Transients in the Local Universe

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Abstract

Two different reasons make the search for transients in the nearby Universe (d$\lesssim$ 100 Mpc) interesting and urgent. First, there exists a large gap in the luminosity of the brightest novae (−10 mag) and that of sub-luminous supernovae (−16 mag). However, theory and reasonable speculation point to several potential classes of objects in this "gap". Such objects are best found in the nearby Universe. Next, the budding and nascent fields of Ultra-high energy cosmic rays, TeV photons, astrophysical neutrinos and gravitational waves (GW) are limited by $\sim$ 100-Mpc horizon either due to physical effects (GZK effect, photon pair production) or instrumental sensitivity (neutrino and GW). Here we describe a key project of a new facility – the Palomar Transient Factory (PTF) – aimed at a comprehensive study of transients in the Local Universe. PTF has recently achieved first light and we look forward to a synergistic program with MAXI.

Key words: Supernovae : Novae — Synoptic Surveys : Palomar Transient Factory — UHECR : TeV : Neutrino : Gravitational Wave Astronomy

1. Background

Variable objects have surprisingly played a major role in the history of astronomy. At the beginning of the previous century, the pulsating Cepheids showed that the Galaxy was much larger than had been assumed before. The empirical relation between the decay time and luminosities of novae yielded meaningful distances to the Andromeda galaxy. Supernovae touched upon the origin of cosmic rays, the synthesis of iron and higher-Z elements and the possibility of collapse of cores leading to the formation of neutron stars. It is worth noting that Zwicky's pioneering wide field optical program began at Palomar. Caltech provided $50,000 which resulted in the construction of the 18-inch Palomar Schmidt telescope[1]. The 18-inch Schmidt essentially started and laid the foundation of the field of supernovae. The success of this program led to the 48-inch Palomar Oschin Schmidt telescope, famous for the two Sky Surveys.

At the end of the previous century, supernovae came back into main stream. The first indication of a new constituent of the Universe, dark energy, was deduced from the dimming of Ia supernovae located at cosmological distances (Perlmutter et al. 1999, Reiss et al. 1998).

Over the last decade, a veritable explosion of progress took place in the field of gamma ray bursts. We now recognize that the GRB phenomenon can be traced to at least three separate classes: long duration bursts (associated with the deaths of certain but hitherto unidentified types of massive stars), short duration bursts with large hardness ratio (associated with the coalescence of compact objects) and short duration bursts with small hardness ratio bursts (traced to flares from magnetars). The first two classes are the most relativistic explosions known in Nature. In both cases a rapidly spinning black hole is expected. Astronomers eagerly await the use of long duration GRBs to probe the very young Universe, physicists regard short duration events as the prime targets for gravitational wave (GW) detectors and soft gamma-ray repeaters are truly Nature's most exotic and unique laboratory for electrodynamics.

Clearly, the study of transients has been a very fruitful endeavor. Here we focus on transients in the local Universe (distance, $d < 200$ Mpc). The rationale for this myopic view is given in §2., §3. and §4.. Our pilot program of searches in the nearest galaxies (10 Mpc) and the nearest clusters (Virgo, Fornax) is summarized in §5.. Next, in §6., we discuss the Palomar Transient Factory (PTF), a key goal of which is a systematic unveiling of transients in the local Universe. We conclude in §7. with a discussion of a possible MAXI-PTF program.

2. Rationale & Motivation: Events in the Gap

A plot of the peak luminosity versus a duration that is characteristic (based on physics or convention) is a convenient way to summarize explosive events. We first focus on novae and supernovae of the type Ia. As can

*1 This venerable telescope can now can be found at the Palomar Museum

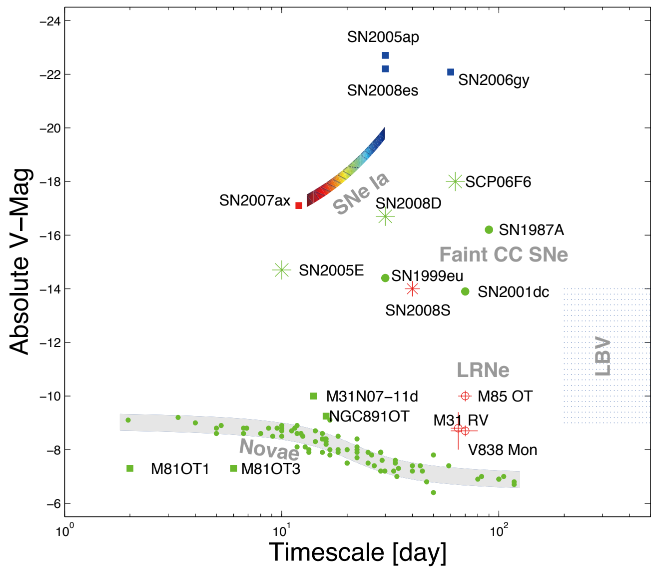

Fig. 1. Cosmic transients phase space (peak V-band luminosity as a function of duration, with color a measure of the true color at maximum). Shown are the known explosive (supernovae) and eruptive (novae, luminous blue variables [LBV]) transients. Also shown are new types of transients (and discussed in §4.): the peculiar transients M 85 OT2006-1, M31-RV and V838 Mon, which possibly form a new class of "luminous red novae,", the baffling transient with a spectrum of a red-shifted Carbon star, SCP 06F6, the shock-breakout X-ray transient (SN 2008D), a possible accretion induced collapse event SN 2005E and a peculiar eruptive event with an extremely red progenitor SN 2008S. Adapted from Kulkarni et al. 2007.

