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Multi-wavelength Observations of Blazar AO 0235+164 in the 2008-2009 Flaring State

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ABSTRACT

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The blazar AO 0235+164 ($z=0.94$) has been one of the most active objects observed by *Fermi* Large Area Telescope (LAT) since its launch in Summer 2008. In addition to the continuous coverage by *Fermi*, contemporaneous observations were carried out from the radio to γ -ray bands between 2008 September and 2009 February. In this paper we summarize the rich multi-wavelength data collected during the campaign (including F-GAMMA, GASP-WEBT, Kanata, OVRO, RXTE, SMARTS, Swift and other instruments), examine the cross-correlation between the light curves measured in the different energy bands, and interpret the resulting spectral energy distributions in the context of well-known blazar emission models. We find that the γ -ray activity is well correlated with a series of near-IR/optical flares, accompanied by the increase in the optical polarization degree. On the other hand, the X-ray light curve shows a distinct 20-day high

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state of unusually soft spectrum, which does not match the extrapolation of the optical/UV synchrotron spectrum. We tentatively interpret this feature as the bulk Compton emission by cold electrons contained in the jet, which requires an accretion disk corona with effective covering factor of 19% at a distance of $100 R_g$. We model the broad-band spectra with a leptonic model with external radiation dominated by the infrared emission from the dusty torus.

46 *Subject headings:* BL Lacertae objects: individual (AO 0235+164) — galaxies:
 47 active — gamma rays: observations

48 1. Introduction

49 Blazars are a class of active galactic nuclei characterized by high flux variability at all
 50 wavelengths and compact (milli-arcsecond scale) radio emission of extreme brightness tem-
 51 peratures, often exceeding the Compton limit (Urry 1999). Their radio spectra are generally
 52 well-described by a power-law shape, with a “flat” spectral index $\alpha < 0.5$ (where the flux
 53 density $F_\nu \propto \nu^{-\alpha}$). Multi-epoch VLBI (Very Long Baseline Interferometry) observations
 54 often show superluminal expansion, and the radio and optical emission is usually highly
 55 polarized. These general properties are well-described as arising in a relativistic jet pointing
 56 close to our line of sight (Blandford & Rees 1978). The jet, presumably deriving its power
 57 from accretion onto a supermassive, rotating black hole surrounded by an accretion disk,
 58 contains ultrarelativistic electrons (with particle Lorentz factors γ_{el} reaching $10^3 - 10^5$, de-
 59 pending on the object). These relativistic electrons produce soft photons from radio up to
 60 UV (or in some cases, soft X-rays) through synchrotron emission, and high-energy photons
 61 up to TeV energies, via the inverse-Compton process which involves scattering of synchrotron
 62 photons (the SSC scenario), as well as scattering of externally produced soft photons (the
 63 External Radiation Compton, ERC, scenario). A contribution to the high energy radiation
 64 can also be provided by synchrotron radiation of pair cascades powered by hadronic pro-
 65 cesses and by synchrotron emission of ultra-high-energy protons and muons (see reviews of
 66 radiative models of blazars by Sikora & Madejski 2001; Levinson 2006; Böttcher 2007).
 67 Noting difficulties of hadronic models to explain the spectra of luminous blazars (Sikora et
 68 al. 2009; Sikora 2011), we investigate in this paper only leptonic models, i.e., the models
 69 which involve production of radiation by directly accelerated electrons. Densely sampled,
 70 simultaneous monitoring observations throughout the entire electromagnetic spectrum from
 71 the radio to γ -ray bands can provide important constraints on such models.

72 When emission lines are absent or weak, with an equivalent width (EW) less than 5 \AA in
 73 the rest frame (see, e.g., Stickel et al. 1991), a blazar is classified as a BL Lac object; otherwise

74 it belongs to the class of flat-spectrum radio quasars (FSRQs). While in a majority of BL Lac
75 objects - especially in those with the νF_ν spectral energy distribution (SED) peaking in the
76 far UV - to X-ray range (the so-called HSP, or “high-synchrotron peaked BL Lac objects”)
77 - detection of emission lines is rare, and if detected, the lines are extremely weak (for recent
78 measurements, see, e.g., Stocke, Danforth & Perlman 2011), in the objects where the SED
79 peaks in the infrared or optical range (the so-called LSP, or “low-synchrotron peaked BL
80 Lac objects”), easily discernible emission lines have been detected often. When detected,
81 such lines provide a measurement of redshift, but also yield crucial information about the
82 details of accretion in the central source. In some cases such as AO 0235+164 (Raiteri et
83 al. 2007), discussed in this paper, and even BL Lacertae (Vermeulen et al. 1995; Corbett et
84 al. 2000), the prototype of the BL Lac class, the EW of emission lines can vary from one
85 observational epoch to another. This is primarily due to large-amplitude variability of the
86 nonthermal continuum, which becomes brighter or fainter with respect to the presumably
87 less-variable emission lines. Regardless, the detailed properties of the emission lines are
88 crucial in establishing the radiative environment encountered by the jet emerging from the
89 nucleus, and thus are indispensable in establishing the most likely source of seed-photon
90 population for inverse Compton scattering. While the most compelling scenario has the
91 internal jet photons dominating this population in the HSP sub-class, and the external
92 photons (from emission-line region, or disk photons rescattered by the medium confining the
93 lines) in FSRQs, the situation with LSP BL Lac objects is unclear.

94 Studies of an LSP blazar AO 0235+164 provide an exceptional opportunity to answer
95 this question. It is one of the original BL Lac objects in the Stein et al. (1976) compila-
96 tion, discovered via optical identification of a variable radio source by Spinrad & Smith
97 (1975). Early observations - as well as the inspection of historical plates - revealed that
98 optical variability can range over 5 magnitudes (Rieke et al. 1976), motivating monitoring
99 observations over a wide range of frequencies since its discovery. The redshift $z_{\text{em}} = 0.94$
100 has been inferred from weak optical emission lines by Cohen et al. (1987), but even earlier
101 optical spectroscopy revealed two absorption line systems, one at $z_{\text{ab1}} = 0.524$, and another,
102 weaker one at $z_{\text{ab2}} = 0.852$ discovered by Burbidge et al. (1976) and by Rieke et al. (1976).
103 The intervening $z_{\text{ab1}} = 0.524$ system has also been detected in absorption in the radio, via
104 the redshifted hydrogen 21 cm line by Wolfe & Wills (1976) and Roberts (1976), but also as
105 a Ly α absorber, revealing damped Ly α properties (Snijders 1982), and implying a *consid-*
106 *erable absorption in other bands*. Detailed studies of that absorbing system by Junkkarinen
107 et al. (2004) allow accurate corrections to be applied to the observed optical spectra in order
108 to determine reliably the intrinsic spectrum of the blazar. Likewise, since the environment
109 in the field of AO 0235+164 is complex and includes several possibly interacting foreground
110 galaxies at $z_{\text{ab1}} = 0.524$ as well as the system at $z_{\text{ab2}} = 0.852$, the *emission* in the optical-UV

111 band (and to much lesser degree, in the soft X-ray band) may be contaminated. One galaxy,
 112 probably a normal spiral, is 1.3 arcsec east, while another object, about 2 arcsec to the
 113 south, is known to be an AGN and could affect the flux of AO 0235+164 when it is very
 114 faint, especially in the bluer part of the spectrum (Raiteri et al. 2005).

115 Historical data for this source are abundant. Radio observations were performed by
 116 many instruments, starting from about 100 MHz up to 300 GHz, and including multi-epoch
 117 VLBI studies (Jorstad et al. 2001). Space and ground-based infrared data are available from
 118 sub-mm (far-IR) down to micron wavelengths (near-IR); optical bands, UBVRI, have been
 119 extensively monitored by many telescopes around the world. AO 0235+164 has also been de-
 120 tected in the high energy band by essentially all soft X-ray observatories including *Einstein*
 121 (Worrall & Wilkes 1990), *EXOSAT* (Ghosh & Soundararajaperumal 1995), *ROSAT* (Made-
 122 jski et al. 1996, Comastri et al. 1997), *ASCA* (Madejski et al. 1996, Junkkarinen et al. 2004),
 123 *Beppo-SAX* (Padovani et al. 2004), *RXTE* (Webb et al. 2000), and *XMM-Newton* (Raiteri
 124 et al. 2008). This source has also been identified as a powerful and strongly variable γ -
 125 ray emitter via observations by *EGRET* onboard the *Compton Gamma-Ray Observatory*
 126 (*CGRO*) in the high γ -ray energy range from 30 MeV to 20 GeV, with six pointings be-
 127 tween 1992 and 1997 providing two detections (Hunter et al. 1993; Madejski et al. 1996) and
 128 four upper limits. The mid-energy γ -ray emission was probed by *COMPTEL* during *CGRO*
 129 Cycle 4 (1994-1995), yielding only upper limits for the flux in the interval of 0.75-30 MeV.
 130 These numerous multi-wavelength observations show that AO 0235+164 is characterized by
 131 extreme variability on long (month-years) and short (intraday) time scales over a wide range
 132 of the electromagnetic spectrum.

133 The study of blazars, of their broad-band spectra and of their complex variability, has
 134 been greatly enriched since the start of scientific observations with the *Fermi* Large Area
 135 Telescope (LAT) in 2008 August (Atwood et al. 2009) thanks to its high sensitivity and
 136 essentially uninterrupted observations afforded by the survey mode. Such new and sensitive
 137 γ -ray observations motivated many multi-band campaigns, often conducted with dedicated
 138 facilities, and AO 0235+164 was (and continues to be) one of the well-sampled targets. This
 139 paper presents the results of the LAT monitoring of AO 0235+164, as reported in Section
 140 2. The description of multi-wavelength observations conducted between 2008 August and
 141 2009 February when the source showed strong activity in γ -rays as well as in radio through
 142 optical and X-ray bands (Corbel & Reyes 2008; Foschini et al. 2008), follows in Section 3. The
 143 analysis of those data, including the discussion of the temporal profiles measured in various
 144 bands and the connection to the γ -ray activity, is reported in Section 4. A significant part
 145 of these data have been independently analyzed by Agudo et al. (2011b). In Section 5 we
 146 present the overall spectral energy distribution (SED) and its temporal behavior, and discuss
 147 the implications of the data on the modeling of emission processes and the structure of the

148 jet in AO 0235+164: there, we argue that while the equivalent width of emission lines in this
 149 object might suggest a classification as a BL Lac object, the isotropic luminosity inferred
 150 from the data indicates it is a quasar. In Section 6, we show models of the broad-band
 151 emission in the context of synchrotron + Compton models. Our consideration of the broad-
 152 band SED suggests that the most likely mechanism for γ -ray emission is Comptonization
 153 of circumnuclear IR radiation from dust, commonly present in quasars. This is a different
 154 scenario from the one proposed by Agudo et al. (2011b), who argued for the synchrotron
 155 self-Compton process. We discuss these two approaches in Section 7. We conclude with a
 156 summary of our results in Section 8.

157 2. *Fermi*-LAT Observations and Data Analysis

158 The LAT, the primary instrument onboard the *Fermi* γ -ray observatory, is an electron-
 159 positron pair conversion telescope sensitive to γ -rays of energies from 20 MeV to > 300 GeV.
 160 The LAT consists of a high-resolution silicon microstrip tracker, a CsI hodoscopic electromag-
 161 netic calorimeter and an anticoincidence detector for the identification of charged particles
 162 background. The full description of the instrument and its performance can be found in
 163 Atwood et al. (2009). The large field of view (~ 2.4 sr) allows the LAT to observe the full sky
 164 in survey mode every 3 hours. The LAT point spread function (PSF) strongly depends on
 165 both the energy and the conversion point in the tracker, but less so on the incidence angle.
 166 For 1 GeV normal-incidence conversions in the upper section of the tracker the PSF 68%
 167 containment radius is 0.8° .

168 The *Fermi*-LAT data of AO 0235+164 presented here were obtained in the time pe-
 169 riod between 2008 August and 2009 February when AO 0235+164 entered a bright high
 170 γ -ray state; and immediately after, dropped to lower states. The data have been analyzed
 171 by using the standard *Fermi*-LAT software package¹. The Pass 6 Diffuse event class and
 172 P6_V3_DIFFUSE instrument response functions (Atwood et al. 2009) were used in our analy-
 173 sis. We selected events within a 15° region of interest (RoI) centered on the source position,
 174 having energy greater than 100 MeV. The data have been analyzed using the Science Tools
 175 software package (version v9r16). In order to avoid background contamination from the
 176 bright Earth limb, time intervals when the Earth entered the LAT Field of View were ex-
 177 cluded from the data set. In addition, events with zenith angles larger than 105° with respect
 178 to the Earth reference frame (Abdo et al. 2009) were excluded from the analysis. The data
 179 were analyzed with an unbinned maximum likelihood technique described by Mattox et al.

¹<http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/>

180 (1996) using the analysis software (`gtlike`) developed by the LAT team².

181 Accurate spectral and flux measurements require a reliable accounting for the diffuse
 182 foreground due to the Galactic interstellar emission, as well as the extragalactic diffuse γ -ray
 183 emission, the residual cosmic ray background, and contamination from nearby sources. The
 184 fitting procedure simultaneously fits for the parameters of the source of interest as well as of
 185 nearby γ -ray sources and the diffuse backgrounds, which in turn have been modeled using
 186 `gll_iem_v02` for the Galactic diffuse emission and `isotropic_iem_v02` for the extragalactic
 187 isotropic emission models³.

188 The sources surrounding AO 0235+164 were modeled using a power-law function:

$$\frac{dN}{dE} = \frac{N(1 - \Gamma)E^{-\Gamma}}{E_{max}^{1-\Gamma} - E_{min}^{1-\Gamma}} \quad (1)$$

189 where N is the normalization factor and Γ the photon index. In the fitting procedure, all
 190 sources within 10° were included in the model with the normalization factor N free, while
 191 the sources located between 10° and 20° had all the model parameters fixed to the 1FGL
 192 catalog values (Abdo et al. 2010a).

