Fermi Discovers a New Population of Gamma-ray Novae

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Novae had not been widely considered as high-energy (> 100 MeV) gamma-ray sources before the launch of the Fermi Large Area Telescope (LAT). In March 2010, the LAT made the first gamma-ray detection of a nova in the symbiotic binary V407 Cygni. The LAT observations uniquely probed the high-energy particle acceleration mechanism in the environs of the V407 Cyg binary system consisting of a white dwarf and its red giant companion. Subsequently in June 2012, two more novae were detected with the LAT, Nova Sco 2012 and Nova Mon 2012, thus heralding novae as a new gamma-ray source class. For Nova Mon 2012, the gamma-ray transient source was discovered first, followed by the optical confirmation of the nova, showcasing how novae can be found with the LAT independently from traditional optical searches. We discuss the LAT detected gamma-ray novae together with observational limits on other optical novae over the first four years of the Fermi mission and reconsider the possible high-energy gamma-ray production mechanisms in novae in light of the new detections.

1. Fermi Discovery of Nova V407 Cyg – the First Surprise

The Fermi Large Area Telescope (LAT) maps the entire sky every ~ 3 hrs with unprecedented sensitivity and localization capabilities in the high-energy (HE; > 100 MeV) gamma-ray energy range. The data are sensitive to and continuously searched for flaring/transient sources by a dedicated group of flare advocates [11] in the Fermi-LAT team via an Automated Science Processing (ASP) [3] pipeline. This surveying capability leads naturally to a search of bright variable gamma-ray sources in the Galactic plane, and has been pursued since early in the mission [e.g., 16]. As part of this flare advocate ASP program, in 2010, a new gamma-ray source was detected by the LAT in the Cygnus region of our Galaxy. Initially dubbed Fermi J2102+4542, the source was bright, being detected over two consecutive days (March 13th and 14th) with > 100 MeV fluxes \( \gtrsim 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1} \). Within the LAT localization error was the symbiotic star V407 Cyg, whose optical outburst detection on March 10 \cite{25} triggered Swift/XRT observations on March 13th and 15th. X-ray emission from V407 Cyg was detected in the Swift observations for the first time, and as importantly, no other X-ray source was found within the LAT error circle. These observations motivated the proposed association of the gamma-ray transient with V407 Cyg \cite{3}, but HE gamma rays from novae were not widely anticipated, so this initially met with some skepticism. However, subsequent analysis found the initial (fainter) LAT detection was indeed on March 10, the day of the optical nova discovery. This temporal coincidence together with the LAT localization, provided convincing evidence that the gamma-ray emission originated from the nova \cite{1}.

The basic picture in the case of V407 Cyg was that high-energy particles could be accelerated in the shock between the nova ejecta and the wind of the red giant (RG) companion as had been proposed in the symbiotic recurrent novae RS Oph by Tatischeff & Hernanz \cite{35}; see also \cite{18}. The gamma-ray production could be due to either \( \pi^0 \) decay produced in interactions of relativistic protons with the material of the RG, or relativistic electrons that interact with the photons and wind of the RG by inverse Compton and bremsstrahlung emission, respectively \cite{1}; see also \cite{21}. The scenarios outlined were however, particular to the symbiotic nature of this nova, thus provided a natural explanation for the non-detection of bright gamma rays from the more commonly observed class of classical novae (CN; Table 1) up to that time.

Table 1: White Dwarfs in Close Binary Systems

| System (Binary) | Classical Novae | Symbiotic Recurrent Novae |
|----------------|-----------------|--------------------------|
|                | compact CV-like | symbiotic-like            |
|                | (WD + Main Sequence) | (Massive WD + RG)       |
| \( a \)        | \( 10^{11} \text{ cm} \sim R_\odot \) | \( \sim 100's R_\odot \) |
| \( P_{\text{rec}} \) | \( \gtrsim 10^4 \text{ yrs} \) | \( < 100 \text{ yrs} \) |
| \( P_{\text{orb}} \) | \( \sim \text{hr} - \text{day} \) | \( \sim \text{years} \) |
| Rate           | \( \sim 35/\text{yr in Galaxy} \) | \( \sim 10 \text{ known} \) |

Summary adapted from \cite{17} and modified for this talk. Cataclysmic Variable (CV), binary separation (\( a \)), recurrence period (\( P_{\text{rec}} \)), orbital period (\( P_{\text{orb}} \)).

