Explosive Transients in the Distant Universe

A White Paper Submitted to the Decadal Survey Committee

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1 Celestial Cinema: The new frontier

Astronomical progress has been closely linked to technological progress. Digital sensors (CCDs and IR detectors) were invented and funded by military and commercial sectors, but their impact on astronomy was profound: 2MASS and SDSS simply could not have been possible without the availability of relatively inexpensive sensors.

Thanks to Moore's law[2] astronomers are assured of exponentially cheaper sensors, computing cycles, bandwidth and storage. This windfall is the basis of the new era of wide-field optical and NIR imaging. Wide-field imaging has become a main stream tool as can be witnessed by the success of SDSS and UKIDSS. Future projects such as SkyMapper, PanSTARRS, Palomar Transient Factory (PTF), and Large Synoptic Survey Telescope (LSST) will add to this legacy by exploring new sky or reaching a greater depth. The renaissance of wide-field telescopes opens new opportunities to explore the transient and explosive sky. Indeed, the field of supernovae began with Zwicky's 18-inch Palomar Schmidt telescope. Wide-field imaging, especially by telescopes with very large etendue[3], allows us to probe an entirely new phase space: the cosmic movie.

In this white paper we focus on cosmological transients and ultra-fast transients. A companion white paper (Kulkarni & Kasliwal) presents a discussion of transients in the local Universe, a topic of considerable interest to stellar astronomy, Gravitational Wave astronomy and other multi-messenger astronomy.

2 Cosmological Transients

The phase space of transients (known and anticipated) is shown in Figure 1. The region marked by a big question mark is presently poorly explored and in some sense represents the greatest possible rewards from a deep wide-field survey such as LSST. The limited length of the white paper does not permit an exhaustive compilation of all possible cosmological transients. Here, we discuss a few representative samples.

Orphan GRB afterglows: Gamma-ray bursts (GRBs) are now established to be the most relativistic (known) explosions in the Universe and as such associated with birth of rapidly spinning stellar black holes. We believe that long duration GRBs result from the deaths of certain types of massive stars [37]. The explosion is deduced to be conical ("jetted") with opening angles ranging from less than a degree to a steradian. The appearance of the explosion depends on the location of the observer (Figure 2). An on-axis observer sees the fastest material and thus a highly beamed emission of gamma-rays. The optical afterglow emission arises from the interaction of the relativistic debris and the circumstellar medium. Due to a decreasing relativistic beaming in the decelerating flow, the light curve will show a characteristic break to a steeper decline at $t_{\rm jet} \sim 1$–10 days after the burst. An observer outside the cone of the jet misses the burst of gamma-ray emission, but can still detect the subsequent afterglow emission. The light curve will first rise steeply and then fade by $\sim$1 mag over a timescale of roughly $\Delta t \approx 1.5 t_{\rm jet}$ (days to weeks). We will refer to these objects as "off-axis" orphan afterglows. The "beaming fraction" (the fraction of sky lit by a gamma-

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[2] The number of transistors in commodity integrated circuits has been approximately doubling every two years for the past five decades.

[3] The product of the field of view and the area of the telescope. The larger the etendue the greater the "grasp" of the instantaneous survey volume. Incidentally, the etendue for a radio telescope is unity.