193 The plots in subsequent sections show only statistical errors for the fit parameters.
 194 Systematic errors arise mainly from uncertainties on the LAT effective area, which is derived
 195 from the on-orbit estimations. These errors could be as large as 10% below 0.1 GeV, <5%
 196 near 1 GeV and 20% above 10 GeV.

197 2.1. γ -ray Light Curve

198 The light curve of AO 0235+164 in the *Fermi*-LAT energy range has been assembled
 199 using 3-day long time bins and covers the first 6 months of data taking from 2008 August 4
 200 to 2009 February 4, when the source was in a high state and a large set of multi-wavelength
 201 observations is available. The light curve is obtained applying the `gtlike` fit across the
 202 overall energy range considered, from 100 MeV to 100 GeV, in each of the selected time
 203 bins. For each time interval the flux and the photon index of AO 0235+164 are determined
 204 using the maximum likelihood algorithm implemented in `gtlike`, following the procedure
 205 outlined in the previous section. The data are modeled with a power-law function with both
 206 the normalization factor and photon index left free in the likelihood fit.

²http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Likelihood

³<http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html>

207 The 6-month γ -ray light curve is reported in Figure 1 together with the photon index
 208 resulting from the likelihood fit in each time bin. The trend in the entire energy range from
 209 100 MeV to 100 GeV shows a clear high-state period followed by a final, narrow, high-flux
 210 peak.

211 The temporal behavior of the source in γ -rays was also studied in two separate energy
 212 ranges, from 100 MeV to 1 GeV and from 1 GeV to 100 GeV and the hardness ratio among
 213 the two bands has been determined. The analysis follows the same procedure described
 214 above to determine the overall light curve and the results are shown in the three bottom
 215 panels of Figure 1.

216 The arrows in the light curves represent 95% upper limits, which are calculated for data
 217 points with a test statistic (TS)⁴ lower than 10 (which corresponds to a significance somewhat
 218 higher than 3σ), or with a value of the ratio between flux error and flux ($F_{err}(E)/F(E)$) ≥ 0.5
 219 in order to obtain meaningful data points.

220 The results show that both the low- and high-energy profiles follow the same trend.
 221 Nevertheless, it is interesting to underline that the narrow peak at the end of the high-state
 222 period is mainly due to an enhanced low-energy flux. The ratio among the two fluxes also
 223 shows a value higher than the average in the same time interval.

224 2.2. γ -ray Spectral Analysis

225 The unbinned `gtlike` analysis has been applied to produce the γ -ray energy spectra
 226 shown in Figure 2. There, we divided the full energy range from 100 MeV to 100 GeV into 2
 227 equal logarithmically spaced bins per decade. In each energy bin a TS value greater than 10
 228 and a ratio between flux error and flux lower than 0.5 was required to quote a flux in that
 229 band, otherwise a 95% upper limit was given.

230 The standard `gtlike` tool was applied in each energy bin, modeling all the point sources
 231 in the region with a simple power-law spectrum with photon index fixed to 2. The normaliza-
 232 tion parameters of all point-like sources within 10° were left as free parameters in the fitting
 233 procedure, while the diffuse background components were modeled as described above in
 234 2.1. Two time intervals were selected for the γ -ray spectral analysis: the first corresponding
 235 to the X-ray flare interval (MJD 54750-54770), the second associated with the subsequent
 236 low γ -ray state (MJD 54780-54840). In those time intervals, both power-law and broken-

⁴The Test Statistics is defined as $TS = -2 \times (\log(L_1) - \log(L_0))$ with L_0 the likelihood of the Null-hypothesis model as compared to the likelihood of a competitive model, L_1 ; see Mattox et al. (1996).

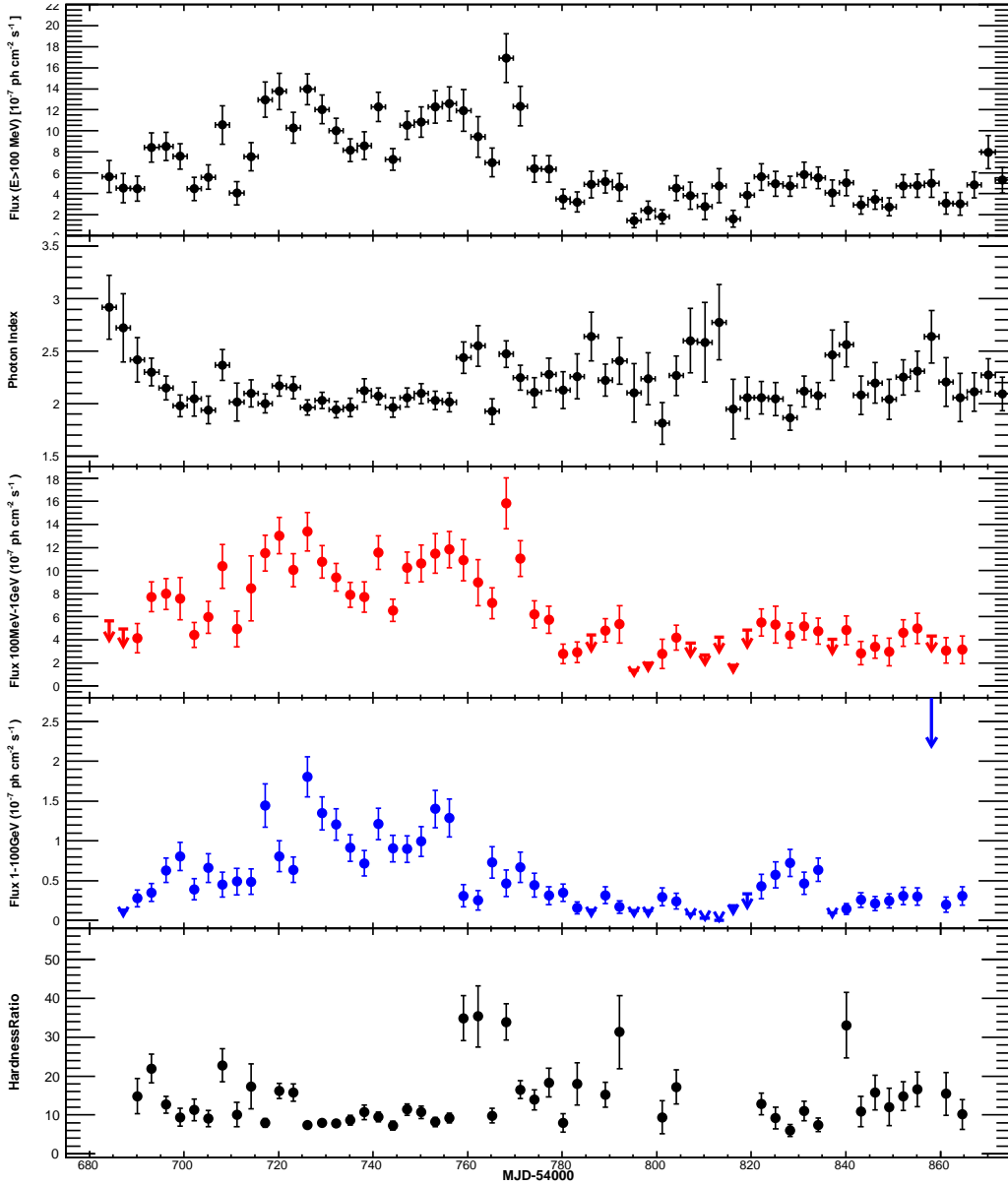


Fig. 1.— *Fermi*-LAT light curve from 2008 August 4 to 2009 February 4 in 3-day time intervals. The first panel from the top shows the flux, in the energy range from 100 MeV to 100 GeV, derived from the `gtlike` fit in the 3-days time intervals, assuming a simple power law spectrum. The second panel shows the photon index Γ in the same energy range from 100 MeV to 100 GeV. The third panel shows the light curve evaluated in the energy range from 100 MeV to 1 GeV. The fourth panel shows the light curve in the energy range from 1 GeV to 100 GeV. The last panel shows the hardness ratio defined as $\frac{F_{100\text{MeV}-1\text{GeV}}}{F_{1\text{GeV}-100\text{GeV}}}$ for the data points having a $\text{TS} > 10$ and $F_{\text{err}}(E)/F(E) > 0.5$ in both energy ranges. The hardness ratio is not evaluated if either of the two fluxes is an upper limit.

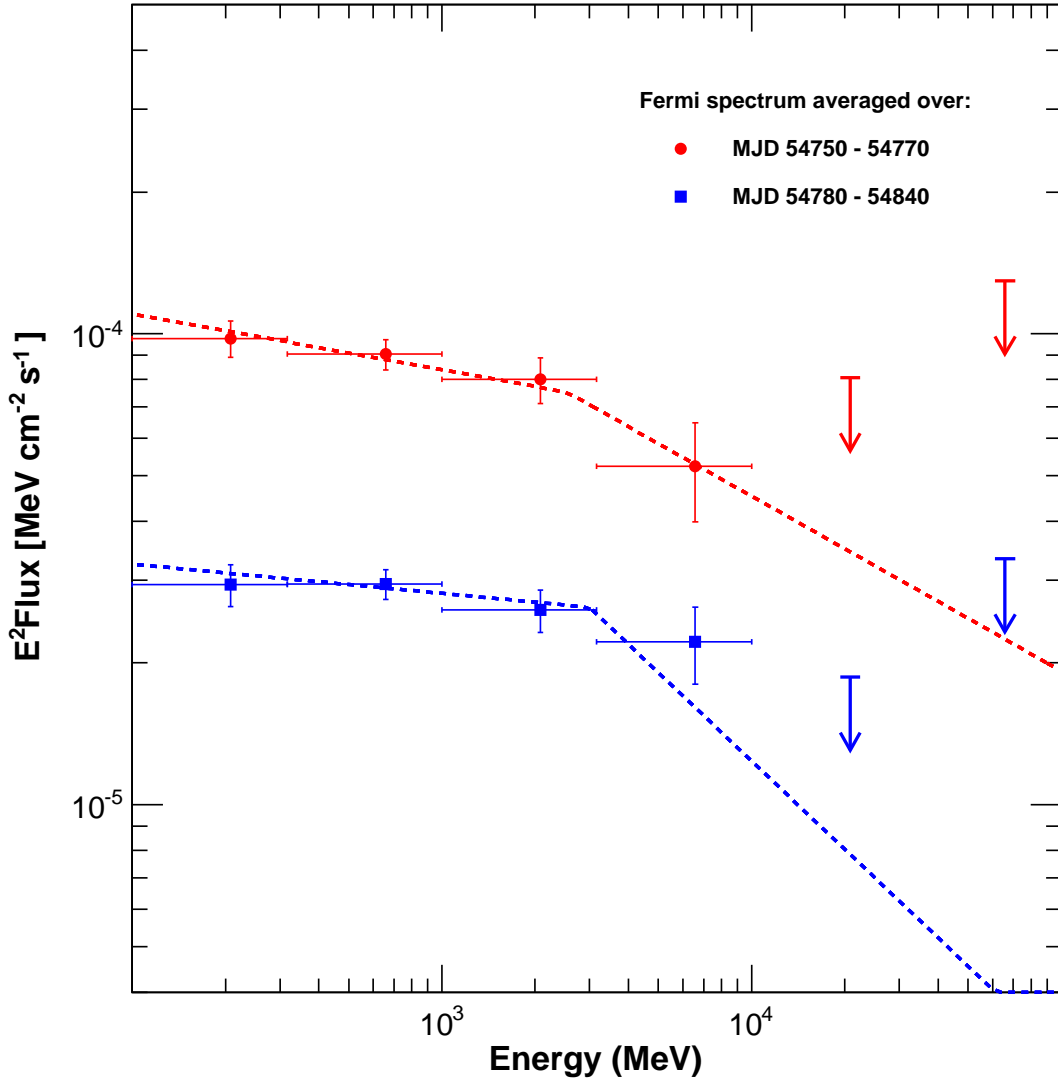


Fig. 2.— *Fermi*-LAT energy spectrum evaluated in different time intervals corresponding to the X-ray flare (red circles) from MJD 54750-54770 and γ -ray low state (blue squares) from MJD 54780-54840.

237 power-law functions provide a good fit of the spectral data. We show the results of the
 238 broken-power-law fit, since it provides a better fit to the high-energy spectrum of the source,
 239 from 100 MeV to 100 GeV, than a simple power law on the larger time intervals, as already
 240 studied in detail by Abdo et al. (2010b).

$$\frac{dN}{dE} = N_0 \times \begin{cases} (E/E_b)^{-\Gamma_1} & ; \text{ if } E < E_b \\ (E/E_b)^{-\Gamma_2} & ; \text{ otherwise} \end{cases} \quad (2)$$

Time Interval	Flux	Γ_1	Γ_2	Break Energy
MJD	$10^{-7} \text{ ph cm}^{-2}\text{s}^{-1}$			GeV
54750-54770	11.05±1.48	2.12±0.16	2.37±0.32	2.6±0.8
54780-54840	3.42±0.65	2.07±0.17	2.77±0.32	3.8±1.2

Table 1: Results of the `gtlike` fit of the γ -ray spectrum during the high and low states.

241 In both time intervals the Γ_1 index remains stable, while Γ_2 increases showing a softening
 242 of the high energy part of the spectrum when the source is in a fainter state, when also an
 243 increase in the break energy is observed. As also can be seen in Figure 1, the high γ -ray state
 244 around MJD 54760 is essentially due to the low energy photons (<1 GeV) and the spectra
 245 in Figure 2 show that the relative difference between the $E^2\text{Flux}$ values above 1 GeV and
 246 below 1 GeV is higher in the time interval around the flare than during the low γ -ray state.

