Looking for Stars and Finding the Moon: Effects of Lunar Emission on LAT Light Curves

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Searches for gamma-ray binaries using power spectra of LAT light curves show the effects of lunar contamination on sources near the ecliptic. This can be removed by excluding times when the Moon is close to a source.

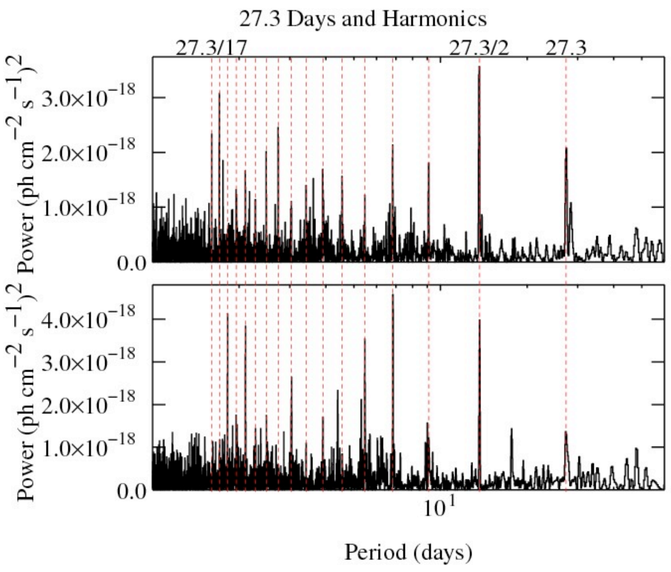
We are conducting a search for new gamma-ray binaries by making high signal-to-noise light curves of all cataloged Fermi sources and searching for periodic variability using appropriately weighted power spectra. The light curves are creating using a variant of aperture photometry where photons are weighted by the probability that they came from the source of interest. From this analysis we find that the light curves of a number of sources near the ecliptic plane are contaminated by emission from the Moon. This shows itself as modulation on the Moon's sidereal period in the power spectra. We demonstrate that this contamination can be removed by selecting times when the Moon was too close to a source.

Introduction: Hunting for Gamma-ray Binaries

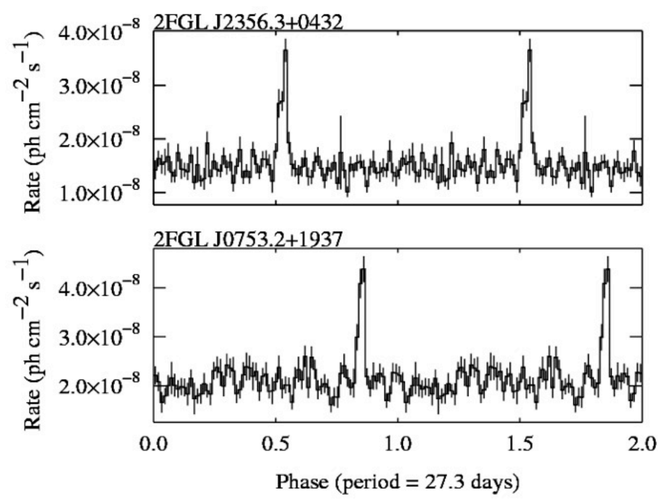
Gamma-ray binaries are expected to show orbitally-modulated gamma-ray emission due to changes in viewing angle and, in eccentric orbits, the degree of the binary interaction. Periodic modulation has indeed been seen in LS 5039 (3.9 day period), LS I +61 303 (26.5 days), Cygnus X-3 (4.8 hours)[6], and 1FGL J1018.6-5856 (16.65 days)[4,5] and emission is orbital phase dependent for PSR B1259-63 (3.4 years)[1]. A search for periodic modulation of gamma-ray flux from LAT sources may thus yield further gamma-ray binaries, potentially revealing the predicted HMXB precursor population. The second Fermi LAT catalog of gamma-ray sources ("2FGL") contains 1873 sources, many of which do not have confirmed counterparts at other wavelengths and thus are potentially gamma-ray binaries.

In order to search for modulation we regularly update 0.1 - 200 GeV light curves for all 2FGL sources and calculate power spectra of these. We use aperture photometry, with photons weighted by the probability that they came from the source of interest to increase the signal-to-noise level. We then calculate power spectra of all light curves to search for periodic modulation. To account for variations in exposure, each time bin's contribution to the power spectrum is weighted by the relative exposure.

Two Unusual Power Spectra



Both 2FGL J2356.3+0432 (top) and 2FGL J0753.2+1937 (bottom) show a complex pattern of peaks in their power spectra. These peaks are harmonics of a 27.3 day period - up to the 17th harmonic is detectable.



Modulation for both sources is caused by sharp "flares" that recur with a 27.3 day period, but with different epochs of maximum flux.

