et al. (1989). Extinction in the UVM2 band is almost 1 mag; had we adopted the most recent prescriptions by Fitzpatrick (1999), we would have obtained a value which is only $\sim$ 1.8% lower.

The transformation of the de-reddened magnitudes into flux densities was obtained by using the method based on the Vega flux scale$^4$; the adopted Vega magnitudes and flux densities are reported inCols. 3 and 4 of Table 3, respectively. The derived 3C 454.3 flux densities corresponding to the July and December pointings are shown inCols. 7 and 10 of Table 3, and plotted as blue and red squares in Fig. 6, respectively.

This figure also shows ground-based optical and near-infrared flux densities from this work as well as from the literature (see description below); all the plotted values have been obtained by correcting for the Galactic extinction, using the same method we used for the OM data. In order to convert dereddened magnitudes into flux densities, we adopted the zero-mag fluxes by Bessell et al. (1998).

Blue and red diamonds in Fig. 6 correspond to the $UBVRI$ data acquired by the NOT during the July and December XMM-Newton pointings, respectively. As we can see from the figure, the ground-based optical flux densities agree fairly well with the OM ones in the overlapping frequency range. Flux densities in the $J$ and $H$ bands from observations performed at Campo Imperatore simultaneously to the July pointing are also displayed (blue diamonds).

In Fig. 6, the above two near-infrared–ultraviolet SEDs are compared to previous faint-state SEDs. One SED (green triangles) was obtained by Villata et al. (2006) from near-infrared and optical observations by the WEBT in late September 2005, just after the end of the big outburst. The faintest-state SED (cyan crosses) was derived from Neugebauer et al. (1979), who observed this source with the 5 m Hale Telescope at Palomar Mountain; the optical data were taken in January 1973, while the near-infrared ones in October 1976. Further near-infrared data points (black plus signs) were derived from the August 1980 observations of Allen et al. (1982). Finally, the purple asterisks refer to data acquired in December 1986 by Smith et al. (1988).

By looking at Fig. 6 we notice that:

- all the optical SEDs have a bump shape, with peak in the $V$–$B$ frequency range;
- the OM data presented in this paper confirm and extend further in frequency the rise of the SED in the ultraviolet that was present in the data of Neugebauer et al. (1979);
- there is also an upturn from the $J$ to the $H$ band;
- going towards lower frequencies, the behaviour of the brightest-state SED is different from that of the lower-state ones, since in the former the SED rise continues, while in all the latter the values in the $H$ band are lower than in the $J$ one. The difference between the $J$ and $H$ values is greater in the July 2006 SED than in the Allen et al. (1982) one, while in the case of Neugebauer et al. (1979) large uncertainties affect the data.

The bump peaking around the $V$ and $B$ bands likely corresponds to the little blue bump observed in quasars between $\sim$ 2000 and 4000 Å in the rest frame. This is due to the contribution of many emission lines produced in the broad line region (BLR), in particular the numerous $Fe$ lines, and Balmer continuum (Wills et al. 1985). Since the 3C 454.3 redshift is $z = 0.859$, $Fe$ lines would mostly contribute to the observed spectrum around the $B$ band, while the flux in the $V$ band would be enhanced by the $Mg$ line and Balmer continuum contributions. In the same way, the flux excess in correspondence of the $J$ band is likely due to a prominent broad $H\alpha$ emission line. This bump is more evident when the beamed synchrotron radiation from the jet is fainter. The lowest-flux SEDs in Fig. 6 (January 1973 and December 2006) show states where the BLR component probably dominates the source emission. In contrast, the steep near-infrared part of the September 2005 SED suggests that in this epoch the synchrotron component was giving a higher contribution, and the BLR component, though still recognizable, begins to be diluted by the synchrotron one.

On the other hand, the rise of the SEDs in the ultraviolet is probably the signature of the big blue bump, corresponding to thermal emission from the accretion disc. Evidences of this thermal component have been found in other quasar-type blazars, such as 3C 273 (von Montigny et al. 1997; Grandi & Palumbo 2004; Türlör et al. 2006), 3C 279 (Pian et al. 1999), and 3C 345 (Bregman et al. 1986).

