2003–2019 Monitoring of the Crab Emission through INTEGRAL SPI, or Vice Versa

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Abstract
The Crab Nebula is used by many instruments as a calibration source, in particular at high energy, where it is one of the brightest celestial objects. The spectrometer INTEGRAL SPI (20 keV–8 MeV), in operation since 2002 October, offers a large data set dedicated to this source, with regular campaigns planned twice per year. We have analyzed the available data to quantify the source behavior on a long-term scale and examine the stability level on timescales from hours to years. As a result, the source flux variability appears to be contained within less than ±5% around an ~20 yr mean value for broad bands covering the 20–400 keV energy domain, above which statistics limits any firm conclusion. In terms of spectral shape, the Band model provides a good description of the observed emission between 20 keV and 2.2 MeV. The averaged spectrum best-fit parameters correspond to a low-energy slope of 1.99 ± 0.01, a high-energy slope of −2.32 ± 0.02, and a characteristic energy $E_c$ of 531 ± 50 keV to describe the curvature joining both power laws. The spectral parameters have then been determined on the revolution timescale (~1–2 days), and their steadiness confirms the source emission stability. As a complementary result, this study demonstrates that the SPI instrument efficiency remains within 5% of its initial value after 17 yr of operation.

Unified Astronomy Thesaurus concepts: Space observatories (1543); X-ray sources (1822); Gamma-ray sources (633); Astronomical radiation sources (89)

1. Introduction

The Crab supernova remnant is one of the rare persistent sources bright enough to provide a significant signal-to-noise ratio in the hard X-ray domain (~100 keV region) on an hour timescale. In addition, its emission appears steady over time, with minimal variations on a timescale of a few years (~2%–3% yr$^{-1}$), around a mean flux that remains stable over longer timescales (Wilson-Hodge et al. 2011). Flux variabilities, including flares, are observed at higher energy (100 MeV and above; Abdo et al. 2011) with no impact at lower energy. Also, the nebula extends over ~5′ and can be considered as a punctual source for the coded mask instruments operating above 30 keV (i.e., all past and current hard X-ray instruments, except NuSTAR; Madsen et al. 2015). All of these properties make it the best tool to test, validate, or correct the instrument’s performance after launch.

Conversely, the assessment of the stability of the Crab emission relies on the (cross)-calibration and stability of the measuring instruments. In this paper, we aim to disentangle both effects (source variability and instrument evolution) using the observations gathered above 20 keV by the SPI spectrometer aboard the INTEGRAL observatory. This is possible because, unlike many instruments, SPI is not calibrated against an ad hoc Crab index; its response matrices are based on extensive ground calibrations and Monte Carlo simulations. Since its launch at the end of 2002, INTEGRAL has regularly pointed toward the Crab Nebula (at least every 6 months) to check the instruments’ performance. This provides an exceptional data set to fulfill this twofold objective.

In the following sections, we give a brief description of the instrument and data set, then detail the photon selection criteria (including multiple events (MEs)) and the analysis procedure. The results obtained are then presented (Section 3), with a discussion of the evolution of the instrument efficiency and source variability in flux and shape, respectively. Additional information is given on the potential emission of a 511 keV annihilation line (Section 4) and the instrument efficiency around 1.5 MeV (Section 5).

Finally, we conclude with a few words about the SPI instrument performance and the standard candle status of the Crab Nebula, in view of future cross-calibration efforts.

2. Instrument, Observations, and Data Analysis

2.1. The “Spectromètre Pour Integral”

The SPI instrument (Vedrenne et al. 2003) operates from 20 keV up to a few MeV, with a coded mask aperture associated with a detector plan consisting of 19 high-purity germanium crystals. The various calibration runs conducted to characterize the instrumental response are reported in Attié et al. (2003). The response matrices have been built through Monte Carlo simulations, validated against ground measurements (Sturman et al. 2003). An overview of the in-flight performance can be found in Roques et al. (2003), while a comprehensive description of the data analysis procedure can be found in Jourdain & Roques (2009) with an update in Roques & Jourdain (2019). We just recall that the INTEGRAL observations are organized by revolutions (or orbits) that last ~3 days, including 0.5 day of interruption due to radiation belts. Each revolution consists of a succession of science windows (scw) lasting ~2–3 ks. The pointing direction changes from one scw to the next in steps of ~2° following predefined patterns. Complete information is available on the ESA INTEGRAL website (https://www.cosmos.esa.int/web/integral/schedule-information). Let us mention that specific annealing procedures are conducted more or less every 6 months to recover the energy resolution (Roques et al. 2003).

