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**NuSTAR OBSERVATIONS OF GRB 130427A ESTABLISH A SINGLE COMPONENT SYNCHROTRON AFTERGLOW ORIGIN FOR THE LATE OPTICAL TO MULTI-GEV EMISSION**

C. Kouveliotou\(^1\), J. Granot\(^2\), J. L. Racusin\(^3\), E. Bellm\(^4\), G. Vianello\(^5\), S. Oates\(^6\), C. L. Fryer\(^7\), S. E. Boggs\(^8\), F. E. Christensen\(^9\), W. W. Craig\(^8\),\(^10\), C. D. Dermer\(^11\), N. Gehrels\(^9\), C. J. Hailey\(^12\), F. A. Harrison\(^4\), A. Melandri\(^13\), J. E. McEnery\(^1\), C. G. Mundell\(^14\), D. K. Stern\(^15\), G. Tagliaferri\(^13\), and W. W. Zhang\(^3\)

\(^1\) Astrophysics Office/ZP12, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA; chryssa.kouveliotou@nasa.gov
\(^2\) Department of Natural Sciences, The Open University of Israel, 1 University Road, P.O. Box 808, Ra’anana 43537, Israel; granot@openu.ac.il
\(^3\) NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; judith.racusin@nasa.gov
\(^4\) Cahill Center for Astronomy and Astrophysics, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125, USA
\(^5\) W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA
\(^6\) Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK
\(^7\) CCS-2, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
\(^8\) Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA
\(^9\) DTU Space-National Space Institute, Technical University of Denmark, Elektrovej 327, 2800 Lyngby, Denmark
\(^10\) Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
\(^11\) Code 7653, National Research Laboratory, Washington, DC 20375-5352, USA
\(^12\) Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
\(^13\) INAF-Osservatorio Astronomico di Brera, via E. Bianchi 46, I-23807 Merate, Italy
\(^14\) Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool Science Park, Liverpool L3 5RF, UK
\(^15\) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

**ABSTRACT**

Gamma-ray bursts (GRBs) release within seconds to minutes more high-energy photons than any other transient phenomenon (Kouveliotou et al. 2012). Their prompt gamma-ray emission is followed by a long-lived (typically weeks to months) afterglow, bright enough for the Nuclear Spectroscopic Telescope ARray (NuSTAR) to observe it in the 3–79 keV energy range long after its prompt emission (∼1.5 and 5 days). This range, where afterglow observations were previously not possible, bridges an important spectral gap. Combined with Swift, Fermi, and ground-based optical data, NuSTAR observations unambiguously establish a single afterglow spectral component from optical to multi-GeV energies a day after the event, which is almost certainly synchrotron radiation. Such an origin of the late-time Fermi/Large Area Telescope >10 GeV photons requires revisions in our understanding of collisionless relativistic shock physics.

**Key words:** acceleration of particles – gamma-ray burst: individual (GRB 130427A) – magnetic fields – radiation mechanisms: non-thermal – shock waves

**Online-only material:** color figures

1. INTRODUCTION

Gamma-ray bursts (GRBs) release within seconds to minutes more high-energy photons than any other transient phenomenon (Kouveliotou et al. 2012). Their prompt gamma-ray emission is followed by a long-lived (typically weeks to months) afterglow, bright enough for the Nuclear Spectroscopic Telescope ARray (NuSTAR) to observe it in the 3–79 keV energy range long after its prompt emission (∼1.5 and 5 days). This range, where afterglow observations were previously not possible, bridges an important spectral gap. Combined with Swift, Fermi, and ground-based optical data, NuSTAR observations unambiguously establish a single afterglow spectral component from optical to multi-GeV energies a day after the event, which is almost certainly synchrotron radiation. Such an origin of the late-time Fermi/Large Area Telescope >10 GeV photons requires revisions in our understanding of collisionless relativistic shock physics.