be seen from Figure 1 novae and supernovae of the Ia type form a distinctly different locus. Brighter supernovae take a longer time to evolve (the "Phillips" relation; Phillips et al. 1999) whereas the opposite is true of novae: the faster the nova decays the higher the luminosity (the "Maximum Magnitude Rate of Decline", MMRD relation; see, for example, Della Valle and Livio 1995).

The primary physical parameter in Ia supernovae is the amount of Nickel that was synthesized. There is almost a factor of 10 variation as we go from the brightest supernova ("1991bg-like") to the dimmest ("1991T-like"). The Phillips relation has been very quantified with high precision and the theory is well understood. In contrast, the MMRD does not enjoy the same quantity or quality of light curves as those of Ia supernovae. Fortunately, dedicated on-going nova searches in M31 and the P60-FasTING project described below (§5.) should vastly increase the number of light curves.

The large gap between the brightest novae (say $M_{\rm V} \sim -10$) and the faintest supernovae ($M_{\rm V} \sim -16$) is hard to miss. The gap beckons astronomers to search the heavens for new populations.

A discussion of potential new classes of events in the gap would benefit from a review of the basic physics of explosions. Here, we restrict to non-relativistic explosions. Given this restriction the assumption of spherical symmetry is not particularly restraining.

An explosion is a ball of matter and photons. An added but important complication is a potential heat source at the center: a hot white dwarf (novae) or gradual release of radioactive energy (supernovae). The primary physical parameters are: the mass of the ejecta ($M_{\rm ej}$), the velocity of the ejecta (v_s), the radius of the progenitor star (R_0) and the total energy of the explosion ($\mathcal{E}_0$). Two distinct sources of energy contribute to the explosive energy: the kinetic energy of the ejecta, $\mathcal{E}_{\rm k} \equiv (1/2)M_{\rm ej}v_s^2$ and the energy in the photons (at the time of the explosion), $\mathcal{E}_{\rm ph}$.

Approximating the explosion by a homogeneous sphere we can write the following equation to describe the gains and losses suffered by the store of heat (E):

$$\dot{E} = \varepsilon(t)M_{\rm ej} - L(t) - 4\pi R(t)^2 P v(t). \qquad (1)$$

Here, $L(t)$ is the luminosity radiated at the surface and $\varepsilon(t)$ is heating rate (energy per unit time) per gram from any source of energy (e.g. radioactivity or a long-lived central source). P is the total pressure and is given by the sum of gas and photon pressure:

$$P = n_i(Z+1)kT + aT^4/3. \qquad (2)$$

Here, n_i is the density of ions, n_e is the density of electrons and it is assumed that all the gas is hot enough to be fully ionized.

Next, we resort to the so-called "diffusion" approximation (see Arnett 1996; Padmanabhan 2000, volume II, §4.8),

$$L = E_{\rm ph}/t_{\rm d}, \tag{3}$$

where $E_{\rm ph} = aT^4V$ is the energy in photons [V is the volume of the sphere, $(4\pi/3)R^3$]

$$t_d = B\kappa M_{\rm ej}/cR \tag{4}$$

is the timescale for a photon to diffuse from the center to the surface. The pre-factor B in Equation 4 depends on the geometry and, following Padmanabhan (*ibid*), we set $B = 0.07$. κ is the mass opacity.

We will make one simplifying assumption: most of the acceleration of the ejecta takes place on initial hydrodynamic timescale, $\tau_h = R_0/v_s$. With this "coasting" approximation we have

$$R(t) = R_0 + v_{\rm s}t. \tag{5}$$

This simplification means that we need solve only one differential equation, namely the energy equation (Equation 1).

First, let us consider a "pure" explosion i.e. no subsequent heating, $\varepsilon(t) = 0$. If photon pressure dominates then $P = 1/3(E/V)$ and an analytical formula for $L(t)$ can be obtained (Padmanabhan, *op cit*):

$$L(t) = L_0 \exp\left(-\frac{t\tau_h + t^2/2}{\tau_h\tau_d}\right); \tag{6}$$

here, $\tau_d = B(\kappa M_{\rm ej}/cR_0)$ is the initial diffusion timescale and $L_0 = \mathcal{E}_{\rm ph}/\tau_d$.