2.2. The Data Set

The following analysis is based on the regular calibration campaigns performed twice a year, from the launch up to 2019. Note that all of these observations are made public immediately.
For specific calibration purposes, most of the Crab observations before 2013 are performed with peculiar patterns, in order to investigate the transparency of the IBIS mask corners and the response matrices for large off-angles for both the SPI and IBIS instruments. These observations have been used to demonstrate that data collected from sources up to 12° from the INTEGRAL pointing axis (i.e., coded fraction ∼50%) give reliable results.

A careful check of both background evolution and goodness of the statistical criteria along the analysis process results in removing exposures affected by radiation belt exit or entry, loss of data, solar activity, or other very bright transient events. For instance, all of the observations including bright outbursts of the nearby pulsar A0535+26 have been ignored in this work. In addition, revolutions encompassing less than 20 “good” scw have been excluded, since the determination of the background (and thus source) flux may be less accurate. The final data set thereby encompasses 56 revolutions corresponding to ∼3600 scw and a total of 7 Ms. To ease the data analysis, the total data set has been split into two sub-data sets: before and after revolution 1170 (see below).

2.3. Main Features of the Data Analysis

The flux extraction relies on a model fitting procedure, including both source and background components. For the Crab observations, the sky model is particularly simple: the Crab Nebula and the Be pulsar A0535+26. Except during flaring episodes, A0535+26 is much fainter that the Crab (by a factor of >50), and its variability around its mean flux is limited. Consequently, the periods with strong outbursts being excluded, the A0535+26 flux can be considered as constant on the revolution timescale during our analysis. Concerning the Crab, the flux extraction has been performed on the scw and revolution timescales, with a view to achieving different scientific objectives.

The peculiar issue of the electronic noise and associated pileup in the high-energy part has been taken into account following the recommendations described in Roques & Jourdain (2019). For the first part of the data set (revolutions before 2012 May 13 = MJD 56,060 = rev 1170), events without the pulse shape discrimination (PSD) flag are ignored above 650 keV, and the fluxes are corrected from the PSD electronic chain efficiency (∼85%). Below 650 keV, we apply the pileup correction factor, estimated to be ∼0.14% of the source flux measured at 60 keV. This correction becomes negligible below 200 keV. For the second part of the mission lifetime (after 2012 May 13), the PSD configuration corresponds to a low-energy threshold value of 400 keV. We thus select PSD flagged events above this energy and apply the appropriate corrections for PSD efficiency or pileup for fluxes above and below 400 keV, respectively.

Additional information is contained in MEs. These events correspond to photons that deposit energy in more than one detector and are used for polarimetric studies. In practice, we consider only double events, hereafter called ME2s, produced by high-energy photons that undergo a Compton interaction in one detector and escape toward a neighboring detector, where they are photoabsorbed. The ME2 contribution is negligible below 90 keV and less than 20% of the total flux at higher energy. However, it will be used in this paper to ascertain the high-energy results. The flux extraction for ME is performed in a similar way as for the “one-detector” events, while the spectral deconvolution is completed with the appropriate matrices (Sturner et al. 2003).

To monitor the temporal evolution of the Crab Nebula over the INTEGRAL mission lifetime, fluxes have been extracted in four broad bands between 24 and 650 keV to produce light curves on the revolution and scw timescales. Then, an analysis in 41 narrower energy bins covering the 24–2200 keV domain has been performed on the revolution timescale for the spectral studies. Fluxes from ME2s have been extracted between 90 and 2200 keV (16 channels), to be fit simultaneously with the corresponding one-detector event spectra. However, with the ME efficiency suffering large uncertainties up to 170 keV, spectral fits will exclude the first five channels. At the end, we get a total of 56 individual spectra in the two data sets.

For practical reasons (different correction parameters), the two observational periods before and after revolution 1170 (22 and 34 revolutions, respectively) have been analyzed separately.

