A&A 468, 97–101 (2007)
DOI: 10.1051/0004-6361:20066570

Astronomy & Astrophysics

ROXA J081009.9+384757.0: a 10^{47} erg s^{-1} blazar with hard X-ray synchrotron peak or a new type of radio loud AGN?

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Received 14 October 2006 / Accepted 13 March 2007

ABSTRACT

We report the discovery of ROXA J081009.9+384757.0 = SDSS J081009.9+384757.0, a z = 3.95 blazar with a highly unusual Spectral Energy Distribution. This object was first noticed as a probable high f_x/f_r, high-luminosity blazar within the error region of a $\approx 10^{-12}$ erg cm^{-2} s^{-1} ROSAT source which, however, also included a much brighter late-type star. We describe the results of a recent Swift observation that establishes beyond doubt that the correct counterpart of the X-ray source is the flat spectrum radio quasar. With a luminosity well in excess of 10^{47} erg s^{-1} ROXA J081009.9+384757.0 is therefore one of the most luminous blazars known. We consider various possibilities for the nature of the electromagnetic emission from this source. In particular, we show that the SED is consistent with that of a blazar with synchrotron power peaking in the hard X-ray band. If this is indeed the case, the combination of high-luminosity and synchrotron peak in the hard-X-ray band contradicts the claimed anti-correlation between luminosity and position of the synchrotron peak usually referred to as the "blazar sequence". An alternative possibility is that the X-rays are not due to synchrotron emission, in this case the very peculiar SED of ROXA J081009.9+384757.0 would make it the first example of a new class of radio loud AGN.

Key words. radiation mechanisms: non-thermal – galaxies: active – galaxies: individual: ROXA J081009.9+384757.0 – X-rays: galaxies

1. Introduction

Active Galactic Nuclei (AGN) come in two main categories depending on the type of radiation we observe from them. AGN in which the observed power is dominated by thermal radiation generated in a disk of material accreted onto a super-massive black-hole (or Thermal-Emission Dominated AGN, the large majority of the population), and AGN in which the observed power is instead dominated by non-thermal radiation emitted by highly energetic particles in a jet of material that moves away from the central black hole at relativistic speeds (or Non-Thermal-Emission Dominated AGN, Giommi & Colafrancesco 2006). Within this paradigm, blazars are the small subset of Non-Thermal-Emission Dominated AGN that happen to be viewed at a small angle with respect to the jet axis. Because of this very special situation, the observed radiation from blazars is strongly affected by relativistic amplification and time contraction that are at the root of their extreme properties, such as super-luminal motion, strong rapid variability and high polarization (Blandford & Rees 1978; Urry & Padovani 1995). Blazars comprise the class of BL Lac objects, distinguished by featureless optical spectra, and of Flat Spectrum Radio Quasars (FSRQs) which instead share all the usual broad emission lines that are typical of AGNs.

One specific property of blazars is that their non-thermal emission spans the entire electromagnetic spectrum. In fact, their Spectral Energy Distribution (SED), when represented in the $\mathrm{Log}(\nu) - \mathrm{Log}[\nu f(\nu)]$ space, is composed of a synchrotron low-energy component that usually peaks between the far infrared and the X-ray band, followed by an inverse-Compton component that has its maximum in the hard X-ray band or at higher energies, and extends into the γ-ray or even the TeV band. BL Lacs with synchrotron peak located at low energy are usually called Low-energy peaked BL Lacs (LBL), while those where the synchrotron component reaches the X-ray band are called High-energy peaked BL Lacs (HBL, Padovani & Giommi 1995). In the following we extend this terminology to all types of blazars. In fact, the SED of almost the totality of FSRQs is very similar to that of BL Lacs of the LBL type, although a number of these quasars (also called HFSRQs or "HBL-like" FSRQs) have recently been found by e.g. Padovani et al. (2003). These objects are, however, rare and their synchrotron emission has never been found to reach the extreme energies observed in TeV detected BL Lacs like MKN501 (e.g., Pian et al. 1998;

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Massaro et al. 2004), 1H 1100-230, MKN 421 and H 1426+428 (Tramacere et al. 2006). A recent survey specifically designed to search for extreme HBL sources resulted in the selection of about 150 BL Lacs and no FSRQs (Giommi et al. 2005).

