Rapid spectral variability of a giant flare from a magnetar in NGC 253

On 15 April 2020 at 08:48:05.563746 UTC, the Gamma-ray Burst Monitor (GBM) onboard the Fermi Gamma-Ray Space Telescope (Fermi) was triggered by an extremely bright, short and spectrally hard event, initially classified as a short γ-ray burst (GRB), GRB 200415A14, which was also detected by several other instruments (refs. 13,15; A. J. Castro-Tirado et al., manuscript in preparation). An offline search using time-tagged event data from the Burst Alert Telescope (BAT) onboard the Neil Gehrels Swift Observatory (Swift), obtained with the Gamma-ray Urgent Archiver for Novel Opportunities (GUANO) 16 onboard the Neil Gehrels Swift Observatory (Swift), obtained with the Gamma-ray Urgent Archiver for Novel Opportunities (GUANO)16 pipeline, also found the event. Using the light travel time of photons detected by the Inter-Planetary Network of satellites, GRB 200415A was triangulated to a 17-arcmin2 region centred at a right ascension (RA) and declination (dec.) (J2000) of 11.88° (00 h 47 m 32 s) and −25.263° (−25°15′ 46″), respectively15. The relatively small error box of the localization overlaps significantly with the Sculptor galaxy (NGC 253)—an active star-bursting intermediate spiral galaxy located about 3.5 Mpc away17—which strongly suggests that GRB 200415A originated from this galaxy.

We use the BAT time-tagged event data to determine the duration due to bandwidth saturation of the high-time-resolution GBM time-tagged event data (Methods). We find the $T_{90}$ duration of GRB 200415A (the time interval over which 5%–95% of the total counts were accumulated) to be $140.8 +0.5 \ pm 0.6$ ms (1σ). Correspondingly, the $T_{50}$ duration of the event (over which 25%–75% of the total counts were accumulated) is $54.7 +0.5 \ pm 0.4$ ms (1σ). Our detailed temporal analysis of the event light curve shows that the rise time (10%–90%) of the first pulse is $T_{\text{rise}} = 57 \pm 23$ μs (1σ) (Fig. 1e).

We performed a timing analysis on the GBM light curve to search for a rotational frequency in the range 0.02–50 Hz, but found no clear pulsation. We also searched the 40–4,000-Hz window for quasi-periodic variations overlaps significantly with the Sculptor galaxy (NGC 253)—an active star-bursting intermediate spiral galaxy located about 3.5 Mpc away17—which strongly suggests that GRB 200415A originated from this galaxy.

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oscillations, which are possible signatures of the seismic vibrations seen in the oscillating tails of confirmed giant flares. A candidate broad quasi-periodic oscillation was found at a frequency of $v = 180$ Hz in the decaying tail of GRB 200415A, with roughly 2.5σ significance (Methods).

We performed time-integrated and time-resolved spectral analyses of the GBM data, focusing on the sub-millisecond structures in the lightcurve (Figs. 1, 2). The very high rate might cause the electronic signals of photons to overlap (pulse pile-up), which would cause their energies to be incorrectly measured and spectral distortions. We evaluated this effect in the brightest interval (interval (2) in Fig. 1) and determined that it was negligible (Methods). Among several spectral models used, we found that a power law with an exponential-cutoff (Comptonized) model fitted the data best; the Comptonized spectral parameters are presented in Table 1 (Methods). The highest-energy photons reliably associated with GRB 200415A have energies of approximately 3 MeV (Methods). Using time-resolved GBM spectral analysis with corrections from the BAT, we find a time-integrated isotropic equivalent energy output of $E_{\text{iso}} = (1.51 \pm 0.021) \times 10^{46}$ erg (Table 1). The peak isotropic luminosity is $L_{\text{iso,max}} = (1.53 \pm 0.13) \times 10^{46}$ erg s$^{-1}$ and the total luminosity of the event is $L_{\text{iso}} = (1.07 \pm 0.17) \times 10^{47}$ erg s$^{-1}$. Our time-resolved spectral analysis shows remarkable sub-millisecond variations (Fig. 2d, e) over a 10-ms interval, encompassing intervals (1), (2) and (3), and part of interval (4). In Fig. 2d, the peak energy ($E_p$) reaches its highest value at the onset of interval (3), but it remains relatively constant throughout most of the event.

