Supernova Environmental Impacts
Proceedings IAU Symposium No. 296, 2013
A. Ray & R. A. McCray, eds.

doi:10.1017/S1743921313009617

Fermi-LAT and WMAP observations of the supernova remnant Puppis A

Marie-Hélène Grondin[1], John W. Hewitt[2], Marianne Lemoine-Goumard[3,4] & Thierry Reposeur[3], for the *Fermi*-LAT collaboration

[1]Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse (UPS)/OMP, F-31028 Toulouse Cedex 4, France

E-mail: `mgrondin@irap.omp.eu`

[2]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

[3]Centre dÉtudes Nucléaires de Bordeaux-Gradignan, Université Bordeaux 1, CNRS/IN2p3, F-33175 Gradignan, France

[4]Funded by contract ERC-StG-259391 from the European Community

Abstract. The supernova remnant (SNR) Puppis A (aka G260.4-3.4) is a middle-aged supernova remnant, which displays increasing X-ray surface brightness from West to East corresponding to an increasing density of the ambient interstellar medium at the Eastern and Northern shell. The dense IR photon field and the high ambient density around the remnant make it an ideal case to study in γ-rays. Gamma-ray studies based on three years of observations with the Large Area Telescope (LAT) aboard *Fermi* have revealed the high energy gamma-ray emission from SNR Puppis A. The γ-ray emission from the remnant is spatially extended, and nicely matches the radio and X-ray morphologies. Its γ-ray spectrum is well described by a simple power law with an index of ~ 2.1, and it is among the faintest supernova remnants yet detected at GeV energies. To constrain the relativistic electron population, seven years of *Wilkinson Microwave Anisotropy Probe (WMAP)* data were also analyzed, and enabled to extend the radio spectrum up to 93 GHz. The results obtained in the radio and γ-ray domains are described in detail, as well as the possible origins of the high energy γ-ray emission (Bremsstrahlung, Inverse Compton scattering by electrons or decay of neutral pions produced by proton interactions).

Keywords. ISM : supernova remnants, ISM: individual objects (Puppis A), cosmic rays

1. Introduction

Supernovae have long been thought responsible for accelerating protons to relativistic energies in our Galaxy. As reported in Brandt (2013) and Lemoine-Goumard (2013), the Large Area Telescope aboard the *Fermi Gamma-ray Space Telescope* has enabled the γ-ray detection of several middle-aged SNRs interacting with molecular clouds.

Among them, the supernova remnant (SNR) Puppis A (aka G260.4–3.4) is an important case to study, as it shows signs of recently encountering a higher ambient density in the vicinity of a nearby molecular cloud (Hwang *et al.* 2005). The remnant displays increasing X-ray surface brightness from West to East (Petre *et al.* 1982) corresponding to an increasing density of the ambient interstellar medium (ISM) at the Eastern and Northern shell (Dubner & Arnal, 1988). The proper motion of fast optical knots gives a dynamical age of 3700 ± 300 years, establishing that the SNR is in the Sedov-Taylor evolutionary phase. At an estimated distance of ~ 2 kpc (Reynoso *et al.* 1995), the diameter of Puppis A is ~ 30 pc, so the remnant is no longer interacting with the circumstellar medium of the progenitor, but with the surrounding ISM. There are two notable regions where the SNR shock has engulfed small denser clouds: the Bright Eastern Knot and the Northern Knot. Besides those, the shock has not yet become radiative for most of the SNR, consistent with the relatively young age and the low density of the surrounding medium.

In addition, SNR Puppis A hosts a central compact object recently identified as a pulsar, PSR J0821-4300, using *XMM-Newton* observations (Gotthelf & Halpern, 2009).

2. *Fermi*-LAT Observations and Data Analysis

The *Fermi*-LAT is an electron-positron pair conversion telescope, sensitive to γ-rays with energies from below 20 MeV to more than 300 GeV (Atwood *et al.* 2009). The following analysis was performed using 36 months of data collected from 2008 August 4 to 2011 August 20 within a $15^\circ \times 15^\circ$ region around the position of SNR Puppis A. Only events with zenith angles smaller than 100° were included to reduce contamination from the Earth limb. We used the P7V6 instrument response functions (IRFs), and selected the 'Source' events. Located at a distance of 3° from the SNR Puppis A, the Vela pulsar is the brightest steady γ-ray source in the sky, from which photons are observed up to 25 GeV (Abdo *et al.* 2010). To avoid any bias on the analysis of the SNR due to this bright nearby pulsar, the following analysis was performed in the off-pulse window of the Vela pulsar. For more details, please see Hewitt *et al.* (2012).