247 3. Multi-wavelength Observations and Data Analysis

248 The multi-wavelength campaign conducted on AO 0235+164 in 2008-2009 saw a wide
 249 international participation. Table 2 reports the list of participating observatories, the energy
 250 bands, the period of observation and the number of collected data points.

251 3.1. Effect of intervening material in the line of sight on the optical, UV and 252 X-ray data

253 Conversion of the observed optical magnitudes into the intrinsic flux densities requires
 254 a special care, because the source emission is absorbed not only in our Galaxy, but also by
 255 the elliptical galaxy in the line of sight at redshift $z = 0.524$, as outlined in the Introduction.
 256 Junkkarinen et al. (2004) tried several different extinction models for AO 0235+164, conclud-
 257 ing that the best fit to their HST/STIS data is obtained by using models of Cardelli et al.

Observatory		Bands	Period of Observation	Data Points
<i>Radio</i>				
GASP-WEBT	Mauna Kea (SMA), USA	345 GHz	54664-54840	10
		230 GHz	54645-54842	23
	Medicina, Italy	5 GHz	54724	1
		8 GHz	54606-54777	7
		22 GHz	54604-54779	7
	Metsähovi (KURP-GIX),Finland	37 GHz	54633-54839	54
	Noto, Italy	43 GHz	54642-54841	8
	UMRAO, USA	5 GHz	54677-54840	16
		8 GHz	54621-54851	20
	F-GAMMA	Effelsberg 100-m	14.5 GHz	54633-54848
2.64			54414-55227	23
4.85 GHz			54414-55227	24
8.35 GHz			54414-55227	24
10.45 GHz			54414-55227	25
14.6 GHz			54422-55227	22
23.05 GHz			54422-55227	17
32 GHz			54616-55227	11
42 GHz			54546-55227	8
IRAM 30-m			86.2 GHz	54382-55228
		142.3 GHz	54382-55228	15
		228.4 GHz	54440-54806	5
		88.9 GHz	54700	1
		169 GHz	54883	1
OVRO			15 GHz	54661-54848
<i>Near-Infrared</i>				
GASP-WEBT	Campo Imperatore	J	54645-54794	87
		H	54645-54794	82
		K	54645-54794	83
Kanata		J	54690-54753	21
		V	54690-54753	21
		Ks	54690-54753	21
SMARTS		J	54662-54847	69
		K	54662-54842	39
<i>Optical</i>				
GASP-WEBT	Abastumani 70 cm	R	54687-54780	287
	Armenzano, 40 cm	R	54699-54727	16
	Calar Alto	R	54712-54887	5
	Crimean 70cm; ST-7	R	54691-54805	218
	Kitt Peak (MDM 130 cm)	R	54745-54801	50
	L'Ampolla	R	54778-54784	2
	Lulin (SLT)	R	54688-54862	120
	Roque (KVA 35 cm)	R	54748-54862	29
	San Pedro Martir 84 cm	R	54709-54773	15
	St. Petersburg	R	54698-54865	41
	Talmassons	R	54728-54843	11
	Tuorla	R	54722-54732	3
	SMARTS		R	54662-54868
B			54662-54871	69
V			54662-54859	68
Steward		R	54743-54832	39
		V	54743-54863	44
SWIFT-UVOT		U	54711-54818	16
		B	54711-54818	16
		V	54711-54818	16
<i>Ultra-Violet</i>				
SWIFT-UVOT		UVW1	54711-54818	16
		UVM2	54711-54818	15
		UVW2	54711-54818	16

Table 2: Observatories participating in the work, periods of observations and number of data points used in this analysis.

258 (1989) with $R_V = 3.1$ and $E_{B-V} = 0.154$ for the Galaxy, and $R_V = 2.51$ and $E_{B-V} = 0.227$
 259 for the $z = 0.524$ system. This model accurately reproduces the 2175\AA absorption feature
 260 produced by the $z = 0.524$ galaxy, but the far-UV end of their spectrum indicated a sharp
 261 hardening. Raiteri et al. (2005) proposed that this far-UV hardening is real and that it
 262 marks the onset of a new spectral component. However, the fact that the shape of this
 263 feature does not change with the overall optical/UV luminosity indicates that the whole
 264 optical/UV spectrum is produced by a single synchrotron component, which intrinsic shape
 265 must be close to a power-law. The far-UV hardening most likely is an artefact of overesti-
 266 mated extinction from the dust in the $z = 0.524$ galaxy. We modify the best-fit extinction
 267 model of Junkkarinen et al. (2004) by replacing the Cardelli et al. (1989) model for the
 268 $z = 0.524$ galaxy with an analytical model of Pei (1992). In the first step, we modify the
 269 “Milky Way” model with parameters listed in Table 4 of Pei (1992) to match the Cardelli et
 270 al. (1989) model for $R_V = 2.51$ and $E_{B-V} = 0.227$. In particular, we adopt $\lambda_{2175\text{\AA}} = 2170\text{\AA}$
 271 and $n_{\text{FUV}} = 5.5$, and we multiply the normalization parameters a_i by additional factors f_i :
 272 $f_{\text{FUV}} = 1.5$, $f_{2175\text{\AA}} = 1.33$ and $f_{\text{BKG}} = 1.05$. In the second step, we turn off the “FUV”
 273 component of the Pei (1992) model for the $z = 0.524$ galaxy by setting $f_{\text{FUV}} = 0$. This
 274 modification affects only the observed wavelengths shorter than $\sim 3300\text{\AA}$, the location of
 275 the 2175\AA feature redshifted by $z = 0.524$, and is necessary to align the FUV spectra with
 276 the optical-NIR spectra (see Figure 7). We stress that extinction at longer wavelengths is
 277 very well constrained by the clear detection of a redshifted 2175\AA feature by Junkkarinen
 278 et al. (2004), and thus cannot be increased. The resulting total extinction values A_λ for the
 279 Swift/UVOT filters are: W2: 2.87; M2: 2.94; W1: 2.52; U: 2.71; B: 1.84; V: 1.46. For the
 280 remaining optical and near IR filters, we use the values from Table 5 of Raiteri et al. (2005):
 281 R: 1.26; I: 0.90; J: 0.46; H: 0.28; K: 0.17. We calculate the incident flux $F_{\text{inc},\lambda}$ in the band
 282 corresponding to λ from the observed (absorbed) flux $F_{\text{abs},\lambda}$ via $F_{\text{abs},\lambda}/F_{\text{inc},\lambda} = 10^{A_\lambda/2.5}$. The
 283 same corrections are applied to the ground-based optical data.

284 In addition, the source photometry is contaminated by the emission of a nearby AGN
 285 (named ELISA by Raiteri et al. (2005)). Hence, we subtracted the ELISA contribution from
 286 the observed flux densities and then corrected for the combined extinction of both galaxies,
 287 following the prescriptions given by Raiteri et al. (2005) and Raiteri et al. (2008).

288 Likewise, the X-ray data need to be corrected for the effect of absorption: here, the
 289 absorption effects of *both* our own Galaxy and the intervening $z = 0.524$ system are con-
 290 siderable. Madejski et al. (1996) and Junkkarinen et al. (2004) argue that the absorption
 291 in the intervening system originates in material with abundances different from Galactic
 292 and, in reality, correct modeling of such absorption should take this into effect. However,
 293 as discussed by Madejski et al. (1996), the combined *ROSAT* and *ASCA* spectral fitting
 294 suggests that this effect is relatively modest, the joint *ROSAT* – *PSPC* and *ASCA* data

295 are adequately fitted by an absorbing column of $2.8 \pm 0.4 \times 10^{21} \text{ cm}^{-2}$ located at $z = 0$.
 296 Since the *Swift* XRT data have somewhat lower signal-to-noise ratio (S/N) than the *ASCA*
 297 observations, we simply adopt such a “local” model for absorption, since the main objective
 298 of our observations was to determine the underlying continuum of the AO 0235+164 rather
 299 than the detailed spectral properties of the absorber. We note that this value is in fact
 300 consistent with the spectral fit to the *Swift* XRT data.

301 3.2. GASP-WEBT

302 The GLAST-AGILE Support Program (GASP) of the Whole Earth Blazar Telescope
 303 (WEBT) was initiated in 2007 with the aim of performing a long-term multi-wavelength
 304 monitoring of bright, γ -loud blazars (Villata et al. 2008a, 2009; D’Ammando et al. 2009;
 305 Raiteri et al. 2010). The GASP optical (R band), near-IR, and radio data are intended
 306 to complement the high-energy observations by the *AGILE* and *Fermi* (formerly *GLAST*)
 307 satellites.

308 AO 0235+164 has been the target of several WEBT campaigns in the past (Raiteri et al.
 309 2001, 2005, 2006, 2008) and it is now one of the GASP sources of highest observing priority.
 310 During the high γ -ray state observed in the second half of 2008, the source underwent an
 311 exceptional optical-to-radio outburst closely monitored by the GASP (Villata et al. 2008b,c;
 312 Bach et al. 2008). The GASP optical data presented here were taken at the following ob-
 313 servatories: Abastumani, Armenzano, Calar Alto, Crimean, Kitt Peak (MDM), L’Ampolla,
 314 Lulin, Roque de los Muchachos (KVA), San Pedro Martir, St. Petersburg, Talmassons, and
 315 Tuorla. Near-IR data in the J , H , and K bands are all from Campo Imperatore. Millimeter
 316 and centimeter radio observations were performed at the SMA (230 and 345 GHz), Noto
 317 (43 GHz), Metsähovi (37 GHz), Medicina (5, 8, and 22 GHz), and UMRAO (4.8, 8.0, and
 318 14.5 GHz) observatories. All IR, optical, and UV data are corrected for the effects of the
 319 intervening absorber (both due to the Milky Way, and the intervening galaxy) as outlined
 320 above.

321 3.3. F-GAMMA

322 During the 2008-2009 flaring period, quasi-simultaneous multi-frequency cm/mm-band
 323 (from 2.64 GHz to 230 GHz) observations of AO 0235+164 were obtained using the Effelsberg
 324 100-m and IRAM 30-m telescopes, within the framework of a *Fermi* related monitoring

325 program of γ -ray blazars (F-GAMMA program⁵, Fuhrmann et al. (2007), Angelakis et al.
326 (2008)).

327 The Effelsberg measurements were conducted with the secondary focus heterodyne re-
328 ceivers at 2.64, 4.85, 8.35, 10.45, 14.60, 23.05, 32.00 and 43.00 GHz. The observations were
329 performed quasi-simultaneously with cross-scans, by slewing over the source position in the
330 azimuth and elevation directions with an adaptive number of sub-scans chosen to reach
331 the desired sensitivity (for details, see Fuhrmann et al. 2008; Angelakis et al. 2008). Con-
332 sequently, pointing offset correction, gain correction, atmospheric opacity correction and
333 sensitivity correction have been applied to the data.

334 The IRAM 30-m observations were carried out with calibrated cross-scans using the
335 single pixel heterodyne receivers B100, C150, B230 operating at 86.2, 142.3 and 228.4 GHz.
336 The opacity corrected intensities were converted into the standard temperature scale and
337 finally corrected for small remaining pointing offsets and systematic gain-elevation effects.
338 The conversion to the standard flux density scale was done using the instantaneous conversion
339 factors derived from frequently observed primary (Mars, Uranus) and secondary (W3(OH),
340 K3-50A, NGC 7027) calibrators.

341 3.4. OVRO

342 Observations of AO 0235+164 at 15 GHz with the Owens Valley Radio Observatory
343 (OVRO) 40-meter telescope were made as part of an ongoing blazar monitoring program
344 (Richards et al. 2011). The 40-m telescope is equipped with a cooled receiver at the prime
345 focus, with a 3.0 GHz bandwidth centered on 15.0 GHz and 2.5 GHz noise-equivalent recep-
346 tion bandwidth. The receiver noise temperature is about 30 K, and the total system noise
347 temperature including CMB, atmospheric, and ground contributions is about 55 K. A dual
348 off-axis corrugated horn feed projects two approximately Gaussian beams (157 arcsec full
349 width half maximum, FWHM) on the sky, separated in azimuth by 12.95 arcmin. Dicke
350 switching between the two beams is performed using the cold sky in the off-source beam as a
351 reference, and a second level of switching is performed by alternating the source between the
352 two beams to cancel atmospheric and ground noise. Calibration is achieved using a stable
353 diode noise source for relative calibration and is referred to observations of 3C 286, for which
354 we assume a flux density of 3.44 Jy (Baars et al. 1977) with about 5% absolute scale error.
355 OVRO flux density measurements have a minimum uncertainty of 4 mJy in 32 s of on-source
356 integration, and a typical RMS relative error of 3%.

⁵<http://www.mpifr-bonn.mpg.de/div/vlbi/fgamma/fgamma.html>

3.5. IRAM Plateau de Bure Interferometer (PdBI)

357

358 The Plateau de Bure Interferometer (PdBI; Winters & Neri (2010)) is able to observe in
 359 three atmospheric windows located around wavelengths of 1.3 mm, 2 mm, and 3 mm. Each
 360 of these bands covers a continuous range of frequencies that are available for observations;
 361 these ranges are 201–267 GHz for the 1.3 mm band, 129–174 GHz for the 2 mm band, and
 362 80–116 GHz for the 3 mm band.

363 Systematic monitoring of AGN is a by-product of regular observatory operations. The
 364 PdBI uses active galactic nuclei as phase and amplitude calibrators. Usually, one or two cali-
 365 brators are measured every ~ 20 minutes for ~ 2 min (per source) throughout an observation.
 366 Antenna temperatures are converted into physical flux densities using empirical antenna ef-
 367 ficiencies as conversion factors. These factors are functions of frequencies and are located in
 368 the range from ~ 22 Jy/K (for the 3-mm band) to ~ 37 Jy/K (for the 1.3-mm band).

