COSMIC EXPLOSIONS (OPTICAL TRANSIENTS)

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One of the principal motivations of wide-field and synoptic surveys is the search for and study of transients. By transients I mean those sources which arise from the background, are detected, and then fade away to oblivion. Transients in distant galaxies need to be sufficiently bright so as to be detectable and in almost all cases these transients are catastrophic events, marking the deaths of stars. Exemplars include supernovae and gamma-ray bursts. In our own Galaxy, the transients are, in almost all cases, cataclysmic rather than catastrophic, e.g. flares from M dwarfs, novae of all sorts (dwarf novae, recurrent novae, classical novae, X-ray novae) and instabilities in the surface layers (S Dor, eta Carina). In the nearby Universe (say out to the Virgo cluster) we have sufficient sensitivity to see classical novae.

This paper is an extended summary of the talk I gave at IAU Symposium New Horizons in Time Domain Astronomy (Oxford, 2011). I first review the history of transients (which is intimately related to the advent of wide-field telescopic imaging; §1). In §2 I summarize wide field imaging projects. The motivations that led to the design of the Palomar Transient Factory (PTF) followed by a summary of the astronomical returns can be found in §3. In §4 I review the lessons learnt from PTF. I conclude that, during this decade, optical transient searches will continue to flourish and may even accelerate as surveys at other wavelengths – notably radio, UV and X-ray – come on line. As a result, I venture to suggest that specialized searches for transients will continue – even into the LSST era. I end the article by discussing the importance of follow-up telescopes for transient object studies – a topical issue given that in the US the Portfolio Review is under way (§5).

1. History: Wide Field Imaging & Phase Space

One could say that large surveys of the sky for star positions, stellar photometry and stellar classification (via low resolution spectroscopy) essentially define the start of the modern era of astronomy. The early returns resulting from the discovery and study of variable stars were stunning. RR Lyrae and Cepheid variables proved to be rather precise yardsticks and astronomers came to appreciate the physical scale of our Galaxy and eventually the physical scale of the Local Universe.

All transients were initially classified as “nova stella” or new stars and the abbreviation novae came to be specifically applied to essentially classical novae. Classical novae were

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1The paper is focused on the search for and study of transients. The needs for this field are quite different from that of variable stars. The reader should bear this distinction in mind when reading this paper.
Figure 1. Phase space of cosmic explosions in the Zwicky era: novae and Ia supernovae. An explosion has several basic parameters: energy of explosion, mass of ejecta, velocity of ejecta, rise time of explosion, peak luminosity and decay time of explosion. Peak luminosity and decay timescale are easily measured and therefore constitute the principal axes of the phase space of transients. The horizontal axis is the decay timescale (1 day to 1 year) and the y-axis is the peak luminosity but shown as absolute magnitude in the V-band. Type II explosions have not been shown because the explosion physics is masked by the envelope. Notice the wide gap between novae and super-novae.

sought for their purported use in determining the distance to the Andromeda galaxy (fast novae are, on the average, brighter than slow ones). Telescopes on Mt. Wilson were pressed into M31 novae observations by E. Hubble and others.

The modern era of transients with controlled cadence and a physics-based enquiry began with F. Zwicky and W. Baade. Recognizing the importance of the then newly invented “Schmidt” type wide-field telescope, Zwicky obtained funds from a wealthy family in Pasadena and had an 18-inch telescope using the Schmidt camera design constructed. The “P18” was the first telescope on the Palomar mountain.

The first major result was the recognition of two distinct families: classical novae and “super-novae” (Baade & Zwicky 1934); see Figure 1. In their very next paper the authors made the bold conjecture that supernovae mark the transmutation of an aging star into a neutron star, a most compact object (which itself was a novel hypothesis first proposed by L. Landau in 1931). The resulting enormous release of gravitational binding energy would accelerate some particles to relativistic velocities or cosmic rays. Next, thanks to the systematic survey carried out by F. Zwicky, families of supernovae were recognized.