2. Interlude

Since the V407 Cyg 2010 gamma-ray detection, the subsequent two years saw little observational progress on gamma-ray emission from novae because no other LAT detections were announced. This was in accord with expectations at the time, as the symbiotic-like recurrent novae are relatively rare, and as outlined in \cite{1}, the gamma-ray production mechanism appeared tied to the presence of a dense RG wind. This
was enforced by the LAT search and resultant non-detections of other optically bright classical novae, binaries consisting of a white dwarf and main sequence star. Although they are much more common than the symbiotic-like recurrent novae (e.g., V407 Cyg; see Table 1), they may be fed by Roche lobe overflow rather than the massive winds from a RG companion. Fig. 1 shows two examples of such LAT non-detections of classical novae. In KT Eri 2009, the peak magnitude of 5.4 [20] was brighter than observed in V407 Cyg 2010, while in another example, V1312 Sco 2011, the peak visual magnitude of 9.5 [32] was typical of a rather faint nova detection. The LAT 5-day binned limits were \( < \sim 10 \times \) fainter than the 1-day observed gamma-ray peak in V407 Cyg 2010. The distance to KT Eri is 6.5 kpc [30], which is significantly larger than that commonly assumed for V407 Cyg (\( \sim 2.7 \) kpc; [22]), and offers another limiting factor in explaining its non-detection with the LAT.

3. Further Surprises in June 2012: Two New LAT Detected Novae

In June 2012, the LAT detected two new novae, four days apart, and at the opposite ends of the sky. They followed different discovery paths, as outlined below. These were different from the V407 Cyg 2010 case in that these were classical novae, and offered new glimpses into the underlying high-energy particle acceleration physics responsible for gamma-ray emission in novae.

3.1. Discovery of Nova Sco 2012

Fermi J1750-3243 was discovered initially in LAT Routine Science Processing [15] analysis in the field of an X-ray binary starting 2012 June 18 and confirmed with the Fermi All-sky Variability Analysis [2]. Subsequent analysis revealed the first gamma-ray daily detection was as early as June 16, with emission lasting for \( \sim 2 \) weeks [6]. In the preliminary analysis (Fig. 2), the gamma-ray (\( > 100 \) MeV) peak of \( \sim 10^{-6} \) ph cm\(^{-2}\) s\(^{-1}\) was on June 21st while the initial detection was as early as the 15th; for further LAT details, see [19].

The Nova Sco 2012 optical discovery resulted from a microlensing survey of the Galactic bulge and was named MOA 2012 BLG-320. It exhibited a 6 mag brightening from June 1-3, with a gradual rise, peaking on June 19-21 [36], coincident with the gamma-ray emission peak/plateau emission seen in Fermi J1750-3243 (Fig. 2). A 1.6 hr periodic modulation of 0.1 mag from May 28-31 [36] was observed although its nature is unclear. A large ejecta velocity is implied from infrared spectroscopy measuring a FWHM of 2200 km/s in the Pa\( \beta \) line on June 17.879 [31]. A faint radio source was also detected, and its steep spectrum is consistent with a synchrotron origin [9]. In this case, Swift/XRT observations obtained starting June 22 did not detect X-ray emission from the source [28], but as in the case of V407 Cyg (§ 1), analysis of the XRT image showed no other significant X-ray sources within...
3.2. Discovery of Nova Mon 2012, and its Fraternity

