Publications of the Astronomical Society of the Pacific, **121**:1334–1351, 2009 December

Exploring the Optical Transient Sky with the Palomar Transient Factory

Arne Rau,[1,2] Shrinivas R. Kulkarni,[1] Nicholas M. Law,[1] Joshua S. Bloom,[3] David Ciardi,[4] George S. Djorgovski,[1] Derek B. Fox,[5] Avishay Gal-Yam,[6] Carl C. Grillmair,[7] Mansi M. Kasliwal,[1] Peter E. Nugent,[8] Eran O. Ofek,[1] Robert M. Quimby,[1] William T. Reach,[9] Michael Shara,[10] Lars Bildsten,[11] S. Bradley Cenko,[3] Andrew J. Drake,[1] Alexei V. Filippenko,[3] David J. Helfand,[12] George Helou,[9] D. Andrew Howell,[13,14] Dovi Poznanski,[3,8] and Mark Sullivan[15]

Received 2008 November 28; accepted 2009 July 13; published 2009 October 5

ABSTRACT. The Palomar Transient Factory (PTF) is a wide-field experiment designed to investigate the optical transient and variable sky on time scales from minutes to years. PTF uses the CFH12k mosaic camera, with a field of view of $7.9\,\mathrm{deg}^2$ and a plate scale of $1''\,\mathrm{pixel}^{-1}$, mounted on the Palomar Observatory 48 inch Samuel Oschin Telescope. The PTF operation strategy is devised to probe the existing gaps in the transient phase space and to search for theoretically predicted, but not yet detected, phenomena, such as fallback supernovae, macronovae, .Ia supernovae, and the orphan afterglows of gamma-ray bursts. PTF will also discover many new members of known source classes, from cataclysmic variables in their various avatars to supernovae and active galactic nuclei, and will provide important insights into understanding galactic dynamics (through RR Lyrae stars) and the solar system (asteroids and near-Earth objects). The lessons that can be learned from PTF will be essential for the preparation of future large synoptic sky surveys like the Large Synoptic Survey Telescope. In this article we present the scientific motivation for PTF and describe in detail the goals and expectations for this experiment.

1. INTRODUCTION

The Palomar Transient Factory (PTF) is an experiment designed to explore systematically the optical transient and variable sky. The main goal of this project is to fill the gaps in our present-day knowledge of the optical transient phase space (Fig. 1). Besides reasonably well-studied populations (e.g., classical novae, supernovae), there exist many types of either poorly constrained events (e.g., luminous red novae, tidal disruption flares) or predicted but not yet discovered phenomena (e.g., orphan afterglows of gamma-ray bursts, GRBs). Here, dedicated wide-field instruments have the best prospect of leading to significant progress.

A number of surveys (summarized in Table 1) have attempted this challenging task and have provided important contributions to our understanding of time-domain science. The majority of these projects, however, have been designed (especially in terms of cadence) to maximize the discovery probability for selected source populations (typically microlensing, classical novae, or supernovae). Thus, large areas of the phase space remain poorly explored at best and are ripe for investigation with PTF.

The aim of this article is to present the scientific goals of PTF and to provide predictions for discoveries during the first four years of operation. In order to give the reader an overview of the project, we start by summarizing the important

[1] Caltech Optical Observatories, California Institute of Technology, Pasadena, CA 91125; arau@mpe.mpg.de.

[2] Max-Planck Institute for Extraterrestrial Physics, Garching 85748, Germany.

[3] Department of Astronomy, University of California, Berkeley, CA 94720-3411.

[4] Michelson Science Center, California Institute of Technology, Pasadena, CA 91125.

[5] Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802.

[6] Benoziyo Center for Astrophysics, Weizmann Institute of Science, 76100 Rehovot, Israel.

[7] Spitzer Science Center, California Institute of Technology, Pasadena, CA 91125.

[8] Lawrence Berkeley National Laboratory, Berkeley, CA 94720.

[9] Infrared Processing and Analysis Center, California Institute of Technology, Pasadena, CA 91125.

[10] Department of Astrophysics, American Museum of Natural History, New York, NY 10024.

[11] Kavli Institute for Theoretical Physics and Department of Physics, University of California, Santa Barbara, CA 93106.

[12] Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027.

[13] Las Cumbres Global Telescope Network, Santa Barbara, CA 93117.

[14] University of California, Santa Barbara, CA 93106.

[15] Department of Physics (Astrophysics), University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK

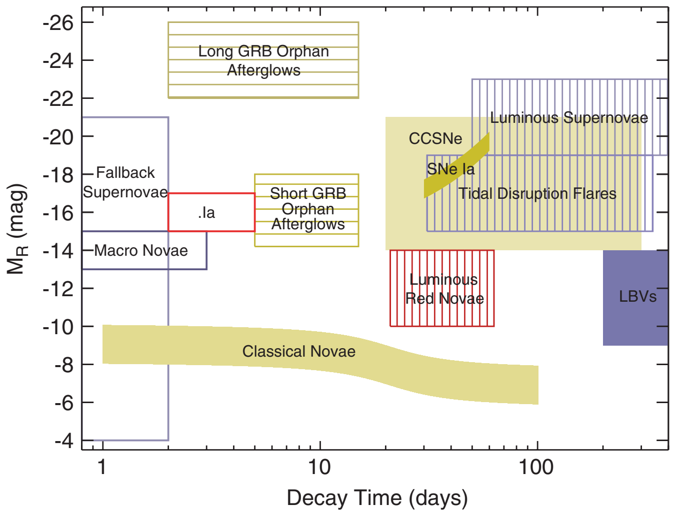

FIG. 1.—R-band peak magnitude as a function of characteristic decay timescale (typically the time to fade from peak by 2 magnitudes) for luminous optical transients and variables. *Filled boxes* mark well-studied classes with a large number of known members (classical novae, Type Ia supernovae [SNe Ia], core-collapse supernovae [CCSNe], luminous blue variables [LBVs]). *Vertically hatched boxes* show classes for which only few ($\lesssim 4$) 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 (fallback 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 4 for a more complete list). Regions indicate the general location of each class and are not exclusive. Outline colors of boxes correspond to the mean $g-r$ color at peak (*blue*, $g-r<0$ mag; *green*, $0 \lesssim g-r \lesssim 1$ mag; *red*, $g-r>1$ mag).

instrumental aspects of PTF and the general survey strategy. Much more detailed discussion of the PTF system, both hardware and software, can be found in a separate publication (Law et al. 2009).

2. PROJECT OVERVIEW

2.1. Instrument

PTF uses the CFH12K mosaic camera (formerly at the Canada-France-Hawaii Telescope) mounted on the Samuel Oschin 48 inch telescope (P48) at Palomar Observatory, California. The camera consists of two rows of six $2\text{k} \times 4\text{k}$ CCDs each, providing a $7.9\,\text{deg}^2$ field of view (FoV) with a plate scale of $1.0''$ pixel^{-1}; see Rahmer et al. 2008 for more details of the camera. Observations will be performed mainly in one of two broad-band filters (Mould-R, sdss-g), but additional narrow-band filters (Hα, Hα_{off}) can be employed at the telescope. Under typical seeing conditions ($1.1''$ at Palomar) the camera achieves a full width at half-maximum intensity (FWHM) ~$2.0''$ and 5σ limiting magnitudes of $R \approx 21.0$, $g' \approx 21.6$ and H$\alpha \approx 18$ mag can be reached in a 60 s exposure.