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2Alerted to Zwicky by W. Baade who knew the inventor Bernhard Schmidt.
3The telescope still exists and will soon be moved to the Palomar Museum; the P18 dome now is our aeronomy center and houses a polar telescope for seeing monitoring.
4Type I and Type II have certainly survived the passage of time. It would be interesting to revisit types III, IV and V that Zwicky had proposed.
The success of P18 motivated Zwicky to seek a larger Schmidt-type telescope and this led to the 48-inch telescope (P48). This telescope saw first light at about the same time as the Palomar 200-inch (circa 1948). P48 undertook two ambitious and comprehensive Northern hemisphere sky surveys (POSS-I and POSS-2). These surveys had a fundamental impact on astronomy and inspired subsequent all sky surveys. Following the POSS program the telescope was modernized (Pravdo et al. 2000) and the photographic plates were replaced by CCDs with ever increasing sophistication: NEAT (Pravdo et al. 2000); QUEST (Baltay et al. 2007); upgraded CFH12K (Rahmer et al. 2008).

2. The Era of (Optical) Synoptic Surveys

It is now clear that we are well into the era of synoptic and/or wide field astronomy. In the 1-m to 2-m category we have the Catalina Sky Survey (CSS), PTF, Pan-STARSS-1 (PS-1), La Silla QUEST and SkyMapper. In the 2-m to 4-m category we have MegaCam/CFHT, the VLT Survey Telescope, Dark Energy Camera/Blanco [expected commissioning: 2012] and the One Degree Imager/WIYN (under construction). Finally in the behemoth category we have Suprime-Cam and soon Hyper-Suprime-Cam [2012] on the Subaru 8.3-m telescope. The Large Synoptic Survey Telescope (LSST), expected by the end of the decade, is also an 8.3-m telescope, but equipped with an imager with a field-of-view about five times larger than that of Hyper Suprime-Cam.

3. The Palomar Transient Factory (PTF)

PTF consists of two dedicated telescopes (see Law et al. 2009): the P48 equipped with a re-engineered CFH12K (Cuillandre et al. 2001) 96-Megapixel CCD mosaic (Rahmer et al. 2008) and a field-of-view of 7.2 square degrees acting as the Discovery Engine and the Palomar 60-inch (P60) equipped with a 4-Megapixel CCD camera acting as the Photometric Engine.

PTF was motivated by two considerations (Rau et al. 2009). First, is the exploration of transients in the sky. With reference to Figure 1 our goal was to find objects in the nova-supernova gap (for which a number of physically motivated scenarios exist). A second motivation is the great promise of entirely new areas of astronomy:

1. High Energy Cosmic Rays.
2. High Energy Neutrinos.
3. Highest Energy Photons.
4. Gravitational Wave Astronomy.

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5Now called the Samuel Oschin telescope after a benefactor whose gift allowed the telescope to be rejuvenated.

6PTF is a collaboration of the following entities: California Institute of Technology, Lawrence Berkeley Laboratory (LBL), Weizmann Institute of Sciences, Las Cumbres Observatory Global Telescope, Columbia University, Oxford University, Infrared Processing & Analysis Center (IPAC) & UC Berkeley. The responsibilities are as follows: image subtraction pipeline (LBL), photometric pipeline (IPAC), classification (UC Berkeley), P60 robotization and operations (D. Fox, B. Cenko & M. Kasliwal), P48 sequencer (E. Ofek), PTF Marshal (R. Quimby) and spectroscopic reduction & archive (A. Gal-Yam).
The sources of interest to these facilities are connected to spectacular explosions. However, the horizon (radius of detectability), either for reasons of optical depth (GZK cutoff; $\gamma\gamma \rightarrow e^\pm$) or sensitivity, is limited to the Local Universe (say, distance $\lesssim 100$ Mpc). Unfortunately, these facilities provide relatively poor localization. The study of explosions in the Local Universe is thus critical for two reasons: (1) sifting through the torrent of false positives (because the expected rates of sources of interest is a tiny fraction of the known transients) and (2) improving the localization via low energy observations (which usually means optical). In Figure 2, we display the phase space informed by theoretical considerations and speculations. Based on the history of our subject we should not be surprised to find, say a decade from now, that we were not sufficiently imaginative.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{phase_space.png}
\caption{Theoretical and physically plausible candidates are marked in the explosive transient phase space. The original figure is from Rau et al. (2009). The updated figure (to show the unexplored sub-day phase space) is from the LSST Science Book (v2.0). Shock breakout is the one assured phenomenon on the sub-day timescales. Exotica include dirty fireballs, newly minted mini-blazars and orphan afterglows. With ZTF we aim to probe the sub-day phase space (see §5).}
\end{figure}