Lunar Gamma-Rays

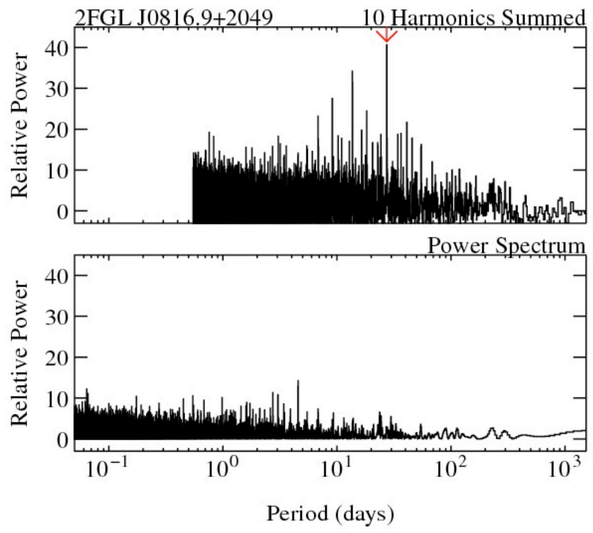
Interactions of cosmic rays with the Moon's surface result in the production of gamma rays. This makes the Moon a rather bright source for the Fermi LAT with a flux above 100 MeV of ~10^{-6} ph cm^{-2} s^{-1} (Abdo et al. 2012), and it was even detectable with EGRET (Thompson et al. 1997). We note that the Sun is also a gamma-ray source. Although the 2FGL catalog notes sources potentially affected by solar emission, no such analysis was done for the Moon (Nolan et al. 2012).

The Moon's sidereal period is 27.321 days. The sharp recurring flares from "J2356.3" and "J0753.2" can be understood as due to repeated passages of the Moon sufficiently close to these sources to affect the light curves.

Optimizing Lunar Detection: Summed Harmonics

Power spectra are not ideal for detecting brief flaring activity as this strongly non-sinusoidal modulation results in the power being spread over a very large number of harmonics. We investigated other period-detection techniques such as phase dispersion minimization (Stellingwerf, 1978) and others. It was found that lunar modulation was best detected by creating a modified power spectrum with each point replaced with a sum of itself and up to the 10th harmonic (cf. Buccheri et al. 1983). This is illustrated below.

From harmonic-summed power spectra of the entire 2FGL catalog we detected approximately 35 sources that suffered from significant lunar contamination.



Lunar contamination of J0816.9 is not directly detected in the power spectrum (bottom). However, the summed harmonic modification of this (top) clearly shows a 27.3 day period due to the Moon.

Summary

- Lunar gamma-ray emission can significantly contaminate the light curves of sources near the ecliptic plane.

- Lunar modulation at 27.3 days is directly detected in the power spectra of a few sources.

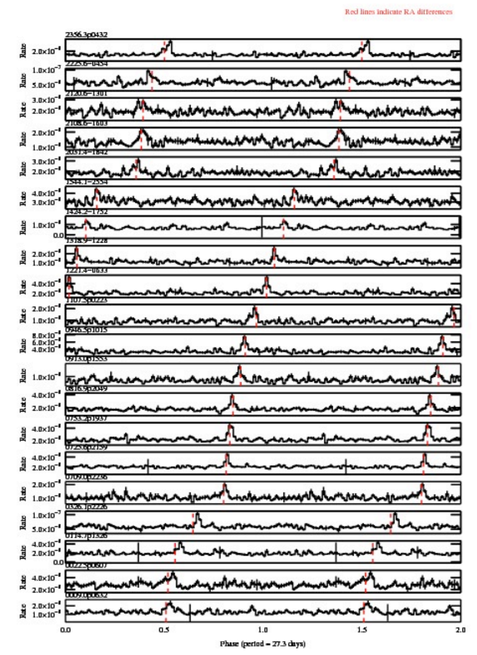
- Adding power-spectrum harmonics (~10) reveals the 27.3 day signal in over 30 2FGL sources.

- Software has been provided to facilitate exclusion of lunar contaminated data.

- We advocate:
(i) lunar filtering should be done for any source close to the ecliptic.
(ii) lunar coordinates should be included in the standard Fermi spacecraft files.

- The summed-harmonic technique is being used to search for gamma-ray binaries that briefly flare for a short fraction of their orbit.

Folded LAT Light Curves

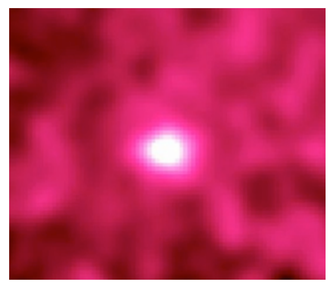


Light curves of several 2FGL sources folded on the Moon's sidereal period. The vertical red lines are offset based only on the RA of each source and so roughly approximate the Moon's path.

Removing the Moon

Fermi spacecraft files do not currently include lunar coordinates. One of us (PSR) has provided a utility ("`moonpos`") that uses the JPL SPICE toolkit to add lunar coordinates. This is available from the FSSC on the User Contributions web page:
http://fermi.gsfc.nasa.gov/ssc/data/analysis/user

The addition of lunar coordinates enables filtering to exclude data obtained when the Moon was close to a source via `gtmktime`. We find that excluding data within 8 degrees of a source removes almost all contamination.



The Moon as seen with EGRET. (Thompson et al. - taken from APOD 1999-04-17.)

Search for Flaring Binaries

The technique of summing harmonics to reveal the presence of lunar contamination is also useful in the search for gamma-ray binaries. For example, the binary PSR B1259-63 is only active for a brief portion of its 3.4 yr orbit. So far no significant (non-lunar) periodic flaring has been detected for any source.

References

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4. Corbet, R., et al., 2011, ATel 3221 ("1FGL J1018.6")
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6. Hill, A., et al., 2011, HEEP conference, 498 (binary review)
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8. Stellingwerf, R., et al., 1978, ApJ, 224, 953
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