

All-sky Monitoring of Variable Sources with Fermi GBM

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Using the Gamma ray Burst Monitor (GBM) on Fermi, we monitor the transient hard X-ray/soft gamma ray sky. The twelve GBM NaI detectors span 8 keV to 1 MeV, while the two BGO detectors span 150 keV to 40 MeV. We use the Earth occultation technique to monitor a number of sources, including X-ray binaries, AGN, and solar flaring activity. Our monitoring reveals predictable and unpredictable phenomena such as transient outbursts and state changes. With GBM we also track the pulsed flux and spin frequency of accretion powered pulsars using epoch-folding techniques. Highlights from the Earth Occultation and Pulsar projects will be presented including our recent surprising discovery of variations in the total flux from the Crab. Searches for quasi-periodic oscillations and X-ray bursts are also possible with GBM all-sky monitoring capabilities. With these results we show how crucial an all-sky monitor is for any future X-ray timing mission.

Fast X-ray timing and spectroscopy at extreme count rates

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Champery, Switzerland

*Speaker.

1. Introduction

All-sky monitors are typically responsible for triggering observations with a main instrument, workhorse science such as monitoring source states and fluxes, and serendipitous science resulting from watching large fractions of the sky nearly all of the time. In this paper, we describe highlights of all-sky monitoring science with the Gamma ray Burst Monitor (GBM) on *Fermi*, including the discovery of variations in the Crab Nebula flux in hard X-rays and results from monitoring accretion-powered pulsars.

2. Observations & Results

The *Fermi* satellite was launched on June 11, 2008. It consists of two instruments, the Large Area Telescope [1], sensitive to gamma rays from 20 MeV to more than 300 GeV and the Gamma Ray Burst Monitor [2], sensitive to gamma rays from 8 keV to 40 MeV. The GBM consists of 12 NaI detectors (8-1000 keV) and two BGO detectors (150 keV - 40 MeV). The results described in this paper are from the GBM NaI detectors.

2.1 Discovery of decline in Crab Nebula flux using the Earth occultation technique

The GBM instrument is not a pointed or focusing instrument. To measure fluxes from individual sources on the sky, we use the Earth occultation technique [3, 4], measuring the change in count rate as a source enters or exits Earth occultation. Our application of this technique uses a catalog of known source locations, for which Earth occultation times are calculated and a window of data containing the occultation time is extracted. These data from GBM detectors viewing the source within 60 degrees of the detector normal are fitted with a quadratic background plus a model resulting from an assumed source spectrum convolved with the changing detector response as GBM scans the sky, and the energy dependent atmospheric transmission function describing the Earth occultation. Other bright sources within the window are fit simultaneously. For the source of interest, the flux is computed by first computing the best scale factor in each energy band for all detectors in the fit, and then applying this scale factor to the reference flux, computed from the assumed model in each energy band. GBM's CTIME (0.256-s, 8 energy bands from 8-1000 keV) and CSPEC (4.096-s, 128 energy bands from 8-1000 keV) data for the NaI detectors were used in the analysis described here. The Earth occultation technique is also applicable to the the GBM BGO detectors.

As of 2011 May, GBM is monitoring a catalog of 107 sources using Earth occultation. Most of these sources were recently active X-ray binaries, plus the Crab, ten active galactic nuclei, two soft-gamma repeaters, and the Sun. In the first two years of Earth occultation monitoring with GBM, six persistent and two transient sources were detected above 100 keV[4]. More than 80 sources have been detected below 100 keV. Preliminary monitoring results can be found on our website¹.

The most remarkable result from GBM Earth occultation monitoring was the discovery that the hard X-ray flux from the Crab nebula is not constant, and in fact, it declined by about 7%

¹<http://gammaray.nasa.gov/gbm/science/occultation>

from 2008-2010 in the 15-50 keV band [5]. Figure 1 shows composite light curves combining overlapping measurements of the Crab pulsar + nebula flux from the Rossi X-ray Timing Explorer (RXTE), INTEGRAL's hard X-ray instruments ISGRI, SPI, and JEM-X, Swift, and Fermi/GBM. With this suite of instruments, we cover a broad range in hard-X/soft gamma-rays (~ 10 keV to > 100 keV) and simultaneously address systematic uncertainties using very different types of instrumentation to demonstrate overall consistency of our Crab results. Six instruments on four satellites agree well from 2008 to 2010, with all instruments registering a $\sim 7\%$ decline in the 15-50 keV Crab nebula + pulsar flux over two years, starting at MJD 54690, and with a similar decline in the 50-100 keV band. Details of the analysis for each instrument are given in [5]. INTEGRAL/SPI data [6] are compared with the other 5 instruments for the first time in this paper. Prior to the launch of Fermi in 2008, increases and decreases in flux at a level of about 3.5% per year were seen in the 15-50 and 50-100 keV bands, back to 1999. In more recent data, since August 2010, all of the instruments show that the Crab has stopped fading and may be beginning to brighten again.

From 1999 to 2010, the pulsed flux measured with RXTE showed only a steady decrease at $\sim 0.2\% \text{ yr}^{-1}$, consistent with pulsar spin-down. The larger $\sim 3.5\% \text{ yr}^{-1}$ variations are not seen in the pulsed emission, indicating that the variations are nebular in origin [5].

In summary, the Crab is variable in hard X-rays and should not be assumed as a constant source suitable for normalizing instrument response functions or calibrating hard X-ray instruments. The variations are seen in the nebular emission, apparently resulting from changes in the shock acceleration or in the nebular magnetic field. Longer baselines and multi-wavelength observations are needed to understand the origin of these variations.

2.2 Monitoring accreting pulsars with GBM

As of May 2011, the GBM accreting pulsar team is currently monitoring 29 accreting pulsars and is performing daily blind searches for new accreting pulsars [10]. For both techniques, GBM data with 0.256-s time resolution for the 8-12, 12-25, and 25-50 keV bands are used. First the background data are fitted with a spline model that accounts for Earth occultation steps from bright sources. Data including solar flares, gamma ray bursts, solar panel occultations and any other problems are excluded from fitting. The remaining data result in typical exposure times of 40 ks per day, although for some sources the exposure time can reach 70 ks per day. For the blind search, power spectra are generated for each of 24 galactic longitude bins plus separate bins for the Small and Large Magellanic Clouds. The algorithm reports peak powers with frequencies and the galactic longitude to find new accreting pulsars and new outbursts of known pulsars that are not currently being monitored. Source specific searches are being performed for 29 sources², searching over a relatively narrow range of frequencies (and frequency derivative for some sources). Orbital parameters are accounted for if known. GBM has the advantage of long observing times and continuous monitoring for these sources.

A recent highlight from GBM pulsar monitoring is the detection of an unusually bright flare near apastron in the ~ 41.5 day orbit of GX 301-2 [11], shown in Figure 2. GX 301-2 comprises an early B-type companion and a 680-s pulsar. Typically, GX 301-2 has a bright flare near periastron and a weak flare near apastron. The bright apastron flare detected with GBM coincides with the

