2003–2018 Monitoring of the Crab Nebula Polarization in Hard X-Rays with INTEGRAL SPI

E. Jourdain\textsuperscript{1,2} and J.-P. Roques\textsuperscript{1,2}

\textsuperscript{1} CNRS, IRAP, 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France
\textsuperscript{2} Université de Toulouse, UPS-OMP, IRAP, Toulouse, France

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Abstract
We analyzed 16 yr of observations dedicated to the Crab (pulsar + nebula) with the SPectrometer on \textit{International Gamma-Ray Astrophysics Laboratory} instrument to investigate its polarization properties. We find that the source presents a substantially polarized emission ($PF = 24\%$) in the hard X-ray domain, with the electric vector aligned with the pulsar spin axis, which is in agreement with other results at various wavelengths. The stability of the polarization characteristics with energy and over the 16 yr covered by the data is remarkable, completing the standard candle status of the source in the spectral domain. The polarization measurements imply that the synchrotron emission is the dominant mechanism of photon production from radio to hard X-rays. The high level of polarized emission points out the steadiness of the source, in particular, of the magnetic field configuration and geometry.

Key words: gamma-ray burst: individual (Crab) – polarization – radiation mechanisms: non-thermal – X-rays: individual (Crab)

1. Introduction
The SPectrometer on \textit{International Gamma-Ray Astrophysics Laboratory} (SPI) is a hard X-ray/soft $\gamma$-ray spectrometer providing an excellent energy resolution in the 20 keV–8 MeV energy range with some imaging capabilities. In addition, the design of the detector plane, with 19 independent crystals, makes possible the measurement of the polarization parameters of the incident radiation for energies above $\sim$100 keV. Indeed, Dean et al. (2008) have analyzed the SPI data of the Crab pulsar (off-pulse emission) and reported the first detection of a polarized emission in the hard X-ray domain. Then, Forot et al. (2008) confirm the polarization of the Crab emission with the Imager on board the on \textit{International Gamma-Ray Astrophysics Laboratory} Satellite (IBIS), which is also aboard the \textit{International Gamma-Ray Astrophysics Laboratory} (INTEGRAL) mission. Since, several instruments have followed, enlarging the investigated energy domain. In this paper, we analyzed the SPI data accumulated on the Crab Nebula since the launch of the \textit{INTEGRAL} mission. The large amount of data allows us to study the polarization characteristics of the source emission both over time and as a function of the energy.

2. Observations and Data Analysis
In this section, we will focus on the information specifically relevant to the polarimetry study. The reader can refer to Vedrenne et al. (2003) for an overview of the SPI instrument and to Roques et al. (2003) for the in-flight performance, while a description of the standard data analysis can be found in Jourdain & Roques (2009) and Roques & Jourdain (2019).

2.1. The Data Set
Since its launch, the \textit{INTEGRAL} observatory performs regular observations of the Crab Nebula, to allow calibration monitoring/updates of the onboard instruments. These observations are performed twice a year, in February–March, then in September. The first campaign in 2003 March, just after the end of the mission performance validation phase, gathered 446 ks of data (useful duration; Revolutions 43–44–45). After that, the biannual campaigns consisted of relatively short exposures ($\sim$50 ks), often dedicated to peculiar configuration tests (off-axis pointings, mask corner study, etc.). Since 2008, each calibration campaign lasts two revolutions, i.e., $\sim$400 ks, twice a year, with, in general, a standard $5 \times 5$ pattern pointing strategy. In addition, shorter observations (45 ks) are planned every four revolutions all along the Crab visibility periods, but these will not be considered in the following. Before starting our analyses, the exposures that present an unstable background or other issues (pointing anomaly, outburst of the neighboring source A0535+262, etc.) have been removed. The final data set encompasses $\sim$6.4 Ms, from 2003 March to 2018 September. Furthermore, to seek for any source evolution, the data set has been split into four periods, as a compromise between a timescale as short as possible and an adequate signal-to-noise ratio. Due to the lack of suitable observations between 2003 March and 2005 October, we consider the 2003 March revolutions separately. The remaining data set has been broken up into three parts of similar useful durations (see Table 1). These four sub-data sets will be referred to with their respective labels, P1–P4, in the subsequent analyses.