Nova Mon 2012 was discovered initially by the LAT as an unidentified gamma-ray transient, Fermi J0639+0548, in late-June. VLA observations were triggered on the Fermi detection, but the source was ∼20° from Sun at the time (in the Monoceros region of the Galaxy) and thus precluded optical and X-ray observations. Due to its similar long-duration in gamma-rays to the V407 Cyg 2010 and Nova Sco 2012 cases (Fig. 2), the possibility that the gamma-ray source could be a nova was noted internally. Aside: After the association of Fermi J1750–3243 with Nova Sco 2012 in late July, I began considering the possible nova origin for other unidentified gamma-ray transients (near and off the Galactic plane), and reasoned that Swift-UVOT optical observations of Fermi J0639+0548 when the source came out of its Sun constraint could test this idea. Instead, on August 14, after discussing some results with collaborator, S.N. Shore, he noted in passing that he had “just activated a ToO at the NOT for the new nova in Mon, it’s a pretty one but likely wasn’t seen by Fermi (but you might check, discovered 9 Aug).” Immediately when I heard the new nova was in Monoceros, I
and indeed, the optical discovery of the possible nova was made on August 9. Coincidentally, there was a nova spectroscopy workshop held at the time at the Observatoire de Haute Provence (OHP) in France and the first amateur spectra were obtained by S. Charbonnel (Durtal Observatory, France; Fig. 4) and J. Edlin (Idaho Falls, Idaho) on August 14, confirming the nova. The initial inspection by I. De Gennaro Aquino of these optical spectra at the OHP and the high resolution Nordic Optical Telescope (NOT) spectrum from August 16 obtained by S. N. Shore indicated a similarity with the Oxygen-Neon (On) type classical nova V382 Vel 1999 approximately 50 days after outburst (Fig. 9.25 therein); see [34] for details. This gave us confidence in associating the LAT transient from June with Nova Mon 2012 detected optically in August. This implied the optical nova was discovered in flat decline phase of its optical lightcurve, consistent with the initial optical magnitudes reported. We inferred peak 4.5 - 5.0 mag [8] in June would have been naked eye and indeed it would have appeared as a new ‘visiting’ star in the Monoceros constellation.

ONE type novae have the highest mass WDs with massive and fast ejecta. The distance to Nova Mon 2012 is about 3.6 kpc [34] and a detected periodicity of 7.1 hr [27, 37] is suggestive of the binary orbital period. As mentioned above, early radio detections (before the optical discovery) were possible due to the VLA observations triggered on the LAT discovery, starting ~ 9 days after the gamma-ray detection [10]. The radio emission exhibited a flat spectrum initially [10] and evolved with a sharply rising (ν^1.7) spectrum that indicates optically thick Bremsstrahlung emission in the ejecta. The radio structure was resolved into a double source [26] indicative of a bi-polar structure, confirmed by the optical line profiles [34]. After the optical discovery, and Fermi association, an X-ray source was discovered with Swift [23] and has since gone through its supersoft brightening [24] and decline [29].

4. Closing Thoughts

The LAT properties for all three gamma-ray detected novae are remarkably similar, with soft spectra and emission detected up to ~few GeV. The gamma-ray lightcurves (Fig. 2) all similarly show fluxes rising over several days with peaks of ~10^{-6} ph cm^{-2} s^{-1} (E > 100 MeV) over consecutive days and overall, are comparably long-duration (~2 weeks at > 3σ, up to ~3 weeks at > 2σ). At face value, this suggests a common gamma-ray emission mechanism. However, their underlying binary systems are dramatically different, so the gamma-ray emission mechanisms are not necessarily the same. Fermi acceleration in the nova shell and interaction with the massive RG wind was determined to play an important role in V407 Cyg [1] and the necessary conditions appear to be a
massive WD and fast and massive ejecta. In comparison with V407 Cyg, the lack of dense environment in the two June 2012 gamma-ray novae make it difficult to explain the origin of the putative shocks that accelerate particles to high energies. The origin of the gamma-ray emission in CN are thus unclear — whether hadronic or leptonic, and the particle acceleration sites. The resemblance between Nova Mon 2012 and other historically bright ONe CN (V1974 Cyg 1992, V382 Vel 1999, and Nova LMC 2000, together dubbed “The Fabulous Four”: [1]) is striking, and provides some early clues in these systems. Future LAT detections (and limits as well) of gamma-rays from novae will help in our understanding and improve our knowledge of the physics of shocks in general.

The initial association of the Fermi J2102+4542 source with nova V407 Cyg 2010 met with some skepticism, simply because nova were not widely considered as potential HE gamma-ray sources. Galactic transients in general have been rare to detect with the LAT and particular regions in the Galaxy are difficult to study due to the bright diffuse emission. The main question after the V407 Cyg nova discovery was whether it was the only nova Fermi had/will see, and what other new transient phenomena will be detected. With the two new CN detections in June 2012, novae are now established as a new gamma-ray source type after 4+ years of Fermi surveying. Continued LAT searches thus have immense discovery potential, including the possible identification of newer, even more rare types of cosmic accelerators, foreseen or unforeseen.

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