The clarity afforded by our singular focus – namely the exploration of the transient optical sky – allowed us to optimize PTF for transient studies. Specifically, we undertake the search for transients in a single band (R-band during most of the month and $g$ band during the darkest period). As a result our target throughput is five times more relative to multi-color surveys (e.g. PS-1, SkyMapper).

Given the ease with which transients (of all sorts) can be detected, in most instances, the transient without any additional information for classification does not represent a useful, let alone a meaningful, advance. It is useful here to make the clear detection between detection\footnote{By which I mean that a transient has been identified with a reliable degree of certainty.} and discovery\footnote{By which I mean that the astronomer has a useful idea of the nature of the transient. At the very minimum we should know if the source is Galactic or extra-galactic. At the next level, it would be useful}. Thus the burden for discovery is considerable since for most...
transients this would require spectroscopy. At the final level is a clear pigeon holing of the transient (classification). The importance of this point was re-iterated, even more forcefully, in the concluding talk (Bloom 2011). It is frustrating to hear some astronomers, especially at august meeting such as this, to claim a discovery merely on the basis that they had observed the transient earlier than others.

Recognizing the above issue we adopted a “No Transient Left Behind” strategy. Three-color photometry on P60 allows for crude classification. Follow up up with low resolution spectroscopy on a bevy of larger telescopes (Palomar 200-inch, KPNO 4-m, WHT 4.2-m and the Lick 3-m). As a result we have amassed a set of nearly 1500 spectroscopically classified supernovae of which a good fraction were detected prior to maximum.

Figure 3. An update of Figure 1 and 2 with new classes and sub-classes of non-relativistic transients. Notice the emerging class of Calcium-rich halo transients, Ia supernovae and two types of Luminous Red Novae (events in the bulges of M85 and V838 Mon; the others are in spiral arms). The color of the symbol is that at maximum light. Apparently the new data show that novae do not obey the classical “Maximum Magnitude Rate of Decay” relation (see Kasliwal 2011).

Given that follow-up is at premium having a small sample of transients with desired or well-understood selection criteria is more valuable than a large sample of transients with a potpourri of properties. Thus choice of pointings and cadence control are critical. We have scoured around the sky to select PTF pointings with large local ($d \lesssim 200$ Mpc) over to have the first level of sub-typing (eg. flare star/DN/CV; Ia/Ibc/II SN). This knowledge is essential given the very large fog of foreground (M dwarf flares, dwarf noave) and background transients (routine supernovae at a late phase, burps from an AGN).

Even so, as in real life, two thirds of the transients are unclassified and left behind.
densities. The nearly one hundred selected pointings contain $\times 4$ more light than randomly chosen pointings (Kasliwal, 2011). Cadence control is even more important. For instance the logistics of obtaining UV spectra of nearby Ia supernovae (important for calibration of Ia cosmology) require that the supernovae be identified 10 to 14 days prior to peak. In 2010 we focused on finding such supernovae and we now have three dozen HST UV spectra of nearby Ia – an order of magnitude in the sample size (Cooke et al. 2011).

