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When A Standard Candle Flickers

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The Crab Nebula is the only hard X-ray source in the sky that is both bright enough and steady enough to be easily used as a standard candle. As a result, it has been used as a normalization standard by most X-ray/gamma ray telescopes. Although small-scale variations in the nebula are well-known, since the start of science operations of the *Fermi* Gamma-ray Burst Monitor (GBM) in August 2008 a $\sim 7\%$ (70 mcrab) decline has been observed in the overall Crab Nebula flux in the 15–50 keV band, measured with the Earth occultation technique. This decline is independently confirmed in the $\sim 15-50$ keV band with three other instruments: the *Swift* Burst Alert Telescope (*Swift*/BAT), the *Rossi X-ray Timing Explorer* Proportional Counter Array (*RXTE*/PCA), and the *INTErnational Gamma-Ray Astrophysics Laboratory* Imager on Board *INTEGRAL* (IBIS). A similar decline is also observed in the ~ 3 - 15 keV data from the *RXTE*/PCA and in the 50 - 100 keV band with GBM, *Swift*/BAT, and *INTEGRAL*/IBIS. The change in the pulsed flux measured with *RXTE*/PCA since 1999 is consistent with the pulsar spin-down, indicating that the observed changes are nebular. Correlated variations in the Crab Nebula flux on a ~ 3 year timescale are also seen independently with the PCA, BAT, and IBIS from 2005 to 2008, with a flux minimum in April 2007. As of August 2010, the current flux has declined below the 2007 minimum.

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1. Introduction

X-ray and gamma-ray astronomers frequently consider the Crab supernova remnant to be a steady standard candle suitable as a calibration source (e.g.,[1 – 4]). Jourdain & Roques (2009) presented over 5 years of *INTEGRAL* (SPI, 20 keV - 8 MeV) observations, with fitted flux normalizations at 100 keV consistent with being constant to within the $\sim$ 3% quoted errors. On the basis of data from *XMM-Newton*, *INTEGRAL*, *Swift*, *Chandra*, *RXTE*, and several earlier missions, Kirsch et al. [1] concluded that the Crab flux can be described at least up to 30 keV by the same spectrum proposed by Toor & Seward [5] three decades earlier: $dN/dE = (9.7 \pm 1.0)E^{-(2.1\pm0.03)}$photons cm^{-2}s^{-1}keV^{-1}, and they describe the Crab as a standard candle.

Driven by the central pulsar's spin-down luminosity, the surrounding remnant consists of a cloud of expanding thermal ejecta and a synchrotron nebula [6] with an integrated luminosity $\sim 10^{38}$ erg s^{-1}. The pulsar provides a shocked wind that accelerates electrons and positrons to energies $\sim 10^7$ GeV and a source of kinetic energy driving turbulent motion of a ring of wisps nearly surrounding the synchrotron nebula. High resolution observations reveal wisps and knots moving at velocities up to 0.7 c from radio to X-ray energies (e.g., [7 – 11]). A central torus and jet structure extending out from the pulsar were observed in X-rays by *Chandra* [12], aligned closely with the pulsar's proper motion [13]. The nebular emission is considered to be a combination of synchrotron radiation up to $\sim$ 100 MeV and a harder inverse Compton spectrum extending up to TeV energies [14].

Variations in the observed Crab nebular flux have been previously reported at various wavelengths, for example, in radio [15], optical [16], and in soft gamma rays [17]. At higher energies (1-150 MeV), large flux changes have been reported [18, 14]. Recently, flares in the $>$ 100 MeV flux were reported by *Fermi*/LAT [19] and *AGILE* [20]. Conversely, at the highest energies, HEGRA [21], H.E.S.S. [22], MAGIC [23], and VERITAS [24] report no evidence for time variability.

2. Observations & Results

2.1 *Fermi* GBM

The GBM instrument (8 keV to 40 MeV) [25] provides nearly continuous full-sky coverage via the Earth occultation technique, adapted from BATSE [26] for GBM [27, 28]. The GBM detector response [29, 30], gain, and energy resolution are stable over time with background lines typically within 1% of their expected position.

The Crab rate measured in the 12-50, 50-100, 100-300, 300-500 keV energy bands with GBM from August 12, 2008 through July 13, 2010 (MJD 54690-55390) decreased steadily by more than 5%: The decrease is 5.4 ± 0.4%, 6.6 ± 1.0%, 12 ± 2%, and 39 ± 13% in the four bands, respectively, relative to MJD 54690. Inclusion of a linear decline in the 12-50 keV band improves reduced χ^2 to 605.8/130=4.66 from 956.3/131=7.30 for a constant Crab [31].

2.2 *RXTE* PCA

Frequent observations with the *RXTE* PCA were made to monitor the radio-X-ray phase of the Crab pulsed emission [32] and for calibration purposes [33, 34]. In the PCA, the Crab is bright ($\sim$ 2500 counts s^{-1} detector^{-1}). Unrejected background from all sources amounts to about 1 mCrab.