The analytical formula allow us to get some insight into pure explosions. For strong explosions, $\tau_h \ll \tau_d$. In this case, the internal energy goes in to PdV work and is rapidly depleted on timescales of τ_h. However, the light curve decays on a much longer scale, thanks to the long diffusion timescale for photons.

The light curve be divided into two phases: a plateau phase which lasts until about $\tau = \sqrt{\tau_d\tau_h}$ after which the luminosity undergoes a (faster than) exponential decay. The duration of the plateau phase is

$$\tau = \sqrt{\frac{B\kappa M_{\rm ej}}{cv_s}} \tag{7}$$

and is independent of R_0. The plateau luminosity is

$$\begin{aligned} L_p &= \mathcal{E}_{\rm ph}/\tau_d \\ &= \frac{cv_s^2 R_0}{2B\kappa}\frac{\mathcal{E}_{\rm ph}}{\mathcal{E}_{\rm k}}. \end{aligned} \tag{8}$$

As can be seen from Equation 8 the peak luminosity is independent of the mass of the ejecta but directly proportional to R_0. To the extent that there is rough equipartition[2] between the kinetic energy and the energy in photons the luminosity is proportional to the square of the final coasting speed, v_s^2.

Pure explosions satisfactorily account for supernovae of type IIp. Note that since $L_p \propto R_0$ the larger the star the higher the peak luminosity. SN 2006gy, one of the brightest supernovae, can be explained by invoking an explosion in a "star" which is much larger (160 AU) than any star (likely the material shed by a massive star prior to its death; see Smith & McCray 2007). Conversely pure explosions resulting from the deaths of compact stars (e.g. neutron stars, white dwarfs or even stars with radius similar to that of the Sun) can be not to be luminous. For such progenitors visibility in the sky would require some sort of additional subsequent heat input.

In the spirit of this discussion (namely, an open ended discussion of new transients) we also consider the case where the gas pressure could dominate over photon pressure. This is the regime of weak explosions. If so, $P = 2/3(E/V)$ and Equation 1 can be integrated to yield

$$L(t) = \frac{L_0}{(t/\tau_h + 1)}\exp\left(-\frac{\tau_h t + t^2/2}{\tau_h\tau_d}\right). \tag{9}$$

In this case the relevant timescale is the hydrodynamic timescale. This regime is populated by Luminous Blue Variables and Hypergiants. Some of these stars are barely bound and suffer from bouts of unstable mass loss and photometric instabilities.

We now turn to new classes of transients. This is an exciting area as judged by the number of speculative papers. The most fruitful ideas result from considerations of binary stars.

First we will consider "supernova"-like events i.e. events in which the resulting debris is heated by radioactivity. One can easily imagine a continuation of the Ia supernova sequence. We consider three possible examples for which we expect a smaller amount of radioactive yield and a rapid decay (timescales of days): coalescence of compact objects, accreting white dwarfs (O-Ne-Mg and Helium).

Following Li & Paczynksi (1998), Kulkarni (2005) considers the possibility of the debris of neutron star coalescence being heated by decaying neutrons. Amazingly (despite the 10-min decay time of free neutrons) such events (dubbed as "macronovae") are detectable in the nearby Universe over a period as long as a day, provided even a small amount ($\gtrsim 10^{-3}\,M_\odot$) of free neutrons released in such explosions.

Bildsten et al. (2007) consider a Helium nova (which arise in AM Cvn systems). For these events (dubbed

*2 This is a critical assumption and must be checked for every potential scenario under consideration. In a relativistic fireball most of the energy is transferred to matter.

".Ia" supernovae), not only radioactive Nickel but also radioactive Iron is expected.

The fate of O-Ne-Mg white dwarfs accreting matter from a companion continues to fascinate astronomers. Such systems exist and the issue is what happens once the mass of the accretor exceeds the Chandrashekar limit. The likely possibility is a neutron star but the outcome depends severely on the unknown effects of rotation and magnetic fields. One possibility is a weak supernova explosion (see Metzger et al. 2008 for a recent discussion and review of the literature). Only a small amount of radioactive Nickel is expected and thus the expectation is a sub-luminous supernova with decay on timescales of a day or so.

An entirely different class of explosive events are expected to arise in massive or large stars: birth of black holes (which can range from very silent events to GRBs and everything in between), strong shocks in supergiants (van den Heuvel 2008) and common envelope mergers. Equations 7 and 8 provide a guidance to the expected appearance of such objects. For the case of the birth of a black hole with no resulting radioactive yield (the newly synthesized material could be advected into the black hole) the star will slowly fade away on a timescale of $\min(\tau_d, \tau)$. Modern surveys are capable of finding such wimpy events (Kochanek et al. 2008).

3. Rationale & Motivation: New Astronomy

Four entirely different fields of astronomy are now being nurtured by physicists: ultra-high energy cosmic rays (UHECR), TeV astronomy, gravitational wave astronomy and neutrino astronomy. For these fields all that matters is transients in the local Universe.