To explain the different SEDs observed in radio and X-ray selected samples of Blazars, Fossati et al. (1998) proposed that blazars form a sequence where the peak energy of the synchrotron component is inversely related to the observed luminosity of the object. Ghisellini et al. (1998) put this hypothesis in a theoretical framework where the sequence would be the result of a competitive balance between particle acceleration and radiative cooling. In this view, hence, only low-power BL Lac objects can reach synchrotron peak energies in the X-ray band, whereas the peak energy of high-luminosity FSRQs cannot go much beyond the far infrared frequency range.

In this paper we report the results of a Swift (Gehrels et al. 2004) observation of one of the most luminous known FSRQ in the X-ray band, ROXA J081009.9+384757.0 = SDSS J081009.9+384757.0, which has a very large X-ray to radio flux ratio $f_x/f_r \simeq 5 \times 10^{-11}$ erg cm^{-2} s^{-1} Jy^{-1}, typical of HBL objects, with synchrotron peak in the X-ray band. We discuss here the impact of this source on the blazar sequence hypothesis. Throughout this paper we use a flat, vacuum-dominated CDM cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$.

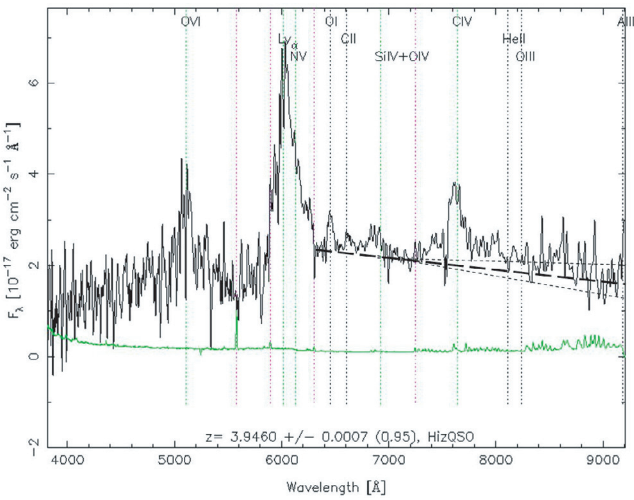

Fig. 1. The SDSS optical spectrum of ROXA J081009.9+384757.0. The dashed line plotted to the right of the Lyman-α line is an estimate of the continuum based on the composite quasar spectrum template of Vanden Berk et al. (2001). The dotted lines represent conservative limits to the slope of the continuum. See text for details.

2. SDSS J081009.9+384757.0 and RX J0810.2+3847

SDSS J081009.9+384757.0 is a high redshift (z = 3.95) object coincident with the compact radio source FIRST J081009.9+384756 which has a radio flux of 27–30 mJy at 1.4 GHz (from the FIRST and NVSS surveys, White et al. 1997; Condon et al. 1998) and 22 mJy at 5 GHz (from the GB6 catalog, Gregory et al. 1996). Figure 1 shows its optical spectrum (taken from the Sloan Digital Sky Survey (SDSS) archive, Data Release 3 (Abazajian et al. 2005) which clearly displays Lyman α forest absorption features together with the strong Hydrogen, Oxygen and Carbon emission lines that are typical of distant QSOs. Since the radio spectral index of FIRST J081009.9+384756 is flat ($\alpha_{1.4-5.\,\rm GHz} \simeq 0.2$, $f(\nu) \propto \nu^{-\alpha}$) and the radio to optical spectral index $\alpha_{\rm ro} = 0.48$, SDSS J081009.9+384757.0 can safely be classified as a FSRQ. Prochaska et al. (2005) report that SDSS J081009.9+384757.0 is a damped Lyman-α system with absorbing clouds of material located at redshifts z = 1.69, 3.0, 3.2 and 3.9. We estimate the slope of the optical-UV continuum to be $\alpha_{\rm o} \simeq 0.5$, (represented by the dashed line in Fig. 1) assuming that the minimum flux between the CIV and SiIV lines at ~7200 Å, (~1450 Å in the rest frame of the QSO), is the continuum emission as in the composite QSO spectrum built by Vanden Berk et al. (2001). Given the presence of strong emission lines it is not simple to associate an error to this slope. The dotted lines in Fig. 1, corresponding to $\alpha_{\rm o} = 1.8$ and $\alpha_{\rm o} = 0.2$, represent conservative limits to the slope of the continuum that we will use later in the paper.