2.2. SPI as a Polarimeter
The SPI polarimetric capacities rely on the Compton interactions of high-energy photons in the detection plane. This latter consists of 19 Germanium crystals, and photons above $\sim$100 keV may diffuse in a first crystal and escape toward another one, where a second interaction occurs and so on, until a photoelectric absorption or final escaping. These events are called “multiple events” (hereafter MEs). The characteristics of the energy deposits and detectors involved contain crucial information on the polarization properties of the incident photons. In Germanium detectors, the fraction of MEs (i.e., Compton interactions with the diffused photon escaping toward the next detector) becomes nonnegligible above
Table 1
Observations Log

| Period Number | Tstart          | Tstop          | Useful Duration | Included Revolutions |
|---------------|-----------------|----------------|-----------------|----------------------|
| P1            | 2003 Feb 19     | 2003 Feb 27    | 446 ks          | 43-44-45             |
| P2            | 2005 Oct 11     | 2011 Oct 7     | 1.94 Ms         | 365-422-483-541-605-665-665-727-774 |
| P3 cont.      | 2012 Apr 10     | 2014 Oct 6     | 1.82 Ms         | 1159-1160-1214-1221-1268-1269 |
| P4 cont.      | 2015 Mar 6      | 2018 Sep 17    | 2.2 Ms          | 1515-1516-1598-1599-1661-1662-1723-1724 |
| P2 cont.      | 2005 Oct 11     | 2011 Oct 7     | 4.16 Ms         | 1327-1328-1387-1461-1462 |
| P3 cont.      | 2012 Apr 10     | 2014 Oct 6     | 2.2 Ms          | 1784-1785-1856-1857-1927-1928-1999-2000 |

Table 2
Crab Nebula Best-fit Parameters with the Band Model

| Period | $\alpha_1$ | $E_{\text{ch}}$ | $\alpha_2$ | $\chi^2$ (dof) |
|--------|------------|-----------------|------------|---------------|
| P1     | 2.00       | 601             | 2.22       | 77.01 (39)    |
| P2     | 2.01       | 620             | 2.25       | 82.4 (39)     |
| P3     | 2.0        | 602             | 2.32       | 71.9 (39)     |
| P4     | 1.99       | 505             | 2.28       | 85.9 (39)     |
| Tot    | 2.0        | 572.3           | 2.27       | 351.2 (165)   |

Note. 0.5% systematic errors included.

3 SE and PE flags correspond to events that lose energy in only one detector (single detector events). If such an event triggers a second specific electronic chain (PSD module, dedicated to a pulse shape analysis), it is flagged as PE; if not, it is flagged SE. See Roques & Jourdain (2019) for details.

\(~90\text{ keV}.\) However, MEs remain minoritarian and represent only \(~20\%\) of the total incident flux integrated above 100 keV. In fact, most of the Compton diffused photons are photo-absorbed in the same detector. This low efficiency implies long integration durations to obtain a good signal-to-noise ratio.

In practice, we consider only photons that hit two adjacent detectors (double events or ME2). This turns out to handle 42 pseudo-detectors (42 possible pairs of adjacent detectors), instead of 19 detectors as done in the standard analysis. Concerning the spectra and light-curve production, the standard analysis tools, used routinely for reconstructing the incident flux from “single detector” events (SE, and “PSD events”, PE) can be applied to ME2 events. The appropriate response matrices have been produced, together with the standard matrices (Sturmer et al. 2003), and the flux extraction procedure is the same. To validate the ME2 fluxes that are considered in the polarimetry study described below, we build the corresponding spectra by deconvolving the ME2 counts with relevant matrices and compare them to the single detector event spectra.