²<http://gammaray.nasa.gov/gbm/science/pulsar>

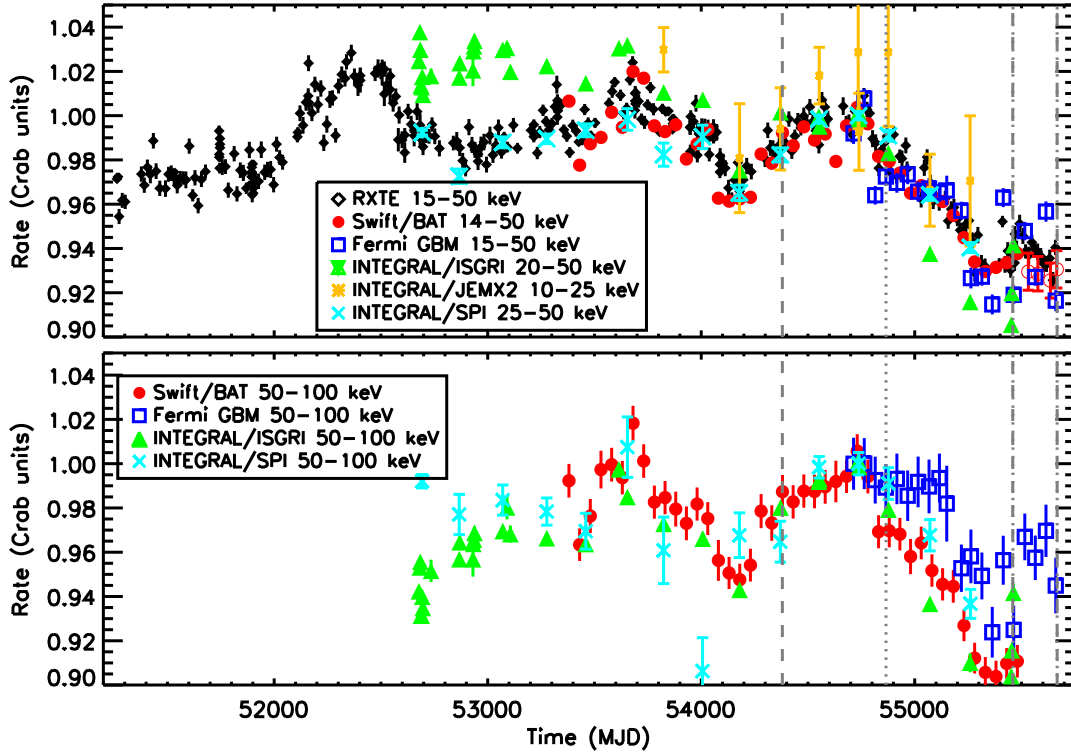


Figure 1: Composite Crab light curves for *RXTE*/PCA (15-50 keV - black diamonds), *Swift*/BAT (Top: 14-50 keV, Bottom: 50-100 keV - red filled circles), *Fermi*/GBM (Top: 15-50 keV, Bottom: 50-100 keV - open blue squares), *INTEGRAL*/SPI (Top: 25-50 keV, Bottom: 50-100 keV - light blue crosses), *INTEGRAL*/ISGRI (Top: 20-50 keV, Bottom: 50-100 keV - green triangles), and *INTEGRAL*/JEM-X2 (10-25 keV, orange asterisks). 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. Vertical lines mark GeV flares from the Crab observed with AGILE ([7], dashed lines) and Fermi LAT ([8, 9], dotted lines).

onset of rapid spin-up beginning 2010 June 25. The spin period changed by 3 seconds during the sharp rise of the flare. This episode of spin-up resembles two episodes observed with BATSE [12] and one observed with GBM in 2009 January.

3. Discussion

In this paper, we have described highlights of serendipitous science from the *Fermi* GBM, specifically from the Earth occultation monitoring and accretion powered pulsar monitoring projects. This science is beyond the primary gamma ray burst science of GBM and is supported by the *Fermi* Guest Investigator program. It is made possible by GBM's large field-of-view (the entire unocculted sky), GBM's broad energy range (8-1000 keV for the NaI detectors), and GBM's time resolution (0.256-s for accreting pulsar monitoring.) GBM's near continuous data with good time resolution enables monitoring of accretion-powered pulsar spin-frequencies, source state changes [13], quasi-periodic oscillations [10], and detections of X-ray bursts [15]. All-sky monitors are valuable not only as triggers for the main instrument, but also for stand alone science.

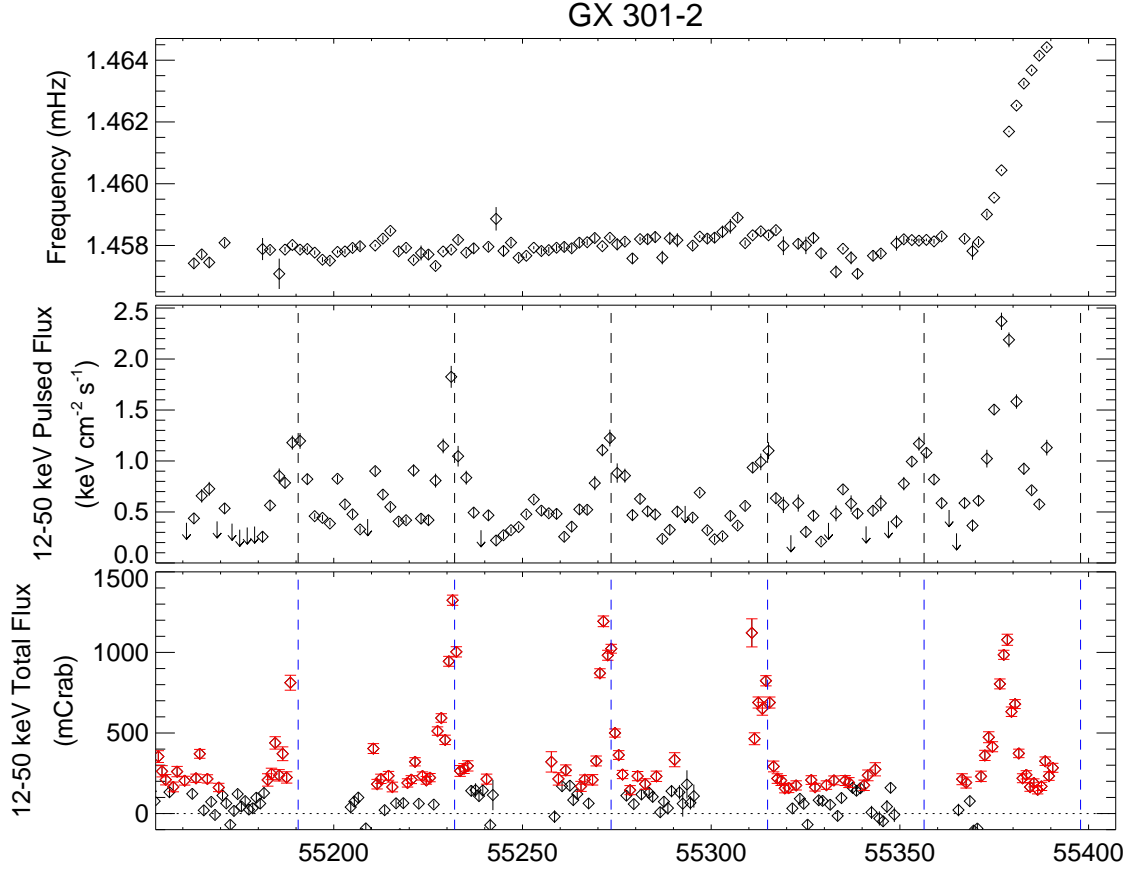


Figure 2: Top: GX 301-2 spin frequency. Center: GX 301-2 pulsed flux in the 12-50 keV band. Bottom: GX 301-2 total flux in the 12-50 keV band measured with GBM Earth occultation. Downward arrows in the center panel are upper limits. Red points in the bottom panel indicate 3- σ or better statistical significance. Gaps in the bottom panel are because GX 301-2 is a high declination source and is not always Earth occulted, meaning that GX 301-2 is continuously visible to GBM for a portion of Fermi’s precession cycle, increasing the exposure time for pulsar monitoring observations..