The position of SDSS J081009.9+384757.0 is within the error circle of RX J0810.2+3847, one of the sources of the ROSAT All Sky Survey (RASS, Brinkmann et al. 2000) and is included in a sample of blazar candidates selected on the basis of their radio, optical and X-ray emission (ROXA, see Turriziani et al. 2007). The association of the r = 19.7 mag (SDSS) quasar with the RASS X-ray source is, however, uncertain because the X-ray error circle also includes the brighter (r = 17.3 mag, SDSS) late type star SDSS J081010.9+384745.6.

The X-ray flux of RX J0810.2+3847 is $\simeq 10^{-12}$ erg cm^{-2} s^{-1} in the 0.1–2.4 keV band.

3. Swift observations and data reduction

The Swift multi-frequency Gamma Ray Burst observatory (Gehrels et al. 2004) observed RX J0810.2+3847 as a "fill-in target" on March 3, 2006. These are short exposures carried out when the satellite is not engaged with GRB observations. Swift carries three instruments on board: the Burst Alert Telescope (BAT, Barthelmy et al. 2005) sensitive in the 15–150 keV band, the X-Ray Telescope (XRT, Burrows et al. 2005) sensitive in the 0.2–10.0 keV band and capable of measuring the position of X-ray sources with a precision of a few arcseconds, and the UV and Optical Telescope (UVOT, Roming et al. 2005). The purposes of the observation were: i) to confirm that the X-ray emission is associated with the high redshift FSRQ SDSS J081009.9+384757.0; ii) to measure its X-ray spectrum between 0.3 and 10 keV; and iii) to obtain simultaneous optical–X-ray data.

3.1. XRT image analysis

The Swift XRT was operated in full imaging Photon Counting mode during the entire observation (5991 s). The data were reduced using the *XRTDAS* software (v1.7.1) developed at the ASI Science Data Center (ASDC) and distributed as part of the HEAsoft 6.0.4 package by the NASA High Energy Astrophysics Archive Research Center (HEASARC). The cleaned level-2 data has been analyzed using the XIMAGE package.

A pointlike X-ray source was clearly detected at RA (J2000.0) = 08h10m10.2s Dec (J2000.0) = +38°47′55.3″ with a net count rate of $(3.2 \pm 0.2) \times 10^{-2}$ cts/s. The XRT position and its associated error circle (4″, 90%, Moretti et al. 2006), shown in Fig. 2 overlaid to the optical image taken from the SDSS archive, are fully consistent with the position of SDSS J081009.9+384757.0 and exclude the brighter late-type star as the counterpart of the X-ray source. Since SDSS J081009.9+384757.0 is the only optical and radio source

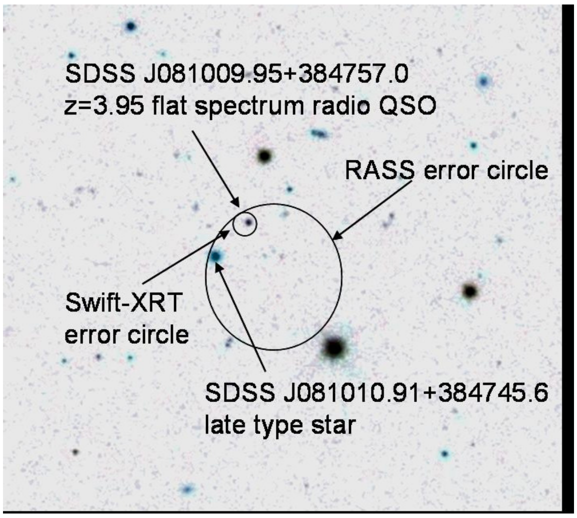

Fig. 2. SDSS optical image covering the 22 arcsec error circle of the X-ray source RX J0810.2+3847. The much smaller (4 arcsec) Swift XRT error region associates beyond any doubt the X-ray source to the flat spectrum radio quasar SDSS J081009.9+384757.0.

within the small XRT error circle, we conclude that this quasar is the optical counterpart of the X-ray and radio sources.