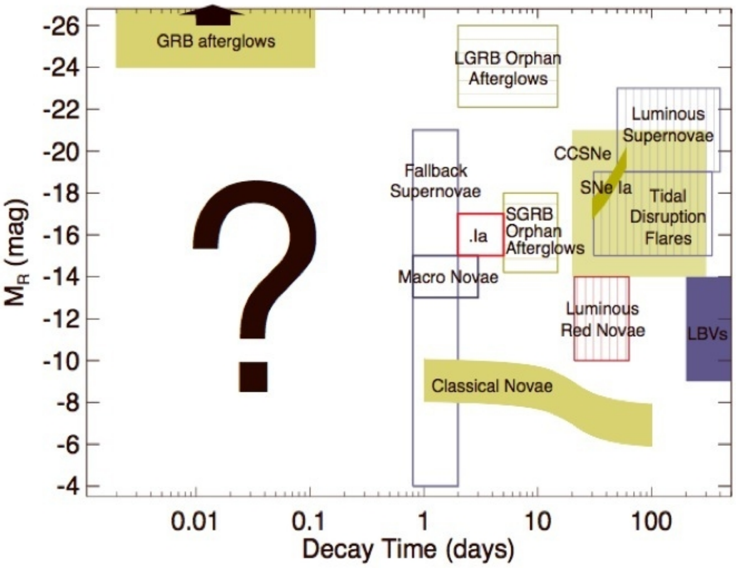

Figure 1: Cosmic transients phase space (peak absolute R-band magnitude vs. decay timescale—typically the time to fade from peak by $\sim$ 2 mag) for luminous optical transients and variables. Filled boxes mark well-studied classes with a large number of known members (classical novae, SNe Ia, core-collapse supernovae [CCSNe], luminous blue variables [LBVs]). Vertically hatched boxes show classes for which only a few candidate members have been suggested so far (luminous red novae, tidal disruption flares, luminous supernovae). Horizontally hatched boxes are classes which are believed to exist, but have not yet been detected (orphan afterglows of short and long GRBs). The positions of theoretically predicted events (fall back supernovae, macronovae, .Ia supernovae [.Ia]) are indicated by empty boxes. The brightest transients (on-axis afterglows of GRBs) extend to $M_R \sim -37.0$. The color of each box corresponds to the mean $g-r$ color at peak (blue, $g-r<0$ mag; green, $0<g-r<1$ mag; red, $g-r>1$ mag). From [27].

rays) is estimated to be between 0.01 and 0.001, i.e. the true rate of GRBs is 100 to 1000 times the observed rate. Since a supernova is not relativistic and is spherical, all observers can see the supernovae that accompany GRBs. Finally, there may exist entire classes of explosive events which are not as relativistic as GRBs (e.g. the so-called "X-ray Flashes" are argued to be one such category; one can imagine "UV Flashes" and so on). Provided the events have sufficient explosive yield, their afterglows will also exhibit behavior shown in Figure 2 (case B). We will call these "on-axis" afterglows with unknown parentage.

Pending SKA[4] the most efficient way to detect all three types of events discussed above is via synoptic imaging of the optical sky. Statistics of off-axis afterglows, when compared to GRBs, will yield the so-called "beaming fraction", and more importantly, the true rate of GRBs. The total number of afterglows brighter than $R \sim 24$ mag visible per sky at any given instant is predicted to be ∼1000, and rapidly decreases for less sensitive surveys [30]. With an average afterglow spending 1–2 months above that threshold, we find that monitoring 10,000 square deg every $\sim$ 3 days with LSST will discover 1000 such events per year. LSST will also detect "on-axis" afterglows. Continuous cross-correlation of optical light curves with detections by future all-sky high energy missions (e.g. EXIST) will help establish the broad-band properties of transients, including the orphan status of afterglows.

It is widely agreed that the detailed study of the associated supernovae is the next critical step in GRB astrophysics and synoptic surveys will speed up the discovery rate by at least a factor of 10 relative to GRB missions. Finally, the discovery of afterglows with unknown parentage will open up entirely new vistas in studies of stellar deaths. This possibility is clarified in the next subsection.

Hybrid gamma-ray bursts: The most popular explanation for the bimodal distribution of GRB durations invokes the existence of two distinct physical classes. Long GRBs typically last 2–100 seconds and tend to have softer γ-ray spectra, while short GRBs are typically

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[4] Square Kilometer Array, planned for the next decade, is designed to cover an instantaneous field of view of 200 square deg at radio frequencies below 1 GHz

harder and have durations below ∼ 2 seconds, sometimes in the millisecond range (see review in [23]). Short GRBs are expected to result from compact binary mergers (NS-NS or NS-BH), and the available limits rule out any significant supernova component in optical emission [2, 7].