References

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- [2] Meegan, C.A. et al. 2009, *ApJ*, 702, 791
- [3] Wilson-Hodge, C.A. et al. 2009, Proc. Fermi Symposium, eConf C091122, [astro-ph/0912.3831]
- [4] Case, G.L. et al. 2011, *ApJ*, 729, 105
- [5] Wilson-Hodge, C.A. et al. 2011, *ApJ*, 727, L40
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All-Sky Monitoring of Variable Sources with Fermi GBM



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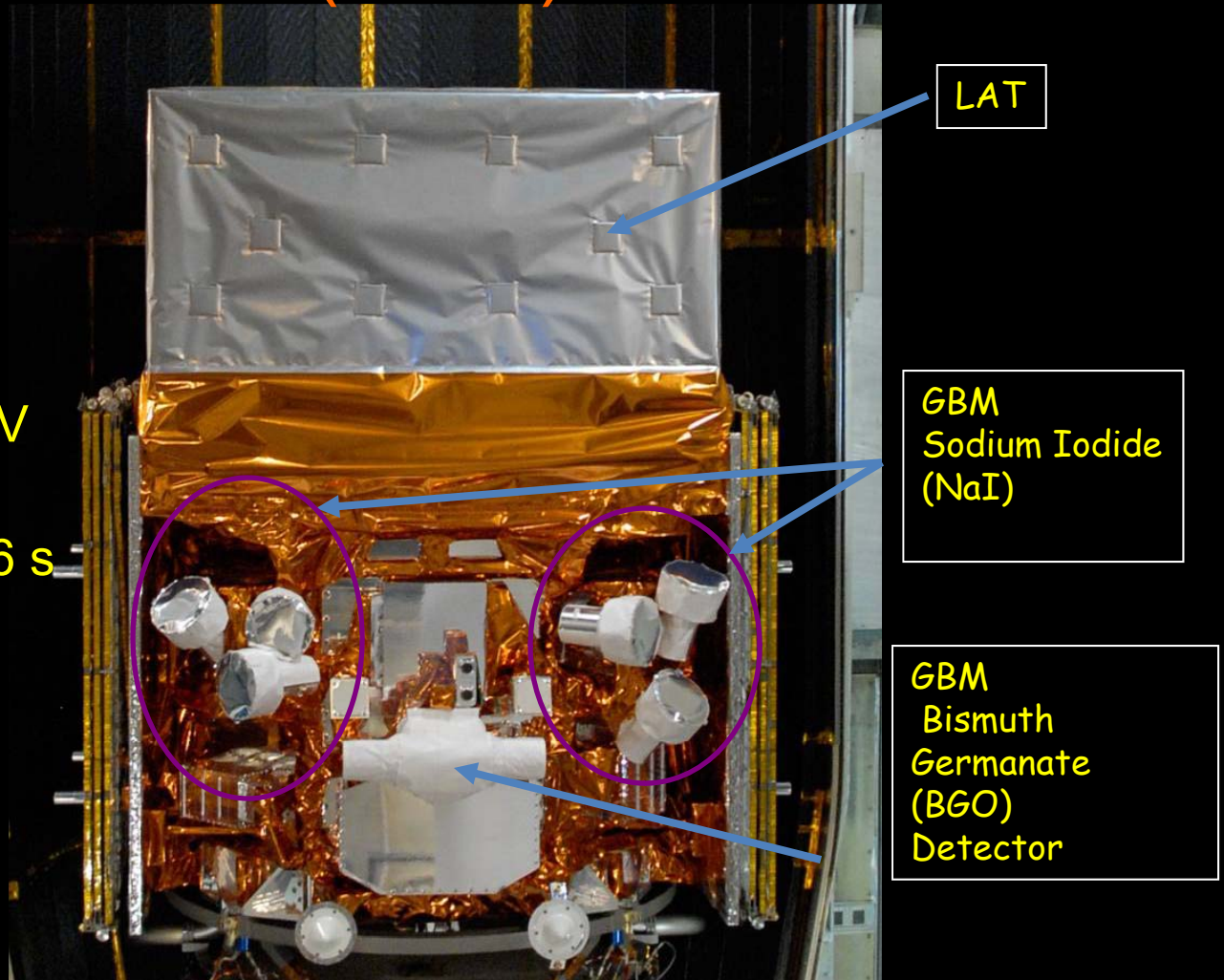
Outline

- GBM and Earth Occultation
- Surprising results for the Crab
- GBM accreting pulsar monitoring
- Summary & Conclusions

Fermi Gamma Ray Burst Monitor (GBM)

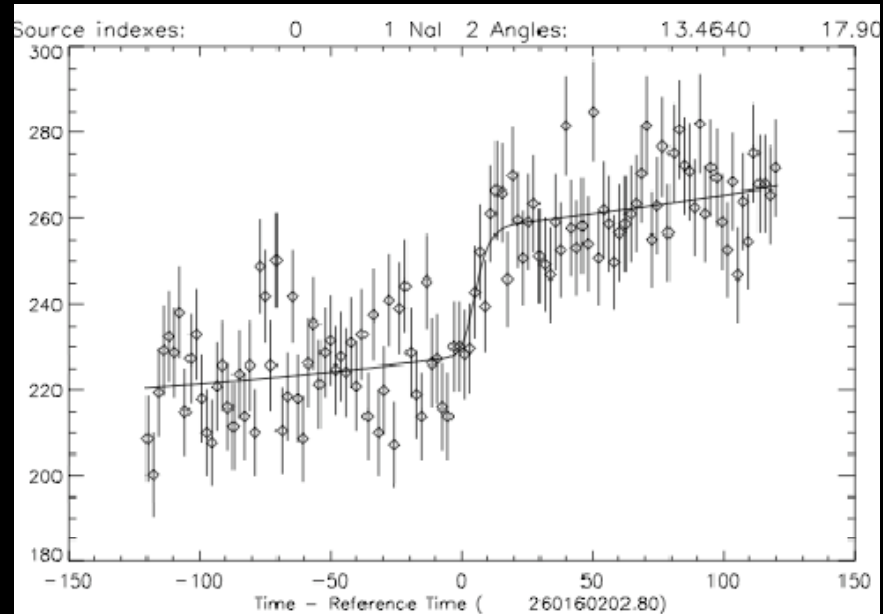
• GBM

- 12 NaI detectors
 - 8 keV - 1 MeV
- 2 BGO detectors
 - 150 keV - 40 MeV
- CTIME data
 - 8 channel, 0.256 s
- CSPEC data
 - 128 channel, 4.096s



GBM Earth Occultation Technique

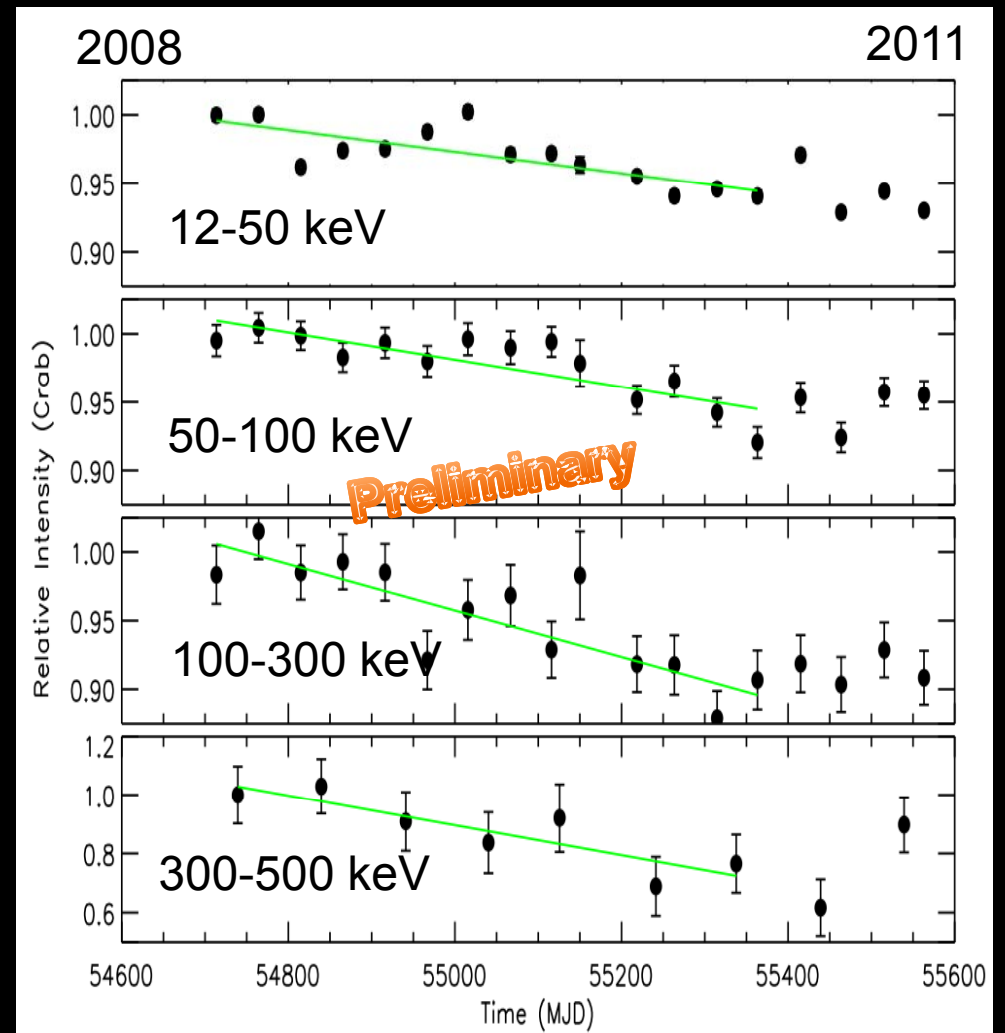
- Current catalog includes 96 sources, primarily recently active X-ray binaries, the Crab, 5 AGN, 2 SGRs, and the Sun
- Fluxes for cataloged sources measured by fitting the change in count rate due to Earth occultation
- Source model: assumed spectrum convolved with changing detector response and atmospheric transmission
- 8 energy bands in NaI or BGO detectors
- 6 persistent and 2 transient sources detected above 100 keV; 50+ sources detected <100 keV. (Case et al. 2011, ApJ accepted)