3. Results

3.1. Broadband Analysis

A synthetic view of the Crab evolution is obtained by looking at the source flux averaged by revolution (see Figure 1) in the four broad bands. Depending on the scheduled planning, the useful durations of the exposure dedicated to the Crab Nebula in the individual revolutions range from 20 to ∼100 scw, i.e., 40 to 230 ks.

From these plots, it appears that the long-term evolution of the Crab is slowly varying around a stable mean flux. The variability level in the range 24–150 keV is of the order of 5%, represented by the two dotted lines in Figure 1. This remains mostly true for the 150–400 keV energy band even though higher variations are sometimes observed. The most important evolution is that reported by Wilson-Hodge et al. (2011) in 2008–2010. A flux decline has been measured by several instruments, implying that it belongs to the source. It is characterized by a linear decrease of ∼3.5% yr−1 between 15 and 100 keV and roughly twice this value between 100 and 300 keV for the period MJD 54,690–55,390. These variations are illustrated by a dotted line in Figure 1, in good agreement with the SPI data. The deviations around these templates present rms values of 0.6%, 1.1%, and 3.7% for the first three energy bands respectively, which can be used as upper limits on the SPI efficiency uncertainties. In 2015, the source recovers the same flux level as in 2009. This may be taken as a strong indication that the instrument efficiency is stable up to that time. For the latest available observations, the Crab emission exhibits a behavior similar to the 2008–2010 episode but remains below the long-term mean yet within the same range (<5%) as previously measured. However, in this case, the observed trend can be attributed to either source or instrument evolution. In the highest energy band (400–650 keV), all fluxes are compatible within 2σ, and the limited signal-to-noise ratios prevent any firm conclusion. A study of the instrument efficiency at higher energy (1.5 MeV) is presented in...
Figure 1. Light curves of the Crab emission in four broad bands along the mission. Each point corresponds to one revolution (∼0.5 to 2.5 days of useful duration), the two panels correspond to the two periods mentioned in the text (before and after 2012 May 13), the dashed lines represent the mean flux, and the dotted–dashed lines represent the ±5% brackets around it. Dotted lines stand for the source decline reported by Wilson-Hodge et al. (2011), with a slope of 3.5% yr⁻¹ from 24 to 150 keV and 7% yr⁻¹ for the 150–400 keV band.
Section 5 by means of the long-term evolution of a specific background line.

To look in more detail at the source evolution, fluxes have been extracted for each INTEGRAL exposure, which generally lasts $\sim$0.5–1 hr.

At this timescale, the source stability is less constrained, due to larger measurement uncertainties. Figure 2 shows that between 24 and 150 keV (the most significant results because they have the highest signal-to-noise ratios), the source flux dispersion is $\pm 15\%$ (dotted–dashed lines) around the mean value (dashed line) or even...
less within each revolution. Several effects contribute to the observed dispersion: statistical error on the measurements, instrumental systematics, and intrinsic source variability. To investigate this point, the histograms of the flux measurements have been built for the first two bands (24–50 and 50–150 keV) and shown in Figure 3 (solid line).

The expected dispersion around the observed mean flux ($F_{\text{mean}}$) due to measurement uncertainties is estimated from the mean value of the statistical errors (see Table 1). The corresponding normal laws are plotted as the dotted–dashed line in Figure 3. At the same time, the observed distributions are broader than the purely statistical ones. They can be described by normal laws, whose parameters (identified as $\mu$ and $\sigma$) are also given in Table 1.

From the comparison of observed and expected values, we deduce that the broadening of the observed distributions in all cases corresponds to an additional variance, attributable to instrumental systematics and/or intrinsic source variability, equal to $\sim 2.5\% – 3.3\%$ of the mean source flux. We note also that 86% (for the first period) and 91% (for the second period) of the measured fluxes on the scw timescale are within $\pm 5\%$ of the respective mean fluxes in the 24–50 keV band. These values become 67% and 69% in the 50–150 keV band.