The procedure specifically developed for the polarization studies has been detailed in Chauvin et al. (2013). The main features are:

1. Selection of ME2 events in the 42 pseudo-detectors. Each pseudo-detector is associated with the total energy deposit (sum of the two measured energies).
2. Simulations of the instrument responses to a polarized emission for 17 polarization angles (PA, from 0° to 170° by step of 10°) and 100 polarization fractions (PF, 0%–100% by step of 1%), considering the Crab localization in the field of view, for each point.
3. Comparison of simulations and observational data for a given set of pointings. Source and background normalizations are estimated by the resolution of an equation system for each (PA and PF) pair:

\[
D_{sd} = x \times G_{sd}^{4}(PF, PA) + y \times B_{sd},
\]

where $D_{sd}$ is the observed count distribution for a science window (or exposure), $s$, in the pseudo-detector, $d$; $x$ is the source normalization; $G4$ is the simulated count distribution for the same $s$ and $d$, as a function of the source PF and PA; $y$ is the background normalization; and $B$ is the background spatial distribution, taken from an empty field observation. The simulated counts are renormalized to the corresponding detector lifetimes. The $x$ and $y$ values are determined through a linear least-

3. Results

3.1. Spectral Analysis

A spectral analysis from both single and multiple events has been performed, in order to compare the respective averaged spectra. For each of the four periods mentioned above, both spectra have been fit simultaneously. The Crab Nebula emission has been described by the Band model (Gamma-Ray Burst Model in XSPEC language), proposed by Band et al. (1993) to model the gamma-ray burst (GRB) spectra. This analytical model reproduces the smooth curvature observed between 20 and \(~\text{1 MeV}\) better than a broken power law (Roques & Jourdain 2019). The same synchrotron origin of both GRB and pulsar emissions further supports this choice. For each period, the shape parameters have been coupled between both spectra, while the individual normalizations are kept free. The results of the spectral analyses are presented in Table 2 and Figure 1. Furthermore, the normalization factors (for $E \approx 170\text{ keV}$) agree within 5% in any period. The data below \(~170\text{ keV}\) suffer from the uncertainties in the ME2 efficiency embedded in the response matrices. These inaccuracies do not affect the polarization results since they have no specific anisotropy on the detector plane. Finally, the perfect agreement between both spectra for each period demonstrates the reliability of the ME2 flux extraction.

3.2. Polarization Study

Once the ME2 events were validated, the procedure described in the previous section has been applied to the total data set. We selected photons with energies between 130 and 436 keV, in order to optimize the signal-to-noise ratio. Note that the events between 196 and 201 keV have been removed, due to the strong background line present at 198 keV.
Assuming constant values all along the 16 yr, we obtain a PA of $120^\circ \pm 6^\circ$ with a PF of $24\% \pm 4\%$. This result is visualized in Figure 2, in the PA–PF plane, with the 2D surface contours calculated from the $\chi^2$ map, at $\chi^2_{\text{min}} + 2.7, 6.18, \text{ and } 11.8$, i.e., $1\sigma, 2\sigma, \text{ and } 3\sigma$ confidence levels for two free parameters. To verify the stability of the source over time, the same analysis has been performed separately for periods P1 to P4. The individual results are displayed in Figure 3. In Figure 4, the evolution of the best-fit polarization parameters are plotted, and compared to the mean values, obtained from the total data set (dashed lines = $1\sigma$ uncertainty interval). No significant evolution is visible; all values are compatible with the respective mean values. To complete our study, we investigated the polarization characteristics of the source over energy. The global energy band (130–436 keV) has been split into three energy bins: 130–196, 201–313, and 313–436 keV. The polarization parameters have been determined for each bin for the total data set. The individual results are displayed in Figure 5, while the evolution of the parameters with energy is shown in Figure 6, together with the result from the total energy range as a reference (dashed lines = $1\sigma$ uncertainty interval). The PA as well as the PF appear, once again, very stable.

