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Variable and transient Galactic gamma-ray sources with AGILE

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Summary. — AGILE has been providing continous monitoring of the Galactic plane in its three years of operation. Thanks to its sensitivity at energies near 100 MeV, AGILE has observed variability and transient behaviour in a number of sources. Simultaneous hard–X-ray coverage, rapid alerts to the astronomical community, and multiwavelength campaigns have provided identifications for some of these sources and placed constraints on others. We provide an overview of these observations and their possible counterparts, including microquasars and colliding wind binaries.

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1. – Introduction

AGILE [1] is a mission of the Italian Space Agency (ASI) dedicated to high-energy astrophysics in the gamma-ray energy range 30 MeV–30 GeV, with a monitor in the hard–X-ray band 18–60 keV [2], operating since April 2007 in a low inclination (2.5°) Low-Earth Orbit at 540 km altitude. The AGILE Gamma-Ray Imaging Detector (GRID) is a pair-tracking telescope based on a tungsten-silicon tracker [3]. The AGILE orbital characteristics are optimal for low-background γ-ray observations [4, 5]. AGILE data are transmitted to the ASI Malindi ground station in Kenya, and quickly transferred to the ASI Science Data Center (ASDC) near Frascati. Data processing of γ-ray data is then carried out at the ASDC and AGILE Team locations, by dedicated and fully automated procedures. The AGILE-GRID is optimized in the 100 MeV–1 GeV range as demonstrated by on-ground and in-orbit calibration and performance [1]. It is characterized by large field of view (2.5 sr) and optimal angular resolution (PSF = 3° at 100 MeV and PSF = 1.5° at 400 MeV). During the period 2007 July-2009 October, AGILE operated in “pointing mode” characterized by pointing periods of typical 10-30 days duration (*e.g.*, [6]). Most of them were concentrated along the Galactic plane. During the first operating phase of the mission, flux sensitivity for a typical 1-week observing period reached the level of several tens of 10^{-8} ph cm^{-2} s^{-1} above 100 MeV. With this observation strategy, AGILE was optimized to search for Galactic and Extragalactic Transients (see, *e.g.*, [7]).

A second operation mode was adopted with the satellite operating in “spinning mode” since November 2009. In this mode, the satellite axis sweeps an entire circle in the sky in approximately 7 minutes. Solar panels are kept perpendicular to the Sun direction by an automatic mechanism, so that the pattern swept on the sky slowly moves with time following the solar panel configuration. The resulting γ-ray daily exposure covers about 70% of the whole sky every day (leaving uncovered only the Sun or the anti-Sun directions) and provides significant continuous monitoring of exposed sources for many months. Depending on the season, the whole sky is then progressively exposed with a typical accumulating pattern. In this paper we will present the main results of the Galactic plane monitoring by AGILE-GRID. Detailed studies of these sources will be presented elsewhere.

2. – Gamma-ray data analysis procedures

The AGILE γ-ray data analysis is performed with the AGILE-GRID software package publicly available at the ASI Data Center web site (`http://agile.asdc.asi.it/`). The analysis uses the FM3.119 filter to reduce the particle background contamination. Only events flagged as confirmed γ-ray events (G class events, corresponding to an on-axis effective area of $\sim 350\,\mathrm{cm}^2$ at 100 MeV) are used. The AGILE photon counts, exposure, and Galactic background maps are generated with a bin size of $0.2^\circ \times 0.2^\circ$ for energies greater than 100 MeV to compute the period-averaged source flux and its evolution. The analysis is performed over a region of 10° radius.

The multi-source likelihood analysis method [8] was used to search for persistent and transient emission from the analysed region; this analysis method iteratively optimizes position and flux of all the sources of the region, taking properly into account the Galactic diffuse γ-ray radiation and isotropic emission [9]. This method evaluates the statistical significance of source detection and determines fluxes and position of the point sources included in the source model. The statistical significance is determined in terms of a Test Statistic (TS) defined as in [8], asymptotically distributed as a χ^2 for 3 degrees of freedom (χ^2_3) [10] when fitting γ-ray sources flux and celestial coordinates. Search for transient emission is made by two automated γ-ray transient search procedures. This search is divided in two steps. In the first step, an automated search analysis (with the criteria to generate maps described above) is performed using integration time windows of 1 day for pointing mode and 2 days for spinning mode and a continuous temporal scan with 1-hour intervals, using two different source extraction algorithms ("Spotfinder" [11, 6] and "HEASARC Ximage/Detect" [12]). In the second step, only the detections with a $\sqrt{\mathrm{TS}} \geq 3$ resulted from the first step are selected. In cases with time-overlapped detections, the detection with the largest value of the $\sqrt{\mathrm{TS}}$ parameter is selected as the flare peak. For this subclass of selected flare peaks, additional manual analysis is performed to take into account additional candidate sources and to further confirm the results [13].