2.2. Observing Strategy

The first few months after first light on 2008 December 13 were used for commissioning of the instrument and software. Initial observations were taken to construct a fiducial reference image of the sky for later use in transient detection.

Following commissioning, PTF will be operating on 80% (~290 night yr^{-1}) of the P48 nights until at least the end of 2012. During this time several predefined long-term surveys and a number of evolving experiments will be performed. The primary experiments are the 5 day cadence survey (5DC), the dynamic cadence experiment (DyC), a monitoring of the Orion star-forming region (see § 3.10), and a narrowband all-sky survey. The respective time allocations, cadences, and photometric filters are summarized in Table 2.

The 5DC experiment will at any given time monitor an active area of ~$2700\,\text{deg}^2$ with a mean cadence of 5 days. Over the year, a total footprint of ~$10,000\,\text{deg}^2$ (largely overlapping with the SDSS) with Galactic latitude $|b| > 30^\circ$, and $-15^\circ < \delta_{\text{J2000}} < 86^\circ$ will be observed. This experiment will be performed using the R-band filter, and typically two 60 s exposures separated by 1 hr will be taken in each epoch. As part of the 5DC, we will also observe ~60 fields containing nearby galaxies. Note that these galaxies (with the exception of M31) will cover only a small fraction of the camera FoV.

The DyC experiment is designed to explore transient phenomena on time scales shorter than 5 days and longer than about 1 minute. Here, several different g and/or R band surveys will be conducted during the first six months of operation. Strategies for subsequent DyC observations will be decided after the initial results have been analyzed.

During bright time, 3π sr narrowband (Hα, Hα_{off}, [O III]) surveys will be conducted. Here, ~4000 tiles covering the sky at $\delta_{\text{J2000}} > -28^\circ$ will be observed at least twice in each filter. The estimated 5σ point source flux limit for the Hα survey will be ~$2 \times 10^{-17}\,\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}$ (~0.6 R). Better sensitivity by a factor of ~60 can be achieved by binning the Hα images to a resolution of $1'$. This sensitivity will constitute an improvement over that of previous surveys by a factor of ~250 (Fig. 2).

2.3. Follow-up Strategies

The key to a successful transient survey lies in the availability of follow-up resources, specifically multicolor imaging and spectroscopy. Most other wide-field searches aim to do both discovery and follow-up observations, with the same instrument, or have spectroscopic follow-up biased heavily toward a specific science goal (e.g., ESSENCE, SNLS, and SDSS-II with SNe Ia). In contrast, PTF will perform multicolor photometry for all candidate transients using a variety of facilities. Here,

TABLE 1

Comparison of PTF with Other Untargeted Transient and Variable Surveys

Survey	D[a] (m)	Scale (arcsec pixel^{-1})	FOV (deg^2)	Cadence	$m_{R,\mathrm{lim}}$[b] (mag)	Coverage (deg^2 night^{-1})	Lifetime	Reference
Palomar Transient Factory	1.26	1.0	7.78	1 minute–5 days	21.0	1000	Ongoing	Law et al. 2009
ROTSE-III[c]	0.45	3.25	3.42	1 day	18.5[d]	450	Ongoing	Quimby 2006
CIDA-QUEST[e]	1.0	1.0	5.4	2 days–1 yr	19.5	276	Ongoing	Baltay et al. 2002
Palomar-Quest	1.26	0.88	9.4	30 minutes–days	21.0[f]	500	2003–2008	Djorgovski et al. 2008
SDSS-II Supernova Search	2.5	0.4	1.5	2 days	22.6	150	2005–2008	Frieman et al. 2008a
Catalina Real-Time Transient Survey	0.7	2.5	8	10 minutes–yr	19.5[g]	1200	Ongoing	Drake et al. 2008
Supernovae Legacy Survey	3.6	0.08	1	3 days–5 yr	24.3	2	2003–2008	Astier et al. 2006
SkyMapper	1.33	0.5	5.7	0.2 days–1 yr	19.0	1000	Start 2009	Schmidt, B., 2009, private communication
Pan-STARRS1 3π[h]	1.8	0.3	7	7 days	21.5	6000	Start 2009	Young et al. 2008
Large Synoptic Survey Telescope	8.4	0.19	9.62	3 days	24.5	3300	Start 2014	Ivezic et al. 2008

[a] Telescope diameter.
[b] Typical limiting magnitude for single pointing.
[c] Texas Supernovae Search (until 2007) and ROTSE Supernovae Verification Project (since 2007).
[d] Unfiltered.
[e] Equatorial variability survey.
[f] RG610 filter.
[g] V band filter.
[h] Pan-STARRS1 3π imaging survey.

a large fraction of Palomar 60 inch (optical; Cenko et al. 2006), LCOGT[16] (optical) Super-LOTIS (optical; Park et al. 1999), KAIT (optical; Filippenko et al. 2001), and PAIRITEL (near-IR; Bloom et al. 2006) time has been set aside. Additional spectroscopy is planned at the Palomar Hale 5 m, MDM Observatory, William Herschel 4.2 m, and Lick 3 m telescopes.

A detailed discussion of all aspects mentioned in this section as well as the data reduction, analysis, and archiving can be found in Law et al. 2009.

3. PTF SCIENCE GOALS

The PTF design is optimized for repeated coverage of a large sky area in a short amount of time. This is crucial for pursuing the primary science goal, namely to investigate the various populations of transients and variables. In addition, it allows the usage of deeper, coadded images to study persistent sources, ranging from Galactic foreground stars to distant galaxies. While it is not possible to predict all of the science that PTF will enable, a few key areas of interest have been defined and will be summarized in this section. Here, we first address transient and variable sources from our neighborhood to high redshift, followed by regularly variable classes and science with the coadded data products. An overview of the sections is given in Table 3, while Table 4 summarizes the properties, universal rates, and PTF predictions for transients and variables.

[16] See http://lcogt.net/.

3.1. Cataclysmic Variables

Cataclysmic variables (CVs) form a broad family of highly variable and dynamical stellar binaries in which matter from a low-mass donor ($M \lesssim 1\ M_\odot$) is accreted onto a white dwarf ($M \approx 1\ M_\odot$; e.g., Warner 1995). Variability, from milliseconds to hundreds of years, arises from different physical processes, and conclusions derived from CVs have been extrapolated, upward or downward in scale, to other phenomena such as active galactic nuclei (AGNs) and X-ray binaries. Despite being studied for several decades, many details concerning the viscous turbulence in the accretion disk, interaction of the accreted matter with the atmosphere of the white dwarf, irregularities

TABLE 2

Summary of Main PTF Experiments

Experiment	Exposure % of total	Cadences	Filter
5DC	41	5 days	R
DyC	40	1 minute–3 days	g, R
Orion	11	1 minute	R
Full Moon	8	...	Hα

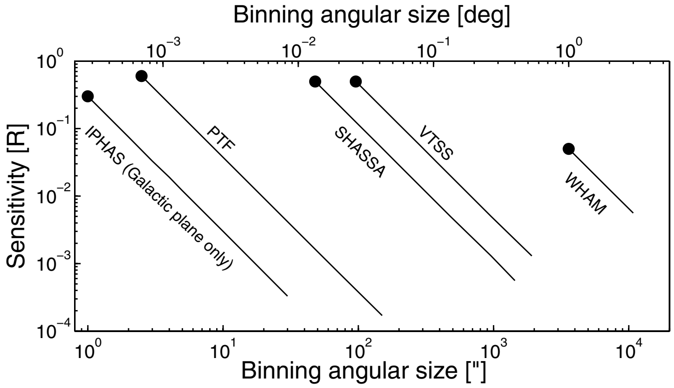

FIG. 2.—The surface brightness sensitivity (Rayleigh, R) of the PTF Hα survey as a function of the angular size. The smallest angular size is determined by the pixel size (*filled circle*). Binning is expected to improve sensitivity in proportion to the square root of the number of pixels. The proposed survey will have better sensitivity by more than 2 orders of magnitude over previous surveys (e.g., SHASSA, Gaustad et al. 2001; VTSS, Dennison et al. 1998). The only survey with superior sensitivity (IPHAS, Walton et al. 2004) is limited to the Galactic plane ($|b| < 5^{\circ}$).

within regular photometric behavior, and the final fate of these objects, are still missing.