- Over 85% of sky viewed every orbit
- Entire sky viewed every ~26 days
- Sensitivity exceeds CGRO/BATSE below 25 keV and above ~1 MeV
- No solar constraints

GBM Observations of the Crab Nebula

- 50-day averages
- Decline in Crab flux (MJD 54690-55390):
 - $5.4 \pm 0.4\%$ 12-50 keV
 - $6.6 \pm 1.0\%$ 50-100 keV
 - $12 \pm 2\%$ 100-300 keV
 - $39 \pm 12\%$ 300-500 keV
- Decline may steepen as energy increases
- No changes in GBM response or calibration
- Flattening since summer 2010

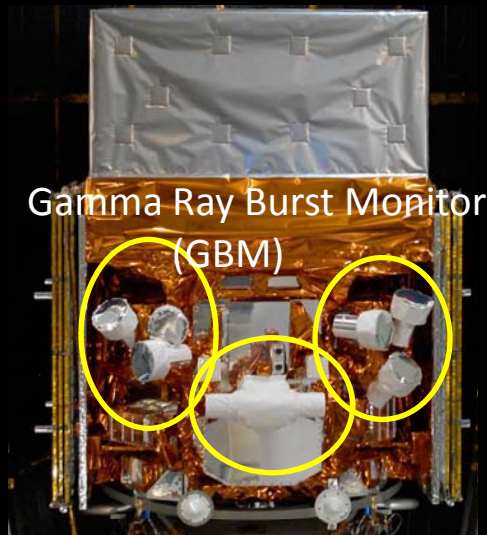


Wilson-Hodge et al. 2011, ApJ, 727, L40

The Satellites

- Good overlap with GBM in time and energy
- GBM
 - 2008 - present
 - 8 keV - 40 MeV
- INTEGRAL
 - 2002 - present
 - JEM-X 3-35 keV
 - IBIS/ISGRI 15keV-10MeV
- RXTE
 - 1995-present
 - PCA 2-60 keV
- Swift
 - 2004-present
 - BAT 15-200 keV

Fermi



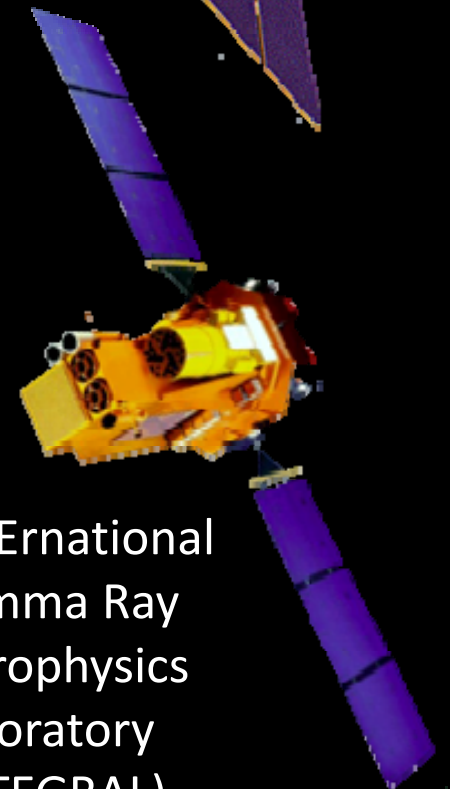
Rossi X-ray Timing Explorer (RXTE)



Swift



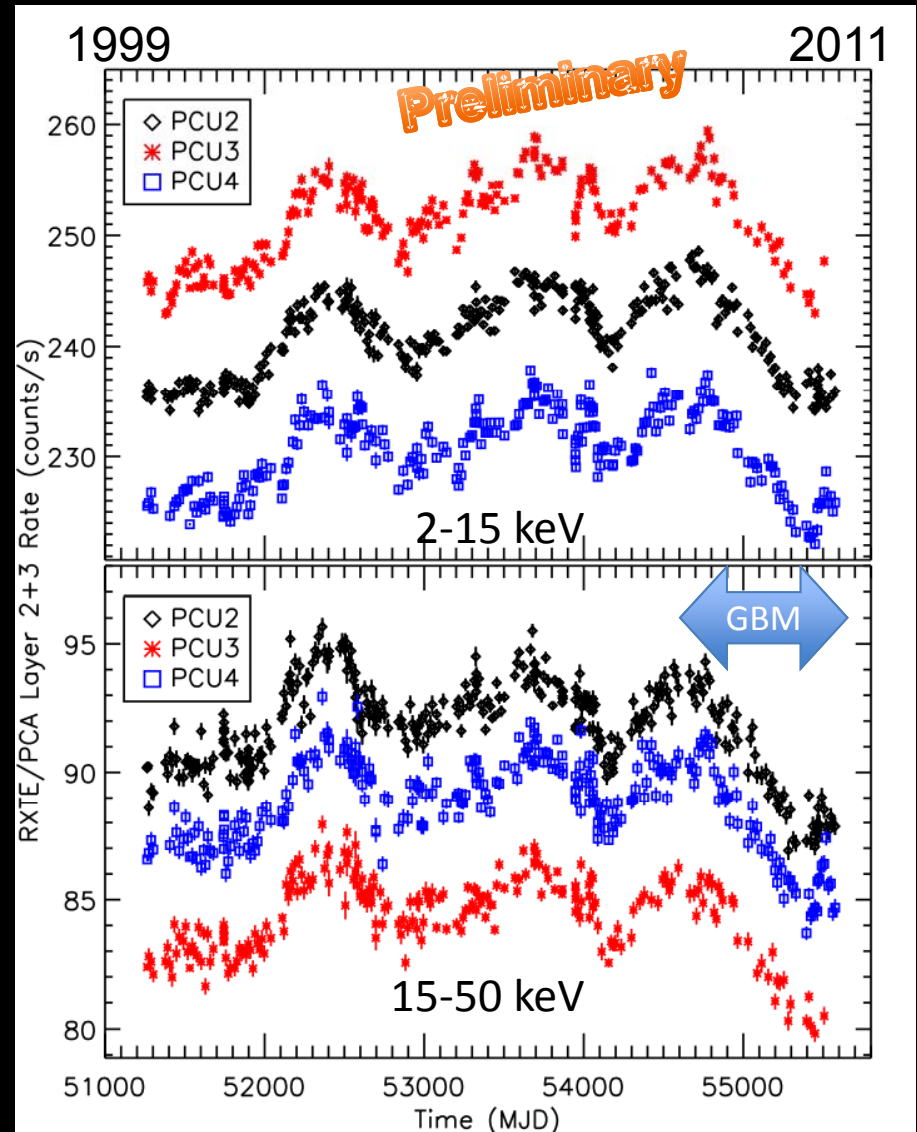
INTErnational
Gamma Ray
Astrophysics
Laboratory
(INTEGRAL)