3.2. XRT spectral analysis

Only about 200 net counts have been detected in our short XRT observation and therefore our spectral fits are poorly constrained.

We have selected photons with grades in the range 0–12 and used default screening parameters to produce level 2 cleaned event files. The XRT 0.3–10 keV spectrum was extracted from a circular region around the source with radius of 20 pixels, which includes 90% of the source photons. In order to use χ^2 statistics, the spectrum was rebinned to include at least 30 photons in each energy channel. For the spectral fitting we used the XSPEC11.3 package and, given the very limited statistics, we only fitted the data to a simple power law spectral model. We first fixed the low energy absorption to the Galactic value ($N_H = 5 \times 10^{20}$ cm^{-2}) in the direction of the source (Dickey & Lockman 1990). The best fit gives a photon index $\Gamma = 1.5 \pm 0.2$ and a reduced $\chi^2 = 1.0$ (3 d.o.f.).

Since SDSS J081009.9+384757.0 is a damped Lyman α system with significant amount of absorption material located at redshifts between 1.69 and 3.9 (Prochaska et al. 2005), an excess of low energy absorption compared to the Galactic value is to be expected. We then fitted the spectrum leaving N_H as a free parameter and obtained best fit values of $N_H = (8 \pm 7) \times 10^{20}$ cm^{-2} and $\Gamma = 1.7 \pm 0.4$. Clearly, the available statistics are not good enough to effectively constrain both spectral parameters. The unabsorbed 2–10 keV flux is $\simeq 10^{-12}$ erg cm^{-2} s^{-1}, similar to that observed by ROSAT, corresponding to the very large isotropic X-ray luminosity of 1.5×10^{47} erg s^{-1}.

X-ray observations of other high-redhift quasars with ROSAT, ASCA and *Beppo*SAX have shown that significant soft X-ray absorption is a common feature of radio loud quasars (Cappi et al. 1997; Fiore et al. 1998; Fabian et al. 2001). This implies that the intrinsic X-ray luminosity of ROXA J081009.9+384757.0 could be higher than reported above and that its X-ray spectral slope could be somewhat steeper than $\Gamma = 1.7$. In this case also the true f_x/f_r value could be even larger than the observed one.

3.3. UVOT observations

UVOT (Roming et al. 2005) is a 30 cm telescope equipped with two grisms and six broadband filters (*V*, *B*, *U*, *UVW1*, *UVM2*, and *UVW2*). During the Swift observation, UVOT obtained series of images in each of the available filters. The exposure time was 462 s in filter *V* and 402 s in filter *B*. The UV filters did not provide useful data since in these bands our high redshift quasar is heavily affected by strong Lyman α absorption.

While all the bright optical sources visible in the SDSS image, including the late-type star and the bright sources to the north and south of the ROSAT error circle (see Fig. 2), are clearly detected in the UVOT *V* and *B* images, SDSS J081009.9+384757.0 was not detected even in the most sensitive *B* filter. Lower limits to the magnitude of SDSS J081009.9+384757.0 are $V > 17.9$ and $B > 20.4$. The limit in the *V* filter is somewhat higher than those obtained with similar exposures because the image in this case was particularly noisy.