An important subclass of CVs is the so-called dwarf novae (DNe), which show quasi-periodic outbursts (on time scales of weeks to years) with amplitudes of 3–8 mag and durations of typically 3–20 days. These transient events are the result of a sudden viscosity change in the accretion disk. The origin of this change is still controversial; instabilities either in the disk (Meyer & Meyer-Hofmeister 1981) or in the secondary star (Bath et al. 1986) or both may be responsible. Increasing the sample of well-studied events will help to distinguish between these models.

TABLE 3
SUMMARY OF SCIENCE DRIVERS DISCUSSED IN § 3

Science Driver	Main Survey	Section
Cataclysmic variables	DyC, 5DC	3.1
Classical novae	5DC	3.2
Luminous red novae, .Ia supernovae	DyC, 5DC	3.3
Type Ia supernovae	5DC	3.4
Core-collapse supernovae	5DC	3.5
Luminous & pair-instability supernovae	5DC	3.6
Blazars	5DC	3.7
Tidal disruption flares	5DC	3.8
(Orphan) GRB afterglows	DyC, 5DC	3.9
Exoplanet transits in Orion	Orion	3.10
Eclipsing objects around cool stars	DyC	3.11
RR Lyrae stars	5DC	3.12
Galactic variable stars	DyC, 5DC	3.13
Microlensing	5DC	3.14
Near-Earth objects	5DC	3.15
PTF as follow-up instrument	ToO	3.16
Coadded & narrowband data	Dyc, 5DC, NB	3.17

The current estimate of the space density of DNe ranges from $\sim 3 \times 10^{-5}$ pc^{-3} (observations; Schwope et al. 2002) to as much as $\sim 10^{-4}$ pc^{-3} (theory; Kolb 1993). For typical values of peak magnitude ($9 > M_R > 4$ mag) and recurrence time scale (1 yr; Rau et al. 2007b), this suggests the detection of about 100 DNe yr^{-1} in the 5DC.

In special cases, the secondary can be another white dwarf or a hydrogen-depleted star in a tight orbit, whose evolution is dictated by gravitational wave radiation. Depending on the orbital period, mass transfer can either be through a stable or unstable disk or via direct impact. These so-called AM CVn stars are of particular interest as they form the dominant population of gravitational wave sources detectable with the future Laser Interferometer Space Antenna (LISA) mission. Merging white dwarfs are also strong progenitor candidates for SNe Ia (e.g., Iben & Tutukov 1984; Webbink 1984) and thus are important tracers of binary stellar evolution.

AM CVn systems with an unstable accretion disk exhibit photometric outbursts similar to those of hydrogen-rich dwarf novae and can be detected as transient events with PTF. However, with an inferred space density of $\sim(1-3) \times 10^{-6}$ pc^{-3} (Roelofs et al. 2007), AM CVn stars are rare compared with normal CVs. Furthermore, only 5%–6% of the population reside within the instability range in which outbursts occur, and He ionization results in much shorter time scales of these events. Thus, only a few of these elusive sources are expected to be found in the DyC experiments.

3.2. Classical Novae

In some CVs the matter accreted onto the primary white dwarf can experience a thermonuclear runaway, driving substantial mass loss from the system. These classical nova eruptions reach absolute peak magnitudes of $-5 \gtrsim M_R \gtrsim -10$ mag ($\langle M_R \rangle \sim -7.5$ mag in M31; Shafter et al. 2009) and fade on time scales of days to weeks (e.g., Warner 2008).

A typical M31-like galaxy produces $\sim 2 \times 10^{-10}$ novae yr^{-1} $L_{\odot,K}^{-1}$ (Ferrarese et al. 2003), translating into ~ 30 yr^{-1}. PTF will repeatedly image 60 large, nearby ($m - M < 29$ mag) galaxies as part of the 5DC. We anticipate ~ 10 novae yr^{-1} galaxy^{-1} to lie above the detection limit. Thus, a typical coverage of three months per year for each galaxy will provide ~ 150 extragalactic classical nova discoveries every year.

The spatial and luminosity distributions of these novae inside their host galaxies will provide invaluable tests of cataclysmic-binary evolution theory. Predictions that fast novae should predominantly arise in spiral arms (della Valle et al. 1994) are still lacking conclusive observational evidence (e.g., Neill & Shara 2004). The expected dramatic enlargement of the number of accurately sampled nova light curves will help to test this prediction.

In addition to targeting nearby galaxies, PTF will place the first meaningful limits on the space density of intergalactic "tramp stars" (Shara 2006) by searching for classical novae

TABLE 4
PROPERTIES AND RATES FOR SELECTED TRANSIENTS AND VARIABLES

Class	M_R (mag)	τ[a] (days)	Universal Rate (UR)	PTF Rate (yr^{-1})	Reference[b] M_R, τ, UR
Dwarf novae	9..4	3..20	3×10^{-5} pc^{-3} yr^{-1}	100	1,2,3
Classical novae	−5..−10	2..100	2×10^{-10} yr^{-1} $L_{\odot,K}^{-1}$	60..150	4,5,6
Luminous red novae	−10..−14	20..60	1.5×10^{-13} $yr^{-1}L_{\odot,K}^{-1}$	1.5	7,7,8
Fallback SNe	-4..-21	0.5..2	10^{-13} yr^{-1} $L_{\odot,K}^{-1}$	1	9,9,9
Macronovae	−13..−15	0.3..3	$10^{-4..-8}Mpc^{-3}yr^{-1}$	0.1	10,10,11
SNe .Ia	−15..−17	2..5	$(4..10) \times 10^{-6}$ Mpc^{-3} yr^{-1}	0.25..2	12,12,12
SNe Ia[c]	−17..−19.5	30..70	3×10^{-5} Mpc^{-3} yr^{-1}	500	13,13,14
Tidal disruption flares	−15..−19	30..350	10^{-6} Mpc^{-3} yr^{-1}	3	15,15,15
Core-collapse SNe	−14..−21	20..300	5×10^{-5} Mpc^{-3} yr^{-1}	200	16,*,17
Luminous SNe	−19..−23	50..400	10^{-7} Mpc^{-3} yr^{-1}	>10	18,18,*
Orphan afterglows (SGRB)	−14..−18	5..15	$3 \times 10^{-7..-9}$ Mpc^{-3} yr^{-1}	<1	*,*,*
Orphan afterglows (LGRB)	−22..−26	2..15	$3 \times 10^{-7..-9}$ Mpc^{-3} yr^{-1}	<1	*,*,*
On-axis LGRB afterglows	..−37	1..15	4×10^{-10} Mpc^{-3} yr^{-1}	0.5	*,19,20