The photon index ($\alpha$) stays relatively constant at $\alpha = 0$ during the event, which would be highly unusual for a short GRB. Figure 2a, b shows exponential-decay trends in both energy flux ($F$) and $L_{\text{iso}}$ over interval (4), which is clearly discerned from the tail of GRB 200415A. The energy-flux decay in Fig. 2 occurs on a timescale of $\tau = 45 \pm 3$ ms; $E_p$ is observed to decay on a longer timescale of $\tau = 100 \pm 1$ ms. This exponential behaviour has been observed in other extragalactic giant-flare candidates. A distinctive $F = E_p^2$ correlation was discovered (Fig. 2f), a signature of a relativistic wind. This unprecedented result is clearly observed in the GBM data for GRB 200415A, which are largely devoid of detector saturation effects. Such saturation effects probably precluded this trend from being cleanly discerned from previous observations of galactic giant flares from the soft γ-ray repeaters SGR 1900+14 and SGR 1806–20.

Finally, we searched for radio emission associated with GRB 200415A in four observations of NGC 253 taken with the Karl G. Jansky Very Large Array (VLA) on 4.3–51.2 days after the event trigger. No significant variable or transient emission was identified.
Previous studies postulated that about 1%–20% of short GRBs could be extragalactic giant flares\textsuperscript{4,20,23}. The sample of galactic giant flares is very small and their properties are ill-determined, owing to instrumental effects from their extreme intensity. Therefore, we first compare the GBM observations of GRB 200415A to the GBM observations of short GRBs\textsuperscript{23}.

### Table 1: Spectral parameters, luminosity and emitted energy for the four time intervals

| Time | $E_p$ (keV) | $\alpha$ | $\mathcal{F}$ ($\times 10^{-5}$ erg cm$^{-2}$ s$^{-1}$) | Correction factor | $L_{iso}$ ($\times 10^{45}$ erg s$^{-1}$) | $E_{iso}$ ($\times 10^{44}$ erg) | Cash statistic/dof |
|------|-------------|----------|-----------------|-----------------|-----------------|-----------------|-------------------|
| (1)  | 4.4 ms to −3.4 ms | 428 ± 71  | $-0.08 \pm 0.23$ | 9.9 ± 1.2 | 1.0  | 151 ± 0.18 | 0.15 ± 0.02 | 4310/633 |
| (2)  | 3.4 ms to −0.8 ms | 997 ± 77  | $-0.21 \pm 0.08$ | 33.7 ± 1.5 | 1.896 | 15.3 ± 1.3 | 3.97 ± 0.33 | 634.5/659 |
| (3)  | −0.8 ms to 3.0 ms | 1856 ± 156 | $-0.11 \pm 0.08$ | 17.5 ± 0.81 | 1.0  | 8.29 ± 0.38 | 3.15 ± 0.15 | 705.5/685 |
| (4)  | 3.0 ms to 136.4 ms | 846 ± 39  | 0.34 ± 0.08 | 2.69 ± 0.06 | 1.036 | 0.58 ± 0.032 | 7.79 ± 0.43 | 736.9/698 |
| $T_{50}$ duration (140.8 ms) | | | | 1.07 ± 0.17 | 15.1 ± 2.46 |

Time intervals are identified in Fig. 1a and are relative to the GBM trigger time. The correction factor of 1.896 for interval (2) corrects for the saturation in this interval by comparing the GBM flux in the 15–350 keV range with the Swift-BAT flux in the same interval. All errors are at the 1σ confidence level. dof, degrees of freedom.

We find that the 64-ms peak photon flux ($P_{iso, catalogue} = 73.7 \pm 2.1$ photons cm$^{-2}$ s$^{-1}$) of GRB 200415A lies at the 97.5th percentile of the short-GRB distribution, the peak energy ($E_{p,catalogue} = 998 \pm 45$ keV) at the 79th percentile and the photon index ($\alpha_{catalogue} = 0.39 \pm 0.09$) at the 88th percentile. GRB 200415A is similarly near the edge of the $\alpha$ distribution for the GRB population detected with the Burst and Transient Source Experiment (BATSE) on the Compton Gamma-ray Observatory\textsuperscript{23}. Consequently, we find the flat, hard spectral slope, high $E_p$ and peak flux during the brightest 64 ms of GRB 200415A (Figs. 1, 2) to be unusual for short GRBs; these features are better explained as the initial spike of a magnetar giant flare from NGC 253. This interpretation is further motivated by similarities between the properties of this event and of previously proposed extragalactic giant-flare candidates\textsuperscript{20,24}. A rapid rise time is characteristic of the onset of a giant flare. The rise time that we determined is considerably shorter than that of any event reported in the GBM catalogues of GBM and BATSE, and is shorter than extreme examples of short variations, such as about 100 μs for GRB 910711 and 2.8 ms for GRB 090228\textsuperscript{26}.

