A review of the multiwavelength studies on the blazars detected by AGILE

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Abstract. We report on the main results on gamma-ray blazars as obtained by AGILE during 4 years in orbit. AGILE detected several flaring blazars, mostly FSRQs, which were studied from radio to TeV energy bands thanks to the rapid dissemination of our alerts. In particular, we carried out several multifrequency campaigns resulted from the synergy with other observatories such as GASP-WEBT (GLAST-AGILE Support Programme of the Whole Earth Blazar Telescope network), REM, Spitzer, Swift, RXTE, XMM-Newton, Suzaku, INTEGRAL, MAGIC, VERITAS. Temporal and SED variabilities were studied in details thanks to the large set of simultaneous data. The most relevant properties of our sample of blazars will be presented with a particular emphasis on the spectral thermal components, time lags, spectral trends (in X-rays and gamma-rays), jet geometry and acceleration mechanism at the inner portion of the jet itself.

1. Introduction
Since its launch in 2007, AGILE (Tavani et al. 2009) has been involved in several multi-frequency campaigns to study the emission mechanisms of the brightest blazars in the gamma-ray sky. This was possible thanks to coordinated (quasi-)simultaneous observations basically obtained by the acceptance of several proposals of monitoring and/or Target of Opportunity (ToO) with X-ray observatories (Swift, Suzaku, INTEGRAL) and an agreement with the radio-optical monitoring provided by the GASP-WEBT (Villata et al. 2008). Moreover, a good cooperation and data sharing has been obtained with the Cherenkov observatories MAGIC and VERITAS, allowing for the exploration of GeV-TeV connection. A large set of multi-frequency data were acquired on ∼ 20 objects detected in flaring states and analyzed in order to investigate possible multi-λ flux correlations and spectral energy distribution (SED) variability. Despite the limited number of the objects in our sample, the wide coverage of the SED of these blazars obtained in different states posed important constraints on the efficiency of their acceleration mechanisms, on the electron population, on the thermal emission variability, on possible time lag between optical and gamma-ray emission and finally on the dissipation region of the gamma-ray emission, which is actually still debated (Marscher et al. 2010, Tavecchio et al. 2010).

Since October 2009, AGILE is prevented to perform pointed observations due to a failure of the reaction wheel, then it now surveys a large fraction of the sky (∼ 80%) rotating at 0.8 degrees/s. The sky scanning mode improved the AGILE capability to detect transient episodes from the brightest blazars. In this paper, we will summarize the main results obtained so far during these multifrequency campaigns.
2. Optical-UV observations in different γ-ray states

Simultaneous gamma-ray and Optical-UV observations are key ingredients to constrain a) the acceleration mechanism efficiency given the evidence/lack of the thermal component in FSRQs; b) the external seed photon component responsible of the IC peak by estimating the accretion disk luminosity, with a better definition of the γ-ray dissipation region; c) possible time lags between synchrotron and IC emissions in low synchrotron peak sources.

2.1. Thermal components

In order to constrain the contribution of the thermal component to the blazar SED, the optical-UV emission has to be monitored during the quiescent states of the source when, more likely, it is not hidden in the non-thermal emission. In particular, simultaneous optical-UV and gamma-ray data are crucial to disentangle among the candidate seed photons (dusty torus, accretion disk, Broad Line Region (BLR), hot corona) in the external Compton (EC) model, posing constraints on the γ-ray dissipation region. The estimate of this component was possible for 2 objects characterized by a strong γ-ray activity, 3C 454.3 and PKS 1510-089.

In particular, during the 18-month long multi-frequency campaign on 3C 454.3 the disk component was observed only during the low gamma-ray states (Fig. 19 in Vercellone et al. 2010). We remind that previous evidences of the blue bump in this blazar were found during multi-frequency campaigns performed between 2005 and 2007 as reported in Raiteri et al. 2008. The derived disk luminosity estimate of $5 \times 10^{46}$ erg s$^{-1}$ in the AGILE campaigns was injected in the model fitting of the SEDs in the higher gamma-ray states, deriving that the accretion disk emission as direct as reprocessed by the BLR was the dominant seed photon source in the IC emission.

