AGILE observations of PSR B1509-58: is QED photon splitting at work in pulsars?

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1 Introduction

PSR B1509–58 was discovered as an X-ray pulsar with the Einstein satellite and soon detected also at radio frequencies (Manchester et al. 1982), with a derived distance supporting the association with the SNR MSH 15-52 ($d \sim 5.8$ kpc). With a period $P \sim 150$ ms and a period derivative $\dot{P} \sim 1.53 \times 10^{-12}$ s$^{-1}$, assuming the standard dipole vacuum model, the estimated spin-down age for this pulsar is 1570 years and its inferred surface magnetic field is one of the highest observed for an ordinary radio pulsar: $B \approx 3.1 \times 10^{13}$ G, as calculated at the pole. Its rotational energy loss rate is $\dot{E} \approx 1.8 \times 10^{37}$ erg/s.

The young age and the high rotational energy loss rate made this pulsar a promising target for the $\gamma$-ray satellites. In fact, the instruments on board of the Compton Gamma-Ray Observatory (CGRO) observed its pulsation at low $\gamma$-ray energies, but it was not detected with high significance by the Energetic Gamma-Ray Experiment Telescope (EGRET), the instrument operating at the energies from 30 MeV to 30 GeV.

The Italian satellite AGILE (Tavani et al. 2009) obtained the first detection of PSR B1509–58 in the EGRET band (Pellizzoni et al. 2009b) confirming the occurrence of a spectral break. Here we present the results of a $\sim 2.5$ yr monitoring campaign of PSR B1509–58 with AGILE, improving counts statistics, and therefore lightcurve characterization, with respect to earlier AGILE observations. With these observations the spectral energy distribution (SED) at $E < 300$ MeV is assessed, where the remarkable spectral turnover is observed.
2 AGILE Observations, Data Analysis and Results

AGILE devoted a large amount of observing time to the region of PSR B1509–58. For details on AGILE observing strategy, timing calibration and γ-ray pulsars analysis the reader can refer to Pellizzoni et al. (2009a,b). A total exposure of \(3.8 \times 10^9\) cm\(^2\) s (\(E > 100\) MeV) was obtained during the 2.5 yr period of observations (July 2007 - October 2009) which, combined with AGILE effective area, gives our observations a good photon harvest from this pulsar.

Simultaneous radio observations of PSR B1509–58 with the Parkes radiotelescope in Australia are ongoing since the epoch of AGILE’s launch. Strong timing noise was present and it was accounted for using the \textit{fitwaves} technique developed in the framework of the TEMPO2 radio timing software (Hobbs et al. 2004, 2006). Using the radio ephemeris provided by the Parkes telescope, we performed the folding of the γ-ray lightcurve including the wave terms (Pellizzoni et al. 2009a). An optimized analysis followed, aimed at cross-checking and maximization of the significance of the detection, including an energy-dependent events extraction angle around source position based on the instrument point-spread-function (PSF). The chi-squared (\(\chi^2\))-test applied to the 10 bin lightcurve at \(E > 30\) MeV gave a detection significance of \(\sigma = 4.8\). The unbinned \(Z^2_n\)-test gave a significance of \(\sigma = 5.0\) with \(n = 2\) harmonics. The difference between the radio and γ-ray ephemerides was \(\Delta P_{\text{radio,γ}} = 10^{-9}\) s, at a level lower than the error in the parameter, showing perfect agreement among radio and γ-ray ephemerides as expected, further supporting our detection and AGILE timing calibration.

We observed PSR B1509–58 in three energy bands: 30–100 MeV, 100–500 MeV and above 500 MeV. We did not detect pulsed emission at a significance \(\sigma \geq 2\) for \(E > 500\) MeV. The γ-ray lightcurves of PSR B1509–58 for different energy bands are shown in Fig. [1]. The AGILE \(E > 30\) MeV lightcurve shows two peaks at phases \(\phi_1 = 0.39 \pm 0.02\) and \(\phi_2 = 0.94 \pm 0.03\) with respect to the single radio peak, here put at phase 0. The phases are calculated using a Gaussian fit to the peaks, yielding a FWHM of 0.29(6) for the first peak and of 0.13(7) for the second peak, where we quote in parentheses (here and throughout the paper) the 1σ error on the last digit. The first peak is coincident in phase with COMPTEL’s peak (Kuiper et al. 1999). In its highest energy band (10–30 MeV) COMPTEL showed the indication of a second peak (even though the modulation had low significance, 2.1σ). This second peak is coincident in phase with AGILE’s second peak (Fig. [1]). AGILE thus confirms the previously marginal detection of a second peak.