The PCA is a relatively simple instrument, with commanded changes in operating conditions limited to the high voltage. Data since the last high voltage change in 1999 for PCU 2,3, and 4 are used in this paper.

The PCA response has two small time-dependent effects, both accounted for in the response matrices: the changing opacity of the front veto layer (negligible in the 15-50 keV band) and a small energy drift in the pulse height channel boundaries. Our observed changes in the Crab rate (see Figure 1 and [31]) are more than 5 times larger than these effects combined.

From MJD 54690-55435 the Crab rate in PCU 2 declined by $5.1 \pm 0.2\%$ and $6.8 \pm 0.3\%$ in the 2-15 and 15-50 keV bands, respectively, relative to MJD 54690 [31]. Similar results, variations of 2-7%, are seen if the bands are further subdivided. In spectral fits to individual PCA observations, the power law index softens and the normalization and absorption column gradually increase with time, with no clear correlation with flux. These light curves were produced using *RXTE*/PCA standard 2 data (129 energy channel, 16-second) that were extracted, background subtracted, deadtime corrected using standard *RXTE* recipes[1] and corrected for the known time dependence of the response.

2.3 *INTEGRAL* IBIS and JEM-X

Here we present results from JEM-X (3 - 35 keV,[35]) and the IBIS/ISGRI (15 keV - 10 MeV, [36]) on-board *INTEGRAL* [37]. The Crab has been observed every spring and fall with *INTEGRAL* since 2002, mainly for calibration purposes. To reduce systematic effects as much as possible, we selected JEM-X and IBIS/ISGRI observations within ($< 0.25^\circ$) and 10° of on-axis. We include only JEM-X data using the latest on-board software (since MJD 53068).

Figure 1 includes ISGRI and JEM-X2 count rates from individual pointings averaged over the 3-day *INTEGRAL* orbit with rms errors. The ISGRI data were analyzed with the Off-line Analysis (OSA) package [38] version 9 with the settings used for the *INTEGRAL* Galactic Bulge monitoring program[2] light curves [39]. Using images from individual pointings, the point-spread function of ISGRI is fitted. These images are integrated in a given energy band after gain, offset, and charge-loss corrections are performed for each event. A time-dependent effective area correction, usually performed by assuming that the Crab flux is constant, has been excluded from these data, meaning that not all systematic effects are taken into account. Known effects include residuals in gain and charge loss corrections, present with an amplitude of $\sim$1-2%, varying on month-years timescales. Similarly, for JEM-X, the ad-hoc piecewise linear correction (added to OSA to reduce time trends in the Crab flux) was excluded from the standard OSA analysis. JEM-X consists of two identical units, JEM-X1 and JEM-X2. During the period of interest, JEM-X2 has mostly been in standby-mode and JEM-X1 the active unit. A gradual decrease has been observed in the sensitivity of JEM-X1, so only JEM-X2 is shown. The scatter in the JEM-X data is large compared to the observed Crab variations, especially below 10 keV. From MJD 54690-55390, the ISGRI 15-50, 50-100, and 100-300 keV flux decreases by 8.2 ± 1.1, 8.3 ± 1.1, and $5.7 \pm 1.0\%$, respectively, relative to MJD 54690 [31].

[1] http://heasarc.gsfc.nasa.gov/docs/xte/recipes/

[2] http://integral.esac.esa.int/BULGE/

2.4 *Swift* BAT

Swift/BAT is a coded aperture telescope operating in the 14 - 150 keV range [40]. The Swift/BAT 14-50 and 50-100 keV light curves (see Figure 1) are based on publicly available 58-month light curves[3] from the Swift/BAT all-sky hard X-ray survey [41, 42] extended to May 30, 2010 by the BAT team. We binned data from individual Swift pointings in 50-day intervals, eliminating pointings of less than 200 seconds duration and those in which less than 15% of the BAT detectors were illuminated by the Crab. The statistical errors on each data point are small (0.1%) and are dominated by systematic errors. We estimate the systematic errors to be $\sim 0.75\%$ by assuming that the long term variations in the lightcurve are due to real variations in the Crab, and that the shorter term variations around that trend are representative of the systematic error. The BAT data show variations in the Crab flux at the level of $\sim 3\%$ yr^{-1}. From MJD 54690-55340, BAT observes a decrease of 6.7 ± 0.7 and $10.4 \pm 0.8\%$ [31], in the 15-50 and 50-100 keV bands, respectively, relative to the rate on MJD 54690, similar to the decrease seen by GBM in the same energy range.