Unfortunately, we could not detect the period-modulated tail of the magnetar, which has a putative energy of $E = 10^{50}$ erg. Such irrefutable evidence for a giant flare was observed over several hundreds of seconds in all three confirmed magnetar giant flares, but is absent in GRB 200415A because it is probably below the detection threshold for GBM, owing to its distance to NGC 253. This feature is similarly undetected for other extragalactic giant-flare candidates\textsuperscript{25}.

The standard picture for the origin of giant flares is the release of energy triggered by the fracturing of the crust of the neutron star by large subsurface magnetic fields, which deposits hot plasma into the inner magnetosphere. Using a giant-flare interpretation, the GBM observations indicate that the MeV-band emission must come from a relativistic outflow that is initially very ‘optically thick’ (opaque). The enormous $L_{iso}\gg 10^{50}$ erg s$^{-1}$ is orders of magnitude larger than the fiducial Eddington luminosity limit ($L_{iso, Edd} = 10^{38}$ erg s$^{-1}$) for a neutron star of solar mass\textsuperscript{22}. This limit defines when radiation pressure associated with electron (Compton) scattering overwhelms gravity and pushes hydrodynamic gas away from the surface to high altitudes. For GRB 200415A, we therefore expect a relativistic wind\textsuperscript{1} with bulk Lorentz factor $\Gamma \sim 1$—that is, with speed $c(1 - 1/c^2)^{1/2}$, where $c$ is the speed of light—to be
present, putatively over the magnetic poles. At high altitudes, the radiation pressure abates and the wind ‘coasts’ with constant $f$. Transparency of the wind to quantum electrodynamic pair production ($\gamma \rightarrow e^+ e^-$) of electrons ($e^-$) and positrons ($e^+$) by 3-MeV photons, detected by GBM, unambiguously implies that $f > 6$ (Methods). This is a more stringent bound than was possible for the $\lesssim 1$ MeV photons seen in the initial spikes of galactic giant flares\(^{28,29}\). This GBM limit is consistent with the stronger constraints due to the detection of GeV photons by Fermi–LAT\(^{23,25}\). High Lorentz factors ($f \geq 100$) are predicted from dynamical models\(^{30}\) of thermal fireballs with high peak energies, which are usually applied in modelling of GRB emission. The high opacity to quantum electrodynamic magnetic pair creation ($\gamma \rightarrow e^+ e^-$) in the inner magnetosphere of magnetars\(^{31}\) indicates that the wind is probably dominated by $e^+$ pairs, with limited baryonic content. The dense wind relativistically boosts its embedded radiation to higher frequencies via the Doppler effect, and beams or collimates it into a radiation emission cone with an opening angle of $\Theta_{\text{coll}} \sim 1/\Gamma$ radians. The observed correlation between the energy flux and the peak energy ($\langle \gamma \rangle \approx \Theta$; Fig. 2) can be readily explained by relativistic Doppler boosting (Methods).

The GBM spectrum is very flat; that is, it has a relatively high value for $\alpha$ in the $\gamma$-ray band. This strongly contrasts with the picture of GRB fireballs, which have spectra that begin to approach a modified blackbody (Wien) form\(^{27}\). The same situation is anticipated for GRB 200415A, with its markedly higher deduced $\alpha$ values. Yet, the radiation is not truly thermal: the $\gamma$-ray emission would increase, peak and then decline, accompanied by spectral hardening and subsequent softening; this is commensurate with the evolutionary sequence displayed in Fig. 1. Such a transient ‘relativistic lighthouse beaming’ effect would generate the decay time ($\tau = 45$ ms) of the tail of a bulk flow with a rotation period of $p = 8$ s and $\Gamma = 30$ (Fig. 2; Methods), given that the rotating beam has an intrinsic coupling of $\tau = p(2\Gamma)$.

### Table 2 | 1–2-GHz VLA radio observations

| Date (utc) | $\Delta T_{\text{max}}$ (days) | 1σ root-mean-squared noise (mJy per beam) |
|-----------|-------------------------------|------------------------------------------|
| 19 April, 16:12:36 | 4.31 | 0.28 |
| 25 April, 16:26:53 | 10.3 | 0.43 |
| 7 May, 15:04:53 | 42.3 | 0.40 |
| 5 June, 12:43:29 | 51.2 | 0.29 |

$\Delta T_{\text{max}}$ time between the initial $\gamma$-ray and X-ray observations of GRB 200415A and subsequent radio observations.

### Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-020-03077-8.

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GBM observations and data processing

Fermi–GBM consists of 12 thallium-doped sodium iodide (NaI) detectors and two bismuth germanate (BGO) detectors. The uncollimated NaI scintillator detectors are clustered into four groups of three detectors at each corner of the spacecraft, arranged such that any cosmic source above the Earth’s horizon will illuminate one cluster. The combined effective spectral range of the NaI and BGO detectors is about 8 keV to 40 MeV. GBM has several data types, which are produced either by a trigger or continuously. Triggered data types include CTIME data (binned to 64 ms resolution with 8 energy channels) and CSPEC data (binned to 1.024 ms with 128 energy channels). The GBM time-tagged event (TTE) triggered data are the tagging of individual counts in the detectors within 5 min of the trigger time and have a relative timing resolution of about 2 μs and 128 energy channels. The energy channels for all these data types are pseudo-logarithmically spaced. More information on these and other data types, as well as other details pertaining to the instrument, can be found in ref. 33.

A bandwidth limit between GBM and the Fermi spacecraft restricts the GBM TTE rate to approximately 375,000 events per second, summed over all detectors and energies 34. When the GBM TTE rate exceeds this value, TTE counts are lost in a manner that is not biased by detector or energy (Fig. 1). Consequently, spectral analysis to obtain spectral shape parameters is still possible, but the flux normalization will be underestimated. During the saturated interval, subintervals may be weighted differently, but the data are still in the correct order. In addition, the transmission of another GBM data type to the spacecraft can block the TTE data, causing a gap. Other GBM data types are not affected by this bandwidth limit but have inadequate temporal resolution for this event.

Owing to high count rates, the electronic signals of the counts can overlap (pulse pile-up), causing incorrect energy measurements and spectral distortions. To check for this in the GBM data for GRB 200415A, we used an analytical method35 that was verified by high-rate measurements with a GBM detector.36 This method was applied to the spectral model and rate of interval (2), for the detector with the highest flux (NaI 1). The spectral shape of the detector counts are only slightly modified by pulse pile-up, with a change in slope below 30 keV and a loss of higher-energy counts starting at 200 keV, reaching a 5% loss above 400 keV. In joint fits, the lower-rate BGO data help to constrain the results. Pulse pile-up is otherwise not included in our analyses.

The localization accuracy of an all-sky monitor such as GBM is limited, especially for short events. Although an initial position for GRB 200415A was promptly determined using GBM37,38 using several methods39,40, each position had several degrees of error. We therefore used the Inter-Planetary Network localization41 to generate detector response matrices.

Each GBM detector was checked to see whether their viewing angles were within 60° of their respective on-axis position to the source, and whether they were blocked by parts of the spacecraft. From this analysis, we identified 6 NaI detectors 0, 1, 2, 3 and 5 and 2 BGO detector 0 as having satisfied these criteria. Spectral parameters were determined by selecting the model that best fitted the data, by looking at variations in the Cash statistic per degree of freedom41. A simple power law, a power law with an exponential cutoff (Comptonized), a broken power law, and combinations of these models were used. The values in Table 1 and Figs. 1 and 2 are spectral parameters derived from the Comptonized model fit to the data, which was found to be the best. The estimated covariance of the optimal values to the fits of the spectral parameters in Fig. 2a, b, f uses the minimization of the sum of the squared residuals. The diagonals provide the variance of the estimated parameter. One-standard-deviation error on the parameters was done by taking the square-root of the diagonals from the covariance matrix. The full fits to the data in Fig. 2a, b, f are \( \mathcal{S} = (9.39 \pm 0.39) \times 10^{-5} \), \( E_p = (1299 \pm 82) \) and \( \mathcal{S} = (5.84 \pm 0.58) \times 10^{-7} \) respectively.

