morphologies controlled, combined with the fact that its monoradical state is stable under ambient conditions, gives this compound great potential for incorporation into organic radical frameworks (*31*, *32*), electronic memory devices (*33*–*35*), semiconductors (*36*), and energy storage devices (*37*).

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Supplementary Materials

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Materials and Methods
Supplementary Text
Schemes S1 and S2
Figs. S1 to S18
Tables S1 to S3
References (*38*–*43*)

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Identification of the Long-Sought Common-Envelope Events

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Common-envelope events (CEEs), during which two stars temporarily orbit within a shared envelope, are believed to be vital for the formation of a wide range of close binaries. For decades, the only evidence that CEEs actually occur has been indirect, based on the existence of systems that could not be otherwise explained. Here we propose a direct observational signature of CEEs arising from a physical model where emission from matter ejected in a CEE is controlled by a recombination front as the matter cools. The natural range of time scales and energies from this model, as well as the expected colors, light-curve shapes, ejection velocities, and event rate, match those of a recently recognized class of red transient outbursts.

Many binary star systems, including X-ray binaries, cataclysmic variables, close double-neutron stars, and the potential progenitors of Type Ia supernovae and short-duration γ-ray bursts, are thought to be formed by common-envelope events (CEEs). Because most stellar-mass binary merger sources for gravitational waves have experienced a CEE in their past, improved knowledge of CEEs should decrease the large uncertainty in theoretically predicted merger rates. However, the short time scale expected for CEEs suggested that we would never directly observe them, allowing us only to draw inferences from the systems produced.

A CEE begins when a binary orbit becomes unstable and decays. This might, for example, be driven purely by tidal forces (i.e., the Darwin instability), although CEEs are more commonly imagined as occurring after a period of rapid mass transfer from one star to the other (*1*). In some cases, the rate of transfer is so high that the receiving star is unable to accrete all the matter without forming a shared common envelope (CE) around the binary. This CE causes drag on one or both stars and hence orbital decay, with orbital energy and angular momentum being transferred to the CE. This may end with a stellar merger or—if the CE is ejected—the binary may survive, typically with a much reduced orbital separation, critical to explaining many observed compact binaries.

When a CEE results in formation of a close binary, it is expected that a substantial proportion of the mass is ejected—typically almost the entire envelope of one of the stars. Some mass can also be ejected in the case of a merger. This partial ejection has two causes (*2*). First, the orbital energy deposited into the CE early in the merger may exceed the binding energy of

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the outer layers. Second, angular momentum transport may be too slow for the angular momentum absorbed by the upper layers of the envelope to be redistributed across the envelope as a whole.

Here we consider the behavior of this ejected matter to try to predict the appearance of CEEs. A situation involving similar physics—Type IIP supernovae—has been studied previously [e.g, (*3–5*)]. In that model, as the ejected stellar plasma expands and cools, recombination changes its opacity, leading to the propagation of a photosphere-defining "cooling wave," which moves inward with respect to the mass variable.

For smooth and spherically symmetric ejecta distributions, the model light curve will have a plateau shape: The area of the photosphere is defined by recombination, and so the emitting surface does not grow with the speed at which the ejected matter itself moves. During this phase, whereas material ejected by the CEE will expand with velocity of the order of magnitude of the initial escape velocity, the photospheric radius should appear almost constant. The luminosity L_P of the emission during the plateau (*3–5*), rescaled to the likely energy range of CEE, is

$$L_P \approx 1.7 \times 10^4 L_\odot \left(\frac{R_{\rm init}}{3.5R_\odot}\right)^{2/3} \left(\frac{E_k^\infty}{10^{46}{\rm erg}}\right)^{5/6} \times \left(\frac{m_{\rm unb}}{0.03M_\odot}\right)^{-1/2} \left(\frac{\kappa}{0.32\ {\rm cm^2 g^{-1}}}\right)^{-1/3} \times \left(\frac{T_{\rm rec}}{4500\ {\rm K}}\right)^{4/3} \quad (1)$$

where $R_{\rm init}$ is the initial radius, E_k^∞ is the kinetic energy of the unbound mass $m_{\rm unb}$ at late times after escaping the potential well, κ is the opacity of the ionized ejecta, and $T_{\rm rec}$ is the recombination temperature. The duration of the plateau t_P with the same assumptions is

$$t_P \approx 17\ {\rm days} \left(\frac{R_{\rm init}}{3.5R_\odot}\right)^{1/6} \left(\frac{E_k^\infty}{10^{46}{\rm erg}}\right)^{-1/6} \times \left(\frac{m_{\rm unb}}{0.03M_\odot}\right)^{1/2} \left(\frac{\kappa}{0.32\ {\rm cm^2 g^{-1}}}\right)^{1/6} \times \left(\frac{T_{\rm rec}}{4500\ {\rm K}}\right)^{-2/3} \quad (2)$$