[a] Time to decay by 2 mag from peak.
[b] References for M_R, τ, and universal rate: (1) Rau et al. 2007b; (2) Sterken & Jaschek 2005; (3) Schwope et al. 2002; (4) Shafter et al. 2009; (5) della Valle & Livio 1995; (6) Ferrarese et al. 2003; (7) Kulkarni et al. 2007; (8) Ofek et al. 2008; (9) Fryer, C.L., 2009, private communication; (10) Kulkarni 2005; (11) Nakar et al. 2006; (12) Bildsten et al. 2007; (13) Jha et al. 2006; (14) Dilday et al. 2008; (15) Strubbe & Quataert 2009; (16) Richardson et al. 2002; (17) Cappellaro et al. 1999; (18) Scannapieco et al. 2005; (19) Fox et al. 2003; (20) Guetta et al. 2005b; (*) see text.
[c] Universal rate at $z < 0.12$

as their proxies. Previous detections of "tramp" planetary nebulae and novae in the Virgo cluster (Feldmeier et al. 2004) and the Fornax cluster (Neill et al. 2005) suggest that 16% to 40% of all stars in rich clusters reside in intracluster space outside of galaxies. PTF will probe whether the same is true of less dense environments like the Local Group, or of intergalactic space in general. In the 5DC, novae originating in a space volume at least 4 times larger than the Local Group can be detected (out to a distance of $D = 2.5$ Mpc). We expect ~16 tramp novae to be found every year if 10% of the stars in and around the Local Group are tramps[17]. Conversely, if zero intergalactic tramps are found, an upper limit on the baryon contribution in the universe from intergalactic tramp stars of ~1%–2% can be set after one year.

3.3. Other Transients in Nearby Galaxies

Observations suggest a paucity of transients between the peak absolute brightness of classical novae ($M_R \gtrsim -10$ mag) and supernovae ($M_R \lesssim -14$ mag). However, recent discovery of a number of enigmatic events in this gap have demonstrated the potential for exciting discoveries with dedicated experiments.

One of these newly emerging classes are the luminous red novae (LRNe), whose origin and explosion physics still pose unsolved puzzles. This elusive group of sources includes only four known members: M31 RV (Rich et al. 1989), V4332 Sgr (Martini et al. 1999), V838 Mon (Brown et al. 2002), and M85 OT 2006-1 (Kulkarni et al. 2007). Their observational properties differ from those of classical novae and typical supernovae by showing a slowly evolving outburst with an optical plateau lasting weeks to months, followed by a strong redward evolution resembling a transition from stellar type ~F to ~M and colder (e.g., Rau et al. 2007a).

Several formation models have been proposed, including stellar mergers (Soker & Tylenda 2003), rare novae (Iben & Tutukov 1992), and supernovae (Pastorello et al. 2007); these scenarios need to be assessed with an increased sample of accurately studied events. Also, the underlying stellar population of the known sample has a large diversity, ranging from a B-star cluster in the Milky Way (V838 Mon; Afşar & Bond 2007) to the bulge of M31 (M31 RV; Rich et al. 1989). This leads to the question of whether the known LRNe form one homogeneous class of objects (with the explosion physics being independent of the stellar population), or if different scenarios apply to each of the individual sample members. Note that two additional sources at the bright end of the distribution, SN 2008S (e.g., Arbour & Boles 2008; Prieto et al. 2008) and NGC300 OT (e.g., Monard 2008), have been found recently. Associations with extreme asymptotic giant branch (AGB) stars have been proposed for these events (Thompson et al. 2008).

Based on rates estimated from the number of known LRNe (1.5×10^{-13} yr^{-1} $L_{\odot,K}^{-1}$; Ofek et al. 2008), we expect to discover >1.5 yr^{-1} during the 5DC coverage of galaxies within 16 Mpc. Over a 4 yr lifetime of PTF, this will more than double the known sample and provide valuable insight into the origin and properties of these rare transients.

[17] This assumes 8 months yr^{-1} observation of the ~2700 deg^2 of the 5DC and ~60 novae yr^{-1} detected in the Local Group (mostly M31 and the Galaxy).

The regular PTF monitoring of nearby galaxies will also allow a search for a number of theoretically predicted, but not yet observationally confirmed, populations of transients. Among these are the faint thermonuclear supernovae from AM CVn binaries (".Ia SNe", one-tenth as bright for one-tenth the time as a SN Ia; Bildsten et al. 2007). Helium that accretes onto the white dwarf primary can undergo unstable thermonuclear flashes. At wide binary separations ($P\mathrm{orb} > 25\,\mathrm{min}$) a large mass will be accumulated before ignition, leading to violent flashes in which high pressure allows the burning to produce radioactive elements to power a faint ($-15 \gtrsim M_R \gtrsim -17$ mag) and rapidly rising (2–5 d) thermonuclear supernova. The local Galactic AM CVn space density implies one such explosion every 5,000–15,000 yr in $10^{11} M_\odot$ of old stars (~2%–6% of the SNe Ia rate in E/SO galaxies), giving an expected DyC yield of a few per year. The first possible manifestations of this class in nature have recently been found with SN 2008ha (Foley et al. 2009) and SN 2005E (Perets et al. 2009).

3.4. Type Ia Supernovae

Observations of SNe Ia provided the first direct and, to date, the best evidence for the acceleration of the expansion of the universe, propelled by some kind of mysterious "dark energy" (Riess et al. 1998; Perlmutter et al. 1999); see Frieman et al. (2008b) for a review. To determine whether the equation-of-state parameter of the dark energy[18] is consistent with Einstein's cosmological constant, enormous efforts are underway to populate the SN Ia Hubble diagram with accurate measurements of hundreds of events at redshifts $0.1 < z < 1.0$. Most noteworthy are the Supernova Legacy Survey (SNLS; Astier et al. 2006), ESSENCE (Miknaitis et al. 2007), and the SDSS SN survey (Frieman et al. 2008a). Future precision cosmology experiments (e.g., Joint Dark Energy Mission) may work at even higher redshifts (up to $z \approx 1.7$).

SN Ia cosmology relies on comparison of the apparent brightnesses of high-redshift events to those at low redshift, to measure accurate relative distances. PTF is expected to discover $\approx$500 SNe Ia yr^{-1} during the 5DC in the nearby smooth Hubble flow ($0.03 \lesssim z \lesssim 0.14$) out of which $\approx$150 yr^{-1} will be followed in detail, all caught well before maximum light and in the lower half of this redshift range.

The discrimination among specific models of dark energy requires a more detailed understanding of SNe Ia and on methods to test for cosmic evolution and other systematic effects, e.g., separation of intrinsic SN color-luminosity relations from dust reddening, impact of the environment, and evolution of the progenitors with redshift. See Howell et al. (2009) for a review of the largest systematic uncertainties affecting SN Ia and methods to mitigate their effects. Owing to the augmented low-redshift statistics and systematics control of the program, the PTF light curves, in conjunction with higher-redshift data, will allow the construction of the most accurate SN Ia Hubble diagram yet.

The purely statistical impact of a large number of low-redshift SNe Ia on the determination of the cosmic parameters is illustrated in Figure 3. A simulated data set of 1000 SNe Ia centered at $z = 0.08$ is paired with 500 SNe Ia distributed in the redshift range $0.2 < z < 0.8$ The constraints on a constant form of the dark energy as well as on the dynamical component are strengthened by a factor of 2 when the local sample is included. These results illustrate the impact that the PTF data set can have in the near future. In addition, current SN Ia analyses are dominated by systematic uncertainties and the homogeous, well-calibrated sampling of PTF will provide an important improvement.