RXTE PCA Crab Light Curve

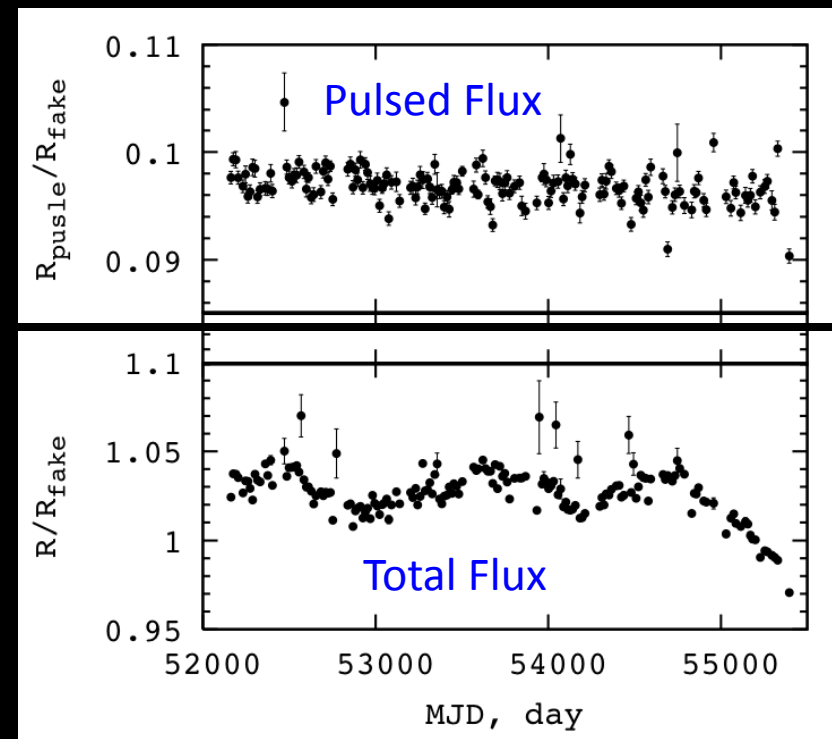
- Extracted light curves using standard 2 data
- Observations shorter than 300 s were excluded
- Background subtracted and deadtime corrected
- Corrected for known time dependence of response
- Selected layers 2+3
- Variations of $5.1 \pm 0.2\%$ (2-15 keV) and $6.8 \pm 0.3\%$ (15-50 keV) visible from MJD 54690-55435 in all 3 PCUs
- Flattening/increase since summer 2010

Wilson-Hodge et al. 2011, ApJ, 727, L40



RXTE Crab Pulsed Flux

- Event mode data (250 μ s, 129 channel)
- 3.2-35 keV, all PCU2 layers
- Pulsed flux shows steady decrease at 0.2% per year – consistent with pulsar spin down.
- The larger $\sim 3.5\%$ per year variation is not seen in pulsed emission
- Likely has nebular origin