369 The PdBI is equipped with dual linear polarization Cassegrain focus receivers. This
 370 makes it possible to observe both orthogonal polarizations – “horizontal” (H) and “vertical”
 371 (V) with respect to the antenna frame – simultaneously. Due to the hardware layout of
 372 the correlators it is not yet possible to observe all Stokes parameters. We collect linear
 373 polarization data on point sources via the Earth rotation polarimetry, i.e. we monitor the
 374 fluxes in the H and V channels as functions of parallactic angle ψ . The source polarization
 375 is derived from the parameterization

$$q(\psi) = \frac{V - H}{V + H}(\psi) \equiv m_L \cos[2(\psi - \chi)] \quad (3)$$

376 Here m_L is the fraction of linear polarization (ranging from 0 to 1) and χ is the polar-
 377 ization angle (ranging from 0° to 180° and counted from north to east). For details, please
 378 refer to Trippe et al. (2010).

3.6. Kanata

379

380 We performed the V -, J -, and Ks -band photometry and polarimetry of AO 0235+164
 381 from 2008 August to 2008 October, using the TRISPEC instrument (Watanabe et al.
 382 2005) installed at the 1.5m Kanata telescope located at the Higashi-Hiroshima Observa-
 383 tory. TRISPEC has a CCD and two InSb arrays, enabling photo-polarimetric observations
 384 in one optical and two NIR bands simultaneously. We obtained 21 photometric data points
 385 in the V , J , Ks bands. A unit of the polarimetric observing sequence consisted of succes-
 386 sive exposures at 4 position angles of the half-wave plates: $0^\circ, 45^\circ, 22.5^\circ, 67.5^\circ$. The data

387 were reduced according to the standard procedure of CCD photometry. We measured the
 388 magnitudes of objects with the aperture photometry technique. We performed differential
 389 photometry with a comparison star taken in the same frame of AO 0235+164. Its position is
 390 R.A.=02:38:32.31, Dec=+16:35:59.7 (J2000) and its magnitudes are $V = 12.720$, $J = 11.248$
 391 and $Ks = 10.711$ (Gonzalez-Perez et al. 2001; Cutri et al. 2003). The photometric data have
 392 been corrected for the Galactic extinction of $A(V) = 1.473$, $A(J) = 0.458$ and $A(Ks) = 0.171$,
 393 as explained in Section 3.1.

394 We confirmed that the instrumental polarization was smaller than 0.1% in the V band
 395 using observations of unpolarized standard stars and hence, we applied no correction for it.
 396 The zero point of the polarization angle is corrected as standard system (measured from
 397 north to east) by observing the polarized stars, HD19820 and HD25443 (Wolff, Nordsieck &
 398 Nook 1996).

399 3.7. SMARTS

400 AO 0235+164 was observed at the Cerro Tololo Inter-American Observatory (CTIO)
 401 as part of a photometric monitoring campaign of bright blazars with the Small and Mod-
 402 erate Aperture Research Telescope System (SMARTS). The source was observed with the
 403 SMARTS 1.3m telescope and ANDICAM instrument (DePoy et al. 2003). ANDICAM is a
 404 dual-channel imager with a dichroic linked to an optical CCD and an IR imager, from which
 405 it is possible to obtain simultaneous data from 0.4 to 2.2 μm . Optical and near-infrared
 406 observations were taken in B, V, R, J, and K bands.

407 Optical data were bias-subtracted, overscan-subtracted, and flat-fielded using the CCD-
 408 PROC task in IRAF. Infrared data were sky-subtracted, flat-fielded, and dithered images
 409 were combined using in-house IRAF scripts. The raw photometry of comparison stars in
 410 the field of the blazar were calibrated using photometric zero-points that were measured
 411 from 2008-2009 observations with ANDICAM of optical (Landolt 1992) and near-infrared
 412 (Persson et al. 1998) primary standards for each filter, correcting for atmospheric extinction
 413 derived from all the standards taken together. The averages of the comparison stars were
 414 used as a basis of differential photometry with respect to the blazar for all observations.
 415 Errors were determined by calculating the 1σ variation in the magnitude of the comparison
 416 stars.

417 Fluxes were computed using values for Galactic extinction from Schlegel, Finkbeiner
 418 & Davis (1998) and subtracting the nearby AGN ‘ELISA’ as described in Raiteri et al.
 419 (2005). In addition, we accounted for the absorption of the $z = 0.524$ system as outlined in

420 Junkkarinen et al. (2004).

421

3.8. Steward Observatory

422 Optical spectropolarimetry and spectrophotometry of AO 0235+164 during fall 2008 was
 423 provided by the monitoring program being conducted at Steward Observatory (Smith et al.
 424 2009). This program utilizes the Steward Observatory CCD Spectropolarimeter (SPOL,
 425 Schmidt et al. 1992a) at either the 2.3 m Bok telescope located on Kitt Peak, AZ, or the
 426 1.54 m Kuiper telescope on Mt. Bigelow, AZ. The publicly available data⁶ include linear
 427 polarization and flux spectra (in 1st order) spanning 4000–7550 Å. General data-taking and
 428 reduction procedures used for this project are described in detail in Smith et al. (2003) and
 429 Smith et al. (2009). For the monitoring of AO 0235+164, a 3" or 4"-wide slit was used for
 430 spectropolarimetry, depending on the observing conditions, and yielding a spectral resolution
 431 of 20–25 Å. An L-38 blocking filter was inserted into the collimated beam for all observa-
 432 tions to prevent significant contamination from 2nd-order light until well past 7600 Å. Total
 433 exposure times of between 24 and 80 minutes were used depending on the brightness of
 434 AO 0235+164 and the sky/seeing conditions. Usually, a high signal-to-noise-ratio measure-
 435 ment ($S/N > 100$) of the degree of polarization (P) is determined from each observation
 436 by taking the median linear, normalized Stokes parameters (q and u) in a 2000 Å-wide bin
 437 centered at 6000 Å. The reported values of P have been corrected for statistical bias as in
 438 Wardle & Kronberg (1973), but this correction is typically not significant because of the
 439 high S/N of the binned data. The position angle (θ) of the optical linear polarization
 440 is calibrated by observing interstellar polarization standard stars (Schmidt et al. 1992b).
 441 Likewise, the flux spectra resulting from the spectropolarimetry are calibrated using obser-
 442 vations of spectrophotometric standard stars (Massey et al. 1988). The flux spectra are
 443 corrected for atmospheric extinction using the the standard extinction curves given in Bald-
 444 win & Stone (1984) and Stone & Baldwin (1983). Flux information for AO 0235+164 was
 445 obtained through differential spectrophotometry of the blazar and a nearby field star ("Star
 446 4"; Gonzalez-Perez et al. 2001). The spectrophotometry employed slits with widths of 7.6"
 447 or 12.7" to minimize seeing- and color-dependent slit losses since the SPOL slit is left fixed
 448 in an east-west orientation on the sky and is not aligned with the parallactic angle. The
 449 wide-slit spectra of AO 0235+164 and the comparison star were convolved with standard
 450 filter transmission curves to determine differential magnitudes and derive the apparent mag-
 451 nitude of the blazar in the V and R bandpasses. The spectrophotometric observations were
 452 much shorter in duration (typically < 5 min) than the spectropolarimetry, but of sufficient

⁶<http://james.as.arizona.edu/~psmith/Fermi>

453 S/N to be used to correct the much higher S/N flux spectra of AO 0235+164 resulting from
 454 the spectropolarimetry for any slit losses associated with the narrower slits used for those
 455 measurements.

456 3.9. *Swift* XRT and UVOT

457 AO 0235+164 was monitored as a result of an approved target of opportunity (ToO)
 458 request by the *Swift* satellite (Gehrels et al. 2004) with weekly observations of $\approx 1 - 2$ ks
 459 performed from 2008 September 2 to 2008 December 18 (Table 3) with the X-ray Telescope
 460 (XRT; Burrows et al. 2005) and with the Ultraviolet/Optical Telescope (UVOT; Roming et
 461 al. 2005).

462 The XRT data were reduced with the standard software (`xrtpipeline v0.12.4`) ap-
 463 plying the default filtering and screening criteria (HEADAS package, v6.9⁷). We extracted
 464 the XRT light curve in the 0.3–10 keV energy band using the software tool `xrtgrblc`. The
 465 source events were extracted from circular regions centered on the source position. Dur-
 466 ing the outburst we excluded the inner 2 pixels of the source to avoid pile-up. Exposure
 467 maps were used to account for the effects of vignetting, point-spread function losses and the
 468 presence of hot pixels and hot columns.

469 Since the source X-ray flux and spectrum are known to vary strongly, co-adding indi-
 470 vidual XRT observations could be misleading. We thus extracted the XRT data from each
 471 individual pointing separately, and fitted individual spectra using `XSPEC`. We rebinned the
 472 XRT data requiring at least 25 counts in each new energy bin. As discussed in Sec. 3.1,
 473 we assumed the combined Galactic and $z = 0.524$ absorption is adequately described by a
 474 column of $2.8 \times 10^{21} \text{ cm}^{-2}$ at $z = 0$: this is in fact consistent with the spectral fit to the
 475 *Swift* XRT data. We determined the unabsorbed X-ray flux by performing the spectral fit
 476 with fixed absorption, and then determining the incident flux by forcing the absorption to
 477 be 0. We include those fluxes in the 2 - 10 keV band in the last column of Table 3. We
 478 note that the source was detected at a sufficiently good signal-to-noise (S/N) ratio to deter-
 479 mine the spectrum unambiguously only in the observations on MJD54711, MJD54758, and
 480 MJD54761. In other observations, we assumed a photon index of $\Gamma = 2$, consistent with
 481 previous X-ray observations of this source in the low state, and note that the error resulting
 482 from such assumption on the inferred flux is comparable to the statistical error quoted in
 483 the last column of Table 3.

⁷<http://heasarc.gsfc.nasa.gov/lheasoft/>

484 The UVOT photometry was done using the publicly available UVOT FTOOLS data
 485 reduction suite and is based on the UVOT photometric system described in Poole et al.
 486 (2008) - but see also Breeveld et al. (2011) for an updated calibration. As discussed above,
 487 we adopted the corrections to the observed flux due to the absorption by the Milky Way plus
 488 the intervening galaxy at $z = 0.524$ as outlined in Section 3.1. The results of *Swift* UVOT
 489 observations are presented in the Table 4.

490 3.10. RXTE

491 As part of our campaign, 30 observations of AO 0235+164 were obtained with *Rossi X-*
 492 *ray Timing Explorer (RXTE)* between 2008 October 18 and 2008 December 27. We analyzed
 493 the data from the Proportional Counter Array (PCA) following standard procedures. We
 494 selected only data from PCU2, the best calibrated module and the only one which is always
 495 turned on. The data were screened in the following way: source elevation above the horizon
 496 $> 10^\circ$, pointing offset smaller than 0.02° , at least 30 minutes away from a South Atlantic
 497 Anomaly passage and electron contamination smaller than 0.1. This resulted in a total
 498 exposure of 192.3 ks. Single net PCA exposures range from 2.1 ks to 14.1 ks. Background
 499 was estimated with standard procedures and the detector response matrices extracted with
 500 the *RXTE* tools (command PCARSO v. 10.1).

501 For the spectral analysis the fitting procedure was done with the *XSPEC* software package.
 502 The spectra from the channels corresponding to nominal energies of 2.6 to 10.5 keV are
 503 adequately fitted by a single power law model, absorbed by a fixed column of 2.8×10^{21}
 504 cm^{-2} at $z = 0$ as determined by the ROSAT and ASCA - in an analogous manner to the
 505 spectral fitting performed to the *Swift* XRT data above. The parameters of the fits are
 506 reported in Table 5; again, the last column reports the unabsorbed X-ray flux.

507 4. Variability of the Source

508 4.1. Multi-wavelength Light Curve

509 In this section we present the results of the multi-wavelength observations conducted
 510 on AO 0235+164 from 2008 August to 2009 January. Figure 3 shows the multi-wavelength
 511 data available. From the top to the bottom are: radio, near-infrared, optical, polarization
 512 degree (%) and polarization angle (deg), UV, X-ray and γ -ray from 100 MeV to 100 GeV
 513 data are grouped together.

Date (MJD-54000)	exposure (sec)	Photon index	$F_{2-10\text{keV}}$ $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$
711.4976	6876	1.91 ± 0.09	3.1 ± 0.3
719.8695	1257	2 (assumed)	3.2 ± 0.4
737.9059	1448	2 (assumed)	3.7 ± 0.3
747.7476	2123	2 (assumed)	4.3 ± 0.3
758.7420	1133	$2.44^{+0.07}_{-0.08}$	17.3 ± 1.4
761.7541	1181	2.60 ± 0.08	15.0 ± 1.2
781.0545	1144	2 (assumed)	2.8 ± 0.3
789.5603	1087	2 (assumed)	4.1 ± 0.4
803.7109	1175	2 (assumed)	4.5 ± 0.5
818.5249	1210	2 (assumed)	4.8 ± 0.4

Table 3: The log of *Swift* observations yielding good XRT data. In all cases, the spectrum was fitted with a power-law model absorbed by gas with Galactic abundances with a column of $2.8 \times 10^{21} \text{ cm}^{-2}$ placed at $z = 0$: such an absorption form is only approximate, but it adequately fits *ROSAT* and *ASCA* data, which in turn possess better signal-to-noise than individual *Swift* pointings (see text). Since the quality of the data at MJD 54719, 54737, 54747, 54781, 54789, 54803, and 54818 have too low a S/N for reliable determination of spectrum, we assumed a photon index of 2 for those pointings.