This model does not depend on the origin of the energy released during the outburst. For Type IIP supernovae, recombination controls the release of the internal energy generated by strong supernova shocks. For CEEs, however, there is no such supernova-provided energy input. Instead, the energy released by recombination itself may dominate the energy budget of many outbursts (*6*). The unbound mass $m_{\rm unb}$ could potentially radiate—simply due to recombination—as much energy as

$$E_{\rm recom} \cong 2.6 \times 10^{46} {\rm ergs} (X + 1.5 Y f_{\rm He}) \frac{m_{\rm unb}}{M_\odot} \quad (3)$$

Here X is the mass fraction of hydrogen and Y is the mass fraction of helium. Hydrogen would initially be ionized in almost all of the likely ejected material from most stars; however, helium may be fully ionized only in some fraction of it, denoted $f_{\rm He}$. The role of recombination in a CEE has hitherto been debated in the overall energy balance, the controversy arising from whether it can be effectively converted into mechanical energy to help eject the CE (*7–9*). This energy budget for the outburst may be increased by the thermal energy of the ejecta. Much of the pre-CEE thermal energy of the ejecta may be expended on adiabatic cooling (*6*). However, the shock heating caused by the CEE could well be substantial in some cases.

To estimate the extent of the parameter space of CEE outbursts, we use the model described above to predict the diversity of real events. We assume that E_k^∞ scales with the gravitational potential at the surface of the primary star (*2*) and use the dimensionless factor ζ to write $E_k^\infty = \zeta(Gm_1^2 f_m)/R_{\rm init}$, where $f_m = m_{\rm unb}/m_1$ is the fraction of the total primary mass m_1 that becomes unbound. From Eqs. 1 and 2, this leads to $L_P \propto (f_m^2 m_1^7 R_{\rm init}^{-1} \zeta^5)^{1/6}$ and $t_P \propto (f_m^2 m_1 R_{\rm init}^2 \zeta^{-1})^{1/6}$. Two families of events seem likely, one for mergers (i.e., $f_m << 1$) and one for CE ejection (i.e., $f_m \leq 1$) (Fig. 1).

In addition to the predicted ranges of outburst energy and duration, this model for CEE outbursts has several noteworthy features. The physics that causes the plateau-shaped light curve should lead to a difference in the phometrically inferred expansion velocity and the actual material velocity (which could be inferred from spectra). The effective photospheric temperature should be ~5000 K for thick ejecta (*4*), and so the outburst color will naturally be red. In addition, once the ejected envelope has fully recombined, the material may suddenly become transparent, unless enough of the ejecta has cooled down sufficiently to produce dust. These characteristics are reminiscent of curious transients with predominantly red spectra that were recently detected in the local universe [e.g., (*10–16*, *17*)]. This empirical class has been dubbed luminous red novae (LRNe), a subset of the even more ambiguously defined class of intermediate-luminosity red transients (ILRTs) (*2*). ILRTs cover a wide range of outburst energies, from 10^{45} to a few 10^{47} ergs (brighter than the brightest novae but still fainter than Type Ia supernovae). They are characterized by spectroscopically inferred expansion velocities of 200 to 1000 km/s—much lower than would be expected for novae or supernovae and also markedly different from the photometric expansion velocities (*18*). In addition, some could be seen as red giants within a dozen years after the outburst (*16*, *19*).

It was not known what ILRTs are or whether they have a common cause; several ideas have been suggested (*2*). A model that considered the possibility that LRNe are caused by stellar mergers—a subset of CEEs—has been independently considered several times for different LRN outbursts, though further examinations of outburst features always showed various drawbacks. However, those problematic features do match expectations from our CEE-driven outburst model (*2*).