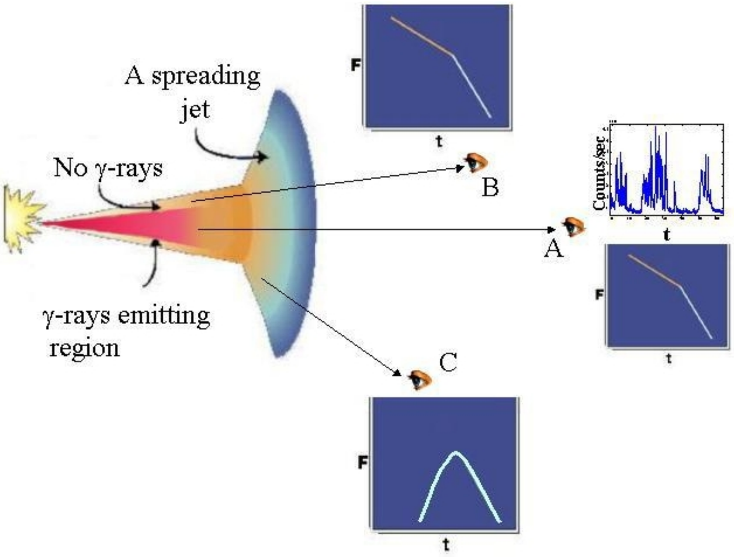

Figure 2: Geometry of orphan GRB afterglows. Observer A detects both the GRB and an afterglow. Observer B does not detect the GRB due to a low Lorentz factor of material in the line of sight, but detects an on-axis orphan afterglow that is similar to the one observed by A. Observer C detects an off-axis orphan afterglow with the flux rise and fall that differs from the afterglow detected by observers A and B (from [23]).

Recent developments suggest a richer picture. Deep imaging of GRB 060614 [5, 8, 10], and GRB 060505 [8, 25] exclude a supernova brighter than $M_V \sim -11$. The data for GRB 060614 rule out the presence of a supernova bump in the afterglow light curve up to a few hundred times fainter than bumps seen in other bursts. The host galaxy of this burst shows a smooth morphology and a low star formation rate that are atypical for long GRB hosts [10]. A very faint (undetected) event could have been powered with a small amount of ^{56}Ni (e.g. [8]), as in the original collapsar model with a relativistic jet, but without a non-relativistic explosion of the star [36]. Such events would fall in the luminosity gap between novae and supernovae discussed in a companion WP (Kulkarni & Kasliwal). Alternatively, a new explosion mechanism could be at play.

Pair-instability and anomalous supernovae: The first stars to have formed in the Universe were likely very massive ($M > 100 M_\odot$) and died as a result of thermonuclear runaway explosions triggered by e^+e^- pair production instability and the resulting initial collapse. The predicted light curve of a pair-instability supernova is quite sensitive to the initial mass and radius of the progenitor, with the brightest events exceeding $M_V \sim -22$ at maximum, lasting hundreds of days and sometimes showing more than one peak [18]. The pair instability should not take place in metal-enriched stars, so the best place to look for the first stellar explosions is the distant Universe at $z \geq 5$, where events would appear most luminous in the K band and take up to 1000 days to fade away due to cosmological time dilation. Short of having an all-sky survey sensitive down to $K_{AB} = 25$, the best search strategy is a deep survey in red filters on a cadence of a few days and using monthly co-added images to boost the sensitivity.

Recently, there have been random discoveries of anomalously bright (SN 2005ap; [26]) and in one case also long-lived (SN 2006gy; [24]) supernovae in the local universe. While there is no compelling evidence that these objects are related to explosive pair instability, there is also no conclusive case that they are not. In fact, star formation and metal enrichment are very localized processes and proceed throughout the history of the Universe in a very non-uniform fashion. Pockets of very low metallicity material are likely to exist at moderate redshifts (z $\sim$ 1–2), and some of those are expected to survive to present times [28]. The anticipated discoveries of pair-instability SN and the characterization of their environments can potentially transform our understanding of the interplay between the chemical evolution and structure formation in the Universe.