The case of PKS 1510-089 is even more intriguing. In this object the thermal component was detected also during the high gamma-ray activity registered by AGILE in March 2008 (D’Ammando et al. 2009), showing synchrotron emission peaked in the infrared energy band. The disk component was still observed during a new high gamma-ray activity detected by AGILE in March 2009, showing a significant variation in UV (a mild in optical) as signature of disk emission enhancement with respect to the past year. However, during the maximum γ-ray activity reached in this campaign, a strong variation at optical-UV energies was also detected. Given the short time scale of this variation, this was interpreted as due to an acceleration process responsible for the shift of the synchrotron energy peak towards higher energies (Fig. 6 in D’Ammando et al. 2011 for details). This behavior is not usually observed in FSRQs being commonly observed in HBL objects.

2.2. Time Lags

Time lags between optical and gamma-ray emissions have been investigated on a few blazars (~4) for which a continuous monitoring in both energy bands - lasting at least one month - was available. Optical−γ-ray correlation was studied by means of a Discrete Correlation Function (DCF; Edelson & Krolik 1988; Hufnagel & Bregman 1992) in order to constrain time lag also below the time binning of the gamma-ray light curves (1-day binning) thanks to the centroid calculation (Peterson et al. 1998; Raiteri et al. 2003). The DCF method applied to our sample revealed hints of delay between optical and gamma-ray variabilities only in the case of the Intermediate BL Lac Object S5 0716+714 (Chen et al. 2008) and of 3C 454.3 (Donnarumma et al. 2009a, Vercellone et al. 2010). In detail, S5 0716+714 was observed simultaneously in optical ($B$) and in γ-ray energy bands between September and October 2007. A DCF analysis performed on this dataset provided a possible delay between optical and γ-ray variations of the order of 1 day (left panel in Fig.1). This 1-day time-lag was consistent with the SSC interpretation provided by the SED modeling, since it is likely associated with the light travel time of the synchrotron seed photons that scatter the energetic electrons.
3C 454.3 was the source best studied by AGILE because of its strong γ-ray activity in the last years. The 18-month long monitoring from radio to gamma-ray energy bands of this source provided a large dataset used in order to corroborate or falsify the possible 12-hour γ-optical delay found in the December 2007 campaign (Donnarumma et al. 2009a). Although the DCF analysis performed on this longer period showed a peak in correspondence with 0-day lag (τ = 0, right panel in Fig.1), the asymmetric shape of DCF as probed also by the centroid distribution (insert plot in Fig.1 right panel), suggested a possible lag occurred at τ = −0.4±0.6 (Vercellone et al. 2010 for details). This result, consistent also with the findings of Bonning et al. 2009, showed that gamma-ray variations could be delayed by few hours with respect to the optical ones, in agreement with the dominance of the EC model provided by the SED modeling: the delay is compatible with the corresponding crossing time of the external seed photons of a typical blob dimensions (Sokolov et al. 2004).

![Figure 1. DCFs between optical and γ-ray light curves as performed for S5 0716+714 (left panel) and 3C 454.3 (right panel); the insert in the right panel shows the DCF centroid distribution. We remind that negative τ means that the optical variability leads the γ-ray one. These figures have been adapted from Chen et al. (2008) and Vercellone et al. (2010).](image)