A particular feature of the LRN outbursts—as opposed to all ILRTs—is the presence of a plateau in their luminosity curves. We compare well-known LRNe (*2*) to the expected CEE diversity in Fig. 1. The agreement is pronounced, especially given the simplicity of the model and the potential complexities it neglects—e.g., how CEE ejecta deviate from spherical symmetry, or how much ζ for mergers might be different from ζ for full envelope ejection (*2*).

M85 OT2006-1 is an LRN with well-known peak luminosity and plateau duration. If the luminosity from M85 OT2006-1 was largely from recombination, ~1.5 $M_\odot$ of plasma would have recombined to provide the observed total energy. This fits with constraints on the progenitor mass (≤2 $M_\odot$) from the stellar population age (*20*). Thus, M85 OT2006-1 plausibly ejected the whole envelope of a low-mass giant. This outburst showed a plateau, with luminosity ≈1 × 10^6 to 2 × 10^6 $L_\odot$ (*21*) for ≈60 to 80 days, and had expansion velocities of 350 km/s (*14*). Our inferred ejecta mass and the observed expansion velocity indicate a kinetic energy of ~1.8 × 10^{48} erg. Then, $R_{\rm init}$ = 45 $R_\odot$, self-consistent with our model, gives L_P ~ 10^6 $L_\odot$ and t_P ~ 70 days.

Another recent outburst, V1309 Sco, is similar to, but fainter than, most LRNe, as it radiated away only ~3 × 10^{44} erg during a ~25-day plateau-shaped maximum in the light curve (*19*). The progenitor was a contact binary with a relatively rapidly decaying orbital period of ~1.4 days. After the outburst, the system appeared to be a single star; therefore, this appears to have been a CEE, leading to a merger (*19*). However, several features of the V1309 Sco outburst, in particular the plateau in the light curve and sudden transparency, were difficult to reconcile with prior theoretical expectations for the appearance of a CEE (*2*).

Because the V1309 Sco progenitor was observed in detail, this system is ideal for testing our model. Beginning with the properties of the premerger contact binary (*19*, *22*), we calculated the amount of material that became unbound during the V1309 merger using two methods—simple energy balance using a one-dimensional (1D) stellar code and a set of 3D hydrodynamical simulations (*2*). Both methods predict that a small mass, ~0.03 to 0.08 $M_\odot$, will become unbound. Complete recombination of this ejected mass would provide enough energy (≥7 × 10^{44} ergs)