Cosmic rays with energies exceeding 10^{20} eV are strongly attenuated owing to the production of pions through interaction with the cosmic micro-wave background (CMB) photons [the famous Greisen-Zatsepin-Kuzmin (GZK) effect]. Recently, the Pierre Auger Observatory (PAO 2007) has found evidence showing that such cosmic rays with energies above 6×10^{19} eV are correlated with distribution of matter in the local 75-Mpc sphere. Cosmic rays with higher energies are suppressed and their "horizon" is correspondingly smaller.

Similarly very high energy (VHE) photons (TeV and PeV) have a highly restricted horizon. The TeV photons interact with CMB photons and produces electron-positron pairs. A number of facilities are now routinely detecting extra-galactic TeV photons from objects in the nearby Universe (Veritas, MAGIC, HESS, CANGAROO).

Neutrino astronomy is another budding field with an expected vast increase in sensitivity. The horizon here is primarily limited by sensitivity of the telescopes. Large field-of-view (FOV) instruments like PTF are well suited to the expected localization of a few square degrees of these instruments.

The same two limitations (a small horizon and poor localization) apply to the exciting field of GW astronomy. The horizon radius is 45 Mpc for `enhanced` LIGO (eLIGO) and about 175 Mpc for `advanced` LIGO (aLIGO). However, the localization will remain poor (limited by the small baseline lengths, relative to the GW wavelength) – tens of square degrees (at best). There is wide spread agreement that the greatest gains will require electromagnetic localization of the event. Unfortunately, all sorts of foreground and background transients *will* be found within such a poor localization. Studying each of these transients will result in significant "opportunity cost". Addressing this opportunity cost is a significant motivation for PTF (see §6.).

Fortunately, the limited sensitivity-limited horizon of GW astronomy is a blessing in disguise. The opportunity cost can be reduced by restricting transients to those overlapping galaxies within the LIGO radius. Our simulations show that electromagnetic localization of LIGO events is quite feasible (Kasliwal et al., in prep).

4. Serendipitous Discoveries

Recent serendipitous discoveries give us comfort and confidence that a systematic investigation of the nearby Universe will be profitable.

In Kulkarni et al. (2007), we report a $M_R = -12$ transient in M85 (initially "rejected" by KAIT as too faint to be a supernova). This elusive group (dubbed Luminous Red Novae, LRNe; see Figure 2) has three other potential members: V838 Mon, M31 RV and V4332 Sgr. Suggested models to explain LRNe are diverse: common-envelope merger, a rare type of novae, low-luminosity tail of supernovae (and even a planet plunging into its parent star!).

Next, Barbary et al. (2008) announced the discovery of SCP 06F6, a transient with a nearly symmetric light curve, discovered during HST observations of a cluster. The transient has no detected host galaxy or star, an amplitude >7 mag and a spectrum oddly similar to a carbon star at z≈0.14 (Gansicke et al. 2008). Another intriguing fact is that the X-ray emission (detected at late times, 100 days) is brighter than the optical emission. It cannot be ruled that this was a primarily an X-ray transient with the optical being a side show. Soker et al. (2008) consider several explanations and favor tidal destruction of a CO white dwarf by an intermediate mass black hole. This object is truly intriguing. However, it cannot be too rare given that it was discovered in a WFPC (field-of-view of 5.7 square arcminutes!) study.

SN 2008S (in NGC6946) and NGC 300-OT had a peak absolute magnitude between $-13 > M_V > -15$. The explosion signature (light curve and spectrum) looks sim-