Tidal disruption events by supermassive black holes: The tidal field of a super-massive black hole (SMBH) is sufficient to disrupt stars that approach within $\sim 5M_7^{-2/3}$ Schwarzschild radii, where $M_{SMBH} = M_7 \times 10^7 M_\odot$ [16]. An optical flare lasting several months is expected when the star disintegrates outside the event horizon, i.e. for $M_7 < 20$. Only a handful of candidate tidal distruptions have been found to date, primarily in the rest-frame UV. The models of tidal disruptions predict optical emission from a hot optically thick accretion disk dominating the continuum and enhanced by line emission from unbound ejecta [33]. The peak brightness can reach $M_R = -14$ to -19 mag approaching that of a supernova. The expected full sky rate of events down to a 24 mag threshold (z $\sim$ 0.3) is $10^4 M_7^{3/2}$ yr^{-1}.

Multi-epoch X-ray and UV observations have already discovered about eight candidates for tidal disruption events in the form of large-amplitude nuclear outbursts (e.g. [6, 11, 12, 20, 34]). The candidate events have large peak luminosities of $\sim 10^{43}$–10^{45} erg s^{-1}, as well as optical-to-X-ray spectral properties and decay timescales broadly consistent with those expected based on modeling of tidal disruptions. The observed event rate per galaxy is 10^{-5}–10^{-4} yr^{-1} [6, 12, 21] , roughly consistent with the predicted rate for stellar tidal disruptions (e.g. [35]). These X-ray and UV outbursts are in some cases observed to induce accompanying optical nuclear variability, in both the continuum and emission lines, that will be detectable with a sensitive wide-field survey [4, 11, 14].

In order to measure the rate of outbursts as a function of redshift, host-galaxy type, and level of nuclear activity, the current event sample must be enlarged by a few orders of magnitude. This will allow an assessment of the role that tidal disruptions play in setting the luminosity function of moderate-luminosity active galaxies (e.g. [22]). A wide-field optical survey sensitive down to a 24 mag threshold would detect approximately 6000 events per year and redefine the level of fidelity with which we can track the rate and other properties of those events throughout the Universe [11]. Good spatial resolution and frequent multicolor photometry are required for a reliable discrimination between tidal disruptions and normal variability associated with Active Galactic Nuclei, as well as chance alignments of SNe. The success of these future programs will critically depend on the ability to promptly identify new tidal disruption events and distribute this information to the astronomical community. The LSST will have such capability and will therefore enable optimized optical spectroscopic and multiwavelength follow-up observations during early stages of the outburst; the currently known cases have been identified after the event is largely over. Prompt and time-resolved optical spectroscopy, for example, will allow the gas motions from the tidally disrupted object to be traced and compared with computer simulations of such events (e.g. [3]). Joint observations with LSST and X-ray missions such as the *Black Hole Finder Probe* (e.g. [13]), *JANUS*, and *eROSITA* will allow the accreting gas to to be studied over the broadest possible range of temperatures and will also constrain nonthermal processes such as Compton upscattering and shocks. Early identifications of tidal disruptions will also have complementarity with *LISA* as these events are expected to create gravitational-wave outbursts (e.g. [19]).

Table 1: Properties and Rates for Optical Transients[a]

Class	M_v [mag]	τ^b [days]	Universal Rate (UR)	LSST Rate [yr^{-1}]
Tidal disruption flares	$-15..-19$	30..350	10^{-6} Mpc^{-3} yr^{-1}	6000
Luminous SNe	$-19..-23$	50..400	10^{-7} Mpc^{-3} yr^{-1}	20000
Orphan afterglows (SGRB)	$-14..-18$	5..15	$3\times10^{-7..-9}$ Mpc^{-3} yr^{-1}	~10–100
Orphan afterglows (LGRB)	$-22..-26$	2..15	$3\times10^{-10..-11}$ Mpc^{-3} yr^{-1}	1000
On-axis GRB afterglows	$..-37$	1..15	10^{-11} Mpc^{-3} yr^{-1}	~50

[a] Universal rates from Rau et al. 2008b; see references therein. [b] Time to decay by 2 magnitudes from peak.