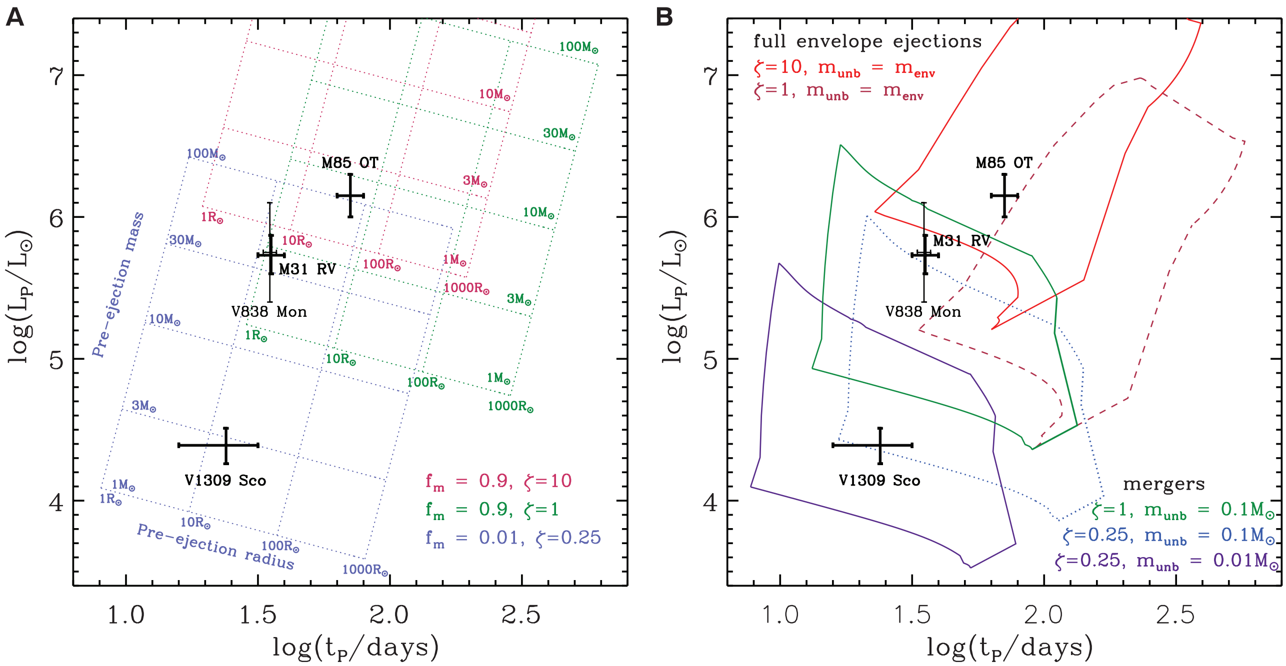

Fig. 1. (**Left**) Model diversity in the L_P–t_P parameter space is indicated by lines representing constant primary mass and radius. f_m is fractional mass loss and ζ is the kinetic energy at infinity, parametrized as a fraction of the binding energy at the surface of the primary star. Stellar mergers are in a regime of little mass ejection, whereas f_m = 0.9 approximates full envelope ejection. (**Right**) Estimated ranges of the plateau luminosity L_P and duration t_P for primary stars with zero-age main sequence (ZAMS) masses from 1 to 150 $M_\odot$. m_{unb} is the ejecta mass. It is assumed that mergers can happen anytime during the primary star's evolution, whereas full envelope ejection can occur only for post–main-sequence primary stars. We used fitting formulae for stellar evolution (*24*), at $Z_\odot$. In both panels, values for L_P and t_P are marked for the outbursts from V1309 Sco, M85 OT, M31-RV, and V838 Mon.

to explain the total energy output of V1309 Sco. The output of the 3D simulations, combined with Eqs. 1 and 2, predicts plateau durations from 16 to 25 days and plateau luminosities of 1.8 × 10^4 to 2.2 × 10^4 $L_\odot$. These values match the observed luminosity ($L_P \sim 2 \times 10^4 L_\odot$) and plateau duration (about 25 days).

Considering the menagerie of theoretically expected outbursts from CEEs, we note that events in the top right of Fig. 1 should be relatively rare [compare with η Car; see (*2*)], and those in the bottom left (stellar mergers) comparatively hard to detect in a magnitude-limited survey. Assuming that the peak luminosity of the outburst is about an order of magnitude higher than L_P, we find that the whole range of L_P and t_P for stellar masses 1 to 150 $M_\odot$ coincides well with the observed domain for luminosities and durations of LRNe suggested in (*23*). We can estimate the rate of CEE-originated outbursts that appear as red transients, by considering what fraction of stars in the galaxy undergo a CEE. We estimate 0.024 such events per year per Milky Way–like galaxy (*2*), of which about half should be more luminous outbursts (results of a CE ejection) and half are lower-luminosity events (powered by stellar mergers). This is consistent with the empirical lower limit for more luminous ILRTs of 0.019 year^{-1} for the Galaxy (*20*), because we do not expect that all luminous ILRTs must be powered by a CEE [though some non-LRN ILRTs, like NGC 300-OT or SN2008S, might potentially also be triggered by CEEs (*2*)].

The question of whether recombination energy can help to unbind a stellar envelope during a CEE is important for understanding the formation and survival of many binary systems (*8*, *9*). Our model suggests that a large fraction of the energy from recombination is commonly radiated away after a CEE. Such luminosity provides a beacon, which helps to illuminate and identify a CE ejection or merger at large distances. The recombination wave also controls the shape of the plateau-shaped light curve of LRNe. We therefore suggest that detecting and characterizing the population of ILRTs will help us understand CEEs.

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Supplementary Materials

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Supplementary Text
Figs. S1 to S4
Table S1
References (*25*–*74*)
Movies S1 and S2

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Identification of the Long-Sought Common-Envelope Events

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When Stars Get Too Close
Stellar outbursts used to come in two classes: supernovae and novae, the complete explosions and the thermonuclear runaways on the surface of evolved stars, respectively. Over the past two decades a class of stellar outbursts emerged with luminosities between those of novae and supernovae––intermediate-luminosity red transients (ILRTs). **Ivanova *et al.*** (p. 433) propose that these ILRTs are the signature of common envelope events in which a lower-mass star in a close binary system is engulfed by matter transferred from its more massive and more evolved companion star.