Based on our exposure we derived the γ-ray flux from the number of pulsed counts. The pulsed fluxes in the three AGILE energy bands were \(F_\gamma = 10(4) \times 10^{-7}\) ph cm\(^{-2}\) s\(^{-1}\) in the 30–100 MeV band, \(F_\gamma = 2.1(5) \times 10^{-7}\) ph cm\(^{-2}\) s\(^{-1}\) in the 100–500 MeV band and a 1σ upper limit \(F_\gamma < 8 \times 10^{-8}\) ph cm\(^{-2}\) s\(^{-1}\) for \(E > 500\) MeV.

Fig. 2 shows the SED of PSR B1509–58 based on AGILE’s and COMPTEL’s observed fluxes. COMPTEL observations suggested a spectral break between 10 and 30 MeV. AGILE pulsed flux at energies \(E > 30\) MeV confirms the presence of a soft spectral break, but the detection of significant emission at \(E > 100\) MeV
AGILE observations of PSR B1509-58

hints to a cutoff at slightly higher energies. As shown in Fig. 2, we modeled the observed fluxes with a power-law plus cutoff fit using the Minuit minimization package (James et al. 1975): \( F(E) = k \times E^{-\alpha} \exp[-(E/E_c)^\beta] \), with three free parameters: the normalization \( k \), the spectral index \( \alpha \), the cutoff energy \( E_c \) and allowing \( \beta \) to assume values of 1 and 2. No acceptable \( \chi^2 \) values were obtained for \( \beta = 2 \), while for an \( \beta = 1 \) we found \( \chi^2 = 3.2 \) for \( \nu = 2 \) degrees of freedom, corresponding to a null hypothesis probability of 0.05. The best values thus obtained for the parameters of the fit were: \( k = 1.0(2) \times 10^{-4} \), \( \alpha = 1.87(9) \), \( E_c = 81(20) \) MeV.

3 Discussion

The bulk of the spin-powered pulsar flux is usually emitted in the MeV-GeV energy band with spectral breaks at \( \leq 10 \) GeV (e.g. Abdo et al. 2010). PSR B1509–58 has the softest spectrum observed among \( \gamma \)-ray pulsars, with a sub-GeV cutoff at \( E \approx 80 \) MeV.

When PSR B1509–58 was detected in soft \( \gamma \)-rays but not significantly at \( E > 30 \) MeV, it was proposed that the mechanism responsible for this low-energy spectral break might be photon splitting (Harding et al. 1997). The photon splitting (Adler et al. 1970) is an exotic third-order quantum electro-dynamics process expected when the magnetic field approaches or exceeds the critical value defined as \( B_{cr} = m_e^2 c^3 / (e \hbar) = 4.413 \times 10^{13} \) G. In very high magnetic fields the formation of pair cascades can be altered by the process of photon splitting: \( \gamma \rightarrow \gamma \gamma \).

In the case of PSR B1509–58 a polar cap model with photon splitting would be able to explain the soft \( \gamma \)-ray emission and the low energy spectral cutoff, now quantified by AGILE observations. Based on the observed cutoff, which is related to the photons’ saturation escape energy, we can derive constraints on the magnetic field strength at emission, in the framework of photon splitting:

\[
\epsilon_{esc}^{sat} \simeq 0.077 (B' \sin \theta_{B,0})^{-6/5}
\]  (1)

where \( \epsilon_{esc} \) is the photon saturation escape energy, \( B' = B / B_{cr} \) and \( \theta_{B,0} \) is the angle between the photon momentum and the magnetic field vectors at the surface and is here assumed to be very small: \( \theta_{B,0} \leq 0.57^\circ \) (Harding et al. 1997). Using the observed cutoff (\( E = 80 \) MeV) we find that \( B' \geq 0.3 \), which implies an emission altitude \( \leq 1.3R_{NS} \), which is the height where also pair production could ensue. This altitude of emission is in perfect agreement with the polar cap models (see Daugherty & Harding 1996). The scenario proposed by Harding et al. (1997) is strengthened by its prediction that PSR B0656+14 should have a cutoff with an intermediate value between PSR B1509–58 and the other \( \gamma \)-ray pulsars. Additionally, PSR B1509–58 (Kuiper et al. 1999, Crawford et al. 2001) and PSR B0656+14 (De Luca et al. 2005, Weltevrede et al. 2010) show evidence of an aligned geometry, which could imply polar cap emission.
The polar cap model as an emission mechanism is debated. From the theoretical point of view, the angular momentum is not conserved in polar cap emission (Cohen & Treves 1972, Holloway 1977, Treves et al. 2010). And a preferential explanation of the observed γ-ray lightcurves with high altitude cascades comes from the recent results by Fermi (Abdo et al. 2010). In the case of PSR B1509–58, the derived γ-ray luminosity from the flux at $E > 1$ MeV, considering a 1 sr beam sweep, is $L_{\gamma} = 5.7^{+0.1}_{-0.5} \times 10^{35}$ erg/s. The conversion efficiency of the rotational energy loss ($\dot{E} \approx 1.8 \times 10^{37}$ erg s$^{-1}$, see §1) into γ-ray luminosity is 0.03. If the γ-ray luminosity cannot account for most of the rotational energy loss, then the angular momentum conservation objection becomes less cogent for this pulsar.