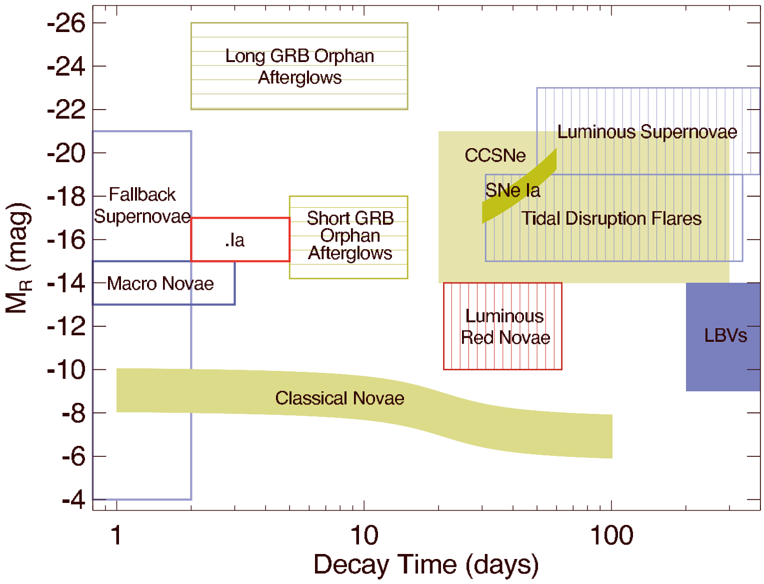

Fig. 2. R-band peak magnitude as function of characteristic decay timescale (typically the time to fade from peak by two magnitudes) for luminous optical transients and variables. Filled boxes mark well-studied classes with a large number of known members (classical novae, SNe Ia, core-collapse supernovae [CCSNe], luminous blue variables [LBVs]). Vertically hatched boxes show classes for which only few (< 4) 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. See text for references related to each science case. The brightest transients (on-axis afterglows of GRBs) and events detectable predominantly in the Milky Way (e.g., dwarf novae) are omitted for clarity (see Table 2 for a more complete list). Regions indicate the general location of each class and are not exclusive. 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 Rau et al. 2008b.

ilar to luminous blue variables (Smith et al. 2008) and hypergiants (Bond et al. 2009). However, this massive star progenitor hypothesis was put in question by the extremely reddened SED of the progenitor (not detected in optical to deep limits, only detected in mid-infrared, Prieto et al. 2008). Thompson et al. (2008) suggest that these two events and the luminous red nova in M85 form a new class of explosive events with very dusty progenitors with a large radius.

Tantalizing evidence of an accretion induced collapse comes from recent study of nebular spectra of SN 2005E (Perets et al. 2009). This transient had an absolute magnitude -14.7) and decayed on timescale of 12 days. It occurred in the halo of a galaxy (~ 30 kpc from nucleus of NGC 1032). Moreover, the measured total ejecta mass is only 0.18 $M_{\odot}$.

Another odd transient is SN 2008ha. It had a spectrum similar to the peculiar type Ia SN 2002cx but it has a very low absolute magnitude of -14. If this is indeed a Type Ia supernova, it would be fainter than the faintest Type Ia known so far (SN 2007ax; Kasliwal et al 2008) by two magnitudes.

All these discoveries (in the space of only two years) demonstrate that the gap is not empty and a new, systematic search has the potential to uncover novel astrophysical transients.

Finally, Soderberg et al. 2008 announced the discovery of a burst of X-rays from SN 2008D in NGC 2770 during an unrelated Swift/XRT observation ($M_V=-15$, uncorrected for 2 mags of extinction). The importance of this discovery is that the discovery was made in the classical X-ray band – a band well suited for all-sky monitors. The outburst may arise from the interaction with the shock with the outer layers of the star (or the circumstellar medium at stellar radius) and is an excellent proxy for the shock breakout emission. A deep, fast cadence search of the nearby Universe is clearly well suited to finding supernovae very early on the rise.

5. Pilot Programs

Our group has undertaken three pilot studies aimed to find transients located in the gap (faint and fast): P60-FasTING, CFHT-COVET and Fast transients in Fornax.

The "Fast Transients In Nearest Galaxies" program was undertaken at the Palomar 60 inch (whence, P60-FasTING). It targets about sixty of the nearest ($<$10 Mpc), brightest (<-18) galaxies to a depth of g$<$21 mag and cadence $<$1 day. Though started in 2007, major pipeline upgrades were made until April 2008. Thus far, P60-FasTING has independently discovered a score of novae, a supernova in M 61 (SN 2008in) and a

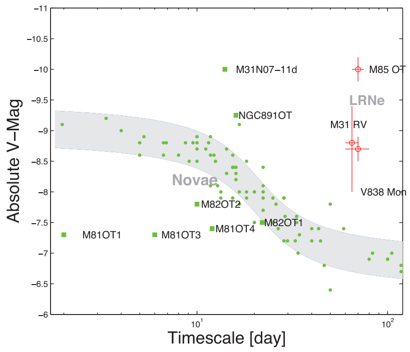

Fig. 3. A plot of the peak absolute magnitudes versus decay timescale of novae discovered by P60-FasTING. The shaded grey region represents the Maximum Magnitude Rate of Decline relationship bounded by $\pm 3\sigma$ (Della Valle and Livio 1995). The data that defined this MMRD are shown by green circles. [Data are preliminary results from Kasliwal et al. 2009b, in prep.]

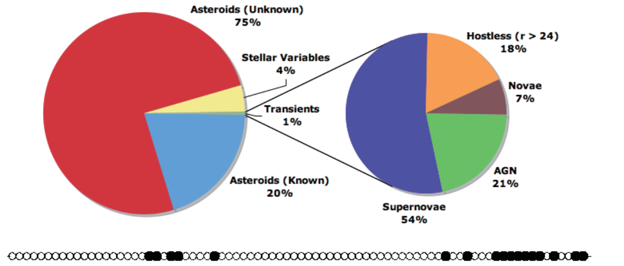

Fig. 4. Twenty eight COVET transients were discovered during our pilot run in 2008A (7 hours). Of these, two were novae in M60, and the remainder were background supernovae and AGN (classified spectroscopically where available and based on offset from host galaxy nucleus otherwise). Transients with no point source or galaxy host to a limiting magnitude of r>24 are classified as hostless. Of the total number of transient candidates, our pipeline automatically rejected 99% as solar-system or galactic. The line of dots (bottom of the figure) indicates which of the 80 nights we got data (filled circles) vs. not (empty circles). We have been granted 30 hours to search 10 fields daily in 2009A. Preliminary version from Kasliwal et al. 2009c, in prep.

luminous blue variable in NGC 925.