**Key words:** acceleration of particles – gamma-ray burst: individual (GRB 130427A) – magnetic fields – radiation mechanisms: non-thermal – shock waves

**Online-only material:** color figures

2. NuSTAR OBSERVATIONS

NuSTAR was launched on 2012 June 13; the instrument’s two telescopes utilize a new generation of hard X-ray optics and detectors to focus X-rays in the range 3–79 keV. We observed GRB 130427A at three epochs, starting approximately 1.2, 4.8, and 5.4 days after the GBM trigger, for 30.5, 21.2, and 12.3 ks (live times). We detected the source in all epochs, obtaining for the first time X-ray observations of a GRB afterglow above 10 keV. The NuSTAR data thus provide an important
missing spectral link between the Swift/X-Ray Telescope (XRT) observations (0.3 – 10 keV; Maselli et al. 2013) and the Fermi/LAT observations (>100 MeV; Ackermann et al. 2013). We processed the data with HEASOFT 6.13 and the NuSTAR Data Analysis Software (NuSTARDAS) v. 1.1.1 using CALDB version 20130509. We extracted source light curves and spectra from circular regions with 75′′ radius for the first epoch and 50′′ radius for the second and third epochs. We used circular background regions (of 150′′, 100′′, and 100′′ radius for each epoch, respectively) located on the same NuSTAR detector as the GRB. Hereafter, we combine the second and third NuSTAR epochs, which were very close in time, to increase the signal-to-noise ratio, and refer to it as the second epoch.

Figure 1 demonstrates the temporal behavior of the multi-wavelength afterglow flux of GRB 130427A. Here we have included data from Swift/XRT, Swift/Ultra-Violet/Optical Telescope (UVOT), and Fermi/LAT. We also include the extrapolated Fermi/LAT light curve derived as described in Section 3. The weighted average of the decay rates during the two NuSTAR epochs (single power-law (PL) fits) is $\alpha = 1.3$ from optical to GeV (see also the figure inset, and the indices next to each instrument in Figure 1). We discuss the implications of the temporal results in Section 5.

3. Fermi OBSERVATIONS

The Fermi/LAT detected GRB 130427A up to almost a day after the trigger time (Figure 1; Ackermann et al. 2013). Fermi/LAT was also observing during both NuSTAR epochs but did not detect the source. We analyzed the “Pass 7” data with the Fermi Science Tools v9r31p1 and the P7SOURCE_V6 version of the instrument response functions, and using the public Galactic diffuse model and the isotropic spectral template. For each epoch, we selected all the events within a region of interest (ROI) with a radius of 10′ around the position of the GRB, excluding times when any part of the ROI was at a zenith angle >100°.

The latter requirement greatly reduces contamination from the diffuse gamma-ray emission originating from the Earth’s upper atmosphere, peaking at a zenith angle of ~110°.

3.1. Fermi/LAT Spectra and Upper Limits

For each epoch we performed an unbinned likelihood analysis over the whole energy range (0.1–100 GeV), using a model composed of the two background components (Galactic and isotropic) and a point source with a PL spectrum (the GRB), plus the contribution from all the known gamma-ray point sources in the ROI (Nolan et al. 2012). We did not obtain a detection in either epoch, and so we computed ULs. We froze the normalization of the background components, and fixed the photon index of the GRB model to 2.17, which is the best-fit value from the smoothly broken power-law (SBPL) fit during the first NuSTAR epoch as reported in Section 4 (the ULs change by less than 10% for any choice of the photon index between 2 and 2.5). We then independently fit the GRB model in three energy bands (0.1–1, 1–10, and 10–100 GeV), using an unbinned profile likelihood method to derive the corresponding 95% LAT ULs (Ackermann et al. 2012). The information contained in such ULs is important to constrain the spectrum, but cannot be handled by a standard fitting procedure. We, therefore, turn to an alternative (but equivalent) method to include the LAT observations in a broadband spectral fit. We obtained the count spectrum of the observed LAT signal (source + background) using gtbin, and the background spectrum using gtbgk, which computes the predicted counts from all the components of the best-fit likelihood model except the GRB. Since there is no significant excess above the background, the two spectra are compatible within the errors, although they are not identical. We also ran gtrspgen to compute the response of the instrument in the interval of interest, and loaded these files in XSPEC v.12.7. This software compares the observed net counts to the number of counts predicted by the model folded with the response of the instrument. By minimizing a statistic based on the Poisson probability, we can treat equivalently a spectrum containing a significant signal, and a spectrum which...
is compatible with being just background. While the former will constrain the model to pass through the data points, the latter will constrain it to predict a number of counts above background compatible with zero. The best-fit model obtained using the LAT spectra computed in this way is, as expected, below the ULs computed with the profile likelihood method.

3.2. Extrapolation of the Fermi/LAT Light Curve

The high-energy (>100 MeV) photon and energy flux light curves are well described by a broken power law (BPL) and PL, respectively, as reported in Ackermann et al. (2013). To extrapolate such light curves to the NuSTAR epochs, we adopted a general approach, based on the well-known Markov Chain Monte Carlo technique, which takes into account the uncertainties on the best-fit parameters along with all their correlations, as follows.