Alternatively, an interpretation of PSR B1509–58 emission can be sought in the frame of the three dimensional outer gap model (Zhang & Cheng 2000). According to their model, hard X-rays and low energy γ-rays are both produced by synchrotron self-Compton radiation of secondary e+e− pairs of the outer gap. Therefore, as observed, the phase offset of hard X-rays and low energy γ-rays with respect to the radio pulse is the same, with the possibility of a small lag due to the thickness of the emission region. According to their estimates a magnetic inclination angle $\alpha \approx 60^\circ$ and a viewing angle $\zeta \approx 75^\circ$ are required to reproduce the observed lightcurve. Finally, using the simulations of Watters et al. 2009), the observed lightcurve from AGILE is best reproduced if $\alpha \approx 35^\circ$ and $\zeta \approx 90^\circ$, in the framework of the two pole caustic model (Zyks & Rudak 2003).

The values of $\alpha$ and $\zeta$ required by the Zhang & Cheng model are not in good agreement with the corresponding values obtained with radio measurements. In fact, Crawford et al. (2001) observe that $\alpha$ must be < 60° at the 3σ level. The prediction obtained by the simulations of Watters et al. better agrees with the radio polarization observations. In fact, Crawford et al. also propose that, if the restriction is imposed that $\zeta > 70^\circ$ (Melatos 1997), then $\alpha > 30^\circ$ at the 3σ level. For these values, however, the Melatos model for the spin down of an oblique rotator predicts a braking index $n > 2.86$, slightly inconsistent with the observed value ($n = 2.839(3)$). Therefore, at present the geometry privileged by the state of the art measurements is best compatible with polar cap models.

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References

1. Abdo, A. A. et al. 2010, ApJS, 187, 460
2. Adler, S. L., et al. 1970, PhRevL, 25, 1061
3. Cohen, R. H. & Treves, A. 1972, A&A, 20, 305
4. Crawford, F., Manchester, R. N., & Kaspi, V. M. 2001, AJ, 122, 2001
5. Daugherty, J. K. & Harding, A. K. 1996, ApJ, 458, 278
AGILE observations of PSR B1509-58

Fig. 1 Phase-aligned $\gamma$-ray light-curves of PSR B1509–58 with radio peak at phase 0. From the top: AGILE > 100 MeV, 20 bins, 7.5 ms resolution; AGILE < 100 MeV, 10 bins, 15 ms resolution; COMPTEL 10–30 MeV and COMPTEL 0.75–30 MeV (from Kuiper et al. 1999).

Fig. 2 SED of PSR B1509–58 (solid line) obtained from a fit of pulsed fluxes from soft to hard $\gamma$-rays. The circular points represent COMPTEL observations. The square points represent AGILE pulsed flux at 30 < $E$ < 100 MeV and 100 < $E$ < 500 MeV. The horizontal bar represents AGILE upper limit above 500 MeV.

6. De Luca, A., Caraveo, P. A., Mereghetti, S., Negroni, M., & Bignami, G. F. 2005, ApJ, 623, 1051
7. Dyks, J., & Rudak, B. 2003, ApJ, 598, 1201
8. Harding, A. K., Baring, M. G., & Gonthier, P. L. 1997, ApJ, 476, 246
9. Hobbs, G., Lyne, A. G., Kramer, M., Martin, C. E., & Jordan, C. 2004, MNRAS, 353, 1311
10. Hobbs, G. B., Edwards, R. T., & Manchester, R. N. 2006, MNRAS, 369, 655
11. Holloway, N. J. 1977, MNRAS, 181, 9P
12. James, F. & Roos, M. 1975, Computer Physics Communications, 10, 343
13. Kuiper, et al. 1999, A&A, 351, 119
14. Manchester, R. N., Tuohy, I. R., & Damico, N. 1982, ApJL, 262, L31
15. Melatos, A. 1997, MNRAS, 288, 1049
16. Pellizzoni et al. 2009a, ApJ, 691, 1618
17. Pellizzoni, A. et al. 2009b, ApJL, 695, L115
18. Tavani, M. et al. 2009, A&A, 502, 995
19. Treves, A., Pilia, M. & Lopez, M. 2010, A&A, submitted
20. Watters, K. P., Romani, R. W., Weltevrede, P., & Johnston, S. 2009, ApJ, 695, 1289
21. Weltevrede, P. et al. 2010, ApJ, 708, 1426
22. Zhang, L. & Cheng, K. S. 2000, A&A, 363, 575