The discovery of long-lasting (∼ 100 s) X-ray flares following short gamma-ray bursts initially called into question whether they were truly classical short-hard bursts\textsuperscript{1,2}. Opinion over the last few years has coalesced around the view that the short-hard bursts arise from the merger of pairs of neutron stars, or a neutron star merging with a stellar-mass black hole\textsuperscript{3-5}. The natural timescales associated with these processes\textsuperscript{6}, however, essentially preclude an X-ray flare lasting ∼ 100 s. Here we show that an interaction between the GRB outflow and a non-compact stellar companion at a distance of ∼ a light-minute provides a natural explanation for the flares. In the model, the burst is triggered by the collapse of a neutron star after accreting matter from the companion. This is reminiscent of type Ia supernovae, where there is a wide distribution of delay times between formation and explosion, leading to an association with both star-forming galaxies and old ellipticals.
months has been the measurement and localization of fading X-ray signals from several short GRBs, making possible the optical and radio detection of afterglows, which in turn enabled the identification of host galaxies at cosmological distances\(^7\)–\(^{10}\). The presence in old stellar populations e.g., of an elliptical galaxy for GRB050724, rules out a source uniquely associated with recent star formation\(^{11}\). In addition, no bright supernova is observed to accompany short GRBs\(^7,\)\(^8,\)\(^{12}\), in distinction from most nearby long-duration GRBs\(^{13}\). The current view of most researchers is that short GRBs arise when a neutron star (NS) binary or neutron star-black hole (BH) binary, which loses orbital angular momentum by gravitational wave emission, undergoes a merger\(^3\)–\(^5\). Current calculations of compact binary mergers suggest that high spatial velocities would take these binaries, in more than half of the cases, outside of the confines of the host galaxy before they merge and produce a burst, in agreement with current observations\(^{14,\)\(^15}\).

Recently, long duration (\(\sim 100\) s) X-ray flares have been observed to follow several short GRBs\(^{16,\)\(^17}\), e.g., GRB050724, after a delay of \(\sim 30\) s. There is also independent support that X-ray emission on these timescales is detected when lightcurves of many bursts are stacked\(^{18}\). One possible interpretation of these (rapidly declining) flares is that a large fraction of energy continues to be emitted by the GRB source for as long as minutes\(^{17}\). This hints at the desirability for a "central engine" lasting much longer than a typical dynamical time scale for a stellar mass compact object. This is in disagreement with theoretical estimates, which suggest that NS-NS and NS-BH mergers will lead to brief energy input episodes, typically of the order of the duration of a short burst\(^6\). It is argued here that the flare emission is, however, naturally produced by the interaction of the extended - possibly magnetically dominated - ejecta emanating from a short
GRB with the envelope of a giant companion star. This more isotropic GRB ejecta component need not necessarily dominate the total burst energetics, but it can be efficiently reprocessed by the envelope of the companion star at distances $\sim 10^{12}$ cm, into an X-ray flare with a luminosity and timescale comparable to the observed values. The portion of the ejecta shell not impacting the star expands undisturbed to large radius ($10^{14} - 10^{16}$ cm) where internal shocks or magnetic dissipation convert its energy into $\gamma$-ray photons as envisioned in standard models\(^\text{19}\). The observer is envisioned here to be located out of the plane of the binary. Soft X-rays produced during the collision, although produced at smaller radii than the $\gamma$-rays, are observed to arrive after the GRB. Under this interpretation, the GRB engine is not required to operate for longer than a typical burst duration of 0.1-1 s. We note here that, in addition to the rapidly declining $\sim 100$ s flare, GRB 050724 rebrightens\(^\text{17}\) after $\sim 10^4$ s. Given its slower decline, this feature has a satisfactory standard\(^\text{19}\) explanation: as the leading edge of fast ejecta moves farther away from the central engine, it starts to decelerate and is caught up by slower-moving material, creating a 'refreshed shock'.

Three snapshots from numerical simulations of a GRB ejecta shell as it expands, makes contact with a red giant star, and ultimately engulfs it, are shown in Figure 1. The interaction begins with the formation of a strong shock as the shell is rapidly decelerated from $\Gamma_i \sim 400$ to $\Gamma_f \sim 1$ in the surface layers of the star, dissipating a large fraction of its kinetic energy. Internal energy is created rapidly and remains at a few $10^{49}$ erg for at least $\sim 100$ s (Figure 2). The initial rise in internal energy takes place immediately after the shell reaches the stellar surface, 30 s after the GRB. A strong shock forms, starting where the two spheres first touch, then subsequently spreads as an
increasingly larger portion of the stellar surface is hit. The rate of energy dissipation as the shell sweeps across the star - for a GRB located approximately one stellar radius from the stellar surface - is roughly given by $\dot{E} \approx E c / (4 R_*) = 7.5 \times 10^{48} (E / 10^{51} \text{ erg}) (R_*/10^{12} \text{ cm})^{-1} \text{ erg/s}$, where $E$ is the total energy in the ejected shell, $c$ is the speed of light and $R_*$ is the stellar radius. This simple estimate yields luminosities that are consistent with those found in numerical calculations shown in Figure 2. A few hundred seconds after the GRB (bottom panel of Figure 1), the shell has almost entirely wrapped around the star and fresh material is no longer being shocked. The internal energy declines rapidly after the GRB flare finishes shocking the star bringing the flare emission to an abrupt end. The decay slope of the corresponding lightcurve may be substantially modified by radiative effects. However, the dissipated energy has the correct magnitude, delay and duration to account for the observed properties of X-ray flares in short GRBs.