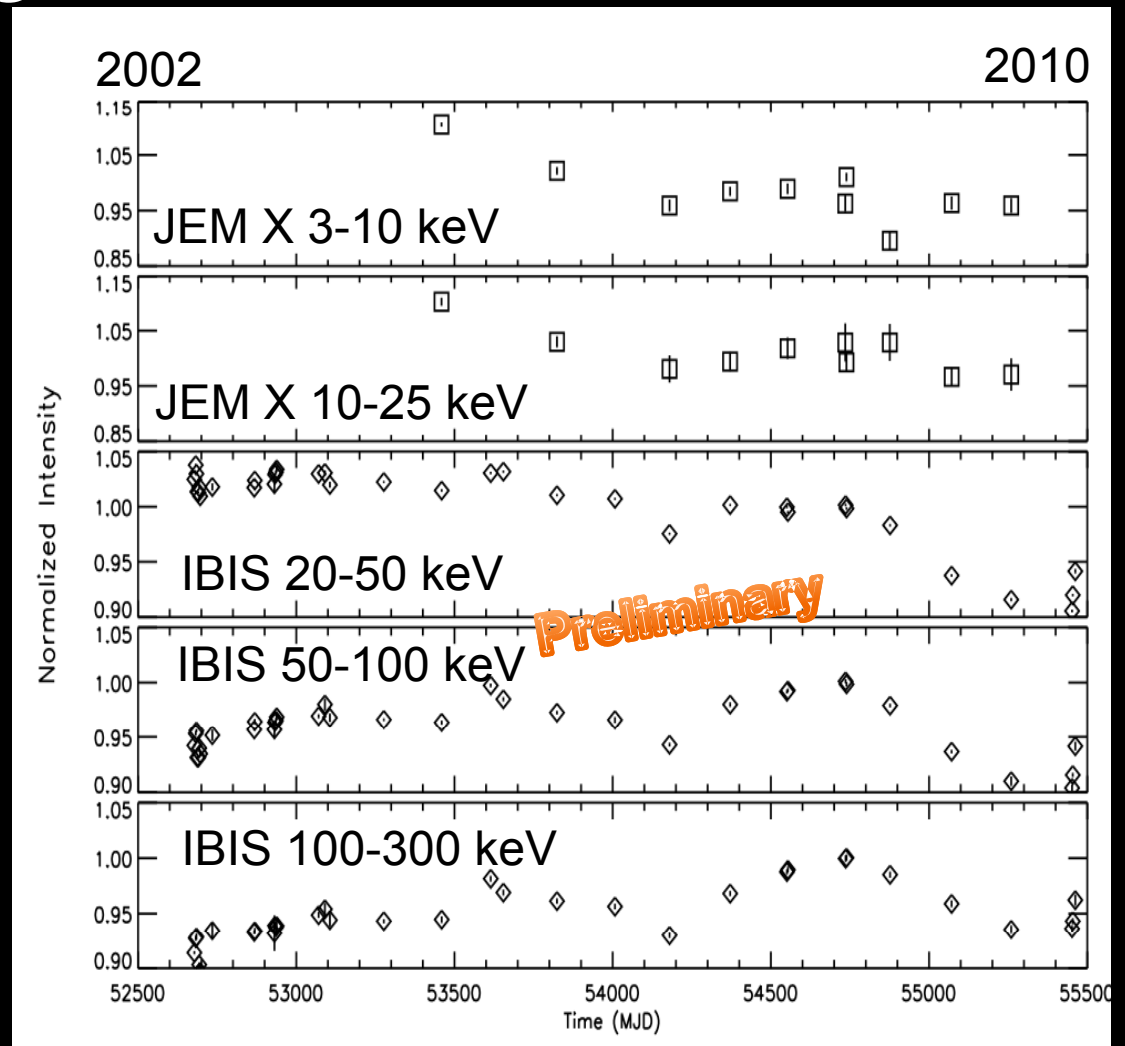


Wilson-Hodge et al. 2011, ApJ, 727, L40

INTEGRAL IBIS and JEM-X Crab Light Curves

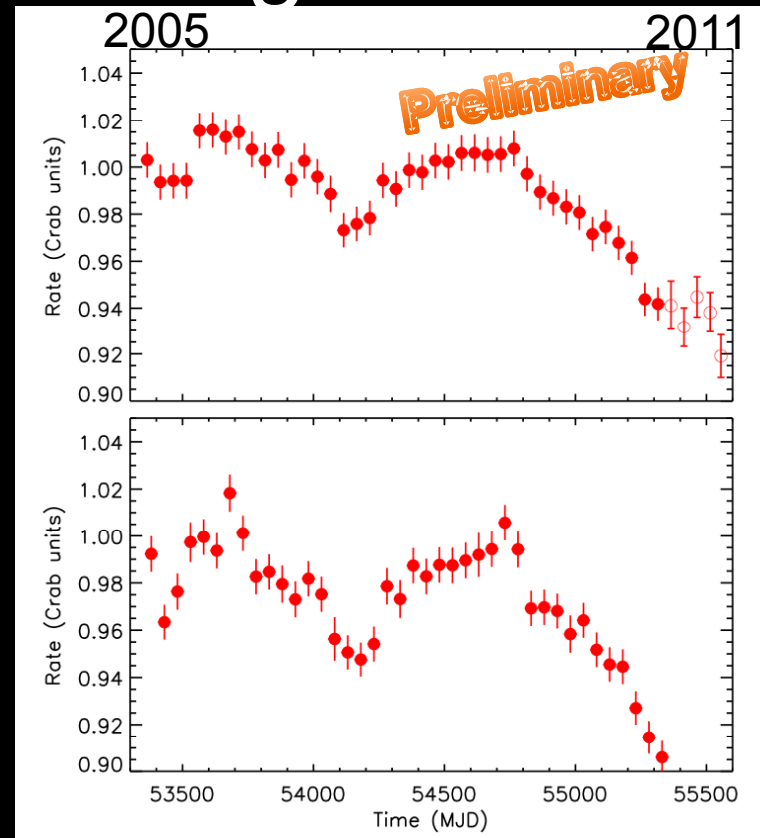
- Publicly available Crab observations
- Produced using OSA 9.0
- Offset $< 10^\circ$ (ISGRI); $< 3^\circ$ (JEM-X)
- Corrections based upon constant Crab are omitted.
- During 2008-2010, a $\sim 8\%$ decline is seen in the 18-40 and 40-100 keV bands (MJD 54690-55340)

Wilson-Hodge et al. 2011,
ApJ, 727, L40



Swift BAT Survey: 14-100 keV Crab Light Curves

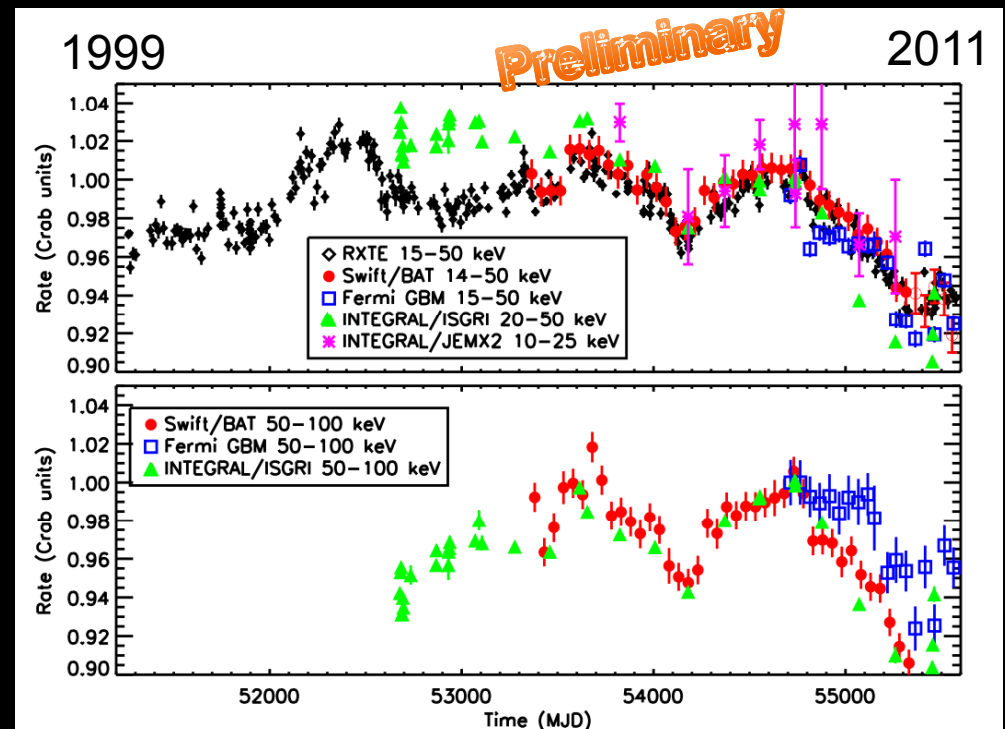
- BAT team 65-month Survey to May 2010
- Transient monitor May-Dec 2010
- Points shown are ~50 day averages
- Constructed from single pointing light curves
- Restricted partial coding fractions to $>85\%$
- Included systematic error of 0.75% of the rate



14-50 keV Flux decline of $6.2 \pm 0.5\%$ observed during MJD 54690-55340

Comparing Instruments

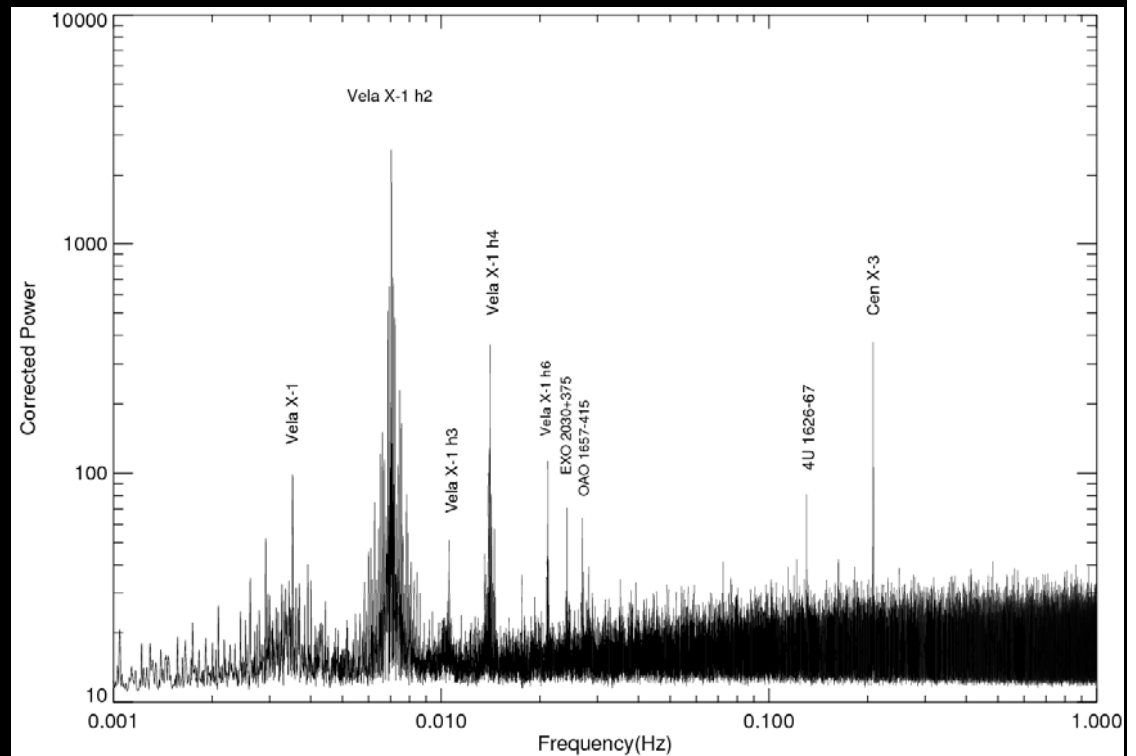
- Light curves for each instrument are normalized to its average rate from MJD 54690-54790.
- RXTE/PCU2 - Black Diamonds)
- BAT - Red Circles
- IBIS/ISGRI - Green triangles
- JEM X2 - Pink asterisks
- GBM - Blue squares
- Instruments on four separate spacecraft show ~7% decline in Crab flux from summer 2008 to summer 2010.



Recent data since summer 2010 suggest the decline has flattened or has possibly begun to recover.