However, the source flux has been shown to vary by a few percent on a timescale of a few years. This must be taken into account.
account to more rigorously access its hour timescale variability. We have thus considered the data in terms of standard deviations relative to the flux average observed in the individual revolutions. To do that, we consider the difference between each scw flux and the average value measured over the revolution, normalized by the error. The corresponding histograms for the first energy band are presented in the right panels of Figure 3. While the statistical part of the dispersion is represented by a normal law (0, 1), the data follow a slightly shifted (μ around −0.35) and broader (σ ~ 1.4) distribution (see Table 1). In both cases, the broadening of the observed dispersion corresponds to an additional variance of ~1. Using the values of Fmean and (Err) reported in Table 1, this results in a level of variability, due to instrumental systematics and/or intrinsic source behavior, ranging between 1.5% and 1.8% of the mean source flux. This quantifies the remarkable steadiness of the Crab emission over periods of several days or weeks.

In the two higher energy bands, the dispersion reaches a much larger factor (up to a few) but is comparable to the measurement uncertainties on this short timescale.

The conclusion of this broadband analysis is twofold: first, the SPI instrument efficiency loss (at least between 20 and 400 keV) is below 5% over more than 17 yr of operation; second, even if the origin of the measured variability remains to be assessed (intrinsic to the source, instrument systematics, or both), the value is modest enough to consider that the Crab emission is constant to first order over decades, with a variability level within ±5%, comparable to the instrumental uncertainties. Furthermore, when looking at timescales of a few days or weeks, the upper limit on source variability or instrument uncertainties is below 2%.

3.2. Spectral Analysis

The Crab Nebula energy spectrum is often described by a power law for most of the energy domains covered by individual instruments. However, the observed slopes are energy- (or instrument-) dependent, indicating a more complex spectral shape when considering the whole electromagnetic emission (see, for instance, Kuiper et al. 2001 and references therein). More specifically, the hard X-ray domain covered by the SPI instrument makes the link between the X-ray domain (observed slope around 2–2.1; Kirsch et al. 2005) and the γ-ray domain (slope of 2.23; Kuiper et al. 2001). A broken power law was long used to described the slope evolution, with a break around 100 keV (e.g., Strickman et al. 1979; Ling & Wheaton 2003). A single curved shape with a slope varying with log(E) has then been proposed (Massaro et al. 2000; Mineo et al. 2006), but this model cannot be extrapolated in a broader energy domain due to the continuous curvature. To avoid an unphysical break while allowing extrapolations toward lower and higher energies, we proposed to describe the broadband spectral emission by the Band model, used by Band et al. (1993) for modeling gamma-ray burst (GRB) emission (GRBM in Xspec language), which joins two power laws by a smooth curvature. This shape better reproduces the smooth slope evolution observed between 20 keV and ~1 MeV than previously proposed models, even though the Band model remains an analytical description, without physical law behind it.

We start our study by analyzing the mean spectra, obtained by summing the spectra belonging to the two periods defined above. We fit together the one- and two-detector event spectra for both periods, imposing the same shape parameters, while the two normalizations are let free (Figure 4). During the fit procedure with Xspec, 0.5% of the systematic has been added. The best-fit parameters are reported in Table 2 together with those obtained for the sum of all observations.

Table 2 also contains the 30–100 keV flux, which is more representative of the source flux than the best-fit normalization parameter, because it is independent of the shape parameter.
values. The parameters of both data sets are in good agreement. Rather than claiming true parameter values (which depend on the SPI calibration systematics), this result assesses the stability of the source spectral shape on long-term scales and, again, that of the instrument response.

To study the evolution of the spectral parameters with time, we have repeated the fit procedure for each individual revolution. To limit the degeneracy between the parameters, in particular between the second slope and the characteristic energy, the second power law has been fixed at the value obtained on the long-term averaged spectrum (2.3) and compatible with the slope observed above a few MeV (Kuiper et al. 2001). This makes the comparison of the parameters obtained for the different periods more informative.

The best-fit values of the remaining four free parameters are presented in Figure 5, together with the \( \chi^2 \) values and the 30–100 keV flux versus time.

The narrow ranges spanned by the low-energy slope and the source 30–100 keV flux quantify the stability of the Crab emission in terms of both shape and intensity. The characteristic energy (which drives the slope change) is less constrained. The two mean values are only marginally compatible (see Table 2). Even though this may point out a true evolution of the source emission above a few hundred keV, we cannot exclude a decrease of the instrument efficiency at high energy (see Section 5).