The large area covered by the 5DC experiment will include a sizable number of relatively nearby, Abell-like galaxy clusters. SNe Ia occurring in these clusters will be of particular interest. The SN rate in galaxy clusters is a useful tool to constrain SN Ia progenitors (e.g., Maoz & Gal-Yam 2004; Sharon et al. 2007), while the fraction of hostless SNe (Gal-Yam et al. 2003), presumably resulting from progenitors that are members of the intergalactic stellar population in clusters, is a useful probe of the fraction of intergalactic "tramp" stars and its evolution with redshift.

PTF's capability to reveal a large number of SN Ia has already been demonstrated by the first discoveries during

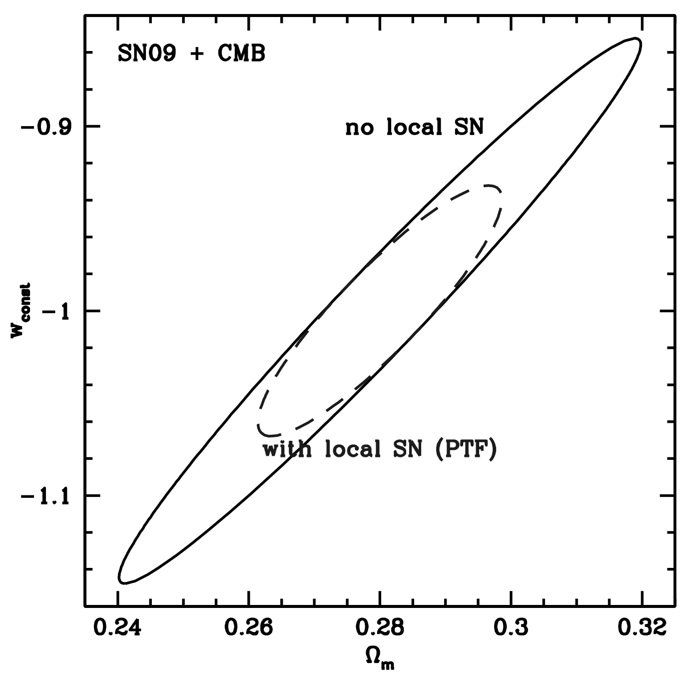

FIG. 3.—Impact of 1000 well-studied, well-calibrated, low-redshift Hubble-flow SNe Ia when mated to near-term simulated high-redshift surveys ($z = 0.9$).

[18] $w = P/\rho$, with P being the pressure and ρ the energy density.

commissioning. Two events were found by searching $589\,\mathrm{deg}^2$ of data taken in a single night on 2009 March 2 (Kulkarni et al. 2009). The first source was detected at 18.62 ± 0.04 mag near the core of an SDSS galaxy with $g = 17.78$ and a redshift of $z = 0.0555$ and spectroscopically identified as SN Ia at the Palomar Hale 5 m telescope. The second event was an independent detection of SN 2009an (Cortini et al. 2009). More information about the first PTF transient discoveries can be found in Law et al. (2009).

3.5. Core-Collapse Supernovae

The study of core-collapse supernovae (CCSNe) is critical to understanding the final stages of massive-star evolution and the formation of neutron stars and black holes, natural laboratories for general relativity. Furthermore, CCSNe produce heavy elements, dust, and cosmic rays; their explosion shocks trigger (and inhibit) star formation; and their energy input to the interstellar medium is a crucial ingredient in modeling galaxy formation.

CCSNe will likely form one of the most luminous and distant populations of transients for PTF. Their typical peak absolute magnitudes[19] range from $M_R = -14$ to -21 mag ($\langle M_R \rangle \approx -17.8$ mag), thus allowing detections out to $z \approx 0.4$ for the most luminous events. Based on discovery statistics from the Supernova Factory project (Aldering et al. 2002), the 5DC is expected to reveal ~200 events yr^{-1} shortly after explosion down to $R \approx 19.5$ mag.

Most nearby SNe are discovered by repeated imaging of catalogued galaxies (e.g., Filippenko et al. 2001). This introduces a possible bias, skewing the resulting sample strongly toward events in large, luminous, metal-rich galaxies (Fig. 4). Previous untargeted surveys have uncovered peculiar SNe, occurring in small, low-luminosity, and probably metal-poor galaxies (e.g., Young et al. 2008). Metallicity has a strong impact on the pre-SN evolution of massive stars, influencing wind mass loss (and thus the final core mass and composition), loss of angular momentum, and the opacity (e.g., Fryer et al. 2007). Also, long-duration GRBs, which are associated with very energetic CCSNe, have been found in faint, low-metallicity host galaxies (e.g., Stanek et al. 2006; Modjaz et al. 2008).

The 5DC provides an untargeted search with thousands of anonymous galaxies in each frame, allowing one to construct a supernova sample without host-galaxy bias. This will provide an accurate picture of the cosmic CCSN population and present observational constraints on theoretical models for low and high-metallicity explosions. Assuming galactic luminosity functions measured by the SDSS at $z = 0.1$ and the linear metallicity-luminosity relation (Tremonti et al. 2004), we can estimate that at least ~15% of the SNe detected by PTF will reside in galaxies which are as metal poor as the Large Magellanic Cloud (LMC), and about 20% of those will reside in galaxies more metal-poor than the Small Magellanic Cloud (SMC).

SNe II-P, a subset of CCSNe, have been shown to be standardizable by an empirical correlation (Hamuy & Pinto 2002; Nugent et al. 2006). Their intrinsic inhomogeneity can be calibrated well and the resulting distance precision for cosmology is about 10% (Poznanski et al. 2009), only slightly worse than that of SNe Ia (7%; Astier et al. 2006). PTF will populate the SNe II-P Hubble diagram with about 20 Hubble-flow events month^{-1} to build an entirely independent and novel test of the cosmology inferred from SNe Ia.

Finally, with dense sampling of virtually every nearby galaxy observable from the northern hemisphere, PTF will be a powerful discovery machine for the most underluminous (or rapidly decaying) events, providing additional clues to the nature of cosmic explosions with very faint optical displays (e.g., Gal-Yam et al. 2006a; Bildsten et al. 2007; Pastorello et al. 2004).

3.6. Luminous Supernovae and Pair-Instability Supernovae

The first stars to form in the universe typically ended their brief lives through pair-instability supernovae (e.g., Barkat et al. 1967; Heger & Woosley 2002), but it was long believed that this exit was not available to the metal-enriched stars of the modern era. Recently, however, the discovery of SN 2006gy has provided what may be the first evidence for such an explosion (Ofek et al. 2007; Smith et al. 2007), and surprisingly, this extremely luminous (brighter than -20 mag for 150 days), long-lived supernova was found in the local universe. The pair-instability mechanism requires a star to meet its end with a substantial mass still bound to it. The rate of such events in the local universe will thus significantly augment our understanding of the top end of the stellar initial mass function as well as the role metallicity plays in shedding mass prior to the explosion. As SN 2006gy-like events are luminous, expected to occur frequently in the early universe, and relatively simple to model, they may serve as cosmological probes in the James Webb Space Telescope era. Events discovered by PTF in the local universe may serve as a proving ground for their utility.

The estimated event rate of ~100 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ suggest that about 20 (200) SN 2006gy-like events yr^{-1} above $R = 18$ mag (21.0 mag) can be discovered during the course of the 5DC. It is important to note that the handful of known events have all been discovered in blind surveys (e.g., Texas Supernova Search, TSS, Quimby 2006; Catalina Real-time Transient Survey, Drake et al. 2009), such as PTF.