The flares observed after the GRB 050724 and GRB 050709 bursts corresponds, for their assumed distances of $z = 0.257$ and $z = 0.16$, to $E_f \sim 6 \times 10^{49}$ erg and $E_f \sim 3 \times 10^{49}$ erg respectively in the $2 - 25$ keV band. How is energy dissipated during the GRB-star interaction (Figure 2) transformed into soft X-ray radiation? One possibility is that the GRB ejecta shell develops a stand-off shock before encountering the stellar envelope. The post-shock region generates turbulent magnetic fields and accelerates electrons which produce a synchrotron power-law radiation spectrum. The magnetic field strength would be of order $10^4$ G at $10^{12} \text{ cm}$, strong enough to ensure that the shock-accelerated electrons cool promptly, yielding a power-law continuum extending into the X-ray band. Some of these X-rays would be deflected along the stellar surface before escaping, but about half (the exact proportion depending on the geometry and flow pattern)
would irradiate the material in the stellar envelope. For the high radiative efficiencies expected in relativistic shocks, radiative heating of the shocked material would be comparable to that of bulk heating\(^{20}\). However, radiative heating deposits energy near the stellar surface in layers with modest scattering optical depth, the temperature being determined by photoionization equilibrium. This shallow radiatively heated layer would be expected to be substantially hotter than a deeper bulk-heated region. For low radiative efficiencies, on the other hand, energy deposition by bulk heating would spread over a highly optically thick layer. In this case, the cooling rate, mainly due to bremsstrahlung, recombination and Comptonization, would be high enough to reduce the temperature of the bulk-heated electrons to the equivalent black body temperatures of \( T \sim \) a few tens of keV. This suggests that, for the conditions envisaged here, most of the flare luminosity in the X-ray band could be thermal. This is consistent with numerical results where a pressure of \( 10^{15} \) dyne cm\(^{-2}\) behind the shock (see the middle panel of Figure 1), corresponds to a black-body temperature of \( \sim 2.5 \times 10^7 \) K and a characteristic photon energy of \( \sim\) a few keV. We note that a radiatively-heated layer with a density up to \( n_e \sim 10^{21} \) cm\(^{-3}\), could produce strong Fe line emission provided that the ionization parameter \( \xi = \beta L/(r^2 n_e) \) exceeds\(^{21}\) \( 10^3 \), where \( L \) is the total luminosity of the GRB outflow and \( \beta \) is the fraction of the power that goes into X-ray continuum. This condition is indeed satisfied unless \( \beta < 10^{-2} \). Thermal X-ray emission could also display line features, and such signatures should certainly be looked for. We note that the GRB shell must be optically thin when its radius is \( \sim 10^{12} \) cm so that the shocked star is visible through the GRB shell. This requires that the GRB ejecta contain \( 10^{-8} \) M\(_{\odot}\) or less and suggests that a magnetically dominated flow may be preferred\(^{22}\).
Shock heating of a binary stellar companion has other interesting consequences. Before the passage of the GRB ejecta, \( \sim 10^{-2} \, M_\odot \) of the envelope of the companion star is compressed by the shock and heated. The deposited energy, a few \( 10^{48} \) erg, will cause the outer layers of the star to expand explosively. This will not, however, produce a supernova, for two reasons. First, the shock temperatures are too low for radioactive elements such as \( \text{Ni}^{56} \) to be produced. Second, the amount of ejected debris is small. Instead, after the expanded envelope becomes optically thin, a faint infrared/optical transient would appear a few weeks after the GRB.