The normalization factors are driven by the low-energy slope best-fit parameter value and are not useful by themselves. However, we note that the normalization factors of the ME2 (for \( E \approx 170 \text{ keV} \)) and one-detector event spectra agree within 10\% or less in any period. This demonstrates the coherence and validity of the data analysis procedure for both kinds of events, including the flux corrections described in 2.3.

### 4. The 511 keV Region

The energy band around 500 keV is of particular interest for all \( \gamma \)-ray emitters. It allows one to test the presence of thermalized positrons in the emitting regions and get unique information on the particle distributions or other source parameters. The potential annihilation line may be modified by several physical factors (acceleration process, medium temperature and density, etc.), impacting the observed central energy and width. Consequently, access to the information is tricky. In order to scan most of the plausible scenarios, we have extracted the source flux in two energy bands centered around the theoretical rest energy: a narrow (10 keV) and a broad (40 keV) one. The resulting light curves (Figures 6 and 7) exclude any transient emission on hour and day timescales, disfavoring any annihilation sites inside the nebula. The production of positrons cannot be excluded, but such particles had every chance to escape far away from the nebula before they slow down and annihilate.

No detection was obtained for the line flux with 2\( \sigma \) upper limits of \( 2 \times 10^{-3} \) and \( 3 \times 10^{-3} \text{ ph cm}^{-2} \text{s}^{-1} \) in a 10 keV wide energy bin for the hour and \( \sim 1–2 \text{ day} \) timescales. When a broader energy region is considered to take into account a potential line shift and/or broadening, the values become \( 3 \times 10^{-3} \) and \( 5 \times 10^{-4} \text{ ph cm}^{-2} \text{s}^{-1} \), respectively. For the total of the observations (7 Ms), the upper limits on any annihilation feature are \( 4 \times 10^{-3} \) and \( 6.5 \times 10^{-3} \text{ ph cm}^{-2} \text{s}^{-1} \) for the narrow and broad features, respectively.

### 5. SPI Efficiency in the MeV Range

The steadiness of the Crab fluxes over the long term can be considered as evidence of the instrument stability within 5\% up to 400 keV. The low signal-to-noise ratio makes it difficult to extrapolate the conclusion well beyond this limit.

However, the SPI efficiency at high energies can be affected by a drift of the lithium ions from the central anode. This drift occurs during each annealing process. This phenomenon increases the effective radius of the anode and thus decreases the collecting volume in the Ge crystal. Consequently, the detector efficiency decreases in an energy-dependent way. We have thus sought a possible calibration source inside the instrument to test the highest energy range. In the large sample of radioactive lines present in the SPI background spectrum (see the detailed study by Weidenspointner et al. 2003), we have identified one that presents suitable characteristics: the \( {^{40}}\text{K} \) line at 1460.82 keV is produced by natural radioactivity (i.e., “the parent isotope is not radioactive because of activation processes in orbit”; Weidenspointner et al. 2003), and its flux is high enough to be easily measurable on the revolution timescale. The determination of the \( {^{40}}\text{K} \) line intensity requires a few precautions. In practice, for all revolutions along the mission lifetime, we have considered the background spectrum, built with the PSD flagged events and recorded on the whole detector plane. In order to avoid a weak variable background line at 1463.95 keV (due to \( {^{72}}\text{Ga} \)), only the left half of the \( {^{40}}\text{K} \) line has been used. Hence, the count spectra have been integrated between 1454 and 1461 keV, to take into account the energy resolution evolution between annealings. Finally, the local continuum (quasi-flat in this spectral region) has been subtracted. The flux is obtained after dividing by the spectrum duration. The resulting values are displayed in Figure 8 for each revolution and averaged over \( \sim 2 \text{ months} \) (20 revolutions). We first note that the \( {^{40}}\text{K} \) light curve presents a long plateau (between revolutions \( \sim 600 \) and \( \sim 1600 \)) before an unexplained step that may point out that part of this evolution is not due to the loss of efficiency. We should also consider that the PSD efficiency is slightly varying with the background (Roques &