Mysterious transient SCP 06F6: The serendipitous discovery of the peculiar transient SCP 06F6 [1] has baffled astronomers and its unique characteristics have inspired many wild explanations. It had a nearly symmetric light curve with an amplitude >6.5 mag over a lifetime of about 200 days with no evidence of a quiescent host galaxy or star at that position down to $i > 27.5$ mag. Its spectrum was dissimilar to any transient or star ever seen before and its broad absorption features have been identified tentatively as redshifted Swan bands of molecular carbon. One of the suggested explanations [9] postulates an entirely new class of supernovae—a core collapse of a carbon star at redshift z = 0.143. However, the X-ray flux being a factor of ten more than the optical flux and the very faint host ($M > -13.2$) appear inconsistent with this idea. In [29] it was proposed that the emission comes from a CO white dwarf being tidally ripped by an intermediate mass black hole in the presence of a strong disk wind. Another extragalactic hypothesis is that the transient originated in a thermonuclear supernova explosion with an AGB carbon star companion in a dense medium. A galactic scenario involves an asteroid at a distance of 1.5 kpc (≈300 km across; mass $\sim10^{19}$ kg) colliding with a white dwarf in the presence of very strong magnetic fields. The nature of this transient remains unknown.

Very fast transients and unknown uknowns: As can be seen from Figure 1 the discovery space of fast transients lasting from seconds to minutes is quite empty. On general grounds there are two distinct families of fast transients: incoherent radiators (e.g. γ-ray bursts and afterglows) and coherent radiators (e.g. pulsars, magnetar flares). It is a well known result that incoherent synchrotron radiation is limited to a brightness temperature of $T_b \approx 10^{12}$ K. For such radiators to be detectable from any reasonable distance (kpc to Gpc) there must be a relativistic expansion toward the observer, so that the source appears brighter due to the Lorentz boost. Coherent radiators do not have any such limitation and can achieve very high brightness temperature (e.g. $T_b \sim 10^{37}$ K in pulsars).

Scanning a large fraction of the full sky on a time scale of ~1 minute is still outside the reach of large optical telescopes. However, large telescopes with high etendue operating on a fast cadence will be the first to probe a large volume of space for low luminosity transients on very short time-scales. One of the LSST mini-surveys, for example, will cover a small number of 10 deg^2 fields every ~15 seconds for about an hour out of every night [17]. Fast transients can also be detected by differencing the standard pair of 15-second exposures taken at each LSST pointing (visit). Given the exceptional instantaneous sensitivity of LSST and a scanning rate of 3,300 deg^2 per night we can expect to find in this way contemporaneous optical counterparts to GRBs, early afterglows, giant pulses from pulsars, and flares from anomalous x-ray pulsars. But perhaps the most exciting findings will be those that cannot be named before we look. The vast unexplored space in Figure 1 suggests new discoveries.