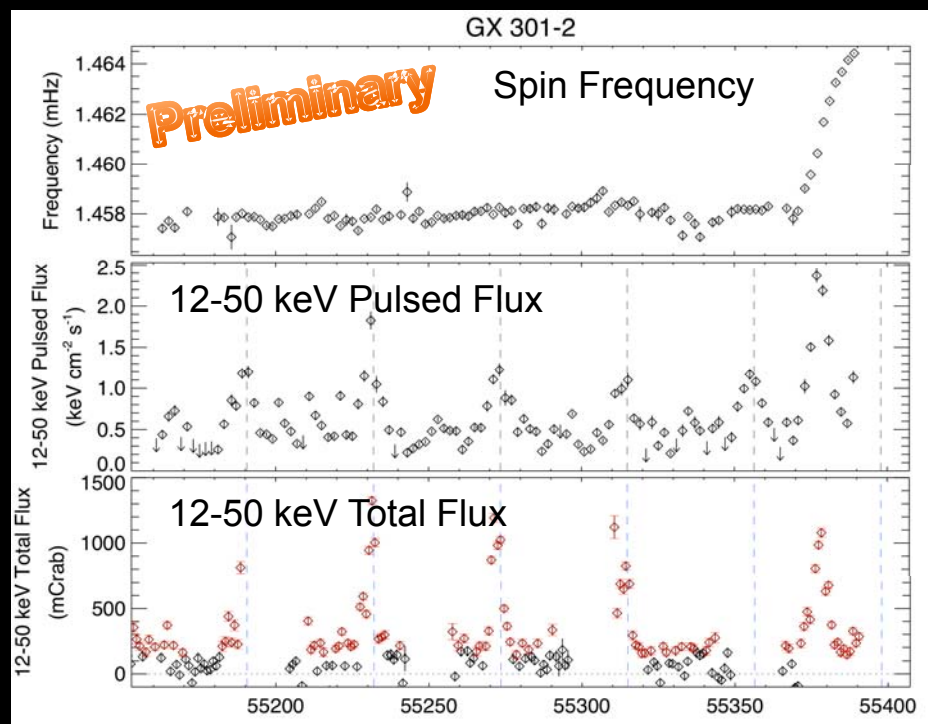
GBM Accretion-Powered Pulsar Monitoring

- Daily blind search for pulsed sources
- Source specific analyses for monitoring known pulsars
- Both are sensitive to periods from 0.5s to ~700s
- Current monitoring includes 25 systems
- Typical exposure times are ~40 ks/day. It can be as high as 70 ks



Power spectrum from the GBM blind pulse search for 2010 Jan 8. Power plotted is the maximum over the 24 galactic longitude bins for each frequency.

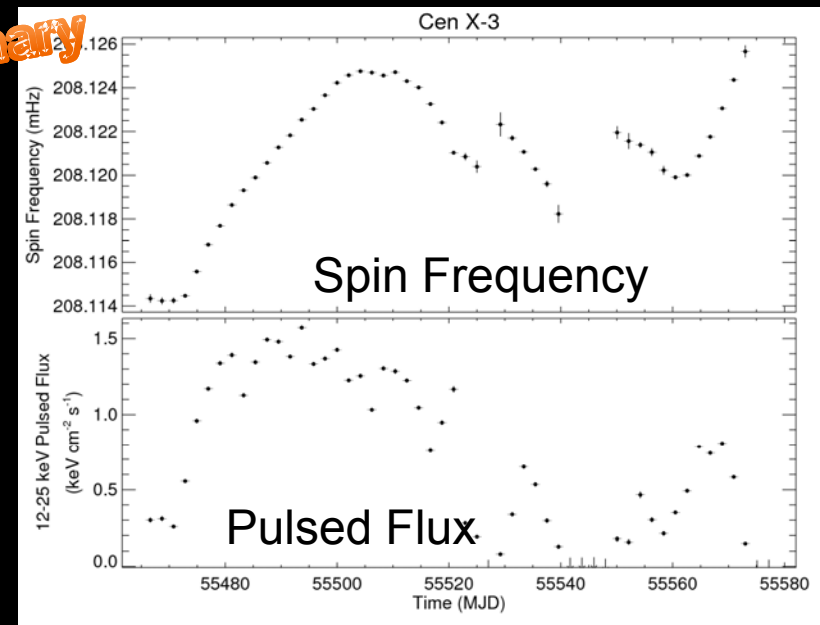
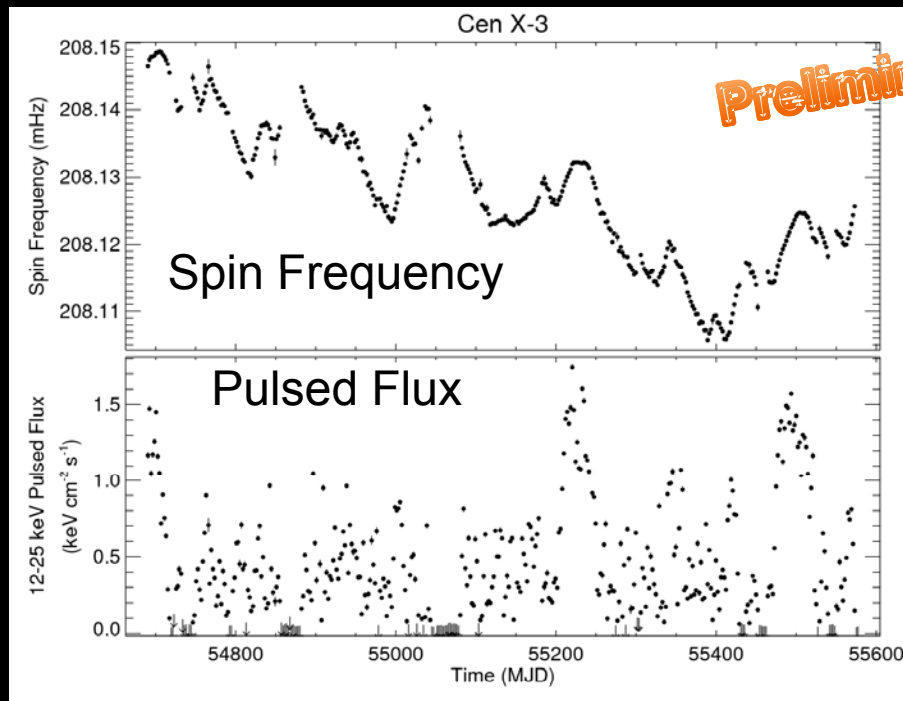
GX 301-2 Rapid Spin-up State



Top: GX 301-2 spin frequency
Center: GX 301-2 12-50 keV pulsed flux
Bottom: GX 301-2 12-50 keV total flux
Dashed vertical lines: periastron passage

- GX301-2 comprises an early B-type companion and a 680 s pulsar
- GX301-2 typically has a bright flare near periastron and a weak flare near apastron.
- GBM detected an unusually bright flare near apastron in ~ 41.5 day orbit (Atel # \square 2712)
- This flare coincides with the onset of rapid spin-up beginning 2010 June 25
- The spin period has changed by 3 seconds during the sharp rise.
- This episode of spin-up resembles two episodes observed with BATSE (Koh et al. 1997) and one with GBM in 2009 January.

Cen X-3 Transitions



- 4.8 s accreting pulsar in an eclipsing 2.1 day orbit with a supergiant
- Sharp and smooth spin state transitions
- Previous observations showed only sharp transitions

Summary & Conclusions

- Four instruments (Fermi/GBM, RXTE/PCA, Swift/BAT, INTEGRAL/ISGRI) show a $\sim 7\%$ (70 mCrab) decline in the Crab from 2008-2010. Recent data suggest a flattening or recovery.
- This decline is not present in the pulsed flux, implying changes in the shock acceleration, electron population or magnetic field structure in the nebula.
- The Crab flickering must be considered when calibrating future X-ray timing instruments.
- Accreting pulsars remain an interesting target for secondary science with X-ray timing instruments.