3. Discussion and Summary

Figure 1 shows composite light curves combining the overlapping results from *RXTE*, *INTEGRAL*, *Swift*, and *Fermi*/GBM. All instruments agree well from 2008 to 2010, with all instruments registering a decline in the Crab 15-50 keV flux of ∼7% (70 mcrab) over the two years starting at MJD 54690, with a similar decline in the 50-100 keV band. PCA and BAT continue to agree back to the start of the *Swift* mission. For *RXTE*, *Swift*, and *INTEGRAL*/ISGRI the latest measurements shown are significantly below the previous minimum. *INTEGRAL*/ISGRI shows evidence for the dip near MJD 54100-54200 and the increase before ∼MJD 53700, with similar but less significant variations seen in JEM-X2. Prior to this time, the PCA measurements show continued variations extending back to ∼MJD 52000, which are not seen with ISGRI in the 20-50 keV band. Known systematic errors in ISGRI energy reconstruction are expected to account for ∼1-2% deviations. Beginning at ∼MJD 54000, there is a strong correlation among the results from the four independent instruments with very different signal to noise characteristics and observing techniques: Earth occultation, coded-mask imaging, and collimated detectors. The range of techniques strengthens the case that the variation is intrinsic to the Crab. We found no apparent correlations between these variations and variations in the *INTEGRAL*/SPI anticoincidence detector count rates or GBM count rates, evidence against local background condition changes as a possible origin, and further supporting a Crab origin. The pulsed flux stability [31] suggests that the observed variations are nebular.

In summary, the widely-held assumption that the Crab is a standard candle, suitable for normalizing instrument response functions and for calibrating X-ray instruments, is now in question. Although obtaining absolute calibrations and instrument normalizations at $\sim 1\%$ is difficult, the results presented here from four independent spacecraft demonstrate that in fact the nebular X-ray/gamma ray emission from the Crab varies at a level of $\sim 3.5\%$ yr^{-1}. The variation is seen in the nebular emission, and so apparently results from changes in the shock acceleration or the

[3] http://swift.gsfc.nasa.gov/docs/swift/results/

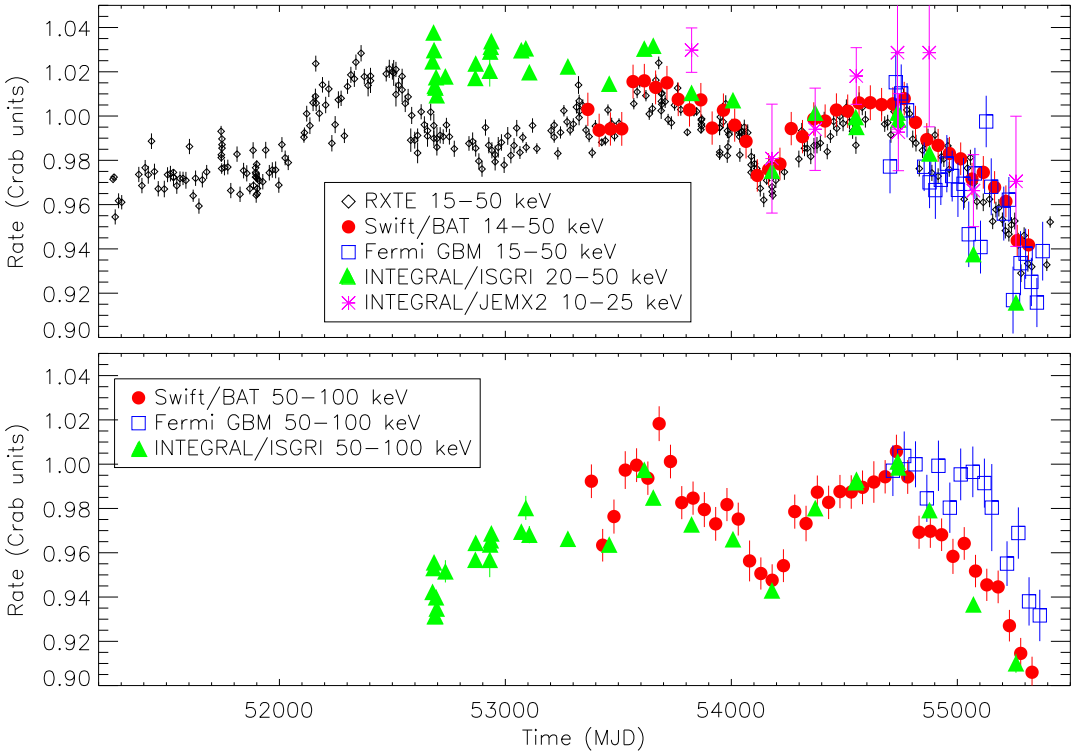

Figure 1: Composite Crab light curves for *RXTE*/PCA (15-50 keV - black diamonds), *Swift*/BAT (Top: 14-50 keV, Bottom: 50-100 keV - red filled circles), *Fermi*/GBM (Top: 15-50 keV, Bottom: 50-100 keV - open blue squares), *INTEGRAL*/ISGRI (Top: 20-50 keV, Bottom: 50-100 keV - green triangles), and *INTEGRAL*/JEM-X2 (10-25 keV). Each data set has been normalized to its mean rate in the time interval MJD 54690-54790. All error bars (except *Swift*/BAT) include only statistical errors.

nebular magnetic field. We cannot predict if the present decline will continue or if the ~ 3 year pattern [31] will persist. Longer baselines and multi-wavelength observations are needed to answer these questions.

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