Date	$M(v)$	$F(v)$	$M(b)$	$F(b)$	$M(u)$	$F(u)$	$M(w1)$	$F(w1)$	$M(m2)$	$F(m2)$	$M(w2)$	$F(w2)$
711.50	16.95 ± 0.05	2.32	17.93 ± 0.04	1.49	18.07 ± 0.06	1.04	18.16 ± 0.06	0.49	18.57 ± 0.07	0.43	18.93 ± 0.06	0.28
719.87	16.79 ± 0.09	2.69	17.81 ± 0.08	1.65	17.75 ± 0.11	1.39	17.99 ± 0.11	0.57	18.23 ± 0.16	0.59	18.47 ± 0.10	0.42
729.65	16.17 ± 0.07	4.76	17.03 ± 0.06	3.41	17.13 ± 0.08	2.46	17.18 ± 0.08	1.21	17.46 ± 0.11	1.20	17.85 ± 0.08	0.75
737.91	16.29 ± 0.06	4.26	17.11 ± 0.05	3.17	17.11 ± 0.07	2.51	17.47 ± 0.08	0.93	17.62 ± 0.11	1.03	18.04 ± 0.08	0.63
740.65	15.89 ± 0.06	6.18	16.80 ± 0.05	4.20	17.00 ± 0.08	2.77	17.17 ± 0.08	1.22	17.37 ± 0.10	1.30	17.78 ± 0.08	0.80
747.75	16.17 ± 0.05	4.76	17.01 ± 0.04	3.46	17.14 ± 0.06	2.45	17.36 ± 0.06	1.03	17.43 ± 0.07	1.23	17.94 ± 0.06	0.69
758.74	15.93 ± 0.06	5.95	16.86 ± 0.05	3.96	16.85 ± 0.07	3.18	16.83 ± 0.07	1.67	17.10 ± 0.09	1.66	17.61 ± 0.07	0.93
761.75	16.05 ± 0.06	5.33	16.92 ± 0.05	3.76	16.99 ± 0.07	2.79	17.09 ± 0.08	1.31	17.29 ± 0.09	1.40	17.55 ± 0.07	0.99
768.80	17.06 ± 0.07	3.30	17.08 ± 0.10	2.58	16.96 ± 0.07	1.47	17.45 ± 0.12	1.08
780.31	17.07 ± 0.16	2.07	17.99 ± 0.15	1.40	17.91 ± 0.19	1.2	18.14 ± 0.17	0.50	18.17 ± 0.28	0.62	18.46 ± 0.15	0.43
781.06	17.31 ± 0.13	1.66	17.85 ± 0.09	1.59	17.97 ± 0.14	1.13	18.08 ± 0.13	0.53	18.39 ± 0.17	0.51	18.63 ± 0.11	0.37
789.56	16.63 ± 0.08	3.11	17.50 ± 0.07	2.21	17.46 ± 0.10	1.81	17.81 ± 0.11	0.68	17.98 ± 0.16	0.74	18.25 ± 0.09	0.52
790.83	16.60 ± 0.11	3.20	17.40 ± 0.09	2.41	17.80 ± 0.16	1.32	17.73 ± 0.14	0.73	18.04 ± 0.18	0.70	18.34 ± 0.13	0.48
803.71	17.66 ± 0.16	1.21	18.77 ± 0.18	0.69	18.63 ± 0.21	0.62	18.79 ± 0.20	0.27	18.51 ± 0.17	0.46	19.19 ± 0.16	0.22
813.64	18.10 ± 0.24	0.81	18.87 ± 0.21	0.63	18.97 ± 0.31	0.45	18.96 ± 0.24	0.23	19.00 ± 0.28	0.29	19.00 ± 0.16	0.26
818.52	17.43 ± 0.15	1.49	18.34 ± 0.15	1.01	18.87 ± 0.32	0.50	18.63 ± 0.20	0.32	19.07 ± 0.23	0.27	19.17 ± 0.17	0.22

Table 4: Results of *Swift* UVOT observations of AO 0235+164. The data are listed for six *Swift* UVOT filters. Each pair of columns corresponds to the observed, uncorrected magnitude M (left entry) and corrected flux density F , in units of milliJansky (right entry). To correct for absorption in the Milky Way plus that at $z = 0.524$, we used the following values of absorption A_λ for the respective UVOT filters: W2: 2.87; M2: 2.94; W1: 2.52; U: 2.71; B: 1.84; V: 1.46. We calculate the incident flux $F_{\text{inc},\lambda}$ in the band corresponding to λ from the observed (absorbed) flux $F_{\text{abs},\lambda}$ via $F_{\text{abs},\lambda}/F_{\text{inc},\lambda} = 10^{A_\lambda/2.5}$. The same corrections are applied to ground-based optical data.

Date	MJD-54000	exposure (s)	photon index Γ	χ_r^2 / d.o.f.	F_{2-10}
18/10/2008 18:56	757.805	2688	2.46 ± 0.13	0.60/9	2.00 ± 0.08
19/10/2008 13:35	758.684	12416	2.55 ± 0.06	0.41/9	2.09 ± 0.04
20/10/2008 13:09	759.566	3024	2.73 ± 0.14	0.62/9	1.79 ± 0.07
21/10/2008 14:16	760.647	6384	2.56 ± 0.10	0.38/9	1.70 ± 0.05
22/10/2008 13:53	761.597	3104	2.34 ± 0.12	0.56/9	1.87 ± 0.07
23/10/2008 18:08	762.773	2976	2.47 ± 0.12	0.58/9	2.03 ± 0.07
25/10/2008 14:08	764.704	12656	2.57 ± 0.07	0.43/9	1.77 ± 0.04
26/10/2008 15:13	765.653	3136	2.71 ± 0.14	0.57/9	1.68 ± 0.08
27/10/2008 13:09	766.567	3200	2.35 ± 0.16	0.83/9	1.41 ± 0.07
28/10/2008 19:01	767.806	2320	2.71 ± 0.21	0.34/9	1.26 ± 0.08
31/10/2008 14:32	770.624	3152	2.24 ± 0.27	0.44/9	0.71 ± 0.06
02/11/2008 17:03	772.850	14448	2.26 ± 0.18	0.29/9	0.53 ± 0.03
03/11/2008 13:07	773.566	3200	2.46 ± 0.40	0.55/9	0.54 ± 0.07
04/11/2008 19:11	774.880	9072	2.72 ± 0.36	0.34/9	0.37 ± 0.04
05/11/2008 18:34	775.858	9680	2.12 ± 0.31	0.48/9	0.35 ± 0.04
06/11/2008 18:07	776.774	3200	1.91 ± 0.55	0.59/9	0.32 ± 0.06
07/11/2008 14:32	777.723	12992	2.50 ± 0.38	0.45/9	0.28 ± 0.03
10/11/2008 16:07	780.696	2880	3.53 ± 0.79	0.79/9	0.38 ± 0.09
11/11/2008 11:11	781.486	3264	2.37 ± 0.61	1.40/9	0.27 ± 0.06
13/11/2008 11:53	783.613	13168	2.37 ± 0.38	0.39/9	0.25 ± 0.03
14/11/2008 12:56	784.625	9888	2.39 ± 0.36	0.59/9	0.30 ± 0.04
15/11/2008 11:00	785.543	9904	2.37 ± 0.36	0.63/9	0.31 ± 0.04
17/11/2008 10:09	787.474	6336	2.50 ± 0.59	0.46/9	0.24 ± 0.05
19/11/2008 09:10	789.429	5568	2.94 ± 0.44	0.81/9	0.39 ± 0.05
20/11/2008 07:10	790.411	12192	1.99 ± 0.36	0.34/9	0.26 ± 0.03
21/11/2008 16:48	791.366	9744	2.92 ± 0.63	0.39/9	0.23 ± 0.04
23/11/2008 10:33	793.492	6432	2.08 ± 0.68	0.42/9	0.21 ± 0.04
27/12/2008 14:06	827.672	9664	2.69 ± 0.50	0.40/9	0.25 ± 0.04

Table 5: Best-fit parameters for the PCA data of each RXTE observation with the absorption fixed at the value measured by ROSAT + ASCA, with the column of $N_H = 28 \times 10^{20} \text{ cm}^{-2}$ with Galactic abundances. Description of columns: (1) and (2) Observing date, (3) Exposure (s), (4) photon index and error, (5) reduced χ^2 and no. of degrees of freedom, (6) Flux in the 2-10 keV band, in units of $10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$.

514 The optical behavior is the best sampled among all. Two main flare peaks are visible
 515 in the period around 2008 October (MJD 54730-54750), and they are surrounded by other
 516 smaller peaks. The radio data show that the flux started to increase smoothly starting
 517 around the middle of 2007 (MJD 54500, which is apparent in Figure 4), reaching its maximum
 518 during the optical flare activity and slowly decreasing when the source returned to a low flux
 519 state in near IR, optical, X-ray and γ -ray bands. The near infrared data show the same
 520 temporal trend as the optical bands. The UV data from *Swift* UVOT do not show the level
 521 of activity seen in the optical band. The X-ray data from *Swift* XRT and RXTE present a
 522 very pronounced peak clearly delayed with respect to the optical activity.

523 The *Fermi* light curve, as already discussed in section 2.1 shows a broad high-state
 524 period followed by a final narrow peak succeeding the X-ray peak before getting to the low-
 525 flux state. Since then (up to the time of submitting this paper in autumn 2011), the source
 526 has been in a very quiet state.

527 Figure 4 shows the light curves constructed from the radio, mm and sub-mm data in an
 528 extended time interval, from 2007 to 2010 June (MJD 54400-55230). In the lowest-energy-
 529 band, the increasing trend of the flux started months before the increased level of activity
 530 seen in the optical and higher energy bands. After the period of the increased radio/mm flux
 531 associated with the optical flaring activity, the source enters a period of gradually declining
 532 flux.

533 4.2. Cross-correlation studies and time delays

534 We searched for correlations of variability between different bands, with the goal to
 535 understand the relationship between the fluxes of AO 0235+164 at different energies. The
 536 cross-correlation studies between the optical R band and γ -ray fluxes are illustrated in the
 537 top panel of Figure 5. Those data have a Spearman correlation coefficient⁸ of 0.75
 538 (Spearman 1904). The relations between the γ -ray and 230 GHz and 345 GHz fluxes have
 539 also been evaluated and the results are shown in Figure 5 in the bottom panel: the Spearman
 540 correlation coefficient between γ -ray fluxes and 230 GHz data is 0.70 showing that there exists
 541 a correlation between the two data sets. On the other hand, the sampling at 345 GHz is
 542 poor, with only a few data points at that frequency and the evaluation of a correlation has
 543 not been performed. In all cases, no correlation is found at 90% confidence level. We note
 544 here that Agudo et al. (2011b), using data collected for this object over a longer time span

⁸Wessa, P. (2011), Free Statistics Software, Office for Research Development and Education, version 1.1.23-r7, <http://www.wessa.net/>

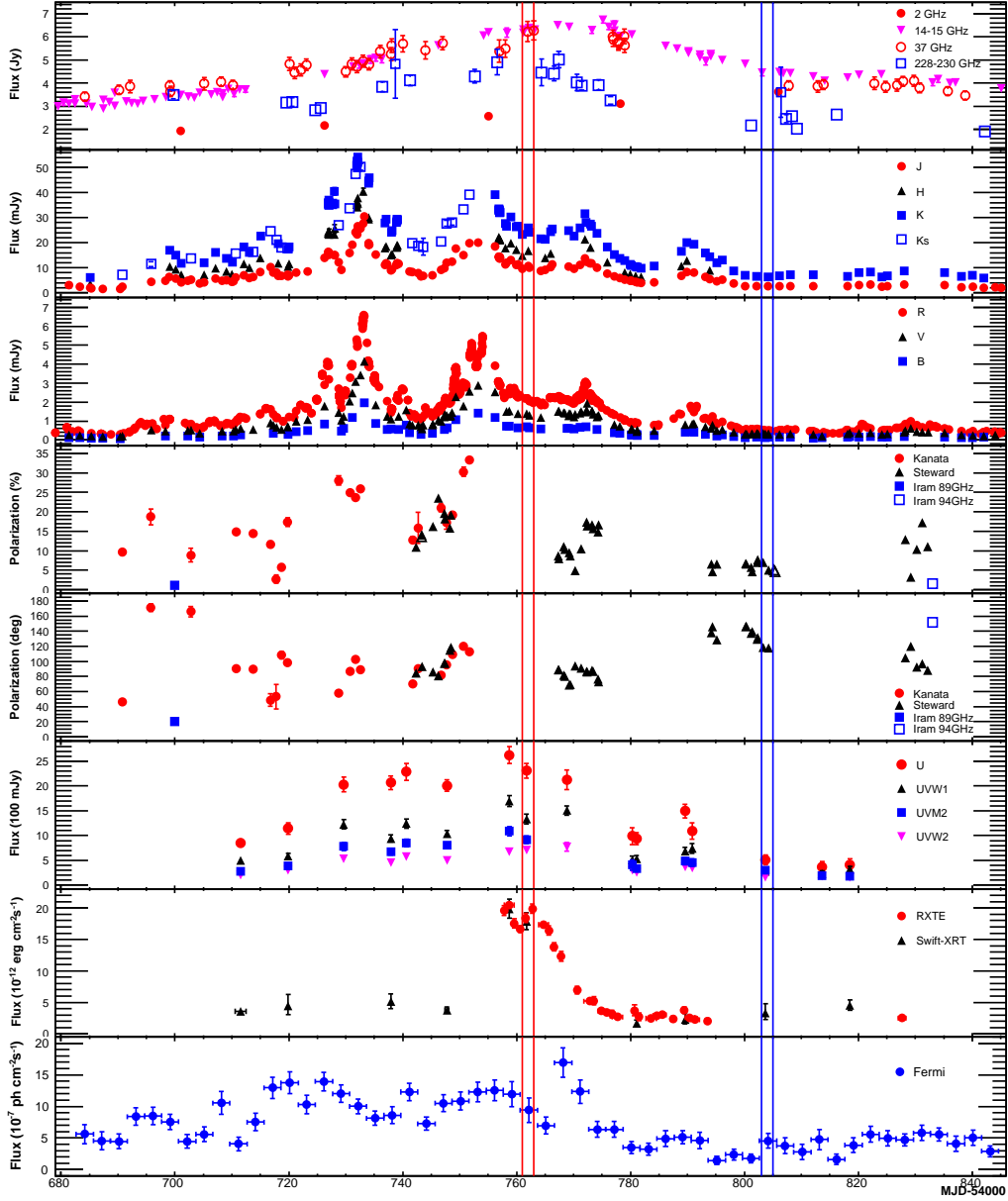


Fig. 3.— AO 0235+164 light curve from 2008 August 4 to 2009 February 4 in different energy ranges. From the top to the bottom: radio, near IR, optical, UV, X-rays and γ -rays above 100 MeV. Panels 4 and 5 from the top report the polarization data from the Kanata optical observatory and IRAM radio telescope. Two double vertical lines mark the epochs for which we extracted the SEDs modeled in Section 6.