4. Discussion

The source ROXA J081009.9+384757.0 was discovered to be a candidate high f_x/f_r – high luminosity blazar in a multi-frequency survey aimed at the discovery of a large sample of new blazars by combining data from the NVSS, RASS, GSC-2, SDSS and 2dF surveys (Turriziani et al. 2007). The association between the radio, optical and X-ray emission for the case of ROXA J081009.9+384757.0 was however uncertain since the error region of the X-ray source RX J0810.2+3847 included two plausible optical counterparts. Our Swift observation establishes without doubt that SDSS J081009.9+384757.0 is the correct counterpart of the ROSAT X-ray source and, consequently, that ROXA J081009.9+384757.0 is a high-redshift blazar with $f_x/f_r \simeq 5 \times 10^{-11}$ erg cm^{-2} s^{-1} Jy^{-1} (~2.5×10^{-11} in the quasar's rest frame) and, consequently, $\alpha_{rx} \approx 0.65$. Such a large amount of X-ray emission compared to the radio flux, even taking into account of K-corrections, has been observed, so far, only in a very small fraction of blazars (less than 1% of the population, see Fig. 4 of Giommi et al. 2006a; see also Padovani et al. 2003), the vast majority of which are BL Lacertae objects, with synchrotron emission reaching very high energies. ROXA J081009.9+384757.0 is the first high luminosity FSRQ to show such extreme broad-band spectral characteristics.

We have built the overall SED of ROXA J081009.9+384757.0 (see Fig. 3) by combining the simultaneous XRT data points and UVOT upper limits with non-simultaneous radio (FIRST, NVSS and GB6) optical, (from SDSS magnitudes), ROSAT data and WMAP upper limits at microwave frequencies. These upper limits were derived from the WMAP three-year data (Hinshaw et al. 2006) considering that the fluctuation maps in all WMAP channels do not show any excess at the location of the source and measuring the local noise in a nearby circular region of 1 degree in diameter (De Bernardis, private communication). The optical fluxes derived from the SDSS *z*, *i* and *r* magnitudes (the *g* and *u* measurements were not used since these are heavily affected by Lyman α forest absorption) are consistent with the UVOT upper limits (particularly with the *B* value) and describe a flat continuum with power that is lower than that at X-ray frequencies, implying that the overall SED cannot peak near the optical band.

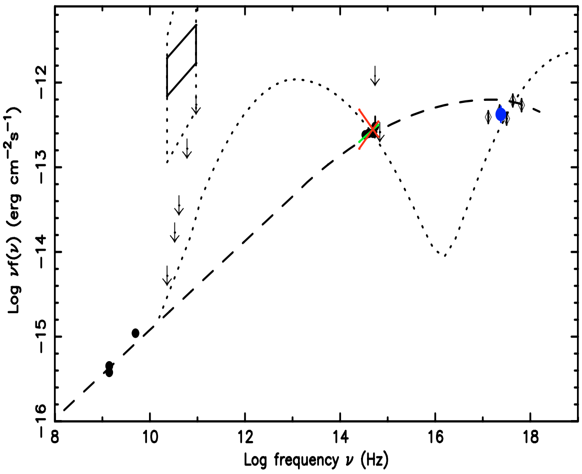

Fig. 3. The SED of ROXA J081009.9+384757.0 built using the radio data from the NVSS, FIRST and GB6 radio surveys, microwave upper limits (at 23, 33, 41, 61 and 94 GHz) from WMAP 3-yr data, optical photometry from the SDSS survey, ROSAT (filled circle) and Swift XRT X-ray data (open diamonds) and UVOT upper limits in the V and B filters. The boxes drawn at microwave frequencies represent the 1σ and the maximum observed flux range from blazars where the X rays are due to inverse Compton radiation (see text for details). The solid lines in the optical band represent our best estimate and conservative upper limits to the slope of the continuum (see also Fig. 1).