Energetics and time-resolved spectra

We divided the lightcurve into four intervals (Fig. 1, Table I). The differential photon number spectrum \( (dN/dE) \) in all four intervals is best described by a power law with an exponential cutoff. The cutoff is parameterized as the peak energy of the \( V_F \) spectrum, \( E_p \). Interval (1) contains the first pulse, which is present in GBM and BAT. It is a clean pulse, not affected by saturation, and there is no overlap with other pulses. Interval (2) includes the brightest part of the lightcurve, which is affected by TTE saturation in GBM. Interval (3) includes the hardest part, with \( E_p = 1.9 \) MeV. Interval (4) includes a featureless decay out to 136.4 ms and contains most of the fluence. The spectral fits for intervals (1), (3) and (4) are illustrated in Extended Data Fig. 2. The comparison of the energetics to short GRBs were over 64 ms,
a timescale generally reported with short-GRB properties in mission catalogues.

**Highest-energy photons**

Extended Data Fig. 3 shows the individual TTE counts in GBM BGO detector 0. The GBM detectors register energy deposits and are unable to identify particle type, nor can they determine photon arrival direction. Therefore, it is impossible to determine with certainty whether any particular TTE is from GRB 200415A, from another γ-ray source or due to other background. Instead, we determine whether a rate increase is statistically significant and therefore associated with GRB 200415A.

We use a Bayesian method applicable to Poisson rate data, for the classic on-source–off-source method of source detection. The method uses data from two time intervals, an off-source or background interval and an on-source interval, to test two hypotheses: (1) that all the TTEs are due to background; and (2) that there are excess TTEs above background in the on-source interval due to the source. The method needs a prior expectation for the source count rate, which we obtain from the spectral fit in the on-source interval. For the 2.5–3.5-MeV energy range, there are 100 TTEs in a 0.99-s background interval and 9 TTEs in a 6.4-ms on-source window (blue box in Extended Data Fig. 3). The calculated probability for a source signal (GRB 200415A) above the background is 0.9999997. This energy range is well above the threshold for γγ pair creation; the two TTEs with the highest energies are 3.0 MeV and 3.1 MeV.

We also consider a higher-energy range, 3.5–10 MeV. In this energy range, there are 88 off-source TTEs and 3 on-source TTEs (red box in Extended Data Fig. 3); the on-source TTEs have energies of 4.0 MeV, 6.7 MeV and 8.8 MeV. The probability that the three on-source TTEs are an excess rate that should be attributed to GRB 200415A is 0.966. Consequently, we do not consider these three TTEs sufficiently significant to use for our Lorentz factor analysis.

The definitive detection of $E_{\text{iso}} = 3$ MeV photons for GRB 200415A by GBM is at an energy well above the pair-production threshold. Dedicated γ-ray instrument observations of the main pulse of galactic giant flares have typically been saturated, and probably suffer from spectral distortions (pulse pile-up). Thin particle detectors have reported usable spectra; for example, the WIND SST silicon detectors measured a spectrum for the 27 December 2004 giant-flare main pulse of SGR 1806–20 extending to 1 MeV, γ-ray detector observations of extragalactic giant flares will probably provide the best results on their spectra, obtaining excellent statistics without spectral distortions due to extreme fluxes.

**The environment of the MeV emission region**

The appearance of emission above the two-photon pair creation ($\gamma\gamma \rightarrow e^+e^-$) threshold of $m_e c^2 = 511$ keV (where $m_e$ is the mass of an electron) in GRB 200415A can be used to provide a lower bound on the wind bulk Lorentz factor $\Gamma$ relative to the magnetar. This is a traditional practice in GRB studies, whereby the bulk motion is used to reduce the pair opacity through relativistic collimation of the radiation field within an angle $\Theta_a \ll 1$. The spectrum of this giant flare, with its emission limited to energies $E < E_{\text{max}} = 3$ MeV, necessitates an individualized calculation of pair opacity. The most conservative estimate corresponds to all observed GBM photons being below the 511-keV threshold in the comoving frame of the plasma or photon gas. Then, $\Gamma > E_{\text{max}}/(m_e c^2) = 6$. Higher values can be obtained with additional assumptions of source spectral extension beyond $E_{\text{max}}$, but are undetectable owing to the radiation background. The pair opacity constraint on $\Gamma$ is more restrictive than it is possible for $E_{\text{max}}$ values appropriate for the SGR 1900+14 and SGR 1806–20 giant flares ($E_{\text{max}} = 1$ MeV). Expectations from isotropic fireball dynamics modelling and Fermi–LAT observations suggest much larger values for the bulk $\Gamma$.