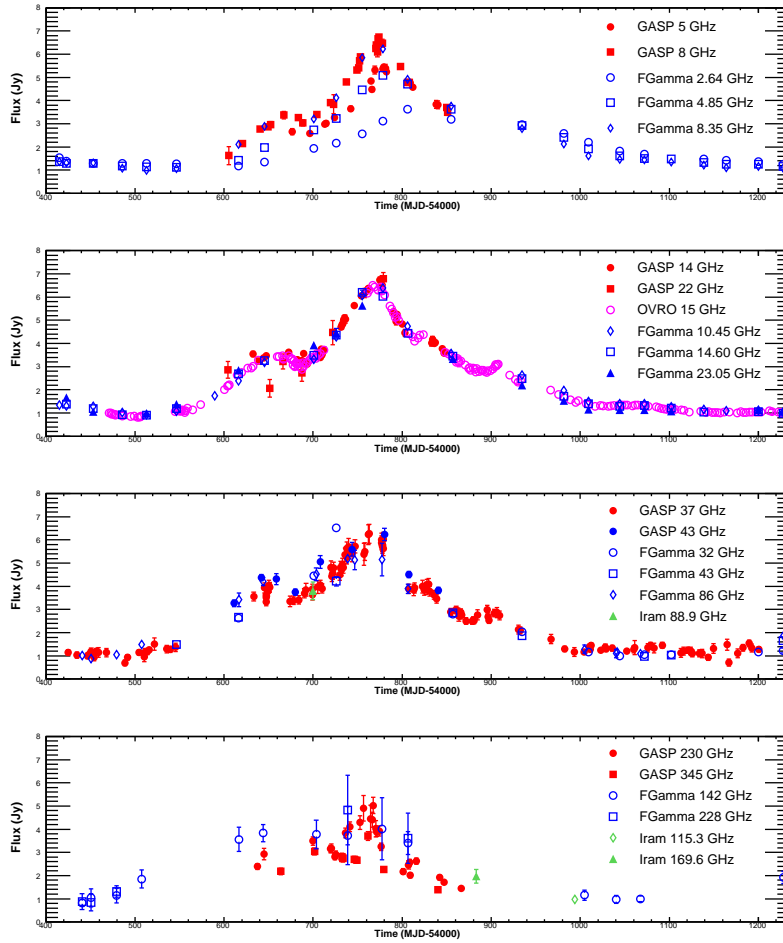


Fig. 4.— Radio, mm and sub-mm light curves of AO 0235+164 from mid 2007 until June 2010 (MJD 54400-55230). In these energy bands the flux began to increase around the middle of 2007 (MJD 54500), months before the start of the optical and higher energy activity of the source.

545 than that covered by our observations, performed a light-curve correlation analysis following
 546 the method described by Agudo et al. (2011a). They found that these bands are correlated
 547 at a 99.7% confidence level. In our case, no correlation is found at 90% confidence level:
 548 it is very likely that the stronger correlation of signals derived by Agudo et al. (2011b) is
 549 caused by their use of a significantly longer time span, amounting to roughly 8 years. All
 550 this suggests that the variability of the source in the γ -ray and radio-to-mm regimes on long
 551 time scales is correlated, but the situation on shorter time scales is less clear.

552 Since the time series in the optical R band and γ -ray are the best sampled in this study,
 553 it was possible to calculate lags/leads between those bands. To this end, we calculated
 554 the discrete correlation function (DCF, Edelson & Krolik 1988). We binned the data sets
 555 in order to smooth the intra-day features in the optical light curves, and to obtain similar
 556 sampling in the γ -ray band. We tried several bin sizes from 1 to 7 days to check how sensitive
 557 the results are to this smoothing procedure. The DCF from the optical and γ -ray data do
 558 not show significant peaks on short time scales (1 day) meaning no optical- γ correlation is
 559 detected over the observing period. Figure 6 shows the result of this DCF analysis when
 560 the light curves are binned over 1 day. A peak can be seen at 15 days (with optical lagging
 561 γ -rays), however the significance is modest. Agudo et al. (2011b) found that, for a similar
 562 period, the optical flux lags the γ -rays by ~ 10 days, but their DCF peak is much broader,
 563 and could be interpreted as being consistent with no lag.

564 4.3. Time dependence of optical polarization

565 As illustrated in Figure 3, the polarization degree and angle are highly variable; the
 566 former correlates with the optical flux and at the two largest flux peaks reaches values 25%
 567 and 35%, respectively. This correlation was studied over a longer period of time (from
 568 2008 August 12 to 2009 February 18) by Sasada et al. (2011), and in the past, during the
 569 outburst of 2006 December, by Hagen-Thorn et al. (2008). A trend of the stabilization
 570 of the polarization angle during flares is seen both in 2006 and 2008, but around different
 571 values, with electric vector polarization angle (EVPA) at $\sim -30^\circ$ and $\sim 100^\circ$ respectively.
 572 Comparing EVPA with the position angle of the parsec-scale jets, Hagen-Thorn et al. (2008)
 573 found that there is a trend of their alignment during high states. However, since the parsec-
 574 scale jet in AO 0235+164 shows large changes of direction with time (Jones et al. 1984;
 575 Chu et al. 1996; Jorstad et al. 2001; Piner et al. 2006) and the jet direction to which EVPA
 576 was compared was inferred from the VLBI maps taken in different epochs, the claimed
 577 alignment could be accidental. Indeed, comparison of EVPA during flux peaks in 2008 with
 578 the direction of the jet determined during the same epoch by VLBI observations does not

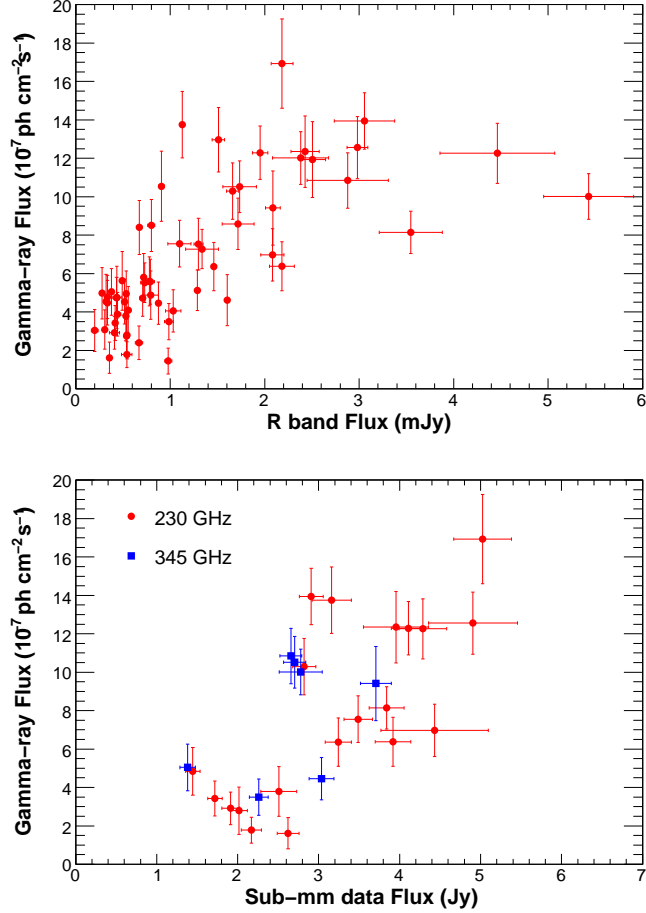


Fig. 5.— Top: Plot of the γ -ray flux vs R band flux; both fluxes are averaged in 3-days time intervals. The data suggest that γ -ray and optical fluxes follow each other, but the correlation is small with γ -ray flux reaching a plateau at the level $\sim 1.2 \times 10^{-6}$ when the optical flux reaches ~ 3 mJy, but not increasing beyond $\sim 1.2 \times 10^{-6}$ when the optical flux increases to ~ 5 mJy. Bottom: Similar plot of γ -ray flux vs high-frequency radio-band flux; both fluxes are averaged in 3-day time intervals. Likewise, there is a general trend of increase in both bands, but the correlation is small.

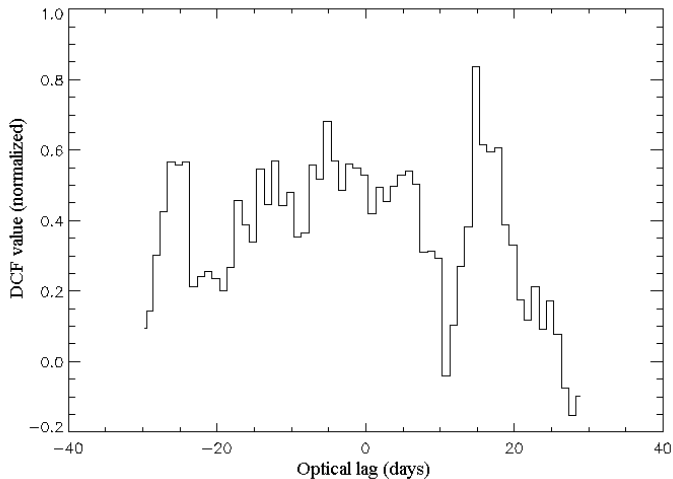


Fig. 6.— Discrete Correlation Function (DCF) calculated between optical R band and *Fermi*-LAT γ -ray data binned over 1-day intervals. Positive values correspond to γ -rays leading the optical signal.

579 confirm such an alignment (Agudo et al. 2011b). On the contrary, both angles are oriented
 580 perpendicular rather than parallel to each other, albeit with a large scatter, with EVPA at
 581 optical flux peaks $\sim 100^\circ$ vs. $\chi_{jet} \sim 0^\circ$. This implies a parallel orientation of the magnetic
 582 fields to the jet and may indicate production of flares in a reconfinement shock (Nalewajko
 583 2009).

584 5. Broad-band Spectral Energy Distribution

585 Our unprecedented time sampling of AO 0235+164 in several spectral bands allows us
 586 to extract accurate instantaneous SEDs, which are needed to correctly interpret the broad-
 587 band emission of the source. We reiterate that in order to build the intrinsic SED and
 588 correctly convert the observed magnitudes to de-absorbed fluxes, extinction must be taken
 589 into account, including both Galactic extinction, and that due to the $z = 0.524$ system. We
 590 discussed in Section 3.1 how the IR, optical, UV data and soft X-rays are affected by the
 591 absorption due to both systems. Following the prescriptions from Junkkarinen et al. (2004),
 592 we assume that the soft X-ray absorption is adequately described by a column density of
 593 $2.8 \times 10^{21} \text{ cm}^{-2}$ at $z = 0$. However, for the far-UV data, we use a modified extinction model
 594 based on the work of Pei (1992).

595 Figure 7 shows the broad-band SEDs obtained by plotting simultaneous radio, NIR,

596 optical, UV, X-ray data in the following two 2-day epochs:

- 597 1. MJD 54761–54763 (shown in red), corresponding to the maximum of the X-ray flare,
598 coincident with a highly variable near-IR/optical/UV state and a high γ -ray state.
- 599 2. MJD 54803–54805 (shown in blue), corresponding to a low state in all bands, following
600 the high-activity period.

601 The plotted data points were extracted from the larger datasets as follows:

- 602 - Radio data: most of the data points are simultaneous measurements. Although the
603 sampling at some particular wavelengths is poor, the available radio light curves show
604 very smooth and slow trends, thus we have also plotted interpolated values based on
605 the extended data set of about 10 days in length, centered on the main observation
606 period.
- 607 - Near-IR/optical/UV: all the data shown are simultaneous measurements made by
608 GASP-WEBT, SMARTS and *Swift* UVOT telescopes.
- 609 - X-ray data: in the first epoch (MJD 54761–54763), we present the *Swift* XRT observa-
610 tion with a butterfly plot. In the second epoch (MJD 54803–54805), the S/N for the
611 *Swift* XRT measurement is too low to allow a good spectral representation and only
612 the flux upper limit is reported.
- 613 - γ -ray data: the γ -ray spectra have been built following the analysis procedure described
614 in Section 2.2. Since the time intervals chosen to build the broad-band SED are too
615 short to allow a good reconstruction of the γ -ray spectrum, longer periods have been
616 used. The first time interval, MJD 54750–54770, corresponds to a period of high γ -ray
617 emission, which includes the X-ray flare period. The high state is followed by a lower
618 emission state whose spectrum is averaged in the interval MJD 54780–54840.