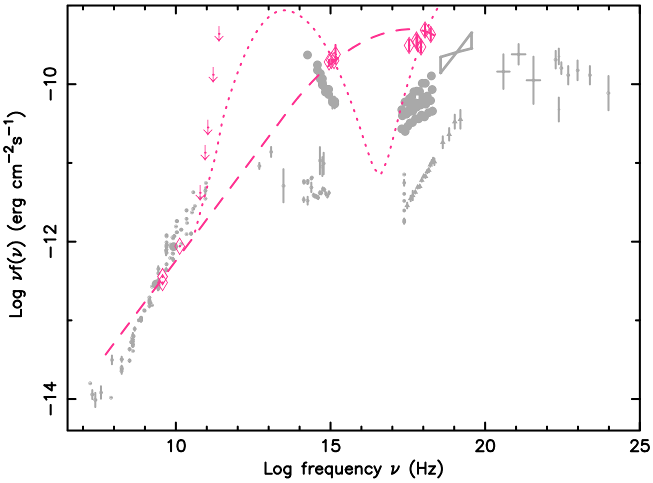

Fig. 4. The SED of ROXA J081009.9+384757.0 (see Fig. 3) is plotted together with that of 3C 454.3 after scaling to match the radio flux and the redshift of this last blazar. The large filled circles are the fluxes observed during the very large flare of 3C 454.3 in May 2005, while the smaller symbols are non-simultaneous historical data taken from the literature (see Giommi et al. 2006b, for details).

The radio through X-ray SED of ROXA J081009.9+384757.0 shown in Fig. 3 can be described by a single component, well approximated by a power-law, that bends only after the UV (dashed line) and reaches the X-ray band with a photon index still rather flat. This is also supported by the consideration that the emitted soft X-ray emission could be larger than that shown in Fig. 3 because of the likely presence of intrinsic and intergalactic absorption (see Sects. 2 and 3.2).

This simple description suggests that the emission is likely due to synchrotron radiation with power that peaks at energies higher than 10 keV (~50 keV in the rest-frame). This is an extremely high energy that has been observed in rare cases during strong flares only in nearby blazars with luminosity at least two orders of magnitudes lower that that of ROXA J081009.9+384757.0 (e.g. MKN501, Pian et al. 1998; Massaro et al. 2004).

The sparse data coverage of the SED, however, leaves room to alternative scenarios for the origin of the broad band emission of this source: in particular, one cannot exclude that X-ray emission is due inverse Compton scattering either in a SSC or in external Compton scenarios. In these cases one has to consider the possibility that the peak of the synchrotron emission would be in the far infra-red with power of the order of $\sim 10^{-12}$ erg cm^{-2} s^{-1} (see the dotted curve in Fig. 3) where no measurements are available, nor useful upper limits can be derived from existing data. However, we regard it as unlikely since in this case: i) the optical spectrum would be in the steeply declining part of the synchrotron component with a slope α_o larger than 2, which is only marginally consistent with Fig. 1 (see also Fig. 3) even without de-reddening the spectrum (see Sect. 2); ii) the f_x/f_r ratio of ROXA J081009.9+384757.0 is much larger than that of known blazars with inverse Compton X-ray spectrum (e.g., Giommi et al. 2006a,c); iii) in Fig. 3 the boxes drawn at microwave frequencies represent the flux expected from the observed ($\pm 1\sigma$: solid box and full-observed-range: dotted box) X-ray to microwave flux ratios in a large sample of WMAP detected sources (Giommi et al. 2006b,c) when the X-rays are due to inverse Compton emission; iv) in the hypothesis that the X-rays are Compton up-scattered microwave-far infrared photons one expects the SED to be peaked in the far infrared. In this case, the low energy spectrum of ROXA J081009.9+384757.0 consistently with the WMAP upper limits, should dramatically flatten after the radio (cm) band and become strongly inverted at microwave frequencies (Fig. 3).

The assumption that the X-ray emission from ROXA J081009.9+384757.0 is not due to synchrotron radiation implies that this object must be characterized by a peculiar overall SED with f_x/f_r and $f_x/f_{94\ \mathrm{GHz}}$ orders of magnitude larger than in normal LBL blazars, and a highly inverted microwave to far-infrared spectrum. Therefore, it should be considered an unusual blazar or possibly the prototype of a new class of radio loud AGN.

A further possibility is to assume that ROXA J081009.9+384757.0 was caught during an extremely large optical and X-ray flare like that of 3C 454.3 in May 2005 (Pian et al. 2006; Giommi et al. 2006a). To test this hypothesis, we plotted in Fig. 4 the SED of both sources after scaling the flux of ROXA J081009.9+384757.0 to match the radio flux and redshift of 3C 454.3. Although the rescaled optical and X-ray fluxes are still substantially larger than that of 3C 454.3, an even larger flare cannot be excluded. However, we regard this explanation as unlikely since both the optical and X-ray flux of 3C 454.3 during the flare of 2005 varied by large factors over time scales of hours or days, while ROXA J081009.9+384757.0 was found approximately at the same flux level in observations separated by several years both in the optical (the source is clearly visible close to the POSS limiting sensitivity of $R \simeq 20$ mag and was detected as a $r = 19.7$ mag object in the SDSS) and in the X-ray band by ROSAT and Swift.