The GBM emission is non-thermal. For a distance $d = 3.5$ Mpc to the Sculptor galaxy, the detected photon energy flux can be mapped to an energy flux $\mathcal{F}(R)$ through a surface located a distance $R$ from the center of the magnetar. The entries in Table 1 for interval (3) indicate that $\mathcal{F}(R) = 2 \times 10^{30}(10^9 \text{ cm}/R)^2$ erg cm$^{-2}$ s$^{-1}$. If this radiation were to be thermal, then this flux should be comparable to the Doppler-boosted Planck spectrum that generates the $E_e$ value for this interval ($E_e = 1.856$ keV). Suppose that the Planck spectrum in the wind frame has some temperature $T_{\text{w}}$. For a wind moving with speed $\beta c$ and $\Gamma = (1 - \beta^2)^{-1/2} > 1$, this yields a temperature $T_{\text{w}} = (\beta^2 T_{\text{obs}})/(3k)$ in the observer's frame, where $\delta_{\text{w}} = [(1 - \beta^2 \cos^2 \theta_{\text{obs}})(\beta^2)]^{1/2}$ is the Doppler factor of the wind for an observer viewing it at an angle $\theta_{\text{obs}}$ to its velocity. $\beta = v/c$ is the relative velocity $v$ to the speed of light $c$ and $k = 1.38 \times 10^{-23} \text{ eV} \cdot \text{K}$ is the Boltzmann constant. The most general, immense energy arises when $\delta_{\text{obs}} \lesssim 1/\Gamma$ is small and the wind is viewed head-on, corresponding to $\delta_w \Gamma > 1$. The energy density of the thermal radiation $\epsilon$ in the wind frame is

$$U_w = \frac{\pi^2 m_e c^2}{15} \frac{\epsilon}{\lambda_e} \Omega_w a^2 = a T_w^4,$$

for dimensionless temperature $\Theta_{\text{w}} = k T_{\text{w}}/(m_e c^2)$, where $\lambda_e = h/(m_e c)$ is the reduced Compton wavelength of an electron, $a = 7.56 \times 10^{-13} \text{ erg cm}^{-2} \text{ K}^{-1}$ is the radiation constant, and $\Theta_{\text{w}}$ is the reduced Planck constant. The corresponding pressure is $P_w = U_w/3$, and its enthalpy is $W_w = U_w + P_w = 4 U_w/3$. Boosting to the star frame, the energy flux of the photons through a surface locally perpendicular to this boost is

$$\mathcal{F}_\text{th}(\delta_w) = \delta_w^2 W_w = \frac{4\pi^2 m_e^2 c^2}{45} \frac{\epsilon}{\lambda_e} \delta_w^2 \Omega_w a^2,$$

so that $\mathcal{F}_\text{th}(\delta_w) \propto \delta_w^4$. We choose bulk $\delta_w = \Gamma = 100$, as deduced from simple spherical dynamics arguments. Setting $\delta_w = k T_{\text{w}}/(m_e c^2)$ yields a thermal energy flux of $\mathcal{F}_\text{th}(\delta_w) = 8 \times 10^{-7}(10^9/\delta_w) \text{ erg cm}^{-2} \text{ s}^{-1}$. This is clearly much larger than the aforementioned flux inferred from observations, and much more so assuming that the radiation emanates from altitudes $r \gtrsim 10^{-10}$ cm, where the plasma becomes transparent to electron scattering. Adopting a smaller Doppler factor ($\delta_w = 10$), which more closely accommodates the $\Gamma = 6$ bound obtained from the pair transparency considerations, increases the thermal flux and makes the disparity with the observed flux much more extreme. Thus, the thermalization in the wind is incomplete, consistent with the inherently non-Planckian form of the spectra at all times. Then, the radiation pressure exerted on the plasma is less than that inferred by applying traditional spherical GRB thermal fireball models, possibly by factors of around 10–100.