Morphology : Figure 1 shows the Test Statistic (TS) map for the region around Puppis A using photons with energies above 800 MeV. Significant emission coincident with Puppis A is clearly detected. The source extension was estimated using `pointlike` (Lande *et al.* 2012) with a uniform disk hypothesis for energies above 800 MeV. The fitted radius is $0.38^\circ \pm 0.04^\circ$, in good agreement with the size of the SNR as seen in the radio and X-rays. We have also examined the correspondence of the γ-ray emission from Puppis A with different source morphologies by using multi-frequency templates above 800 MeV. The radio template, the X-ray template and the uniform disk all produce improvements from the 2FGL 3-point source model, while having fewer degrees of freedom, the X-ray template providing the best log-likelihood of our fit.

Spectrum : Using the X-ray template (shown by green contours on Fig 1), we performed a spectral analysis between 200 MeV and 100 GeV using `gtlike`, a binned maximum likelihood method implemented in the *Science Tools* distributed by the *Fermi* Science Support Center (FSSC). The *Fermi*-LAT data are well described by a power-law with a flux above 200 MeV of $(1.6 \pm 0.2_{stat} \pm 0.2_{syst}) \times 10^{-8}$ ph cm^{-2} s^{-1} (renormalized to the whole phase interval) and a photon index of $2.09 \pm 0.07_{stat} \pm 0.09_{syst}$. Using radio template and the uniform disk (defined hereabove) yields consistent results within the statistical errors. Whatever the extended model considered for the spectral analysis, no evidence for cutoff or break is visible.

Temporal analysis : To check if the X-ray pulsar PSR J0821-4300 could contribute, at least partially, to the detected γ-ray emission, we folded the photon arrival times using an ephemeris from Gotthelf & Halpern (2009) and the Fermi plugin distributed with the `TEMPO2` software. No significant evidence of pulsation could be found. This confirms that with a small spin-down luminosity, PSR J0821-4300 is unlikely to be a γ-ray emitter.

3. WMAP Data Analysis

We used the 7-year all-sky data of the *Wilkinson Microwave Anisotropy Probe (WMAP)* to extend the radio spectrum of Puppis A to higher frequencies. Five bands were analyzed with effective central frequencies ($\nu_{\rm eff}$) of 23 to 93 GHz (Jarosik *et al.* 2011). To

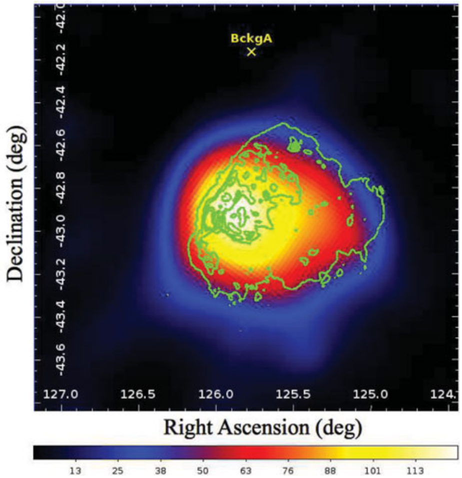

Figure 1. Test Statistic (TS) map in celestial coordinates of the SNR Puppis A. Only photons with energies above 800 MeV in the off-pulse window of the Vela pulsar were selected. The TS was evaluated by placing a point-source at the center of each pixel, Galactic diffuse emission and nearby sources being included in the background model. X-ray contours (green) are overlaid for comparison (Hewitt *et al.* 2012).

obtain *WMAP* flux densities we used template fitting of the flux-corrected 1.4 GHz radio image (Castelletti *et al.* 2006). This template image was smoothed with the *WMAP* beam profiles, and then fit in each band with a constant times the smoothed template plus a sloping planar baseline. To avoid contamination from the nearby Vela-X PWN, the template fit is restricted to a circular region within a 2° radius. To fit the radio spectrum, we exclude data below 300 MHz, which may suffer from low-frequency absorption by thermal electrons along the line of sight. We derived a best-fit 1 GHz flux density of 141 ± 4 Jy and a radio spectral index of –0.56 ± 0.01.

4. Discussion

We attempted to reproduce the *WMAP* and *Fermi*-LAT data by considering three scenarios dominated by each of the three plausible emission mechanisms : inverse Compton (IC) scattering, Bremsstrahlung and proton-proton interaction. We assumed similar injection spectra for protons and electrons, which implies that the spectral index of the particle spectrum below the cutoff energy is determined and fixed at ~ 2.1 by modeling the radio spectrum as synchrotron radiation by relativistic electrons. Modeled spectral energy distributions (SEDs) are presented in Figure 2 (see Hewitt *et al.* 2012 for more details). Simple constraints can be derived from these models. For instance, the electron-to-proton ratio needs to be larger than 0.1 for leptonic scenarios, and thus in excess of the ratio found for local cosmic-ray abundances, to inject a reasonable energy content in radiating electrons. In the same way, for the inverse-Compton dominated scenario, the average gas density needs to be lower than 0.3 cm^{-3} to reduce the Bremsstrahlung component. Although the hadronic scenario seems to be preferred, each emission mechanisms is able to fit the data with the current statistics. Future observations at high radio frequencies and at higher γ-ray energies will help to differentiate between leptonic and hadronic emission models.