It is in the classical field of novae that P60-FasTING appears to have made some progress. In addition to a dozen novae in M 31, our search found five novae in M 81, two in the nearby starburst M 82, and one in NGC 891. As can be seen from Figure 3 several of these novae appear to be outliers on the canonical Maximum Magnitude Rate of Decline (MMRD; Downes and Duerbeck 2000, della Valle and Livio 1995) relation. Despite the photometric peculiarity, they are spectroscopically similar to regular novae.

The large scatter of the new novae suggests that in addition to the mass of the white dwarf, other physical parameters (such as accretion rate, temperature) also govern the photometric signature of novae and that novae are not viable standard candles. We note that this may in part be an observational bias as this search was designed to be more sensitive to fainter and faster novae than previous searches.

Second, we undertook a search of nearby clusters of galaxies with the 3.5-m Canada France Hawaii Telescope (CFHT) – "Coma and Virgo Exploration for Transients" (whence COVET). This search utilizes the MegaPrime Camera which has a field of view of one sq deg, pixel scale of $0.18''$ pix^{-1}, and is on the telescope every dark fortnight of the month. Given that our project requires searching for faint targets overlapping bright galaxies, the fine pixel scale is advantageous in measuring the convolution kernels for image subtraction (see Figure 3). Our real-time pipeline was designed to probe deep into the cores of bright galaxies with a high detection efficiency.

COVET's pilot project (2008A) targeted the rich nearby galaxy super-cluster, Virgo (16 Mpc) to a depth of r<22.5 and cadence of 1 day. Despite a modest total investment of 7 hrs of on-sky time in 2008A and non-optimal sampling, we discovered twenty eight transients – twenty six background supernovae/AGNs and two novae in M 60 (see Figure 4).

The primary lesson that we learnt is the extensive fore- and back-ground "fog". The primary foreground fog (99%) are asteroids and stellar variables. We rejected the former by looking for movement between two images (taken over the same night and separated by about 15 minutes in time) and the latter by looking for a known stellar counterpart in the SDSS archive. The background fog is composed of supernovae and AGNs in small, faint galaxies. Some had no stellar/galaxy counterpart to r >24. The only two transients of interest (i.e. located in VIRGO) discovered were the two novae in M60, an elliptical galaxy. In 2009A, we have been granted 30 hours to search Virgo (7 sq deg, 42% of cluster light) and Coma (3 sq deg, 60% of cluster light).

Third, a search for extremely fast hour-timescale transients was undertaken targeting twenty three members of the Fornax cluster (Rau et al. 2008a). This is the second richest close (17 Mpc) cluster. Galaxies were imaged with the Wide Field CCD Re-imaging Camera on the 2.5-m du Pont telescope at a cadence of 32 min on ten nights from October through December of 2006. Asteroids were eliminated via repeated imaging. Unlike COVET the B band was used for observations. Two previously known supernovae (both in NGC 1316, a galaxy in the Fornax cluster) and five uncataloged stellar variables (two flare stars, two W UMa-type eclipsing binaries and one δ Scuti). Clearly, this approach (blue band, high cadence) appears well suited to the discovery of foreground stellar variables.

Our pilot surveys highlighted the importance of understanding the overwhelming numbers of fore- and background transients. This experience is similar to that of the transients found in the Deep Lens Survey (Kulkarni & Rau; see also Rau et al. 2006, Rau et al. 2007 & Drake et al. 2008). We have come to appreciate the importance of a a well-defined follow-up strategy. Next, we also learnt the importance of a real-time, robust and efficient transient detection pipeline. Follow up is easy when the transient is bright!

6. The Palomar Transient Factory

The first author of this paper conceived the Palomar Transient Factory (PTF) in response to the scientific prospects discussed earlier: explosive events in the gap (§2.) and the urgent need for a thorough understanding of transients in the local Universe arising out of New Astronomy (§3.). PTF is now a multi-institution[3] program devoted to a comprehensive study of transient objects. A full description of the magnificent anticipated science returns from PTF can be found in Rau et al. (2008b).

PTF consists of two telescopes: the Palomar 48-inch Oschin Schmidt telescope (P48) equipped with a refurbished CFH12K camera[4] (Rahmer et al 2008), the automated Palomar 60-inch telescope (P60) equipped with a CCD photometer (Cenko et al. 2006) and the PAIRITEL near-IR 1.3-m telescope equipped with a JHK (simultaneous) imager (Bloom et al. 2006). The data are analyzed in near real time at the Lawrence Berkeley Laboratory. The classification engine is run at UC Berkeley and the final archive (post 1-day) is done by the Infrared Processing & Analysis Center (IPAC).