619 The overall SED, plotted in Figure 7, appears quite similar to that measured for other
620 blazars. There is one marked difference: at least for the first period, the X-ray spectrum is
621 soft, yet it is not located on the extrapolation of the optical/UV spectrum. For this to be
622 the case, extinction would have to be significantly greater, with the error at the level of at
623 least 50%, which we consider unlikely. Assuming that we adopted the correct extinction, the
624 broad-band SED does show a distinct feature in the soft X-ray band, separate from the two
625 broad peaks forming the SED in most blazars, and we discuss its origin below.

6. Modeling of the Broad-Band Spectrum

626

627 AO 0235+164, like many other luminous, low-frequency-peaked BL Lac objects, shows
 628 broad emission lines (Cohen et al. 1987; Nilsson et al. 1996; Raiteri et al. 2007). Using the
 629 emission-line spectrum reported in Raiteri et al. (2007), correcting the line flux for extinction,
 630 and assuming that the contribution of the lines measured by them to the total luminosity of
 631 broad emission lines (BEL) is the same as in the composite spectrum of quasars (Francis et al.
 632 1991), we find $L_{\text{BEL}} \sim 4 \times 10^{44} \text{ erg s}^{-1}$. For the typical covering factor of the broad-line region
 633 (BLR) $\xi_{\text{BEL}} \sim 0.1$ this implies a luminosity of the accretion disk of $L_d \sim 4 \times 10^{45} \text{ erg s}^{-1}$.
 634 With such a high accretion luminosity, if observed directly, i.e. without being overshadowed by
 635 the jet nonthermal radiation, AO 0235+164 would satisfy a formal criterion to be classified as
 636 a quasar (see also Murphy et al. 1993). This means that, according to the AGN unification
 637 models, it should possess a typical dusty torus, a strong source of thermal infrared radiation
 638 (IR) with a typical covering factor of $\xi_{\text{IR}} \sim 0.1$ (e.g., Haas et al. 2004). Recent mid-IR
 639 interferometric observations for a sample of nearby AGN show that such tori can extend
 640 beyond 10 pc from the central black hole (Tristram & Schartmann 2011). The mass of the
 641 black hole (BH) in this object is likely to be in the range $M_{\text{BH}} \sim 2 - 6 \times 10^8 M_{\odot}$ (Liu et al.
 642 2006; Raiteri et al. 2007; Wu et al. 2010), which implies the Eddington ratio $L_d/L_{\text{EDD}} \geq 0.1$.

643

In order to determine which process dominates the high-energy emission, whether it is
 644 ERC or SSC, one can estimate their luminosity ratio as $L_{\text{ERC}}/L_{\text{SSC}} \simeq u'_{\text{ext}}/u'_{\text{syn}}$, where u'_{ext}
 645 is the co-moving energy density of the external radiation, which depending on the source
 646 location could be dominated either by u'_{BEL} or u'_{IR} , and u'_{syn} is the co-moving energy den-
 647 sity of the synchrotron radiation. These energy densities scale like $u'_{\text{BEL(IR)}} \simeq \Gamma_j^2 u_{\text{BEL(IR)}} \simeq$
 648 $\Gamma_j^2 \xi_{\text{BEL(IR)}} L_d / (4\pi r_{\text{BEL(IR)}}^2 c)$ for $r \leq r_{\text{BEL(IR)}}$, respectively, and $u'_{\text{syn}} \simeq L_{\text{syn}} / (4\pi R^2 \mathcal{D}^4 c)$, where
 649 $r_{\text{BEL}} \sim 0.1(L_{\text{d},46})^{1/2} \text{ pc}$ is the characteristic radius of the broad-line region, $r_{\text{IR}} \sim 2.5(L_{\text{d},46})^{1/2} \text{ pc}$
 650 is the inner radius of the dusty torus, R is the emitting zone radius related to its distance
 651 by $r = R\Gamma_j$, $\Gamma_j = (1 - \beta_j^2)^{-1/2}$ is the jet Lorentz factor and β_j is the jet velocity in units
 652 of c (Sikora et al. 2009). Considering the emitting zone located at either characteristic ra-
 653 dius, i.e. $r \simeq r_{\text{BEL(IR)}}$, and neglecting the distinction between the Doppler factor \mathcal{D} and the
 654 Lorentz factor Γ_j , we obtain $L_{\text{ERC}}/L_{\text{SSC}} \simeq \xi_{\text{BEL(IR)}} \Gamma_j^4 (L_d/L_{\text{syn}})$. In the case of AO 0235+164,
 655 we observe $L_d/L_{\text{syn}} \sim 0.01$ and thus $L_{\text{ERC}}/L_{\text{SSC}} \simeq 160(\xi_{\text{BEL(IR)}}/0.1)(\Gamma_j/20)^4$. Hence, even
 656 for a moderate bulk Lorentz factor, in order for the SSC component to dominate the ERC
 657 component, one requires covering factors 2 orders of magnitude lower than typically assumed
 658 in quasars.

659

In this Section, we verify the ERC scenario by fitting the observed SEDs with one-zone
 660 leptonic models (Moderski et al. 2003). We follow the evolution of relativistic electrons
 661 injected into a thin spherical shell propagating conically with a constant Lorentz factor

662 Γ_j undergoing adiabatic and radiative losses due to the synchrotron and inverse-Compton
 663 emission. The external radiation includes broad emission lines of characteristic photon energy
 664 $E_{\text{BEL}} \sim 10$ eV and infrared dust radiation of characteristic energy $E_{\text{IR}} \sim 0.3$ eV. We
 665 attempted to fit the high state of MJD 54761-3 with a 'blazar zone' located either within
 666 (ERCBEL model) or outside the BLR (ERCIR model). In the ERCBEL model, the electron
 667 break inferred from the synchrotron spectrum is too low to reproduce the γ -ray spectrum
 668 above ~ 1 GeV. This problem is absent in the ERCIR model (red lines in Figure 7). This is
 669 because Comptonization of IR photons is subject to much weaker Klein-Nishina suppression
 670 in the GeV band than Comptonization of optical/UV emission-line photons. The parameters
 671 of the ERCIR model are: location $r = r_{\text{IR}}$, Lorentz factor $\Gamma_j = 20$, opening angle $\theta_j = 1/\Gamma_j =$
 672 2.9° (hence the Doppler factor $\mathcal{D}_j = \Gamma_j$), magnetic field strength $B' = 0.22$ G, viewing angle
 673 $\theta_{\text{obs}} = 2.3^\circ$. Electrons are injected with a doubly-broken energy distribution with $\gamma_{\text{br},1} = 100$,
 674 $\gamma_{\text{br},2} = 5800$, $p_1 = 1.5$, $p_2 = 2.03$, $p_3 = 3.9$.

675 The rate of electron energy injection is $\dot{E}'_{e,\text{inj}} \sim 4.8 \times 10^{43}$ erg s $^{-1}$. Over co-moving time
 676 $\Delta t' \sim r_{\text{IR}}/(2\Gamma_j\beta_j c) \sim 4 \times 10^6$ s, the total injected electron energy is $E'_{e,\text{inj}} \sim \dot{E}'_{e,\text{inj}}\Delta t' \sim 1.9 \times$
 677 10^{50} erg. At the end of the injection the total number of electrons is $N_e = 6.6 \times 10^{54}$ and their
 678 total energy in the co-moving frame $E'_e \sim 1.1 \times 10^{50}$ erg. The average efficiency of electron
 679 energy losses is $\eta_{e,\text{loss}} = 1 - (E'_e/E'_{e,\text{inj}}) \sim 0.42$. The electron flux is $\dot{N}_e \sim \pi\Gamma_j R^2 c N_e/V' \sim 1.2 \times$
 680 10^{49} s $^{-1}$, where $V' \sim 4\pi R^3/3$ is the volume of the emitting region in the co-moving frame and
 681 $R \sim \theta_j r$ is the jet radius. The electron energy flux is $L_e \sim \pi\Gamma_j^2 R^2 c E'_e/V' \sim 4.1 \times 10^{45}$ erg s $^{-1}$
 682 and the proton energy flux is $L_p \sim \pi\Gamma_j^2 R^2 c N_p m_p c^2/V' \sim 3.6 \times 10^{47}$ (n_p/n_e) erg s $^{-1}$, where
 683 $N_p \sim N_e(n_p/n_e)$ is the total number of protons and (n_e/n_p) is the lepton-to-proton number
 684 ratio. The magnetic energy flux is $L_B = \pi\Gamma_j^2 R^2 c u'_B \sim 4.4 \times 10^{45}$ erg s $^{-1}$. The resulting
 685 jet magnetization parameter is $\sigma_B \sim L_B/L_p \sim 0.012(n_e/n_p)$, and the radiative efficiency
 686 is $\eta_{\text{rad},j} \sim L_{\text{obs}}/(2\Gamma_j^2 L_p) \sim 0.022(n_e/n_p)$, where $L_{\text{obs}} \sim 6.4 \times 10^{48}$ erg s $^{-1}$ is the observed
 687 bolometric luminosity of the source. The relation between the jet power and accretion
 688 disk luminosity is $L_p/L_d \sim 91(n_p/n_e)$. Parameterizing the jet production efficiency by
 689 $L_p \sim \eta_j \dot{M}_{\text{acc}} c^2$ and the radiative efficiency of the accretion disk $L_d \sim \eta_{\text{rad},d} \dot{M}_{\text{acc}} c^2$, where
 690 \dot{M}_{acc} is the accretion rate, we obtain $n_e/n_p \sim 91(\eta_{\text{rad},d}/\eta_j)$. For $\eta_{\text{rad},d} \sim 0.1$ and $\eta_j \sim 1$, we
 691 have $n_e/n_p \sim 9.1$ and hence $\sigma_B \sim 0.11$ and $\eta_{\text{rad},j} \sim 0.2$. We are thus able to match the
 692 jet power with the accretion power onto the central black hole, adopting a reasonably low
 693 jet magnetization, which allows formation of strong shock waves. The ratio of electrons to
 694 protons is consistent with the results of Sikora & Madejski (2000). This model predicts the
 695 observed variability time scale $t_v \simeq (1+z)R/(c\Gamma_j) \sim 8$ days, consistent with the time scale
 696 of the significant variations of the optical and γ -ray flux.

697 As we noted above, the X-ray spectrum, at least during the first of the two epochs
 698 considered here, is too soft to be interpreted as an SSC component and cannot be the high-

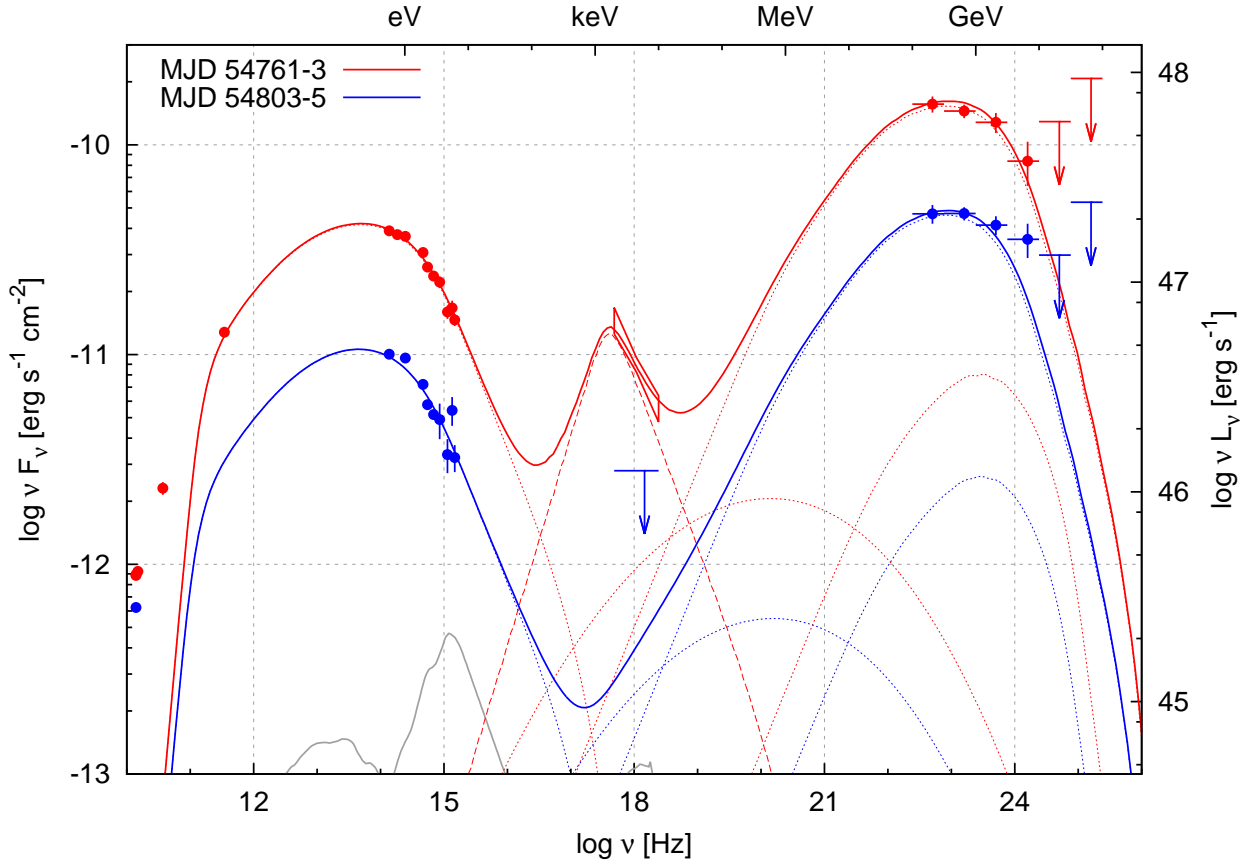


Fig. 7.— Numerical models fitted to observed spectral states of AO 0235+164, dominated energetically by the Comptonization of the infrared radiation from the dusty torus (ERCIR). *Red lines* show a fit to the high state (MJD 54761-3), including the bulk-Compton feature (*dashed line*). *Blue lines* show a fit to the low state (MJD 54803-5). *Dotted lines* indicate individual spectral components, in order of increasing peak frequencies: synchrotron, SSC, ERCIR, ERCBEL. *Solid lines* show the sums of all individual components. Note that presented models do not cover the radio production which at $\nu < 100\text{GHz}$ is strongly synchrotron-self-absorbed for our source parameters and must originate at much larger distances from the BH than a few parsecs. The *gray line* shows the quasar composite SED adopted from Elvis et al. (1994) and normalized to the accretion disk luminosity $L_d = 4 \times 10^{45} \text{ erg s}^{-1}$.