The most luminous supernova yet identified is SN 2005ap, found by the TSS (Quimby et al. 2007). Smith et al. (2008) suggest that SN 2005ap may be physically similar to SN 2006gy, and Quimby et al. (2007) note a possible connection to the engines powering GRBs. With only weakly diluted blackbody

[19] Determined from 72 CCSNe from Richardson et al. (2002), assuming $\mathrm{M}_B - \mathrm{M}_R \approx 0$ mag.

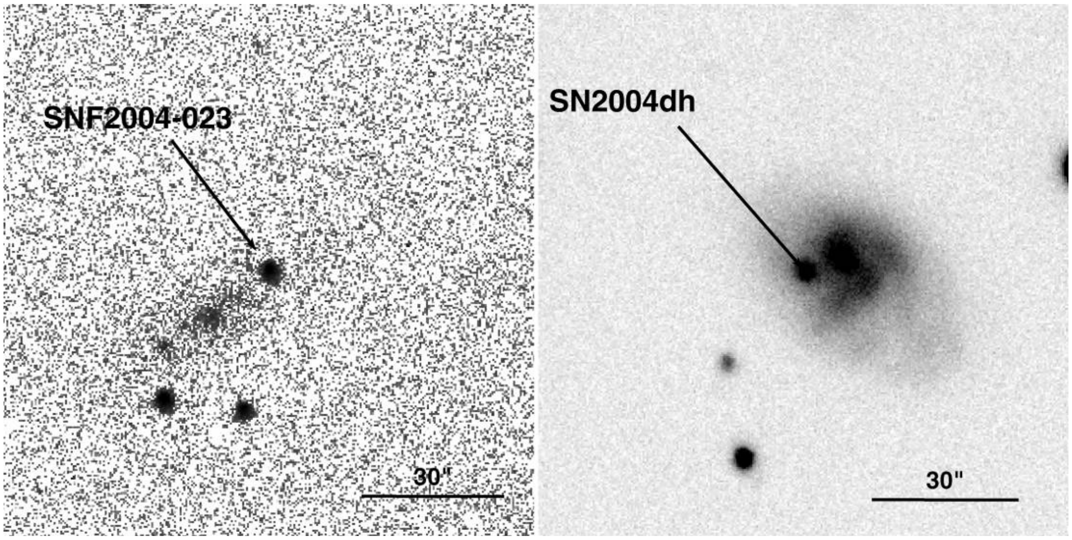

FIG. 4.—Comparison of two CCSNe at similar redshift and magnitude from the Caltech Core-Collapse Program (Gal-Yam et al. 2007). *Left,* a SN (SNF2004-023) discovered in an untargeted search (SNfactory; Wood-Vasey et al. 2004); *right*, SN 2004dh, found in a targeted search (Lick Observatory Supernova Search; Li et al. 2000). Note the LMC-like faintness of the host in the left panel compared to the host of SN 2004dh. Such low-luminosity (and probably low-metallicity) hosts are likely to produce new types of SNe. Thus, a sample drawn from an untargeted survey such as the PTF 5DC will provide a more accurate picture of the cosmic SN population.

spectra and rapid photometric evolution, SN 2005ap-like events offer another possible probe of the early universe, and PTF can help reveal their physical identities. While a rate cannot accurately be measured from a single event, we speculate that SN 2005ap-like events are roughly half as common as sources similar to SN 2006gy.

While there is not yet any conclusive evidence that SN 2005ap, SN 2006gy, or any of the extremely luminous SNe are indeed related to pair-instability explosions, there is no conclusive evidence that they are not. PTF will significantly expand the sample of well-studied luminous SNe and perhaps provide an answer as to whether or not PISNe occur in the local universe.

3.7. Blazars

The light curves of blazars (AGN with the jet pointed toward the observer; e.g., Urry & Padovani 1995) are dominated by Doppler-boosted instabilities and other phenomena associated with relativistic outflows, rather than by the accretion-driven variability of ordinary AGN. Thus, variability is one of their most notable characteristics, offering both a method for discovery and insight into their physics.

Blazars are likely the dominant contributors to the cosmic gamma-ray background (Narumoto & Totani 2006; Giommi et al. 2006). They also form the main foreground population at high radio frequencies, and an understanding of them will be essential for proper modeling of the cosmic microwave background radiation at high angular frequencies, such as for the Planck mission (see, e.g., Giommi et al. 2006; Giommi et al. 2007; Wright et al. 2009). Moreover, a growing number of blazars has been detected at TeV energies (e.g., Horan & Weekes 2004; Horns 2008). Even more intriguingly, beamed AGN are perhaps among the most plausible sources of ultrahigh energy cosmic rays, reaching energies of 10^{21} eV (e.g., Dermer 2007). These cosmic accelerators are bound to play an increasingly important role in the future of astro-particle physics.

The *Fermi* mission will play a dominant role in the studies of blazars over the next several years. Ground-based studies from synoptic sky surveys like PTF will provide valuable complementary data for maximum scientific returns. First, archival analysis of multiepoch data from PTF, combined with other, previous and ongoing synoptic surveys such as Palomar Quest (Djorgovski et al. 2008) or the Catalina Sky Survey (Drake et al. 2009), can be used to define purely variability-based (or variability and color-based) samples of blazars. This will provide an important check on the selection effects in the more traditional, radio-based samples. Archival light curves and measures of variability can be used in a joint analysis with data from radio to gamma rays. This will result in larger, more complete samples of blazars, crucial for the studies described here.

Second, real-time detection of optical flares of blazars, correlated with the gamma-ray data stream from *Fermi*, can be used to detect gamma-ray loud blazars at fainter flux levels than would be statistically justifiable from the gamma rays alone, or would lead to new blazar discoveries on their own. These detections can be used to trigger other follow-up observations; a joint analysis of such multiwavelength, synoptic observations of blazar flares could lead to better constraints for theoretical models. Such statistical monitoring of large areas of the sky is complementary to the more traditional follow-up monitoring of selected samples of known blazars (e.g., Carini 2004). We estimate that PTF will see at least a few tens of potential *Fermi* blazars per clear night, of which roughly one will have a strong optical blazar flare.

Blazars are known to vary significantly on all time scales where data exist, with the power spectra well represented by a power law, so in principle an arbitrarily large fluctuation can occur given a sufficiently long time interval. In practice, fluctuations at a level of several tenths of a magnitude are common on time scales of hours or days, and fluctuations at a level of 1 or 2 mag are commonly seen on time scales of months, but with rise or fall times as short as a day or even less. This should be contrasted with the variability of normal quasars, where typical variations on a scale of several tenths of a magnitude occur on a time scale of years, and dramatic (e.g., magnitude or greater) changes are extremely rare on the time scales probed by the existing observations.

3.8. Tidal Disruption Flares

Stars passing within a distance of $5M_7^{-2/3}$ Schwarzschild radii of a supermassive black hole (SMBH) of $M_{\rm SMBH} = 10^7 M_7 M_\odot$ will be torn apart by the strong tidal gravitational field (e.g., Hills 1975; Rees 1988). While for $M_7 \gtrsim 20$ the disruption of a main-sequence star happens inside the event horizon, for less massive SMBHs this should give rise to a detectable flare of emission. To date, only a few candidate tidal disruption flares (TDFs) have been found, primarily in the *ROSAT* All Sky Survey archive (e.g., Komossa & Bade 1999; Komossa & Greiner 1999) and in rest frame-UV monitoring of otherwise dormant galaxies (e.g., Renzini et al. 1995; Gezari et al. 2006, 2008).