4. Discussion and Conclusion

With the SPI spectrometer aboard INTEGRAL, we benefit from a large amount of observations in the hard X-ray domain,
dedicated to an emblematic source, the Crab Nebula. Particularly interesting is the possibility to investigate the polarization properties of this source for the last 16 yr. In the considered energy range (above 100 keV), the polarimetry studies are less straightforward than in optic or radio. Concerning SPI, these measurements are based on the Compton interactions of the high-energy photons in the detector plane. During a Compton interaction, the polarization of the incident flux is traced by the angle distribution of the diffused photons. This distribution can be reconstructed on the SPI detector plane, thanks to its 19 individual crystals. Considering the complexity of the polarimetry studies, it is crucial to ensure the reliability of the results through the reliability of the reconstructed fluxes. This check has been done.

Figure 3. Same as in Figure 2 for the four periods defined in Table 1.

Figure 4. Left: evolution of the SPI polarization parameters with time, in the 130–436 keV energy range. The errors quoted are 1σ for two parameters of interest. Right: results from various instruments. The corresponding periods of observation are indicated on the X-axis. In both panels, dashed lines represent the 1σ uncertainty interval for our SPI total data set best-fit values.
thanks to the spectral analysis of the same photons as those used in the polarization analysis. This step testifies that the observed polarized emission comes from the Crab Nebula.

Then, we determined the characteristics of the polarized emission of the Crab Nebula, with a robust signal-to-noise ratio, at PA = 120° ± 6° and PF = 24% ± 4% and established their stability over the 16 yr of INTEGRAL operations. Moreover, it has been shown that these values do not vary with energy, from 130 to 436 keV. Also, they are in good agreement with those obtained with the 2003 observations by Chauvin et al. (2013), INTEGRAL IBIS (Forot et al. 2008), PoGO+ (Chauvin et al. 2017), Cadmium Zinc Telluride Imager instrument on AstroSat (Vadawale et al. 2018), and Soft Gamma-Ray Detector on Hitomi (Hitomi Collaboration et al. 2018), when they consider (as done here), the total (pulsar + nebula) Crab emission (right panel of Figure 4). Lastly, our value is comparable to those reported in optical by Słowińska et al. (2009). The polarization properties, even for a source known for its long term stability like the Crab, are most probably variable in space and time: indeed, a more complex behavior appears clearly as soon as instruments are able to realized spatially or phase-resolved analyses (see, for instance, Słowińska et al. 2009). However, the global measurements contain the dominant properties of the source and help to capture a macroscopic picture of this complex region.

The detection of a high PF is the definite argument for a synchrotron origin of the hard X-ray emission. Put together with radio and optical studies, this also proves that the same component produces photons from radio to ∼MeV region. The unchanged PF, deduced from our analysis, reflects the well-known stability of the source. Concerning the second parameter, the measured PA corresponds to an electric vector aligned with the spin axis of the central object (124°; Ng & Romani 2004) and is also in line with the optical measurements (Słowińska et al. 2009). The source steadiness is still more
important in this case, since any variability of the angle weakens or even removes the observable information. Indeed, a variation of the PA smears the angular distribution of the scattered events, thus reducing the observed PF.

Harding & Kalapotharakos (2017) developed a detailed simulation code to reproduce the expected emission from this kind of object, including polarization properties. They consider synchrotron radiation at optical to hard X-ray energies and provide phase-averaged and phase-resolved predicted fluxes, PAs, and PFs. The predicted values cannot be directly compared to observations. However, the expected PFs in the sub-Mev region range from 10% to 30%, depending on the assumed geometry, is nicely similar to the values deduced from our observations. This demonstrates that simulation and data analysis works in the polarimetry domain are in the process of significantly improving our understanding of pulsar physics and high-energy photon production in general.

Polarization measurements provide a complementary window that is particularly valuable for understanding the mechanisms involved in the production of the high-energy emission of compact objects. The Crab Pulsar and its nebula enjoy a special status in the hard X-ray domain. The stability of the spectral emission, in shape as well as in intensity, is advantageous, particularly for getting high signal-to-noise ratios by accumulating data over long periods, or offering in-flight calibration facilities for high-energy instruments. Our results show that it could serve as a reference source in the polarimetry domain also from an instrumental as well as a modeling point of view.