The GBM emission is subject to prolific Compton or Thomson scattering by electrons and positrons, which shape the non-thermal spectrum. The observer-frame pair density $n_\gamma$ of the wind couples to the radiation density $n_e$ through a multilayered interplay between expansion dynamics, the geometry of the flaring magnetic field lines that guide the outflow at altitudes below $10^{-10}$ cm, radiative transfer in a strongly magnetized plasma, and magnetic opacity and pair equilibria in the wind frame. The complexities of these are beyond the scope of this paper. Yet, for a mean electron energy $\langle m_e c^2 \rangle$ in the observer frame, we connect $n_e$ to the emitted energy flux via a simple estimate $n_e \langle m_e c^2 \rangle = \mathcal{F}(R)$ for some unknown radiative efficiency $\epsilon$ that is anticipated to not be vastly different from unity. Using Table 1 for interval (3) indicates that $\mathcal{F}(R) = 2 \times 10^{-30}(10^9 \text{ cm}/R)^2$ erg cm$^{-2}$ s$^{-1}$. Assuming $\epsilon = 1$, we discern that at the stellar surface (where $\Gamma = 1$) $n_e = 8 \times 10^{-32} \text{ cm}^{-3}$ and the optical depth $\tau_e = n_e \sigma_T R$ to Thomson scattering (of cross-section $\sigma_T = 6.65 \times 10^{-25} \text{ cm}^2$) is probably about $5 \times 10^4$. $\tau_e$ does not drop below unity until altitudes of $R > 10^9$ cm, because $n_e \approx R$ and the magnetic field line colatitude $\theta$ and radius $R$ satisfy $\sin^2 \theta = R$ in the flaring dipolar field geometry. Magnetic reduction of the scattering opacity can lower this transparency radius by a decade or so, and concomitantly decrease the radiation pressure and lower the ultimate bulk Lorentz factor.
A key GBM result is the exponentially decaying tail of the flux in the interval (4) (3–136.4 ms), after the initial spike (Fig. 2). During this decay, which is on a timescale $\tau = 45$ ms, there is a distinctive $\mathcal{F} \sim F_{p}^{\delta}$ correlation (Fig. 2). This is the hallmark of a relativistic wind. The intrinsic couplings of observer frame flux ($\mathcal{F} \sim F_{p}^{\delta}$) and peak energy ($E_{p} = \delta_{0}$) identified above are true for a relativistic boost from the wind frame regardless of whether the photons are thermalized in the wind or not. Combined, they naturally generate the observed $\mathcal{F} \sim F_{p}^{\delta}$ correlation at an approximately fixed emission radius. A distribution of $\delta_{0}$ is anticipated when sampling flare evolution, because $\theta_{\text{obs}}$ changes substantially as the magnetar rotates, precipitating spread in the $E_{p}$ and $\mathcal{F}$ distributions. Flaring of the magnetic field lines when sampling different emission radii may modestly broaden these distributions.

The extremely short rise time ($T_{\text{rise}} = 80$ µs) corresponds to a physical scale of $cT_{\text{rise}} = 2.4 \times 10^{7}$ cm. The decay time of the tail is a factor of about 550 longer. These times can potentially constrain emission region sizes that are vastly smaller than those inferred for GRBs from their variability times. Yet this connection is affected by the physical rotation of the magnetar. The decay timescale of the tail is $\tau = 45$ ms corresponds to a stellar rotation through an angle of $\delta \theta = 2^\circ$ for a magnetar of typical period ($p \approx 8$ s). This type of duration is naturally expected for relativistic beaming of radiation from outflows with $f = 1/\theta_{\text{coll}} = 30$ for $\theta_{\text{coll}} = 2^\circ$. Even if the physical angular extent of the emission region exceeds $\theta_{\text{coll}}$, Doppler boosting dictates that the dominant signal will arise when the instantaneous observing angle to the wind velocity is of the order of $\theta_{\text{obs}} \lesssim \theta_{\text{coll}}$. Thus, a picture emerges in which we might be seeing in the GBM, Swift–BAT and KONUS–Wind signals is produced through stellar rotation of the Lorentz cone of Doppler-boosted emission in and out of our view. Accordingly, temporally scales of $\tau = p/(2\tau_{f})$ may be signatures of the relativistic beaming structure associated with the giant flare wind convolved with the rotation of the magnetar, termed a relativistic lighthouse sweeping effect. The greater Doppler boosting near the $\theta_{\text{obs}} \lesssim \theta_{\text{coll}}$ core of the Lorentz cone would yield harder spectra near the peak of intensity and softer spectra in its ingress and egress, as is observed in Fig. 1.

**Quasi-periodic search and analysis**

Quasi-periodic oscillations (QPOs) have been observed previously during three giant flaring episodes, from SGR 0526–66, SGR 1806–20 and SGR 1900+14, at frequencies of $18–625$ Hz. Of these, the QPO detections for SGR 1806–20 and SGR 1900+14 were restricted to the oscillating tails well after the conclusion of the initial spike. These periodicities have been interpreted as signatures of torsional subsurface seismic oscillations triggered by the cataclysmic rupturing of the crust seeding the giant flares.

We searched for a spin frequency over the range $v = 0.02–50$ Hz using an unbinned and a logarithmically binned periodogram; in particular, we searched for signals with at least $P < 0.01$ (corrected for the number of frequencies and segments). We did not detect any signal that could be associated with stellar rotation.