699 energy tail of the synchrotron component since it does not lie on the extrapolation of the
700 optical-UV spectrum (but see the caveats above, related to the corrections for extinction).
701 Instead, it can be explained by Comptonization of external radiation by a population of rel-
702 atively cold electrons (Begelman & Sikora 1987; Ravasio et al. 2003). Such bulk Compton
703 radiation is expected to be produced in a jet much closer to the black hole than the non-
704 thermal blazar radiation, at distances at which cooling of even mildly relativistic electrons is
705 very efficient. There the jet is still in the acceleration phase and, therefore, its bulk Lorentz
706 factor is expected to be smaller than in the blazar zone. But noting that according to mag-
707 netohydrodynamical models the acceleration process is very smooth (see, e.g., Komissarov
708 et al. 2007) and that the bulk Compton radiation must be significantly Doppler boosted to
709 be visible in the blazar spectra, the dominant contribution to bulk-Compton radiation is
710 expected to be produced at distances which are already well separated from the base of the
711 jet (Sikora et al. 2005; Celotti et al. 2007). We consider a stationary emitting region at char-
712 acteristic radius $r_b \sim 100R_g \sim 6 \times 10^{15}$ cm, where $R_g = GM_{\text{BH}}/c^2$ is the gravitational radius
713 of the central black hole of mass $M_{\text{BH}} \sim 4 \times 10^8 M_\odot$. The bulk Lorentz factor is $\Gamma_b \sim 10$
714 and the Doppler factor is $\mathcal{D}_b = 1/[\Gamma_b(1 - \beta_b \cos \theta_{\text{obs}})] \sim 16$. Bulk-Compton luminosity is
715 given by the approximate formula

$$L_b \simeq N_{e,b} |\dot{E}_{e,\text{IC}}|_b \frac{\mathcal{D}_b^3}{\Gamma_b}, \quad (4)$$

716 where $N_{e,b}$ is the number of electrons enclosed in the $\Delta r \sim r_b$ portion of a jet, $|\dot{E}_{e,\text{IC}}|_b =$
717 $(4/3)c\sigma_T u_{\text{ext},b} \Gamma_b^2$ is the rate of production of Compton radiation by a single electron, and
718 $u_{\text{ext},b} = \xi_b L_d / (4\pi r_b^2 c)$ is the energy density of external radiation field, which at distances
719 $\leq 100R_g$ is very likely to be dominated by rescattering of disk radiation by electrons in the
720 accretion disk corona of covering factor ξ_b . The energy spectrum of the external radiation is
721 approximated by a broken power-law distribution $u_{\text{ext},b}(E) \propto E^{-\alpha_i}$ with $\alpha_1 = 0$, $\alpha_2 = 1.8$ and
722 $E_{\text{br}} = 10$ eV (Richards et al. 2006; Shang et al. 2011). The electron flux is $\dot{N}_{e,b} \sim N_{e,b} c / r_b$.
723 Assuming that it matches the electron flux in the blazar zone ($\dot{N}_{e,b} \sim \dot{N}_e$), we calculate the
724 total number of electrons producing the bulk-Compton component to be $N_{e,b} \sim 2.4 \times 10^{54}$.
725 We find that the X-ray spectrum of luminosity $L_b \sim 8.7 \times 10^{46}$ erg s $^{-1}$ can be reproduced
726 with cold electrons for $\xi_b \simeq 0.19 (r_b / 6 \times 10^{15} \text{ cm})$.

727 Multi-wavelength light curves show that X-rays do not correlate with radiation in other
728 spectral bands. This suggests that X-ray variability of the bulk-Compton radiation can be
729 caused by local wiggling of the jet, e.g. caused by variations of the average direction of non-
730 axisymmetric outflows generated near the BH. Jet wiggling can also explain independent
731 variability in the blazar zone. We have fitted the low state (MJD 54803-5) with an ERCIR
732 model (blue lines in Figure 7) very similar to the one for the high state, changing only
733 the viewing angle, from $\theta_{\text{obs}} = 2.3^\circ$ to $\theta_{\text{obs}} = 3.7^\circ$, and the magnetic field strength, from

734 $B' = 0.22$ G to $B' = 0.20$ G. With the new viewing angle, the observer is placed outside
 735 the jet opening cone and the observed luminosity decreases due to a lower effective Doppler
 736 factor. The change in the magnetic field strength reduces the synchrotron luminosity by
 737 $\sim 30\%$ relative to the ERC luminosity. The overall spectral shape is matched without any
 738 adjustment in the electron energy distribution.

739 7. Discussion

740 Multi-wavelength observations of blazars, including AO 0235+164, show that events
 741 associated with periods of greater activity occur over the entire electromagnetic spectrum,
 742 from radio to γ -rays. Light curves taken in different spectral bands correlate on time scales
 743 longer than a month, while on shorter time scales correlations are weaker and some lags are
 744 claimed. In particular, monthly lags of the radio signals following the γ -rays are observed
 745 (Pushkarev et al. 2010). This is interpreted in terms of the synchrotron opacity at radio
 746 frequencies and indicates that γ -rays are produced at distances from the BH that are several
 747 parsecs smaller than the position of the radio cores. Whether γ -ray emission is smoothly
 748 distributed over several decades of distance (Blandford & Levinson 1995), or is associated
 749 with specific locations of energy dissipation in a jet, is still debated. The localized dissipation
 750 zones could be related to: reconnection of magnetic fields which may operate efficiently at
 751 distances < 0.01 pc, where the magnetization parameter σ is expected to be large (Nalewajko
 752 et al. 2011); internal shocks resulting from collisions between the jet portions moving with
 753 different velocities (Spada et al. 2001), which become efficient at distances at which σ drops
 754 below 0.1; oblique/reconfinement shocks which are formed at distances at which interactions
 755 of a supersonic jets start to feel the influence of the external medium (Hughes et al. 2011;
 756 Daly & Marscher 1988; Komissarov & Falle 1997; Nalewajko & Sikora 2009).

757 Using the SED of AO 0235+164, we showed in Section 6 that the spectrum of this object
 758 can be reproduced using a model where the dissipation takes place at a distance of $r \sim 1.7$ pc
 759 from the BH and production of γ -rays is dominated by Comptonization of NIR radiation of
 760 hot dust. The activity of AO 0235+164 during the same epoch was analyzed independently
 761 by Agudo et al. (2011b). They included the VLBI imaging data, and concluded that the
 762 γ -ray emission zone is associated with the 7 mm radio core (i.e. at ~ 12 pc from the BH)
 763 and propose that production of γ -rays is dominated by a turbulent multi-zone SSC process.
 764 We comment on these differences below, noting that we perform detailed modelling of the
 765 broad-band spectrum of the object.

766 As the long term radio light curves of AO 0235+164 indicate, the active season in 2008
 767 started about 200 days before reaching the maximum. During this period of time any portion

768 of the jet propagates over a distance of $\Delta r \sim c\Gamma^2 t_{obs}/(1+z) \geq$ tens of parsecs, i.e. much
 769 larger than the length of a 'blazar zone' inferred from the time scales of the short term flares.
 770 Such flares are very likely to be produced by inhomogeneities of the flow, radiating when
 771 passing through the region where energy dissipation is intensified. Particularly prominent
 772 flares are seen in the optical light curves. Their ~ 10 -day time scales imply that the extension
 773 of the dissipative zone is

$$\Delta r \sim \frac{ct_{fl}}{(1+z)(1-\beta \cos \theta_{obs})} \sim 1.7 \text{ pc} \left(\frac{t_{fl}}{10 \text{ days}} \right) \left(\frac{\Gamma}{20} \right)^2 (\mathcal{D}/\Gamma), \quad (5)$$

774 which nicely corresponds with the location of the blazar zone derived from our model. In
 775 order to form such flares at a distance of 12 pc, a Lorentz factor of $\Gamma \sim 50$ is required.
 776 Interestingly, a similarly large Lorentz factor is required in the Agudo et al. (2011b) model
 777 to explain the observed $t < 20$ -day time scale of the flux decay at $\lambda = 1$ mm. This can
 778 be inferred by taking into account that radiative cooling of electrons emitting at 1 mm is
 779 inefficient and that the time scale of the flux decrease, as determined by the adiabatic losses,
 780 is $t_{ad} \simeq (R/c)(1+z)/(\theta_j \Gamma \mathcal{D})$. VLBI observations of AO 0235+164 do not exclude such a
 781 large value of the bulk Lorentz factor (Jorstad et al. 2001; Piner et al. 2006).

782 Finally we comment about the objections made by Agudo et al. (2011b) regarding the
 783 application of ERC models for the production of γ rays in AO 0235+164. They pointed
 784 out that in this model it is impossible to explain the lack of correlation between short-term
 785 variations of the γ -ray and optical fluxes because of a lack of variations of the external ra-
 786 diation field. However, in the fast cooling regime, variations of the inverse-Compton flux
 787 are determined not by variations of the seed radiation field but by variations of the electron
 788 injection function. It does not matter whether the seed radiation is external or internal,
 789 so this criticism may also be applied to the SSC models. Hence, the lack of a clear corre-
 790 spondence between variations in these two spectral bands must have a different origin than
 791 fluctuations in the background radiation. They can be related to variations of the Doppler
 792 factor and magnetic fields in the kinematically and geometrically complex dissipative zone.
 793 In particular, this can be the case if such a zone is associated with the oblique and/or recon-
 794 finement shocks, which in AO 0235+164 is indicated by roughly perpendicular orientation
 795 of the optical EVPA with respect to the jet axis (see Section 4.3).

796 8. Conclusions

797 *Fermi*-LAT detected enhanced activity in the high-redshift BL Lac object AO 0235+164
 798 during the first 6 months of operations. We present the results of an intensive multi-
 799 wavelength campaign covering radio, mm, near-IR, optical, UV and X-ray bands, as well

800 as optical polarimetry. Extinction in the optical/UV/X-ray band, complicated by the exis-
 801 tence of an additional absorbing system at intermediate redshift, has been carefully taken
 802 into account. We proposed a modification to the extinction model introduced by Junkkari-
 803 nen et al. (2004) and used by Raiteri et al. (2005) that corrects a spurious spectral feature
 804 in the FUV band.

805 The γ -ray spectrum is consistent with a broken power-law. Hints of spectral variabil-
 806 ity can be seen in episodic increases of the (1-100 GeV)/(0.1-1 GeV) hardness ratio. The
 807 brightest γ -ray flare is much more pronounced in the 0.1-1 GeV energy band.

808 The γ -ray activity is roughly correlated with the activity in the optical/near-IR band.
 809 There is a possible delay of 15 days of the R-band flux with respect to the γ -ray flux. The
 810 optical flux is also correlated with the optical polarization degree, which reaches values up
 811 to 35%. At the same time, the optical polarization angle is close to 100° with moderate
 812 scatter. As is typical for blazars, the activity in the radio band is smoother and begins
 813 months before the optical/ γ -ray activity, while the radio-flux peaks are delayed by several
 814 weeks with respect to the higher energy bands.

815 The behavior of the source in the X-ray band is distinct from other bands, as it shows a
 816 20-day high state delayed by a month from the main optical/ γ -ray flare. The X-ray spectrum
 817 during the high state is unusually soft, $\Gamma \sim 2.6$, and is inconsistent with the extrapolation of
 818 the optical/UV spectrum, unless we assume a much stronger extinction. We interpret this
 819 X-ray component as the bulk-Compton emission, i.e. Comptonization of the accretion-disk
 820 radiation reprocessed at the distance of $\sim 100 R_g$, in the region of ongoing jet acceleration
 821 and collimation. Such a feature has been tentatively reported before in a few sources, however
 822 the present case is still not definitive. The short duration of the high X-ray state can be
 823 explained by a rapid “wiggling” of the inner jet.

824 The broad-band SEDs extracted for two different activity states are, with the exception
 825 of the X-ray feature, typical for luminous blazars. We interpret the broad-band SEDs in
 826 the standard leptonic scenario, with the low-energy bump due to synchrotron radiation and
 827 the high-energy bump due to Comptonization of the external infrared radiation from the
 828 dusty torus (ERCIR). The energetic constraints are very tight, because, if the jet power is
 829 comparable to the Eddington luminosity of the central black hole, the required radiative
 830 efficiency of the jet is $\sim 20\%$, the magnetization is $\sigma_B \sim 11\%$ and the pair-to-proton ratio
 831 is $n_e/n_p \sim 9$. The bulk Compton feature in the high X-ray state requires, if the electron
 832 number flux is to be matched to the model of the flaring state, a covering factor of the
 833 accretion disk corona $\xi_b \sim 19\%$. An alternative interpretation of the high-energy bump with
 834 the SSC emission requires a very low covering factor for the dusty torus, in conflict with the
 835 observations of quasars.

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