| Period   | \( \alpha_1 \)   | \( E_1 \)  | \( \alpha_2 \)   | \( N_1 \)       | \( N_{\text{ME2}}/N_1 \) | \( F \)          | \( \chi^2 \) (dof) |
|----------|-----------------|------------|-----------------|----------------|------------------------|-----------------|---------------------|
| 1 + 2    | 7.02 Ms         | 1.99 ± 0.01| 531 ± 50        | 2.32 ± 0.02    | (7.52 ± 0.2) \( 10^{-4} \) | 1.02            | (1.30 ± 0.01) \( 10^{-8} \) | 77.5 (47)          |
| 1        | 2.73 Ms         | 1.99 ± 0.02| 565 ± 40        | 2.31 ± 0.04    | (7.53 ± 0.2) \( 10^{-4} \) | 1.0             | (1.31 ± 0.01) \( 10^{-8} \) | 60.6 (47)          |
| 2        | 4.29 Ms         | 1.98 ± 0.01| 507 ± 40        | 2.33 ± 0.02    | (7.55 ± 0.1) \( 10^{-4} \) | 1.03            | (1.29 ± 0.01) \( 10^{-8} \) | 79.6 (47)          |

Note. The 0.5\% systematic errors were included with data during the fit. Quoted errors are statistical only.
Jourdain 2019; a decrease of 4% is observed between revolutions 43 and 885 (corresponding to a first solar minimum) and 4.4% between revolutions 43 and 1933 (second solar minimum). Thus, while the $^{40}$K flux evolution reflects an “apparent” efficiency loss of $\sim30\%$ at 1460 keV without any supplementary correction, we can derive an upper limit for the detection efficiency loss of $\sim25\%$ at this energy after 17 yr of operation.

6. Discussion and Conclusion

We have used a large data set of observations dedicated to the Crab Nebula to investigate both the SPI instrument and Crab emission temporal evolution. From an instrumental point of view, we have demonstrated that the SPI germanium detector efficiency remains remarkably unchanged (within 5%) up to 400 keV after 17 yr in space and 33 annealing realizations. To investigate the efficiency evolution at higher energy, we have used the $^{40}$K line as an internal source calibration in the 1.5 MeV region. Even though this parameter is less easy to constrain, we have estimated that the efficiency loss is less than $\sim25\%$.

Because its calibration matrices rely on an extensive campaign of ground calibrations coupled with Monte Carlo simulations, SPI is able to provide an absolute measurement of the Crab flux and...
spectral shape above 20 keV, as well as their evolution over time. This work completes the studies performed by Wilson-Hodge et al. (2011) and Kuiper et al. (2001) and confirms that the Crab emission presents a modest variability over a timescale of a couple of years. However, its steadiness over larger timescales is definitively established. The spectral shape also appears to be

Figure 6. Top: evolution of the Crab flux in a narrow band (506–516 keV) around the 511 keV line. Each point corresponds to 1 scw (~0.5–1 hr) timescale. Bottom: same as the top panels, with each point corresponding to one revolution (~0.3–2.5 days of useful duration). The dashed lines trace the mean values (averaged over the panel data set).

Figure 7. Same as Figure 6 for a broader energy band (490–530 keV).

Figure 8. Evolution of the flux contained in the $^{40}$K line. The same data averaged over ~2 months are displayed below the original data (flux divided by 2 for clarity). The horizontal lines represent the first and last 2 month averaged values. The dotted vertical line at MJD = 56,000 demarcates the two sub-data sets presented throughout the paper.
stable over time. This outcome deserves to be examined in the context of the huge flares occasionally observed in the GeV domain. While the amount of energy dissipated in the nebula is then important, the SPI observations imply that the global configuration of the nebula and the physical mechanisms at work are not significantly impacted.

As a concluding remark, we point out that the small deviations presented by the Crab flux around the 20 yr mean values are commensurable with the uncertainties of the instrument calibrations. Consequently, this source remains the best “standard candle” candidate, in particular for cross-calibration purposes, in the high-energy domain. Indeed, it offers an easy way to compare instrument responses without requiring simultaneous observations.

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Software: Xspec V12.9.1 (Arnaud 1996), SPIDAI (SPI data analysis tool developed at IRAP; https://sigma-2.cesr.fr/integral/spidai).

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