For more GBM results

- GBM Earth occultation monitoring

<http://gammaray.nsstc.nasa.gov/gbm/science/occultation/>

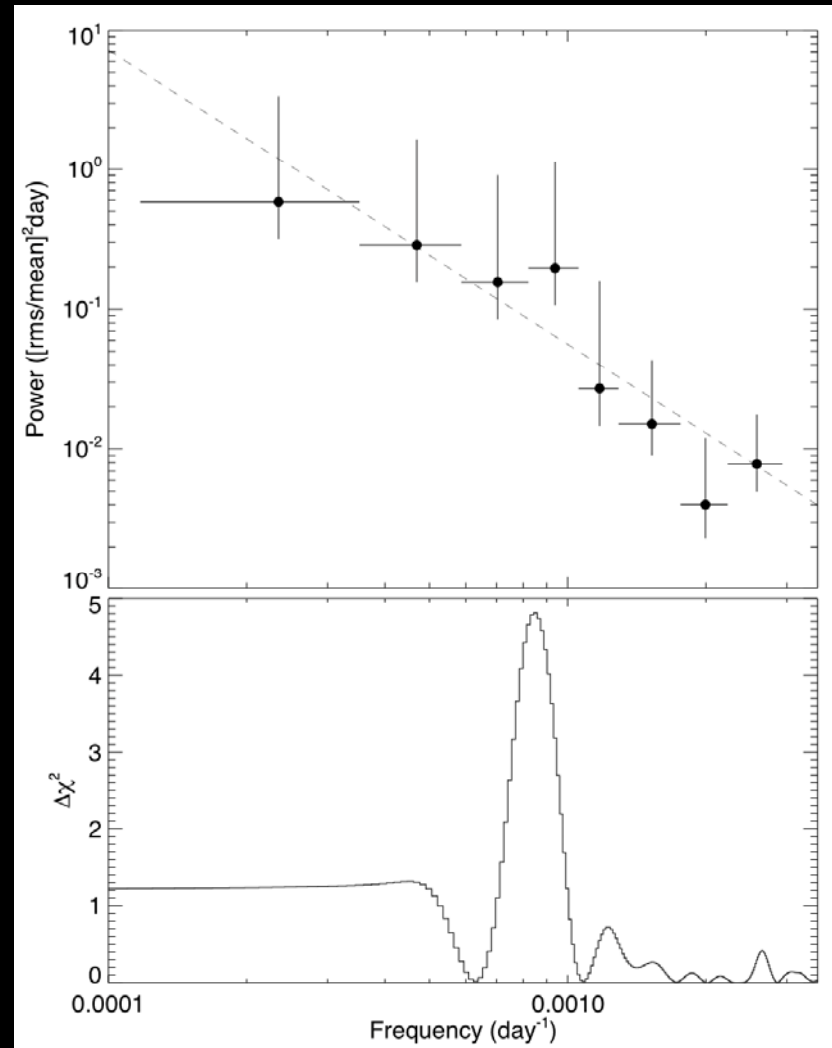
- GBM accreting pulsar monitoring

<http://gammaray.nsstc.nasa.gov/gbm/science/pulsars/>

Backup

RXTE PCA – Search for Periodicity

- PCA light curve has 3 peaks. Is there a periodicity?
- Power spectrum from evenly binned 15-50 keV PCU 2 data (3 bins per year). Power law index 2.1 ± 0.4
- Frequency search – fitted quadratic + sinusoid.
- Highest peak 1176 ± 96 days, only 2σ



High Energy Activity from the Crab

AGILE detection of enhanced gamma-ray emission from the Crab Nebula region

ATel #2855; M. Tavani (INAF/IASF Roma), E. Striani (Univ. Tor Vergata), A. Bulgarelli (INAF/IASF Bologna), F. Gianoni, M. Trifoglio (INAF/IASF Bologna), C. Pinori, F. Verrecchia (ASDC), A. Argan, A. Trois, G. De Paris, V. Vittorini, F. D'Ammando, S. Sabatini, G. Piano, E. Costa, I. Donnarumma, M. Feroci, L. Pacciani, E. Del Monte, F. Lazzarotto, P. Soffitta, Y. Evangelista, I. Lapshov (INAF-IAST-Rm), A. Chen, A. Giuliani (INAF-IAST-Milano), M. Marisaldi, G. Di Cocco, C. Labanti, F. Fuschino, M. Galli (INAF/IASF Bologna), P. Caraveo, S. Mereghetti, F. Perotti (INAF/IASF Milano), G. Pucella, M. Rapisarda (ENEA-Roma), S. Vercellone (IASF-Pa), A. Pellizzoni, M. Pilia (INAF/OA-Cagliari), G. Barbiellini, F. Longo (INFN Trieste), P. Picozza, A. Morselli (INFN and Univ. Tor Vergata), M. Prest (Universita' dell'Insubria), P. Lipari, D. Zanello (INFN Roma-1), P.W. Cattaneo, A. Rappoldi (INFN Pavia), P. Giommi, P. Santolamazza, F. Lucarelli, S. Colafrancesco (ASDC), L. Salotti (ASI)

on 22 Sep 2010; 14:45 UT

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Subjects: Pulsars

Referred to by ATel #: [2856](#), [2858](#), [2861](#), [2866](#), [2867](#), [2868](#), [2872](#)

AGILE is detecting an increased gamma-ray flux from a source positionally consistent with the Crab Nebula.

Integrating during the period 2010-09-19 00:10 UT to 2010-09-21 00:10 UT the AGILE-GRID detected enhanced gamma-ray emission above 100 MeV from a source at Galactic coordinates (l,b) = (184.6, -6.0) +/- 0.4 (stat.) +/- 0.1 (syst.) deg, and flux $F > 500 \text{ e-8 ph/cm}^2/\text{sec}$ above 100 MeV, corresponding to an excess with significance above 4.4 sigma with respect to the average flux from the Crab nebula ($F = (220 \pm 15) \text{ e-8 ph/cm}^2/\text{sec}$, Pittori et al., 2009, A&A, 506, 1563).

We strongly encourage multifrequency observations of the Crab Nebula region.

No corresponding flare in X-rays with INTEGRAL (Atel # 2856), Swift (Atel # 2858, 2866), or RXTE (Atel # 2872) or NIR (Atel #2867). No evidence for active AGN near Crab (Swift, Atel # 2868).

Fermi LAT confirmation of enhanced gamma-ray emission from the Crab Nebula region

ATel #2861; R. Buehler (SLAC/KIPAC), F. D'Ammando (INAF-IAST Palermo), E. Hays (NASA/GSFC) on behalf of the Fermi Large Area Telescope Collaboration

on 23 Sep 2010; 17:34 UT

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Subjects: >GeV, Pulsars

Referred to by ATel #: [2866](#), [2867](#), [2868](#), [2872](#)

Following the detection by AGILE of increasing gamma-ray activity from a source positionally consistent with the Crab Nebula occurred from September 19 to 21 (Atel #[2855](#)), we report on the analysis of the >100 MeV emission from this region with the Large Area Telescope (LAT), one of the two instruments on the Fermi Gamma-ray Space Telescope.

Preliminary LAT analysis indicates that the gamma-ray emission ($E > 100 \text{ MeV}$) observed during this time period at the location of the Crab Nebula is $(606 \pm 43) \times 10^{-8} \text{ ph/cm}^2/\text{sec}$, corresponding to an excess with significance >9 sigma with respect to the average flux from the Crab nebula of $(286 \pm 2) \times 10^{-8} \text{ ph/cm}^2/\text{sec}$, estimated over all the Fermi operation period (only statistical errors are given). Ongoing Fermi observations indicate that the flare is continuing.

The flaring component has a spectral index of 2.49 ± 0.14 . Its position, Ra: 83.59 Dec: 22.05 with a 68% error radius of 0.06 deg, is coincident with the Crab Nebula.

Fermi will interrupt its all-sky scanning mode between 2010-09-23 15:49:00 UT and 2010-09-30 15:49:00 UT to observe the Crab Nebula. Afterwards regular gamma-ray monitoring of this source will continue. We strongly encourage further multifrequency observations of that region.

For this source the Fermi LAT contact person is Rolf Buehler (buehler@stanford.edu).

The Fermi LAT is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV. It is the product of an international collaboration between NASA and DOE in the U.S. and many scientific institutions across France, Italy, Japan and Sweden.

Change in Crab pulsar by factor of 2 @ 200 MeV, 10 at 1 GeV from 1971 to 1973 (Griesen et al 1975, ApJ, 197, 471).