Each data point in Figure 2 represents a photon flux derived from a likelihood fit with 1σ confidence intervals (Ackermann et al. 2013). Hence, we can assume a Gaussian joint likelihood $L$ and minimize the corresponding $-\log(L)$ to find the best-fit parameters, which is equivalent to a standard least-squares fit (or to minimize $\chi^2$). We can then apply the Bayes rule that the posterior distribution for the parameters is directly proportional to the prior distribution multiplied by the likelihood. If we take an uninformative prior, then the posterior distribution is directly proportional to the likelihood itself. Therefore, sampling the likelihood function with a Markov Chain Monte Carlo technique is equivalent to sampling the posterior distribution. By using, e.g., the Goodman & Weare (2010) algorithm, we can then obtain many sets of parameters, $p_i$, which are drawn from the posterior distribution, with all the relations between them taken into account. Using these sets of parameters, $p_i$, we can build a distribution of a certain quantity of interest $f(p_i)$. Taking the median and the relevant percentiles of the distribution, we can then extract a measure of $f$ and its 1σ confidence interval. In this way, we computed the shaded region in Figure 2 and the expected flux only in the first NuSTAR epoch, which starts shortly after the last detection from Fermi/LAT. The second NuSTAR epoch started too late for any extrapolation to be meaningful.

Figure 2 exhibits the Fermi/LAT photon flux light curve with 1σ confidence intervals derived with such method. We used the same method to compute the flux extrapolation for the first NuSTAR epoch (the magenta dashed cross in Figure 3).

4. BROADBAND AFTERGLOW

We extracted light curves and spectra during the NuSTAR epochs from Swift/UVOT, and Swift/XRT using the standard HEASOFT reduction pipelines and the Swift/XRT team repository (Evans et al. 2009), as well as Liverpool Telescope data using in-house software (Maselli et al. 2013). For the first epoch, we compare the extrapolation of the LAT temporal and spectral behavior (Ackermann et al. 2013) to our multi-wavelength light curves and spectra.

Figure 3 shows two spectral energy distributions (SEDs) spanning from optical (i’ band) to γ-rays (~GeV). We first fit each epoch independently (excluding Fermi/LAT data) with two functional forms (Table 1)—single PL and BPL—each multiplied by models for both fixed Galactic and free intrinsic...
The Small Magellanic Cloud extinction curve fits our data best and we use (host) extinction (zdust)\textsuperscript{17} and absorption (phabs), respectively,

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BPL is significantly better, with a PL; however, the second epoch fit is better to the synchrotron radiation theoretical expectation (Granot & Sari\textsuperscript{20}).

Our results are broadly consistent with those of Perley et al. (2013) who derived radio to GeV afterglow spectra of GRB 130427A covering 0.007–60 days after trigger. Their results also suggest that the forward shock emission indeed dominates at or above the optical during our NuSTAR epochs.

### Table 1

Broadband Spectral Fits during the NuSTAR Epochs

<table>
<thead>
<tr>
<th>Model\textsuperscript{1}</th>
<th>Epoch</th>
<th>O+X \textsuperscript{2}</th>
<th>N \textsuperscript{2}</th>
<th>L \textsuperscript{2}</th>
<th>ΔΓ \textsuperscript{2}</th>
<th>Γ \textsubscript{1}</th>
<th>Γ \textsubscript{2}</th>
<th>E \textsubscript{c} \textsuperscript{2}</th>
<th>χ\textsuperscript{2}/dof</th>
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<tr>
<td>PL</td>
<td>1</td>
<td>Yes</td>
<td>Yes</td>
<td>...</td>
<td>...</td>
<td>1.72 ± 0.02</td>
<td>...</td>
<td>...</td>
<td>457.6/422\textsuperscript{a}</td>
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<tr>
<td>PL</td>
<td>2</td>
<td>Yes</td>
<td>Yes</td>
<td>...</td>
<td>...</td>
<td>1.77 ± 0.02</td>
<td>...</td>
<td>...</td>
<td>105.1/104\textsuperscript{b}</td>
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<tr>
<td>BPL</td>
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<td>Yes</td>
<td>Yes</td>
<td>Free</td>
<td>1.70 ± 0.01</td>
<td>1.89\textsuperscript{0.08}\textsuperscript{0.4}</td>
<td>9.3\textsuperscript{1.3}\textsuperscript{1.4}</td>
<td>419.3/420\textsuperscript{c}</td>
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<tr>
<td>BPL</td>
<td>2</td>
<td>Yes</td>
<td>Yes</td>
<td>Free</td>
<td>1.77</td>
<td></td>
<td></td>
<td></td>
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<td>Yes</td>
<td>...</td>
<td>0.5</td>
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<td>2.21</td>
<td>17 ± 1</td>
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<td>BPL</td>
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<td>Yes</td>
<td>...</td>
<td>0.5</td>
<td>1.77 ± 0.01</td>
<td>2.27</td>
<td>32\textsuperscript{14}\textsuperscript{3}</td>
<td>103.7/103\textsuperscript{e}</td>
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Fits to Optical+X-ray+NuSTAR +LAT confirm presence of break and demonstrate best-fit physical model