In the case of the BL Lacertae object AO C0235+164, a UV–soft X-ray bump is recognizable in several SEDs, but whether this component is thermal radiation from the disc or rather another synchrotron component from the jet is not clear yet (Raiteri et al. 2005, 2006a,b).

The presence of these non-jet components, which mostly affect the blue part of the spectrum, allows us to understand why the variability amplitude in the near-IR and optical bands increases with wavelength (i.e. the redder-when-brighter behaviour), as noticed in Sect. 2. Indeed, when the jet emission decreases, the non-jet contribution sustains the source flux more in the blue than in the red.

4. Broad-band spectral energy distribution

The broad-band SED of 3C 454.3 is shown in Fig. 7. The near-IR-to-UV SEDs corresponding to the XMM-Newton pointings of July and December 2006, which were displayed in Fig. 6 and discussed in the previous section, are now complemented by the X-ray spectra presented in Sect. 3.1 and by radio data from 5 to 43 GHz that were taken at the same time or within 3 days from the XMM-Newton observations. The comparison between the UV and X-ray data clearly shows the UV excess. As discussed in the previous section, this excess is most likely due to the thermal emission from the accretion disc.

We notice that, while the radio-to-optical state was fainter in December than in July 2006, in the X-ray domain it was the opposite. However, a clear fit to the high-frequency radio data in Fig. 7 reveals that this part of the radio spectrum was harder in December than in July, suggesting a larger flux in the mm bands, whose photons are inverse-Comptonized to the X-ray frequencies we observe with XMM-Newton.

4 See http://xmm.esac.esa.int/sas/7.0.0/watchout/
Table 3. Results of the OM observations of 3C 454.3.

<table>
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<th>Filter</th>
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<th>Vega [mag]</th>
<th>Vega Vega [erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$]</th>
<th>$t_{exp}$ [s]</th>
<th>$N_{H}$ [mag]</th>
<th>$S_{X}$ [mJy]</th>
<th>$t_{exp}$ [s]</th>
<th>$N_{H}$ [mag]</th>
<th>$S_{X}$ [mJy]</th>
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<td>July 2–3</td>
<td>3C 454.3</td>
<td>3C 454.3</td>
<td>Dec. 18–19</td>
<td>3C 454.3</td>
<td>3C 454.3</td>
</tr>
<tr>
<td>B</td>
<td>0.462</td>
<td>0.030</td>
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<td>2900</td>
<td>16.82 ± 0.01</td>
<td>1.205 ± 0.01</td>
<td>1402</td>
<td>17.05 ± 0.02</td>
<td>0.975 ± 0.018</td>
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<tr>
<td>U</td>
<td>0.539</td>
<td>0.025</td>
<td>3.20 $\times 10^{-9}$</td>
<td>2901</td>
<td>16.03 ± 0.02</td>
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<td>16.24 ± 0.02</td>
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<tr>
<td>W1</td>
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<td>3.68 $\times 10^{-9}$</td>
<td>4499</td>
<td>15.82 ± 0.03</td>
<td>0.908 ± 0.025</td>
<td>3001</td>
<td>16.03 ± 0.03</td>
<td>0.748 ± 0.021</td>
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<tr>
<td>M2</td>
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<td>0.025</td>
<td>4.33 $\times 10^{-9}$</td>
<td>4600</td>
<td>15.89 ± 0.04</td>
<td>0.857 ± 0.032</td>
<td>7520$^*$</td>
<td>15.90 ± 0.04</td>
<td>0.849 ± 0.031</td>
</tr>
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</table>

$^*$ Three subsequent exposures of 3100, 3099, and 1321 s.

The spectrum shown in the figure, corresponding to observations performed in June 2000, was derived from the ASI Science Data Center (http://www.asdc.asi.it/).

5 The spectrum shown in the figure, corresponding to observations performed in June 2000, was derived from the ASI Science Data Center (http://www.asdc.asi.it/).