Another goal is to decrease the latency between detection and discovery. During 2011 we made efforts to decrease the latency and were (very luckily) rewarded with the discovery of a Ia supernova in the very local Universe, PTF11kly in Messier 10, just 11 hours after the explosion (Nugent et al. 2011). The proximity and near natal discovery allowed us and other astronomers to shed fundamental new light on the progenitor of a Ia supernova.

With 38 refereed publications (a mean rate of 1 publication per month) PTF has been productive. Five PhD theses and nearly a dozen of postdocs have been and are being supported. In addition to the two results summarized above, key discoveries and findings include the clear identification of a class of luminous supernovae whose spectra show no hydrogen (Quimby et al. 2011), the gradual “coloring of the phase space” (Figure 3), the demographics of core collapse supernovae (Arcavi et al. 2010) and an apparently exotic nuclear event (PTF10iya; Cenko et al. 2011).

4. Lessons Learnt

First and foremost, a clear vision for the project must be articulated. In this regard, Figure 2 was an essential exercise in motivating PTF. As discussed earlier detection is merely the first (and easy) step. Discovery requires much harder work and in almost all cases follow up spectroscopy (access to follow up telescopes) and a deep knowledge of astronomy (expert knowledge) is needed. These two demands can easily exceed that needed for the search itself.

Next, cadence control is absolutely essential to produce quality transients worthy of follow-up. Fourth, a horizontal structure with essentially independent key project teams allows for motivated teams to undertake efficient and rapid follow-up. A corollary is that strong scientific leadership is essential to resolve overlapping interests. Fifth – a truism – software pipelines have to be fully functional before the searches begin. Sixth, as illustrated by the case of PTF11kly, the collaboration should be flexible enough to take advantage of new findings and/or organic advances in the field.

10http://www.astro.caltech.edu/ptf. PTF began routine operations summer of 2009. Half of the Fall season was lost to the Great Station Fire.
11M. Kasliwal – Transients in the Local Universe; I. Arcavi – Demographics of Core-collapse Explosions; D. Levitan – AM CVn stars; S. Ben-Ami – Early Emission from SN; A. Waszczak – Small bodies in the Solar System
12In this respect we followed Zwicky’s morphological approach to problem solving which stresses the importance of a sensible (consistent with physics) exploration of phase space and not merely an aspiration based approach.
13In fact, I predict, that increasingly the same transient will be detected in parallel by more than on-going survey. Surveys with high cadence control will have an advantage over multi-purpose surveys.
We plan to strictly implement these lessons in the next phase of PTF ("iPTF") which will run for 2013 & 2014. For this phase we are on course to completing a high throughput ultra-low resolution ($\lambda/\Delta\lambda \approx 100$) IFU spectrograph (SED Machine\cite{14} and optimized for spectral classification.

5. Future: Beetles & Behemoths

One may reasonably ask: is there a need for more synoptic surveys since even a modest aperture synoptic survey can generate more data than can be digested? This is a meritorious question. My reply is that there is a need for highly focused projects. I list three case studies. CSS, a survey based on 1-m telescope equipped with a routine CCD detector, is remarkable for its harvest of NEOs and pinpointing (with considerable heads-up) the fiery entry of 2008TC3 (Boattini et al. 2009). The case for PTF with its laser like focus on transients can be found in CFHT SN Legacy Survey (CFHT; Conley et al. 2011) has made deep contributions to Ia cosmology. The Medium Deep Survey of PS-1 has proved to be adept at identifying luminous supernovae (Chomiuk et al. 2011). The nightly cadenced SDSS Stripe 82 project has made contributions across board – SN cosmology, AGN variability, stellar variability, tidal disruption events (e.g. van Velzen et al. 2011). It appears that focused projects have the ability to trump general-purpose larger facilities which are subject to competing cadence demands.

The second reason that I remain bullish of modest aperture searches is that the earnest exploration of the phase space has just begun. The phase space with decay time of less than a day (for which there are several plausible scenarios) and the entire physics of the rise time of explosive transients is essentially wide open.