3. Soft X and γ-rays

Thanks to several ToO observations performed by Swift/XRT during the long term multi-λ campaign on 3C 454.3, it was possible to detect temporal and spectral variabilities in the soft X-rays during the enhanced γ-ray activity. As for the spectral variability, the data acquired so far showed a “harder-when-brighter” trend in soft X-rays, although a small deviation from this trend occurs at F(2 − 10 keV)< 2 × 10^{-11} erg cm^{-2} s^{-1} (Vercellone et al. 2010). We note that a similar trend is common in FSRQs as reported in Abdo et al. 2010a. Moreover, AGILE data suggested a possible “harder-when-brighter” trend in the γ-ray data, although we cannot draw any firm conclusion due to the larger errors in the spectral slopes. Moreover, many other ToOs observations were preformed by Swift, during the γ-ray "giant flares" of 3C 454.3 detected by AGILE in December 2009 (Pacciani et al. 2010) and in November 2010 (Vercellone et al. 2011). These allowed for the investigation of the spectral trend at higher fluxes, showing a saturation of the photon index with increasing flux (Fig. 2, left panel). We interpreted the “harder-when-brighter” trend as due to a higher accretion rate or a larger value of the bulk Lorentz factor coupled with a slightly lower value of the magnetic field, while the saturation at higher flux values, may be ascribed to a balance of the SSC contribution to EC from the disk (a significant component in the raising tail of the IC emission). A detailed interpretation of this trend is reported in Vercellone et al. 2011.
Figure 2. Left panel: the photon index vs $F_{2-10\text{keV}}$ relation as inferred by several Swift/XRT observations of 3C 454.3. Right panel: from top to bottom Optical ($R$-band), millimeter (220 GHz) and $\gamma$-ray light curves of 3C 454.3, adapted from Vercellone et al. 2010.

4. Radio-Optical-$\gamma$-rays
Simultaneous radio, optical and gamma-ray observations are shedding light on the study of the jet geometry. In particular strong correlation between radio (43 GHz) and gamma-ray emissions have been observed during bright $\gamma$-ray flares of some blazars, as in the case of PKS 1510-089 (Marscher et al. 2010). In addition, long term optical polarimetric monitoring revealed that significant variations of the polarization angle occurred slightly before or in coincidence with a bright gamma-ray flare (see the case of 3C 279 reported in Abdo et al 2010b). These correlated multi-$\lambda$ variabilities gave rise to several hypotheses on the jet structure and dynamics. Among them, there are the requirement of a non axisymmetric magnetic field or a jet wobbling across the line of sight or a bending jet.

In this respect, we found a possible hint of a bending jet in 3C 454.3 on the basis of the radio (220 GHz), optical ($R$) and gamma-ray light curve behavior observed during the 18-month long multiwavelength campaign (Fig. 2, right panel). In detail, in 2007 (MJD= 54200 − 54460) the more pronounced fluxes and variability of the optical and $\gamma$-ray emissions seem to favor the inner portion of the jet as the more beamed one. On the other hand, the higher mm flux emission and its enhanced variability during 2008 (MJD= 54600 − 54800), together with the dimming trend in the optical and in the $\gamma$-ray bands, could indicate that the more extended region of the jet became more aligned with respect to the observer line of sight. This behavior resembles that of BL Lacertae (Villata et al. 2009), which could be interpreted in the framework of a change in orientation of a curved jet, yielding different alignment configurations within the jet itself. This scenario has been recently supported by Raiteri et al. 2011. By analyzing radio, Optical-UV, X-ray and gamma-ray simultaneous observations between April 2008 and March 2010 of 3C 454.3, they interpreted the long term multi-frequency variability in terms of an inhomogeneous bending jet, where the synchrotron radiation is produced in outer and wider jet regions - which in turn may change also their orientation- while the frequency increases. However, it is worth noting that during the latest flare (Vercellone et al. 2011), which is also the brightest ever observed in 3C 454.3, the mm (230 GHz), optical-UV, X-ray and $\gamma$-ray emissions show quasi-simultaneous variations. In this case, it is difficult to explain the correlated variabilities in terms
of the bending jet model, but we have to remind that the November 2010 γ-ray flare seems quite peculiar if compared with the events previously occurred in this blazar (see Vercellone et al. 2011 for details).