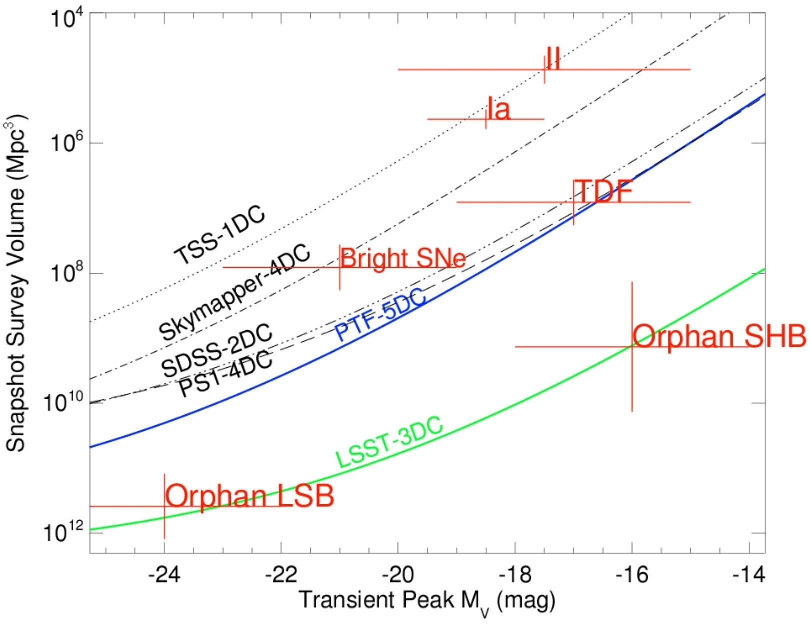

Figure 3: Volume probed by various surveys (in specified cadence period) as a function of transient absolute magnitude. Red crosses represent the minimum survey volume needed to detect a single transient event. The uncertainties in the rates and luminosities translate to the displayed "error". LSST will cover 10,000 square degrees every 3 days down to the limiting magnitude r = 24.7, and will have the grasp to detect rare and faint events such as orphan afterglows in a single snapshot. PTF-5d (blue-solid) is more sensitive than TSS (dotted), Skymapper (dot-dashed), SDSS-SN (double-dot dashed) and competitive with PanStarrs1 (PS1-MD, long dashed). Lines for each survey represent one transient event in specified cadence period. For example, TSS discovers one Ia supernova every day - however, since Ia supernovae have a lifetime of one month, TSS discovers the same Ia supernova for a month. [Original figure provided by L. Bildsten, UCSB.]

3 Telescope networks: discovery engines of the future

The way we learn about the world was revolutionized when computers—a technology which had been around for more than 40 years—were linked together into a global network called the World Wide Web and real-time search engines like Google were first deployed. Similarly, the next generation of wide-field surveys is positioned to revolutionize the study of astrophysical transients by linking heterogeneous surveys with a wide array of follow-up instruments.

In Figure 3 we compare the ability of various surveys to detect cosmological transients. LSST will be the instrument of choice for finding very rare and faint transients, as well as probing the distant Universe ($z \sim 2$–3) for the most luminous events. It will have the data collecting power more than 10 times greater than any existing facility, and will extend the time-volume space available for systematic exploration by 3 orders of magnitude. In Table 1 we summarize the expected event rates of cosmological transients that LSST will find.

The main challenges ahead of massive time-domain surveys are timely recognition of interesting transients in the torrent of imaging data and maximizing the utility of the follow-up observations [32]. For every orphan afterglow present in the sky there are about 1000 supernovae SN Ia [30] and millions of other variable objects (quasars, flaring stars, microlensing events). LSST alone is expected to deliver tens of thousands of astrophysical transients every night. Accurate event classification can be achieved by assimilating on the fly the required context information: multi-color time-resolved photometry and host galaxy information from the survey itself, combined with broad-band spectral properties from external catalogs and alert feeds from other instruments—including gravitational wave and neutrino detectors. While the combined yield of transient searches in the next decade is likely to saturate the resources available for a detailed follow-up, it will also create an unprecedented opportunity for discovery. Much of what we know about rare and ephemeral objects comes from very detailed studies of the best prototype cases, the "rosetta-stone" events. Beside the traditional target of opportunity programs that will continue to play a vital role, over the next few years we will witness a global proliferation of dedicated rapid follow-up networks of 2-m class imagers and low resolution spectrographs [15, 31]. But in order to apply this approach to extremely data intensive sky monitoring surveys of the next decade, a fundamental change is required in the way astronomy interacts with information technology.

Filtering time-critical actionable information out of ~ 30 Terabytes of survey data per night [17] is a challenging task. In this regime, the system must be capable of automatically optimizing the science potential of the reported alerts and allocating powerful but scarce follow-up instruments. In order to realize the science goals outlined in previous sections, the future sky monitoring projects must integrate state of the art information technology such as computer vision, machine learning, and networking of the autonomous hardware and software components. A major investment is required in the development of hierarchical, distributed decision engines capable of "understanding" and refining information such as partially degenerate event classifications and time-variable constraints on follow-up assets. A particularly strong emphasis should be placed on: 1) new classification and anomaly detection algorithms for time-variable astronomical objects, 2) standards for real-time communication between heterogeneous hardware and software agents, 3) new ways of evaluating and reporting the most important science alerts to humans, and 4) fault-tolerant network topologies and system architectures that maximize the usability. The need to delegate increasingly complex tasks to machines is the main driver behind the emerging standards for remote telescope operation and event messaging such as RTML (Remote Telescope Markup Language) and VOEvent. These innovations are gradually integrated into working systems, including the GCN (GRB Coordinates Nework), a pioneering effort in rapid alert dissemination in astronomy. The current trend will continue to accelerate over the next decade.

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