5. Conclusions

The unprecedented outburst of 3C 454.3 in 2005, affecting the source emission from the near-IR to the X-ray frequencies, was first followed by a huge millimetric and then by a long-lasting, extraordinary, high-frequency radio outburst. After that, the blazar underwent a multifrequency faint-state period from mid 2006 to April 2007, which was characterized by moderate variability in the near-infrared and optical bands. The variability amplitude was larger at longer wavelengths, consistently with the results of e.g. Bregman et al. (1986) for the quasar-type blazar 3C 345, whereas the general feature of BL Lac-type blazars is to show larger-amplitude flux changes at higher frequencies (e.g. Villata et al. 2004; Papadakis et al. 2007; Wu et al. 2007).

After the radio peak of late February 2006, at the higher radio frequencies we observed the fast outburst dimming phase, with the transition from the inverted radio spectrum, which characterised the long-lasting outburst, to the usual, softer one. According to Villata et al. (2007), the fast drop at all the higher radio frequencies and the absence of any flux increase at the lower ones suggest that the event that perturbed the inner radio emitting region has propagated outwards, in a jet region that is misaligned with respect to the line of sight. Hence, we see now only the “quiescent” emission of the source, i.e. a higher flux density at larger wavelengths, since this radiation comes from outer and more transparent emitting regions.

The faint state allowed us to recognize important spectral features, which are usually hidden by the beamed synchrotron emission from the jet. The first is the little blue bump in the optical band, peaking around the V and B bands, and likely due to the contribution of Fe II and Mg II emission lines and Balmer continuum produced in the BLR (Wills et al. 1985). Another minor bump seems to peak in the J band, and this is most likely the signature of a broad and prominent Hα line.
Fig. 7. Broad-band spectral energy distribution of 3C 454.3. Data acquired by the XMM-Newton instruments (EPIC and OM) in July and December 2006 are shown in blue and red, respectively. The same colours are used to plot simultaneous low-energy (radio-to-optical) data taken by the WEBT observers (see text for more details). X-ray spectra resulting from previous satellite pointings are also shown, in particular those obtained from the Chandra, INTEGRAL, and Swift (XRT and BAT instruments) observations in 2005. Swift-XRT spectra are complemented by simultaneous near-IR-to-UV data from the REM telescope and UVOT detector (Giommi et al. 2006), while radio-to-optical data from the WEBT (open circles) indicate brightness levels during the Chandra and INTEGRAL pointings.

But the major feature, which was clearly revealed by the data acquired by the Optical Monitor onboard XMM-Newton, is the spectral break in the $U$ band, with the transition from a soft optical spectrum to a hard UV one. This suggests the presence of a big UV bump most likely due to thermal emission from the accretion disc, as already recognized in few other quasar-type blazars, but not yet in 3C 454.3.

These BLR and thermal emission components explain why the optical and near-infrared light curves show an increasing variability amplitude when going from the higher to the lower frequencies, as well as the redder-when-brighter behaviour noticed by Villata et al. (2006). Indeed, when the jet emission decreases, the blue part of the optical spectrum cannot go below a certain level because of the non-jet contributions.

A power-law model with Galactic photoelectric absorption gives a fair fit to the XMM-Newton X-ray spectra. Some amount of extra absorption ($\sim 20\%$ for the July observation and $\sim 40\%$ for the December one) yields better results from a statistical point of view. Since the need of even much higher values of extra absorption was claimed by various authors when analysing past X-ray data, taken during both bright and faint states, this might suggest the presence of absorbing material with variable column density, as observed for AO 0235+164 (Wolfe et al. 1982) and suggested for BL Lacertae (Ravasio et al. 2003). However, it is worth mentioning that the highest $N_H$ values have been found when analysing the more uncertain BeppoSAX and Swift data.

The possibility that the requirement of extra absorption actually hides an intrinsic curvature of the soft-X-ray spectrum is not supported by our results. Indeed, applying curved models to the XMM-Newton data does not produce significant curvatures and does not improve the goodness of fit with respect to the single power-law case.

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References

Angione, R. J. 1971, AJ, 76, 412

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