https://doi.org/10.1017/S1743921313009617 Published online by Cambridge University Press

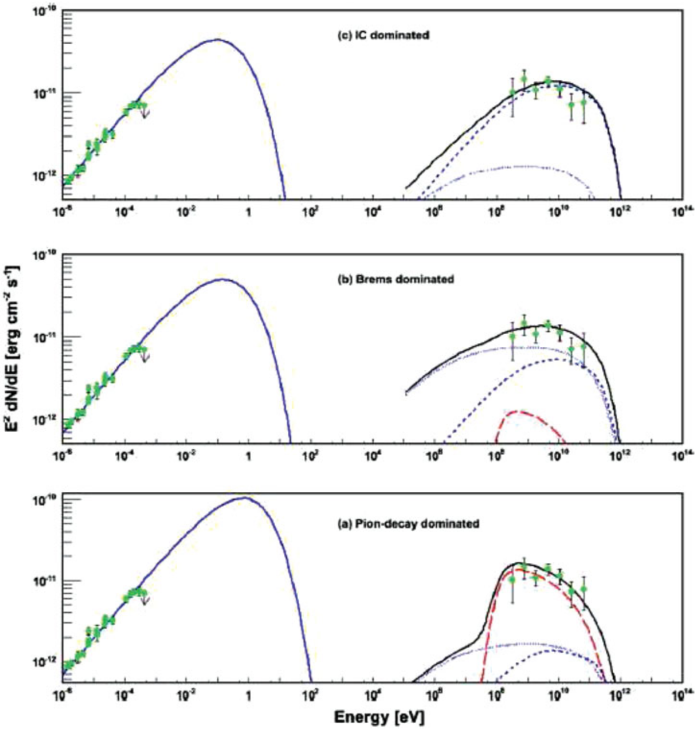

Figure 2. SED models for which IC (top), Bremsstrahlung (middle) and π^0-decay (bottom) are the dominant emission mechanism. In each model the radio data are fit with a synchrotron component. All models show the contributions of π^0-decay (long dashed, red), Bremsstrahlung (dotted, blue), and IC emission (dashed, blue) from CMB, IR dust photon field, and stellar optical photons. The sum of the three γ-ray components is shown as a solid black curve. The Fermi spectrum was renormalized to the whole phase interval.

The *Fermi* LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

References

Abdo, A. A., *et al.* 2010, *ApJ*, 713, 154
Atwood, W. B., *et al.* 2009, *ApJ*, 697, 1071
Brandt *et al.* for the *Fermi-LAT* collaboration, 2013, *these proceedings*
Castelletti, G., Dubner, G. M., Golap, K., & Goss, W. M., 2006, *A&A*, 459, 535
Dubner, G. M. & Arnal, E. M., 1988, *A&AS*, 75, 363
Gotthelf, E. V. & Halpern, J. P., 2009, *ApJ*, 695, 35
Hewitt, J. W., *et al.* 2012, *ApJ*, 759, 89
Hwang, U., Flanagan, K. A., & Petre, R., 2005, *ApJ*, 635, 355
Jarosik, N., Bennett, C. L., Dunkley, J. *et al.* 2011, *ApJS*, 192, 14
Lande, J., *et al.* 2012, *ApJ*, 756, 5
Lemoine-Goumard, M., 2013, *these proceedings*
Petre, R., Kriss, G. A., Winkler, P. F., & Canizares, C. R., 1982, *ApJ*, 258, 22

https://doi.org/10.1017/S1743921313009617 Published online by Cambridge University Press

Reynoso, E. M., Dubner, G. M., Goss, W. M., & Arnal, E. M., 1995, *AJ*, 110, 318

Discussion

SAHA L: What is the electron to proton ratio for Puppis A? Is it consistent with e/p ratio observed in the galaxy?

GRONDIN: The electron to proton ratio in the IC dominated and Bremsstrahlung dominated scenarios is estimated to be 1, which is significantly larger than what is observed in the galaxy. In the hadronic scenario, the e/p ratio is ~ 0.02 which seems a more reasonable value.

RAY: Will more data help distinguish different emission mechanisms in Pup A?

GRONDIN: Yes, first because it will decrease the statistical error bars. Then, TeV observations may also help to disentangle the different scenarios.