<table>
<thead>
<tr>
<th>Model\textsuperscript{1}</th>
<th>Epoch</th>
<th>O+X</th>
<th>N</th>
<th>L</th>
<th>ΔΓ</th>
<th>Γ \textsubscript{1}</th>
<th>Γ \textsubscript{2}</th>
<th>E \textsubscript{c}</th>
<th>χ\textsuperscript{2}/dof</th>
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<td>Yes</td>
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<td>...</td>
<td>1.72 ± 0.01</td>
<td>...</td>
<td>...</td>
<td>489.1/434\textsuperscript{f}</td>
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<td>Yes</td>
<td>UL\textsuperscript{3}</td>
<td>...</td>
<td>1.76 ± 0.01</td>
<td>...</td>
<td>...</td>
<td>130.6/116\textsuperscript{g}</td>
</tr>
<tr>
<td>SBPL</td>
<td>1</td>
<td>Yes</td>
<td>Yes</td>
<td>UL\textsuperscript{3}</td>
<td>Free</td>
<td>1.70 ± 0.01</td>
<td>1.91 ± 0.03</td>
<td>9.4\textsuperscript{1.4}\textsuperscript{2.0}</td>
<td>428.5/432\textsuperscript{h}</td>
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<tr>
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<td>Yes</td>
<td>Yes</td>
<td>UL\textsuperscript{3}</td>
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<td>1.69 ± 0.01</td>
<td>2.91\textsuperscript{0.53}\textsuperscript{0.49}</td>
<td>96\textsuperscript{51}\textsuperscript{53}</td>
<td>422.7/430\textsuperscript{i}</td>
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</tbody>
</table>

Notes. \textsuperscript{1} (PL) power law, (BPL) broken power law, (SBPL) smoothly broken power law. \textsuperscript{2}O+X = Optical+Swift/XRT + Swift/UVOT; N = NuSTAR; L = Fermi/LAT; ΔΓ = Γ \textsubscript{2} − Γ \textsubscript{1}; E \textsubscript{c} = break energy in keV. \textsuperscript{3}This fit includes the LAT spectra. \textsuperscript{4}This spectral fit is shown in Figure 3.

\textsuperscript{a} PL is an adequate fit.

\textsuperscript{b} PL is a good fit.

\textsuperscript{c} BPL is a better fit than PL, F-test = 19.1 (P = 1.6 × 10⁻⁹).

\textsuperscript{d} Cannot constrain break.

\textsuperscript{e} BPL (ΔΓ = 0.5) is a better fit than PL, F-test = 28.5 (P = 1.5 × 10⁻⁷).

\textsuperscript{f} BPL (ΔΓ = 0.5) is not significantly better fit than PL, F-test = 1.3 (P = 0.25).

\textsuperscript{g} PL is not a very good fit.

\textsuperscript{h} BPL is a better fit than PL, F-test = 30.5 (P = 3.9 × 10⁻¹³), break is needed.

\textsuperscript{i} SBPL is a better fit than PL, F-test = 16.9 (P = 7.2 × 10⁻¹³).

\textsuperscript{j} SBPL is a better fit than PL, F-test = 12.3 (P = 3.5 × 10⁻¹¹).

\textsuperscript{17} The Small Magellanic Cloud extinction curve fits our data best and we use it exclusively for continuity.