We searched for QPOs in the NaI GBM data for GRB 200415A using the same methodology used to search for QPOs in the GBM data for SGR J0501+4316, over the range $v = 40–4,000$ Hz. Owing to telemetry packets dropping shortly after the peak, we searched three segments independently: the initial spike, $T_{\text{split}} = [5–5.5]$ ms; the fall time, $T_{\text{split}} = [7, 160]$ ms; and a long segment of 200 s after the initial spike to look for potential neutron-star pulsation nominally in the range 0.05–1 Hz in the putative subbackground emission. We find no credible signal in the initial spike or the long segment. In the burst decay, we find a potential broad QPO candidate with moderate significance at $v = 180$ Hz. Because the signal is broad, we use three different strategies to establish its significance. First, we determine that the trial-corrected $P$ value (probability) for a logarithmically rebinned periodogram under the assumption of pure white noise is $P = 8.3 \times 10^{-4}$. However, the frequency of the candidate places it at the edge of the frequency regime in which stochastic variability in the form of red noise is important. To test whether the QPO could be explained by a combination of the overall decay of the lightcurve and the associated window function, we fit the lightcurve of this segment with an exponential function, and draw 1,000 sets of parameters from a multivariate Gaussian using the best-fitting solution and inverse Hessian derived from the optimization. We use these parameters to generate simulated lightcurves from the exponential function by adding white noise and generating periodograms in the same way as we did for the data. The $P$ value for a QPO at that frequency under the assumption of an exponentially decaying lightcurve is $P = 0.023$, indicating that although less decisive a decay, a potential QPO is possible.
Data availability
y-ray data from CGRO–BATSE, Swift–BAT and Fermi–GBM are available in public repositories on NASA’s High Energy Astrophysics Science Archive Research Center (HEASARC; https://heasarc.gsfc.nasa.gov/w3Browse/all/batsegrb.html; https://heasarc.gsfc.nasa.gov/W3Browse/swift/swiftgrb.html and https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html, respectively); catalogues of these data are provided as citations. The raw VLA data are publicly available (https://archive.nrao.edu). The calibrated VLA data and images are available from the corresponding authors on reasonable request.

Code availability
Standard software packages, such as rmfit for GBM and XSPEC for other instruments, are available online (https://fermi.gsfc.nasa.gov/ssc/data/analysis/rmfit/ and https://heasarc.gsfc.nasa.gov/docs/software.html, respectively). The codes used to determine the significance of the BGO photons, to construct the BAT TTE detector response matrices and to determine the rise time are available from the corresponding authors on reasonable request. The VLA data were analysed using publicly available software (CASA). The procedure for detecting and quantifying the QPOs is publicly available in Stingray (https://stingray.readthedocs.io/en/latest/). The algorithm used to determine the pulse pile-up of the GBM data is available in ref. 35. The SwiMM code is not publicly available; however, response functions can be used to reproduce our spectral results; these are available from the corresponding authors on reasonable request.

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Extended Data Fig. 1 | The duration of GRB 200415A. The $T_{90}$ (green) and $T_{50}$ (purple) durations were calculated using the Swift–BAT data in count space. The errors are at the 1σ confidence level.
Extended Data Fig. 2 | Spectra and fitted models in three time intervals for GRB 200415A. The $\nu F_\nu$ spectra (top) and Comptonized fitting residuals (bottom) are shown for intervals (1) (left), (3) (centre) and (4) (right) of GRB 200415A. The three spectra are devoid of any instrumental effects attributed to bandwidth saturation. The fit parameters are listed in Table 1. These figures show the robustness of the fits to the data ($1\sigma$ confidence), which are used in the main text and in Fig. 1d, and are a direct result of the unrivalled temporal and spectral quality of the GBM data. Arrows on the error bars are due to the lower or upper limits being unconstrained. The solid blue lines are the best fits to the data.
Extended Data Fig. 3 | Energetic photons from GRB 200415A. The grey histogram represents the counts with energies of 0.2–40 MeV (left axis). Individual TTEs of GBM BGO detector 0 are shown as black circles, superimposed over the grey histogram, with photon energies in MeV (right axis). The blue rectangle indicates energies of 2.5–3.5 MeV in intervals (2) and (3); the red rectangle shows energies of 3.5–10 MeV. We conclude that the highest photon energy unambiguously associated with GRB 200415A is 3 MeV.