The flare emission is predicted to be dominated by an optically thick accretion disk with a temperature $T_{\rm eff} \approx 3 \times 10^5 M_7^{-1/4}$ K (Ulmer 1999), peaking in the far-UV. Line emission from unbound (ejected) material (Strubbe & Quataert 2009) is expected to significantly enhance the blackbody continuum flux in the optical. This can lead to a peak absolute magnitude in the rest frame of $M_R \approx -15$ to -19 mag (see also Strubbe & Quataert 2009, and observationally confirmed by Gezari et al. 2008), roughly comparable to the absolute magnitude of a supernova. The single-epoch PTF sensitivities suggest that the TDF population will be probed to ~$200 M_7$ Mpc ($z = 0.05$), corresponding to a volumetric rate of $40 M_7^{3/2}$ yr^{-1} over the entire sky or about 3 yr^{-1} in the 5DC.

One of the principal difficulties in pursuing these events is in distinguishing TDFs from nuclear SNe and ordinary AGN variability. Here both the particular light curve (a rapid rise over days to weeks followed by a power-law decline[20]) and spectral evolution provide valuable guidance. Historical variability limits from the Deep Sky project[21] can further constrain patterns of low-level AGN activity.

We expect roughly 10% of rapidly rising events in galactic nuclei to be TDFs (as opposed to SNe). Having ~2 kpc resolution at $z = 0.05$, we must contend not only with nuclear transient events but the light of the host-galaxy bulge itself. Thus, events from lower-mass (10^5–10^6 $M_\odot$) SMBHs may be more reliably identified since their bulges are expected to be comparatively faint.

Even if the yield from PTF is only a few ironclad cases, the ensuing multifrequency investigations will have great value in providing feedback for TDF models and influencing strategies for future TDF observing campaigns. These discoveries will provide a window into the demographics of SMBHs and detailed follow-up observations could allow for an entirely new way of measuring black hole mass, thus offering an independent test of the $M_{\rm SMBH} - \sigma_*$ relation of galaxies (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002).

3.9. Untriggered and Orphan GRB Afterglows

By far the most luminous (up to $M_R = -37$ mag) transients that PTF may detect are the afterglows of GRBs for which the ultrarelativistic collimated outflows are pointed toward the Earth. GRB statistics from BATSE onboard *Compton Gamma Ray Observatory,* (*CGRO*) suggest that a few such events happen every day in the universe (Paciesas et al. 1999), corresponding to ~$0.02\,{\rm deg}^{-2}$ yr^{-1}. Out of these, ~50% remain brighter than $R = 20$ mag for at least 1000 s and can in principle be discovered blindly[22] with PTF. These untriggered afterglows may appear as fast transients in a single or pair of images of the 5DC; however, the expected rate is very small (~0.5 yr^{-1}).

A more numerous population of transients is predicted by the collimated nature of GRBs, observationally suggested by the "jet breaks" in afterglow light curves (e.g., Harrison et al. 1999; Stanek et al. 1999; Frail et al. 2000, 2001). These orphan afterglows arise when the initial GRB, and its associated afterglow light, are directed away from the observer. Here, the deceleration of the relativistic outflow, the associated decrease in special-relativistic beaming, and the hydrodynamic spreading of the collimated jet combine at the jet-break time, $t_{\rm jet}$, to irradiate a rapidly increasing fraction of the sky (e.g., Rhoads 1999). Observers illuminated during this transition will detect a steeply rising ($\Delta t \approx t_{\rm jet}/10$) transient that proceeds to behave as a post-jet break, on-axis afterglow. It will fade as a power law ($F_\nu \propto t^{-\alpha}$) with $\alpha \approx 2.3$, referenced to the (unconstrained) burst time, resulting in a decay by ~1 mag over a time scale of $\Delta t \approx 1.5 t_{\rm jet}$. Note that the typical observed jet-break times for GRBs are ~1 to 10 d.

[20] The decline of interloping SNe should be exponential.

[21] At http://supernova.lbl.gov/~nugent/deepsky.html.

[22] By this we mean, not by follow-up observations in response to a trigger with high-energy observations.

Predicted event rates for PTF are a function of the estimated GRB rate at low redshift (Guetta et al. 2005a; Nakar et al. 2006), the observed optical afterglow luminosity distribution (Kann et al. 2008), and the estimated beaming (or jet break) distributions (Guetta et al. 2005a; Nakar et al. 2006). There are substantial uncertainties in each of these functions; thus, even upper limits from well-defined orphan afterglow searches can be used to constrain interesting properties of the GRB population.

The discovery of an orphan afterglow would serve as a dramatic confirmation of the "jet model" for GRBs. Multiple events would begin to map out the beaming distribution and, in addition, provide inputs to physical models of relativistic outflows. Perhaps the most intriguing possibility relates to the merging compact object model of the short bursts (Fox et al. 2005). Detectable short-burst orphan afterglows will arise from a relatively nearby ($D \lesssim 20$ Mpc) merger event, potentially within range of current gravitational wave detectors. By providing a temporal window to searches, and thus increasing their sensitivity, the discovery of an orphan afterglow could even in the best case provoke a first direct detection of gravitational waves (Nakar et al. 2006).

Rapidly evolving "no-host" transients identified in previous orphan afterglow searches (Becker et al. 2004; Rau et al. 2006; Malacrino et al. 2007) are now attributed to flare-star activity (Kulkarni & Rau 2006). The upper limits on event rates derived from these surveys are consistent with an expectation for detection of a few orphan afterglows per year in PTF survey work, assuming that the foreground "fog" of flare star and CV activity (Rau et al. 2007b) can be successfully penetrated.

3.10. Transiting Exoplanets Around Young Stars

The majority of the ~300 currently known exoplanets have been found around relatively old stars (1–7 Gyr; Saffe et al. 2005). In contrast, little is known about the distribution and frequency of planets orbiting stars of 1–100 Myr age. These objects have broadened spectral lines ($>$200–500 $\mathrm{m\,s^{-1}}$), which complicate, and make more difficult, the discovery of planets via radial-velocity variations. Here, the detection of planetary transits is a more promising method.

Observations of transiting planets allow one to determine important physical characteristics and place significant constraints on the internal structure of planets (Burrows et al. 2000). Specifically, the radius (obtainable only for transiting planets) provides a direct estimate of the age, composition, and surface temperature (Saumon et al. 1996). Studies show the existence of "inflated" planets with unexpectedly large radii or low densities (e.g., WASP-1b, HAT-P-1b; Bakos et al. 2006; Cameron et al. 2007) that current models fail to explain (Pont et al. 2007). Next, assessing the distribution and frequency of planets around young stars can also set detailed constraints on the time scales of formation and evolution of planetary systems (e.g., Baraffe et al. 2003).