\textsuperscript{18} This value corresponds to the cooling break for our inferred photon index and external density profile (Granot & Sari\textsuperscript{2002}).
predict a maximum synchrotron photon energy, \( E_{\text{syn, max}} \), derived by equating the electron acceleration and synchrotron radiative cooling timescales, assuming a single acceleration and emission region (Guilbert et al. 1983; de Jager et al. 1996; Kirk & Reville 2010; Piran & Nakar 2010). In the context of late-time \( \text{Fermi}/\text{LAT} \) high-energy photons, this was first briefly mentioned as a problem for a synchrotron origin for GRB 090902B (Abdo et al. 2009), and later discussed more generally and in depth by Piran & Nakar (2010). The long-lasting (∼1 day) \( \text{Fermi}/\text{LAT} \) afterglow included a 32 GeV photon after 34 ks, and altogether five >30 GeV photons after >200 s. All five significantly exceed \( E_{\text{syn, max}} \), by factors of 6.25 for \( k = 0 \) and 9.20 for \( k = 2 \) (using Equation (4) of Piran & Nakar 2010). This led to suggestions that the \( \text{Fermi}/\text{LAT} \) high-energy photons were not synchrotron radiation, but instead arose from a distinct high-energy spectral component (Ackermann et al. 2013; Fan et al. 2013).

Such a component may arise, for example, from synchrotron self-Compton (Fan et al. 2013). This mechanism was predicted to dominate at high photon energies at late times (Panaitescu & Kumar 2000; Sari & Esin 2001), but has rarely been detected in the late X-ray afterglow (Harrison et al. 2001; Yost et al. 2002). Other possible origins of the high-energy emission involve long-lived activity of the central source, producing a late relativistic outflow that provides seed synchrotron photons or relativistic electrons that might scatter either their own synchrotron emission or that of the afterglow shock (Fan & Piran 2008). In GRB 130427A, however, there are no signs of prolonged central source activity (such as X-ray flares) beyond hundreds of seconds. Another option is a “pair echo” involving TeV photons emitted promptly by the GRB, which pair-produce with photons of the extragalactic background light; for low enough intergalactic magnetic fields the resulting pairs can produce detectable longer-lived GeV emission by upscattering cosmic microwave background photons (Plaga 1995; Takahashi et al. 2008). However, in this case the flux decay rate is expected to gradually steepen and the photon index to soften, in contrast with observations. A different possibility is pair cascades, induced by shock-accelerated ultra-high-energy cosmic rays (Dermer & Atoyan 2006).

For any of these alternative models to work, there needs to be a transition from synchrotron emission (at low photon energies) to the alternative model (at high energies). We expect that if a distinct spectral component dominated the emission at GeV energies, it would naturally show up in a broadband SED. By combining optical, XRT, \( \text{NuSTAR} \), and \( \text{Fermi}/\text{LAT} \) UL data we have shown that the SED at ∼1.5 days is perfectly consistent with the theoretically expected SBPL spectral shape from optical to GeV energies, without any unaccounted for flux, and that the flux at all these energies decays at a similar rate. This strongly suggests a single underlying spectral component over a wide energy range. For low energies, the most viable emission mechanism for such a spectral component is synchrotron radiation, suggesting that the entire SED is produced by synchrotron emission.

Therefore, our results strongly suggest that the late-time \( \text{Fermi}/\text{LAT} \) high-energy photons in GRB 130427A are indeed afterglow synchrotron radiation, and provide the strongest direct observational support to date for such an afterglow synchrotron origin of late-time >10 GeV \( \text{Fermi}/\text{LAT} \) photons. As was already pointed out (e.g., Piran & Nakar 2010), such an origin challenges particle acceleration models in afterglow shocks. In particular, at least one of the assumptions in estimating \( E_{\text{syn, max}} \) must be incorrect, requiring a modification of our understanding of afterglow shock physics. While many authors were aware of this potential problem, the \( \text{NuSTAR} \) results make it much harder to circumvent. One possible solution may lie in changing the assumption of a uniform magnetic field into a lower magnetic field acceleration region and a higher magnetic field synchrotron radiation region (Kumar et al. 2012; Lyutikov 2010). These might arise for diffusive shock acceleration (Fermi Type I) if the tangled shock-amplified magnetic field decays on a short length scale behind the shock front (where most of the high-energy radiation is emitted), while the highest energy electrons are accelerated in the lower magnetic field further downstream (Kumar et al. 2012).

Another possibility is direct linear acceleration in the electric field of magnetic reconnection layers, which have a low magnetic field (Uzdensky et al. 2011; Cerutti et al. 2012, 2013). This would require, however, a significant fraction of the total energy in the flow to reside in magnetic fields of alternating sign. This is not expected in GRB afterglows, but it could occur in the magnetic-reconnection induced decay of the tangled shock-amplified field mentioned above, which initially reaches near-equipartition values just behind the shock. While the exact solution is still unclear, our results provide an important challenge for our understanding of particle acceleration and magnetic field amplification in relativistic shocks.

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