In contrast to other synoptic surveys (e.g. PanSTARRS, SkyMapper) PTF is designed with only one goal in mind: the study of transients. This translates to two key design requirements: (1) high throughput for transient object astronomy and (2) end-to-end follow-up planning. As explained below, these two demanding key design goals are met by the innovative multi-telescope strategy.

In the context of transient studies, high throughput means either large cadence (revisiting the same piece of sky many times) or a high sky coverage rate (as measured, say, by the number of square degrees surveyed per hour). For PTF, throughput is maximized by undertaking observations in only two bands, a green filter for dark time and a red filter for bright time. Relative to other efforts (which typically employ five to six filters) this stratagem immediately gives a factor of 2 to 3 increase in throughput. However, color information is valuable and here is where the multi-telescope strategy pays off. Color information for newly found transients are obtained by photometric observations on P60 and PAIRITEL. [In conventional approaches, e.g. SDSS, the same wide field imager obtains the color of all objects, transients or otherwise – but at the cost of throughput.]

Next, a transient that is not classified with some degree of certainty is a wasted transient. A transient without good followup is unlikely to result in a paper. In short, it is important to leave no transient behind.

The P60 and PAIRITEL multi-color data form the basis of rapid classification. Another important input is the presence or absence of a putative host galaxy. The `DeepSky`[5] data is efficient at identifying variable stars and variable AGN (for both of which quiescent emission is expected). Transients deemed as interesting are then broad-cast to the PTF collaboration for further spectroscopic follow up at Palomar, Lick, MDM, Keck and McDonald Observatories.

PTF is organized by key projects (Supernovae, Novae, Variable Stars, Flare Stars, Transients in the nearby Universe, Galactic Dynamics, Pre-main sequence Stars etc; see Rau et al. 2008). PTF has two main observing strategies designed to satisfy the needs of these key projects: Dynamic Cadence (`DyC`) aimed at studying the sky on timescales of minutes to days and the five Day Cadence (`5DC`) optimized for supernova searches (see Table 1).

Table 1. PTF Cadence.

Experiment	% Exposure	Cadences	Filter
`5DC`	41	5 d	R
`DyC`	40	1 min–3 d	g, R
`Orion`	11	1 min	R
`Full Moon`	8	–	Hα, [O III]

Notes: The % Exposure is the fraction of time devoted to the specific experiment.

6.1. Key Project: Transients in the Local Universe

A systematic search and study of transients in the local Universe ($d \lesssim 200$ Mpc), especially those in the gap (-10 to -16 mag) and fast transients (duration of few days), is one of the key projects of PTF. Our current knowledge and speculations relevant to this key project is summarized by the way of rates (some based on observations, other based on speculation) in Table 2.

*3 California Institution of Technology, Columbia University, Infrared Processing & Analysis Center, Lawrence Berkeley Laboratory, Las Cumbres Observatory Global Telescope, Weizmann Institute of Science & UC Berkeley.

*4 Built by the Canada-France-Hawaii Observatory and used on CFHT until a few years ago.

*5 The `DeepSky` project offers a simple access to all the wide field data collected by P48, over the past decade. The data have been fully reduced (i.e. photometric and astrometric calibration applied). These data provide a decade long, if irregular, history of the Palomar sky. This effort is a result of the efforts of Dr. Peter Nugent of the Lawrence Berkeley Laboratory.

Table 2. Properties and Rates for Optical Transients[a]

Class	M_R [mag]	τ^b [days]	Universal Rate (UR)	PTF Rate [yr^{-1}]
Dwarf Novae	9..4	3..20	3×10^{-5} pc^{-3} yr^{-1}	100
Classical novae	$-5..-10$	2..100	2×10^{-10} yr^{-1} $L^{-1}_{\odot,K}$	60..150
Luminous red novae	$-10..-14$	20..60	$> 1.5 \times 10^{-13}$ yr^{-1} $L^{-1}_{\odot,K}$	>1.5
Fallback SNe	$-4..-21$	0.5..2	10^{-13} yr^{-1} $L^{-1}_{\odot,K}$	1
Macronovae	$-13..-15$	0.3..3	$10^{-4..-8}$ Mpc^{-3} yr^{-1}	0.1
SNe .Ia	$-15..-17$	2..5	$(4..10) \times 10^{-6}$ Mpc^{-3} yr^{-1}	0.25..2
SNe Ia	$-17..-19.5$	30..70	[c] 3×10^{-5} Mpc^{-3} yr^{-1}	500
Core-collapse SNe	$-14..-21$	20..300	5×10^{-5} Mpc^{-3} yr^{-1}	200

[a]Table from Rau et al. 2008b; see references therein.

[b]Time to decay by 2 magnitudes from peak.