5. The GeV-TeV connection
AGILE was involved in two main campaigns with Very High Energy (VHE) observatories, both performed during the June 2008 observations of the W Comae field aimed to follow a VHE γ-ray flare from this blazar announced by VERITAS. The observations started on 2008 June 9 and lasted about 1 week. During these observations the two blazars present in this field, Mrk 421 and W Comae were detected by AGILE. Mrk 421 was first detected by AGILE with its hard X-ray monitor, SuperAGILE (Feroci et al. 2007), showing an increasing hard X-ray activity, culminating in a flux level of $\sim 55$ mCrab in the energy range 20-60 keV. No significant γ-ray emission above 100 MeV was observed by AGILE-GRID integrating on daily-time scale, however by collecting all the 1-week data, Mrk 421 was detected by the GRID ($E > 100$ MeV) with a flux of $(42 \pm 13) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$, consistent with the highest flux observed by EGRET. The soft X-ray monitoring provided by the RXTE/ASM together with a ToO observation performed by Swift/XRT showed that the source reached its historical maximum, i.e. $\sim 2.6 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$. TeV data were not acquired during the brightest X-ray flare and then also in correspondence with the γ-ray detection. However the data acquired during the pre-flare activity suggested a correlation between soft, hard X-ray and TeV emissions. On the basis of these evidences and on the relative variations observed in soft X-rays and in VHE gamma-ray light curves, the variability of the Spectral Energy Distribution of Mrk 421 in June 2008 was ascribed to an acceleration process in a standard synchrotron self Compton (SSC) leptonic model rather than to a new injection of relativistic electrons (see Donnarumma et al. 2009b for further details).

As described above, AGILE performed a ToO on W Comae field to follow a flare of W Comae detected by VERITAS between 2008 June 7 and 9, which corresponding flux was 2.5-3 times higher than the previous flare observed in March 2008 (Acciari et al. 2008). AGILE-GRID detected the source only between June 12 and 13, at a flux level of $(90 \pm 32) \times 10^{-8}$ photons cm$^{-2}$ s$^{-1}$, roughly a factor of 1.5 higher than the highest flux detected by EGRET (Hartmann et al. 1999). In the rest of the observing period, AGILE-GRID provided only 3-σ upper limits ($< 60 \times 10^{-8}$ ph s$^{-1}$ cm$^{-2}$ for a 2-3 day time scale, see Acciari et al. 2009). Soft X-rays observations from both Swift/XRT and XMM-Newton satellites were also performed, which showed an interesting flux variability (a factor of 2) on hour time scale. On the same time scale, a slightly lower variability ($\sim 1.5$) was also observed in UV data. Moreover, radio, Optical and near-IR observations were provided by Noto, UMRAO Metsähovi radio telescopes and the GASP-WEBT consortium: no significant variability was observed in optical R-band and radio (14.5, 37 GHz) data. The simultaneous γ-ray and VHE gamma-rays led to disentangle between the simple SSC model and the need of an additional source of photon field likely originating from a near nuclear dusty torus which emission peaked at $1.5 \times 10^{14}$ Hz. Further details on the multifrequency campaign are provided in Acciari et al. 2009.

6. Future plans
AGILE accumulated four years of data, covering the whole sky. The forthcoming AGILE 2nd source catalog (Bulgarelli et al. in preparation) will contain a high number of extragalactic sources both associated with low energy counterparts and still unidentified. Moreover, a deep investigation on $\sim 60$ extra-galactic ($|b| > 10$) source candidates derived by the Quick look analysis is now ongoing. Among our objectives on these data and the future ones, there is the plan to extend our spectral analysis below 100 MeV as it was already done in the case of Crab (Vittorini et al. 2011) and 3C 454.3 (Vercellone et al. 2011). In particular, the inspection of
the energy range (50-200 MeV) would be particularly relevant in the study of the so-called MeV blazar, with IC emission peaking at MeV energies. Future multi-frequency campaigns on these objects will be planned to understand if they belong to a peculiar class of objects or they are a transitory class defined by the location of the $\gamma$-ray dissipation regions (Sikora et al. 2002). In this respect, during a recent AGILE multi-\lambda campaign the high $z$ (2.507) blazar PKS 1830-211 (Donnarumma et al. 2011), previously classified as a MeV blazar (De Rosa et al. 2005), was highly variable in gamma-rays without any significant counterpart at lower frequencies (near-IR, Optical, X-ray energy bands). This peculiar behavior was interpreted in a framework of a 2-component leptonic model in which an important role was also attributed to a blob-cloud interaction. It will be interesting to investigate if this gamma-ray only flaring activity is a common behavior among the MeV blazars.

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