The multi-source likelihood method is very efficient for relatively strong sources. It provides a pre-trial assessment of statistical significance that needs to be corrected when used in repeated systematic searches. For this reason an independent method, that takes into account multiple comparison corrections, was developed [10]. It is based on the False Discovery Rate technique (FDR [14-16]) a statistical test taking into account the corrections for multiple testing, as needed for example in repeated systematic searches. The FDR method allows us to control the expected rate of false detections (due to background fluctuations) within a selected sample. The FDR method ensures that this rate is controlled, while accounting for the post-trial correction of a single detection significance [14]. In the AGILE data analysis procedures, this method is used for a blind search for (persistent or transient) sources in large daily counts maps of the Galactic plane. The null hypothesis for these daily maps is the (background dominated) counts distribution of the Galactic plane. The random fluctuations and the diffuse gamma-ray emission of these daily maps are well described by Poissonian distributions in AGILE-GRID data. Candidate sources in the daily maps are identified as significant deviations from the average distribution that applies to that specific day. The FDR method is used also at the source level. In this case the search is optimized for flaring episodes in the counts light curve extracted from the position of a single candidate source location. In the (verified) assumption that the average source flux at a given position is typically below the instrument sensitivity, unless it is producing (rare) flares, the null hypothesis in this case is obtained by measuring the distribution of photon counts for the specific sky location observed at intervals of one day.

3. – Variable Galactic sources

The Galaxy hosts a large number of sources emitting γ-rays in the high energy band. Radiation in this energy range provides a wealth of information on relativistic phenomena near compact objects as well as on the generation, propagation and interaction of high energy cosmic rays. Several source classes have been recently identified by ground-based and satellite gamma-ray detectors. They include massive molecular clouds, accreting compact objects, rotating neutron stars and their wind nebulae, massive binary systems, remnants of supernova explosions, Galactic candidate jet sources and colliding winds sources in close systems. More details on the association of point-like γ-ray sources are provided in the first AGILE [6] and Fermi-LAT [17] catalogs. The identification of a source class is often based on temporal evolution and coordinated multiwavelength observations. AGILE has provided the alerts of transient gamma-ray emission from several source candidates. In some cases a clear source identification was provided by means of correlated studies.

3˙1. *Eta Carinae*. – Extensive observations by the gamma-ray AGILE satellite of the Galactic region hosting the Carina nebula and the remarkable colliding wind binary Eta Carinae during the period 2007 July-2009 January were reported in [18]. AGILE detected a gamma-ray source (1AGL J1043-5931) consistent with the position of η- Car. If 1AGL J1043-5931 is indeed associated with the Carina system, the AGILE data provide the first detection above 100 MeV of a colliding wind binary. A 2-day gamma-ray flaring episode of 1AGL J1043-5931 on 2008 Oct. 11-13 possibly related to a transient acceleration and radiation episode of the strongly variable shock in the system was also reported [18]. The steady emission from this source was also detected by Fermi-LAT [19].