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Appendix

Tests of Polarization Tools

The SPI polarimetric capacities rely on the Compton interactions of high-energy photons in the detection plane. In the case of a linearly polarized flux, the azimuthal angle distribution of the Compton scattered photons is no longer isotropic. This means that the angular distribution of the diffused photons lays out a specific patterns on the detector plane, which is directly related to the polarization properties. Consequently, the polarization analysis relies on the SPI response, in the specific case of Compton events (or MEs for multiple events). It is thus important to check that this response is precisely known. This guarantees a reliable extraction of the Compton events and also permits us to identify the spatial distributions corresponding to different polarized fluxes.

The SPI simulations used in the polarization analysis are based on the Integral Mass Model (Ferguson et al. 2003), translated from GEANT3 into the GEANT4 tool, with further improvements, including the anticoincidence system configuration and the central mask pixel transparency (Chauvin et al. 2013). Each simulation is based on millions of photons, with a parameterizable energy distribution probability (matching the analyzed source spectral shape) and is randomly distributed over a large surface to ensure the illumination of the whole instrument. For one photon fired, all the information are stored (involved detectors, energy deposits, etc.). To finalize a run, the data are processed in the same way as the observational data.

We used instrumental data obtained during the ground calibration campaign for a mono-energetic (unpolarized) radioactive source at 661 keV to assess that the GEANT4 simulations correctly reproduce the instrument response for both single and multiple detector events. Since the GEANT4 software package (Geant4 Collaboration et al. 2003) includes the polarization physics (as validated by Mizuno et al. 2005), we activated this functionality in our code to get simulated count patterns for a set of PAs. This allows us to check that the spatial distributions of MEs are in agreement when considering the unpolarized simulation. Moreover, it demonstrates that a polarized incident flux results in an anisotropy of the Compton event distribution on the detection plane. For instance, the difference between the unpolarized data mentioned above and a 20° polarized simulation has been evaluated to ~20% (see Figures 4 and 5 in Chauvin et al. 2013).

ORCID iDs

E. Jourdain @ https://orcid.org/0000-0001-9932-3288

References

Band, D., Matteoson, J., Ford, L., et al. 1993, ApJ, 413, 281
Chauvin, M., Florén, H.-G., Friis, M., et al. 2017, NatSR, 7, 7816
Chauvin, M., Roques, J. P., Clark, D., & Jourdain, E. 2013, ApJ, 769, 137
Dean, A. J., Clark, D. J., Stephen, J. B., et al. 2008, Sci, 321, 1183
Ferguson, C., Barlow, E. J., Bird, A. J., et al. 2003, A&A, 411, L19
Forot, M., Laurent, P., Grenier, I., et al. 2008, A&A, 688, L29
Geant4 Collaboration, Agostinelli, S., Allison, J., et al. 2003, NIMPA, 506, 250
Harding, A. K., & Kalapotharakos, C. 2017, ApJ, 840, 73
Hitomi Collaboration, Aharonian, F., Akamatsu, H., et al. 2018, PASJ, 70, 113
Jourdain, E., & Roques, J. P. 2009, ApJ, 704, 17
Mizuno, T., Kamae, T., Ng. J. S. T., et al. 2005, NIMPA, 540, 158
Ng, C.-Y., & Romani, R. W. 2004, ApJ, 601, 479
Roques, J. P., & Jourdain, E. 2019, ApJ, 870, 92
Roques, J. P., Schanne, S., Von Kienlin, A., et al. 2003, A&A, 411, L91
Słowińska, A., Kunbach, G., Kramer, M., & Stefancescu, A. 2009, MNRAS, 397, 103
Sturmer, S. J., Shrader, C. R., Weidenspointner, G., et al. 2003, A&A, 411, L81
Vadawale, S. V., Chattopadhyay, T., Mithun, N. P. S., et al. 2018, NatAs, 2, 50
Vedrenne, G., Roques, J. P., Schönfelder, V., et al. 2003, A&A, 411, L65