The most likely conclusion seems that ROXA J081009.9+384757.0 is the first high-luminosity FSRQ with synchrotron peak in the hard X-ray band. Its X-ray luminosity of $\sim 1.5 \times 10^{47}$ erg/s, one of the largest ever observed in any AGN, has been found to be persistent and approximately constant between the ROSAT and the Swift observation which are separated by ~10 years.

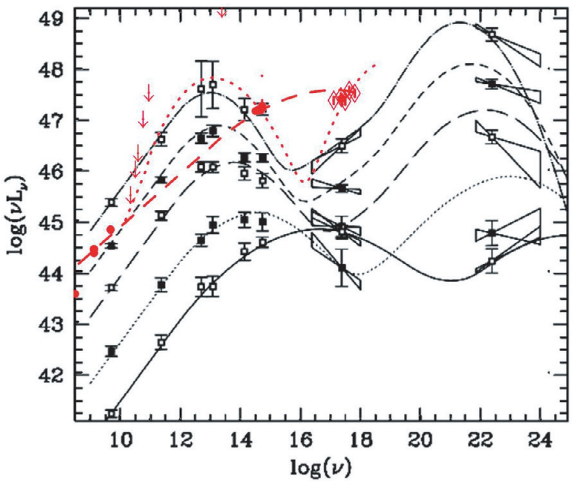

Fig. 5. The SED of ROXA J081009.9+384757.0 shown Fig. 3 (converted to luminosity) is overlaid to the Blazar sequence plot of Fossati et al. (1998).

An important consequence of the likely scenario where the synchrotron peak of ROXA J081009.9+384757.0 is in the hard X-ray band is that this object would strongly contradict the claimed anti-correlation between luminosity and synchrotron peak energy, often referred to as the "Blazar sequence" (Fossati et al. 1998; Ghisellini et al. 1998, see Fig. 5). We recall that the validity of this scenario has also been questioned by a number of studies involving large samples of blazars selected in a variety of ways (e.g., Giommi et al. 1999; Padovani et al. 2003; Caccianiga & Marchã 2004; Nieppola et al. 2005; Giommi et al. 2006b,c; Padovani 2007).

If the synchrotron emission of ROXA J081009.9+384757.0 indeed peaks in the hard X-ray band, then the peak of the inverse Compton component in a SSC scenario would well be into the γ-ray band. This object is therefore a very good target for GLAST to determine the spectral shape of the inverse Compton component.

The possibility that such a high-energy synchrotron peak would be due to a very high Doppler beaming, say $\delta > 50$, is not satisfactory because the optical continuum would be so intense to overwhelm the emission lines, which instead are very prominent. If the beaming is instead more typical of blazar-like objects (e.g. $\delta \simeq 10$), then ROXA J081009.9+384757.0 should be capable of accelerating electrons up to the TeV range and therefore it is similar to the near HBL sources detected in this energy range.

The presently available data do not allow us to describe the SED of ROXA J081009.9+384757.0 with a coverage that is sufficient to safely establish its nature. Future detailed (observational and theoretical) studies of such a peculiar object will hence shed light on its energetic, relativistic effects and the cosmological impact.

It is also important to know whether it is a unique source or the prototype of new class of very high luminosty AGNs. The search for other high-z FSRQ, based on a multifrequency approach, is therefore of crucial relevance for the physics of this family of extragalactic blazar-like sources.

Acknowledgements. The authors acknowledge the financial support for ASDC by the Italian Space Agency (ASI). We are grateful to P. De Bernardis for providing the WMAP upper limits. We thank G. Fossati for providing an electronic version of the "Blazar sequence" figure originally published in Fossati et al. (1998). This work is partly based on data taken from the NVSS, FIRST, ROSAT and SDSS archives. We thank the anonymous Referee for useful comments and suggestions.

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