[c]Universal rate at z< 0.12.

Our search strategy is two-fold. First, we will extensively follow-up all optical transients that are spatially coincident with galaxies known to be within 200 Mpc found in either the `DyC` or the `5DC` experiment. We have compiled a detailed catalog of all galaxies known to be within this distance by synthesizing information from several different surveys. Based on this, we have selected the top hundred luminosity over-densities in the local universe which would be observed at a fast cadence with PTF (`DyC`). Targeting luminosity concentrations probes more star-light than random pointings by more than a factor of four. We note that the current catalog is incomplete[6]: fifty percent at 200 Mpc (Figure 5).

Second, to pursue transients that are in a galaxy not previously known to be within 200 Mpc, we will target fast-evolvers (timescale < 7 days) for follow-up spectroscopic observations and follow up imaging observations (to identify putative host galaxies). Fast transients lie in the least explored regime observationally and are least likely to be ordinary (routine Ia or routine core collapse) supernovae. Moreover, as extensively discussed in §2. theoretical models for transients in the gap also predict short lifetimes.

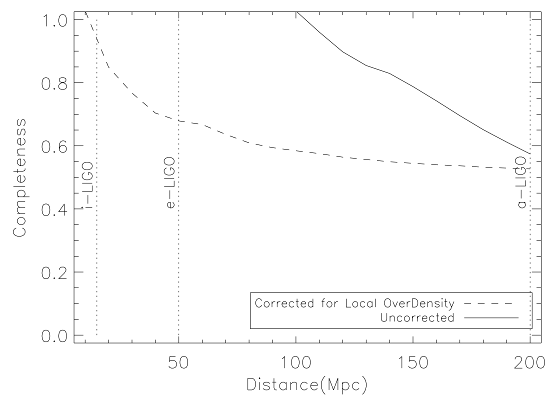

Fig. 5. Fraction of total theoretical light that is accounted for by galaxies in the catalog as a function of distance. A correction has been applied for the local overdensity by scaling the Schechter function by the observed luminosity brighter than L-star. This correction is applied every 10 Mpc and is a factor of three at 10 Mpc and one at 200 Mpc. From Kasliwal et al. 2009a, in prep.

7. PTF & MAXI

On Dec 13, 2008 PTF achieved first light. All indications are that the system is working as per specifications (except, as was determined in pre-commissioning lab tests, one of the twelve CCDs is dead; the effective solid angle is thus $7.79 \times 11/12 = 7.13$ square degrees). The on-sky performance will be reported shortly (Law et al. 2009).

The Japanese Space Station scientific module MAXI (Matsuoka et al. 2007) is expected to be in operational on the International Space Station (ISS) by May 2009. The field of view of MAXI is $2 \times 1.5 \times 160$ square degrees (Gas Slit Camera) and $2 \times 1 \times 90$ square degrees (Solid State Camera); the first factor of two refer to the horizontal and vertical sets. In one revolution period of ISS (about 91.3 minutes) almost 90% of the sky is scanned by the Gas Slit Camera system. For the minimum crossing time of 30 s, the 5-σ flux density is 7 mCrab $= 1.75 \times 10^{-10}$ erg cm^{-2} s^{-1} (2–10 keV band); see Ueno et al. (2004). We will refer to this as the one-orbit detection limit.

The MAXI one-orbit detection can be compared with the X-ray outburst of SN 2008D (7×10^{-10} erg cm^{-2} s^{-1}; 0.3–10 keV band) and duration of 400 s (Soderberg et al. 2008). Clearly, MAXI is well positioned to detecting similar events out to 50 Mpc. The covering fraction of

*6 A long term goal of PTF is to comprehensively the sky for star-forming galaxies (through narrow band filter survey) and improve the completeness and thus increase the yield of the transients in the local Universe.

MAXI for such events is small, 0.006. Using Table 2 one such event is expected over a 5-year lifetime of MAXI.

Separately, the 5-σ luminosity at a distance of 50 Mpc is $5 \times 10^{43}\,\mathrm{erg\,s^{-1}}$ (1-orbit) and $5 \times 10^{42}\,\mathrm{erg\,s^{-1}}$ (100-orbit). Nearby versions of the slow transient SCP 06F6 (§4.), assuming that the prototype was located at a cosmological distance of $z \sim 0.1$ or about 400 Mpc, will be detected by MAXI. As can be gathered from Table 2 all events with a rate of few percent of the SN rate (Ia or core-collapse) should be seen by PTF.

The basic approach of our key project (correlating the position of transients to the catalog of nearby galaxies) is well suited to the 0.1-degree localization of MAXI. The nearly complete sky coverage of MAXI (every ISS orbit) and the expected rapid transmission of the data (Matsuoka et al. 2007) means that we will have nearly contemporaneous X-ray coverage. The detection of X-ray flux provides a critical discriminant between thermal and non-thermal/highly shocked sources. We eagerly await the launch of MAXI!

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