Finally, we offer a few comments on the progenitor systems in which this interaction can naturally occur. Models in which the short GRB results from the collapse of a rapidly rotating neutron star in a close binary system provide a natural scenario. In the model, the neutron star accretes matter from the stellar companion, eventually collapsing to form a black hole. The angular momentum in the equatorial region of the rapidly-spinning system is too large to be swallowed immediately when the black hole forms. The expected outcome, after a few milliseconds, would therefore be a spinning black hole orbited by a torus of neutron-density matter. The mass in these disks is found to range from \( M_t \sim 10^{-3} - 10^{-2} M_\odot \). If magnetic fields anchored in the disk do not thread the black hole, then a relativistic outflow powered by torus accretion can at most carry the gravitational binding energy of the torus. The extractable energy in this case is several times \( 10^{50} \, \epsilon (M_t/10^{-3} \, M_\odot) \) ergs, where \( \epsilon \) is the efficiency in converting gravitational energy into relativistic outflow. If magnetic fields of comparable strength thread the black hole, its rotational energy offers an extra (and even larger) source of energy that can in principle be extracted via the Blandford-Znajek mechanism\(^{24} \).
Not surprisingly, there is more than one way to produce a rapidly rotating, neutron star in a close binary\textsuperscript{15} including, for example, a common envelope evolution in which a neutron star is enveloped by the expanding atmosphere of a giant companion. Alternatively, a binary initially containing two massive stars, could form a neutron star and helium star binary. During the common envelope phase, the neutron star may accrete over one solar mass and collapse\textsuperscript{25}. Thus, we expect these systems to be associated with star forming regions. Reminiscent of what is observed in type Ia supernovae, the model predicts a wide distribution of delay times between formation and explosion, and in turn the association of short hard GRBs with both star forming galaxies and with ellipticals dominated by old stellar populations\textsuperscript{10}.

Neutron stars inspiralling into a stellar envelope can accrete at rates vastly exceeding the Eddington limit if the flow develops temperatures high enough to allow neutrinos to radiate the gravitational binding energy. The fate of the neutron star depends on a sensitive balance between the rate at which it accretes and the rate at which energy is deposited into the common envelope\textsuperscript{26}. Its chances for survival are therefore diminished both by increasing the accretion rate and by augmenting the epoch of common-envelope evolution. Observationally, several binary pulsars are known whose properties are consistent with the neutron star having survived a phase of common-envelope evolution. Camilo et al.\textsuperscript{27} identify four pulsars which have relatively large companion masses in excess of $0.45M_\odot$. These systems are likely to have undergone deep common-envelope evolution with low-mass companions\textsuperscript{28} $(1 - 3M_\odot)$. If the neutron star is to be able to accrete a large mass during inspiral, the initial distance between the two stars after the first mass transfer exchange should not be much larger\textsuperscript{25} than $R_s$. This ensures that a companion star struck by the
expanding GRB outflow will intercept a large fraction of the ejected material, thus ensuring the production of a bright flare.

Much progress has been made in understanding the nature of cosmological gamma-ray bursts. Still, various alternative ways of triggering the explosions responsible for short GRBs remain: NS-NS or NS-BH binary mergers, spun-down supramassive NS\textsuperscript{29} and accretion induced collapse of a NS. The presence of X-ray flares may help distinguish between viable progenitors. In the absence of a supernova-like feature, the interaction of GRB ejecta with a stellar binary companion may be the only observable signature in the foreseeable future shedding light on the identity of the progenitors of cosmological short bursts.

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Collision of GRB ejecta with a companion red giant star showing the logarithm of pressure at $t = 10s$ (top), $t = 42s$ (middle) and $t = 184s$ after the GRB. The observer is located envisioned to be out of the binary plane toward the top of the figure. In the top panel, the small orange circle is the GRB ejecta and the larger purple sphere is a red giant star with radius $1.5 \times 10^{12} \text{ cm}$. The ejecta form a spherical shell containing $2 \times 10^{25} \text{ g} (10^{-8} M_\odot)$ expanding at nearly the speed of light. 30 seconds after the GRB, the ejecta collide with the surface of the red giant and are rapidly decelerated in a strong shock. The internal energy produced during the collision is capable of explaining the energetics of the observed X-ray flares. The middle panel shows the GRB blastwave and shocked star 12 seconds after impact. The dark red region is the X-ray emitting region. In the bottom panel, the blastwave has wrapped around the star. At this time, the energy of the blastwave is mainly kinetic. The orange region in the middle panel and the green region in the bottom panel show the reflected ejecta shell traveling leftward toward to GRB source. The undisturbed shell expands close to the speed of light for at least two orders of magnitude in radius before producing the prompt GRB. We used the RAM code to solve the conservative equations of special relativistic hydrodynamics. The computational domain for the simulations was $0 < r < 1.2 \times 10^{12} \text{ cm}$ with a maximal resolution of $\Delta r = 4.7 \times 10^7 \text{ cm}$ for 1D and $-1.2 \times 10^{13} \text{ cm} < z < 1.2 \times 10^{13} \text{ cm}$, $0 < r < 1.2 \times 10^{13} \text{ cm}$, with $\Delta z = \Delta r = 7.32 \times 10^8 \text{ cm}$ for 2D. A gamma law equation of state with $\Gamma = 4/3$ was used and the ambient density was 100 baryons $\text{ cm}^{-3}$.

Figure 2  Total internal energy. As the cold GRB shell collides with the stellar surface a large fraction of the energy in the blast wave is converted to internal energy in a shock. Internal energy
is produced with magnitude, duration and delay appropriate for being the source of X-ray flares observed to follow short GRBs. The sharp decline in the flare is easily explained by the finite time the companion's surface is actively shocked. In this figure, the remaining internal energy is being reconverted to kinetic energy and is not expected to contribute to the flare lightcurve.