Finally, currently, the transient game is dominated by optical synoptic facilities and projects. The next to join this club would be radio facilities at both meter and decimeter wavelengths (EVLA, LOFAR, MWA, upgraded GMRT, APERTIF, MeerKAT). With some luck synoptic space based projects may also happen during this decade (e.g. LIMSAT\cite{16} in the UV, rejuvenation and repurposing of WISE for thermal IR searches and a Lobster-type mission in the X-rays). One can easily imagine joint studies with optical facilities.

Projects such as PTF, CSS and PS-1 demonstrate that there is ample scope for 1-m to 2-m class surveys to continue well into this decade. The magnitude limit of 21 is ideally suited to classification spectroscopy. Going fainter is only an advantage if one has the ability to discriminate between the “unknown unknowns” against the dense fog of known transients or if there is a compelling reason to do so (e.g. using luminous supernovae as tracers of star formation). Recall that follow-up at the 22-mag requires 6 times as much as follow-up time as a 21-mag event.

\cite{14}http://sites.google.com/site/nickkonidaris/sed-machine. The SEDM will replace the imaging photometer.

\cite{15}The optical synoptic revolution is a result of Moore’s law for computing and optical sensors. The radio revolution is being driven by exponential advances in computing, RF technology, advances in interferometric imaging algorithms and LNSD architecture.

\cite{16}This is a cluster of 12-cm aperture telescopes with a total of 1,000 square degrees and promoted by an ad hoc group of astronomers from Israel, Caltech, India and Canada.
Currently, in the US there is a debate on the future of existing facilities. In Astronomy, discoveries keep the field exciting and large telescopes (especially spectroscopy) and theory provide the physical understanding. The reasons to build increasingly larger telescopes and the motivation for great facilities has and will remain strong. However, discoveries primarily result from surveys (e.g. discovery of very high redshift quasars from SDSS and UKIRT) and/or concerted efforts on modest-size telescopes (e.g. planets around normal stars; the discovery of the first brown dwarf).

Hopefully the reader is by now convinced that the discovery potential for the sub-field of transients has been and will continue to be large. As such one should let many ideas bloom. The cost of searches with modest-size telescope is affordable. For instance, the total cost of PTF (capital and 4-year operating costs) is $3M. Repurposing the present collection of 2-m to 4-m existing telescopes to support (mainly light curves and spectroscopy) the ongoing surveys is a cost effective way to continue doing cutting-edge research. The current imbalance of big/expensive/facility over small/focused projects is neither cost effective nor strategic and, as is now being realized, financially not sustainable.

So enthused I am with the prospects and promises of focused transient searches with assured follow-up that, along with my colleagues, I am now proposing a second generation of PTF. We propose to fully populate the focal plane of P48 (40 square degree) and equip two other telescopes with the SED Machine (for rapid spectral classification; §4) and a robotic laser Adaptive Optics system (for rapid photometry in crowded host galaxy fields. The primary focus of this three-telescope facility is to probe the sub-day phase space (see Figure 2). I propose to name this as the Zwicky Transient Facility (ZTF) after the founder of our field. First light is expected in 2015. Should interesting sub-minute bursts be discovered then we will upgrade ZTF with CMOS. Hopefully ZTF, a beetle, will prove to be productive even as general purpose behemoths come on line.

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The hard work and creativity of the members of PTF have made the project productive. I would like to specially acknowledge the following colleagues: L. Bildsten, J. Bloom, S. B. Cenko, R. Dekany, A. Gal-Yam, M. Kasliwal, R. Laher, N. Law, P. Nugent, E. Ofek, R. Quimby, R. Smith & J. Surace. The excellent staff of the Caltech Optical Observatories made it possible for re-engineering of CFH12K and refurbishment of P48. The low downtime, despite the age of P48 and P60, is a testament to the amazing crew at Palomar mountain.

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\[^{17}\text{http://www.astro.caltech.edu/Robo-AO}\]
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