3˙2. *Cygnus X-3*. – AGILE reported the detection of transient gamma-ray emission above 100 MeV from the microquasar Cygnus X-3, an exceptional X-ray binary which sporadically produces powerful radio jets (see [20] and references therein). The region around Cygnus X-3 is complex, hosting star formation sites, OB associations and several prominent γ-ray sources. The good AGILE angular resolution satisfactorily resolves the field surrounding Cyg X-3 at gamma-ray energies. A dominant source positioned at $0^\circ.4$ from the Cyg X-3 position is the steady gamma-ray pulsar 1AGL J2032+4102/0FGL J2032.2+4122. Integrating all AGILE data, we find a weak (4.6 sigma) gamma-ray source consistent with the Cyg X-3 position with flux compatible with that reported by the Fermi-LAT catalog [17]. Four gamma-ray flares (each lasting 1-2 days) were detected by the AGILE satellite simultaneously with special spectral states of Cygnus X-3 during the period mid-2007/mid-2009. Continuous monitoring of these sources allowed to detect other flaring episodes [13]. These flares were found by an independent multi-source maximum likelihood search for transients in all available AGILE data. The statistical significance of all flares was individually assessed by both the maximum likelihood analysis and False Discovery Rate method. These flares are all associated with quite special Cyg X-3 radio and X-ray/hard–X-ray states. Remarkably, all gamma-ray flares occur during distinct minima of the hard–X-ray lightcurve. Gamma-ray flares occur then only during soft–X-ray states or their transitions to or from quenched hard–X-ray states. Moreover we found that 3 out of 4 gamma-ray flares are distinctively produced before major radio flares. Our results show clearly that the flaring gamma-ray emission occurs only at special transitional states, which are associated with bright soft–X-ray states and/or the very low radio emission which precedes major radio flares [20]. Fermi-LAT obtained consistent results and independently identified Cyg-X3 as a variable gamma-ray source, through the detection of its orbital period [21].

3˙3. *Cygnus X-1*. – Cygnus X-1 (Cyg X-1) is the archetypal black-hole (BH) binary system in our Galaxy. AGILE reported the main results of an extensive search for transient gamma-ray emission from Cygnus X-1 carried out in the energy range 100 MeV–3 GeV, during the period 2007 July-2009 October [22]. During the observation period the source was in the "hard"–X-ray spectral state. AGILE reported an episode of significant transient gamma-ray emission detected on 2009, October 16 in a position compatible with Cyg X-1 optical position. This episode, which occurred during a hard spectral state of Cyg X-1, showed that a 1-2 day time-variable emission above 100 MeV can be produced during hard spectral states, having important theoretical implications for current Comptonization models for Cyg X-1 and other microquasars. Another flaring episode was detected by AGILE from 2010, June 30 to 2010, July 2 [23]. Except for these flaring episodes, no significant persistent gamma-ray emission was detected by AGILE [22]. By integrating all available data we obtain a 2 σ upper limit for the total integrated flux of $3 \times 10^{-8}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$ in the energy range 100 MeV–3 GeV [10,22]. The reported flaring episodes are not confirmed so far by Fermi-LAT.

3˙4. *Gamma-Cygni region*. – Another variable source reported by AGILE is 1AGL J2022+4032, coincident with the interior of the radio shell of the supernova remnant Gamma Cygni (SNR G78.2+2.1) and its Pulsar Wind Nebula in the Cygnus Region. The source has recently been identified by Fermi-LAT as a γ-ray pulsar, LAT PSR J2021+4026 [24]. AGILE presented long-term observations of 1AGL J2022+4032 showing that the flux variability of 1AGL J2022+4032 appears to be greater than the level predicted from statistical and systematic effects. AGILE evaluated the possibility that the γ-ray emission may be due to the superposition of two or more point sources, some of which may be variable, considering a number of possible counterparts, among which the most probable is a nearby X-ray quiet microquasar, more likely than the hypotheses of a background blazar or intrinsic γ-ray variabilty of LAT PSR J2021+4026 [25].

4. – Conclusions

AGILE has been uccesfully observing Galactic Variable sources since the beginning of its mission. The AGILE-GRID is well suitable for such searches due to several reasons. It has a large field of view, its sensitivity is optimized in the $\sim$ 100 MeV range, the fast data transmission and processing allow fast alerts to be provided to the community via a dedicated automated process with various statistical tools and a scientific team devoted particularly to the search for gamma-ray transient events. Because these procedures were planned well in advance [7] based on previous EGRET data analysis experience (*e.g.*, [26]), several important results on Variable Galactic Sources science based on AGILE observations have been obtained. The possible discrepancies with the results obtained by Fermi-LAT have been explained by means of different observing and sensitivity. A complete study of the 1AGL sources variability, taking into account two variability indeces, applied already in the study of Gamma-Cygni [25], is in preparation.

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