During 40 consecutive nights in each of the first three years after commissioning, PTF will provide high photometric precision measurements (0.1%–2%) for ~$50,000$ stars toward the Orion region. Approximately 5%–10% of these stars will be young stars (1–10 Myr; Carpenter et al. 2001). The large number of dedicated consecutive nights results in a $\gtrsim 90\%$ sensitivity to orbital periods of $P_{\mathrm{orb}} \lesssim 10$ days (see Fig. 5). If the fraction of the systems with favorable inclination is ~10% and the planetary distribution and frequency are similar to those of main-sequence stars (1 out of 150; Marcy et al. 2004), we anticipate 10–15 transiting planets to be found with this experiment. However, even a null detection would set valuable limits on the presence of giant planets with short period orbits. The transit search is based upon a box-shaped matched filter algorithm and uses frequency filtering and variability-fitting to reduce the effects of the intrinsic variability of the stars (e.g., Airgrain et al. 2007). These techniques have been very successful in finding small transit signals in intrinsically variable stars (e.g., CoRoT-7b; Leger et al. 2009).

The transit survey is most sensitive to Jupiter-sized (and mass) planets in few day orbits around stars of $\lesssim 1\ M_{\odot}$. Follow-up observations will include high spatial resolution imaging to search for background eclipsing binaries, and medium resolution spectroscopy and radial velocity monitoring (~500 $\mathrm{m\,s^{-1}}$ precision) to rule out stellar or brown companions. Jupiter-sized planets in short orbital periods produce radial velocity variations on the order of a few hundred meters per second. Higher-precision monitoring (50–200 $\mathrm{m\,s^{-1}}$), coupled with the known orbital period determined from the photometric observations, should provide sufficient precision to confirm the presence or absence of the candidate planets.

The Orion observations will also provide a unique data set for a variety of aspects of stellar astrophysics. The high-precision time-series data will enable the search for, and characterization of, eclipsing binary systems suitable for testing star formation and evolution models, characterizing the activity and rotation periods of young stars, and identifying and characterizing previously unknown young stars in the Orion region.

3.11. Eclipsing Objects Around Cool Stars

Current radial-velocity surveys for extrasolar planets preferentially target bright FGKM stars with masses within a factor of 2 of $M_{\odot}$. Thus far only ~10 planetary systems have been detected around stars with masses $<$0.5 $M_{\odot}$ and radial-velocity surveys of M dwarfs have been limited to the brightest M0 to M3 stars (e.g., Endl et al. 2006; Johnson et al. 2007). The higher-mass M dwarfs that have been probed have a low Jupiter-mass planet companion frequency ($< \sim 2\%$; e.g., Johnson et al. 2007), but theory predicts a large population of lower-mass planets (Ida & Lin 2005; Kennedy & Kenyon 2008). The characteristics of the lower-mass M dwarf planet population are essentially unknown, mostly because the stars are too faint for current radial-velocity planet searches. As M dwarfs are the

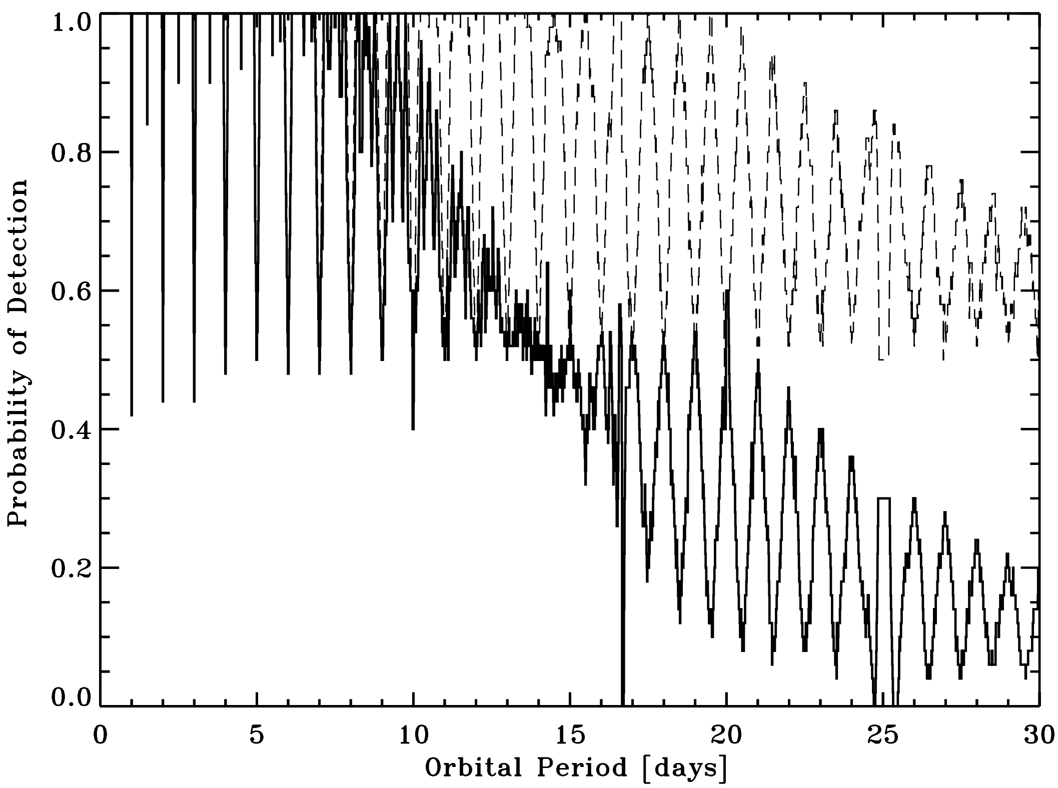

FIG. 5.—Prediction of the window function for the Orion program. The *dashed lines* and *solid lines* correspond to the detection probabilities of one and two transits, respectively. The white (photon) noise is assumed to be 0.01 mag, and the red (systematic) noise is assumed to be 10% of the total photometric noise. Other input parameters are stellar/planetary radius $= 1.0/0.1\ R_\odot$, 40 consecutive nights, and a 1 minute observing cadence.

most common stars in our galaxy, there is a clear gap to be addressed in our knowledge of the galactic planetary population.

The PTF R-band DyC experiment offers an opportunity to search M dwarfs for stellar eclipses and planetary transits. The survey is expected to greatly increase the number of known eclipsing cool star systems (vital for calibration of the mass-to-luminosity relation at the low end), to obtain detailed statistics on the population of close substellar companions, to watch for variability and activity, and ultimately to be capable of detecting low-mass transiting planets.

By specifically targeting faint M dwarfs, we greatly reduce the normally extreme precision requirements for planet transit surveys. Going down to $m_R = 20.0$, the faintest stars in the survey will have a signal-to-noise ratio (S/N) of approximately $10\ \text{image}^{-1}$, sufficient to detect planets as small as Saturn ($0.087\ R_\odot$) around M5 dwarfs (~$0.2\ R_\odot$) with $\text{S/N} = 2$ in each of many observations during transits. With photometric precision of a few percent on bright M dwarfs, PTF could detect Neptune-radius planets.

In each R band high-cadence PTF field, we will be able to search a few thousand M dwarfs for transitory flux decreases, depending on galactic latitude. By covering a very large sample of stars, but at relatively low photometric precision and with observation gaps, this survey will be complementary to targeted cool star transit surveys such as the MEarth project (Irwin et al. 2009).

Assuming a representative DyC observing setup, we expect to search approximately 10^5 M dwarfs yr^{-1} for companions in a variety of orbits. Scaling against other M dwarf eclipsing binary surveys, the survey could find tens of new M dwarf eclipsing binary systems per year. Assuming that 2% of M dwarfs have giant planetary companions with periods <30 days, in a uniform period distribution, and modeling detection probability factors from the survey cadences, transit lengths, weather losses, and the inclination ranges of the possible systems, PTF also has the potential to detect several bona fide transiting planet systems per year. Follow-up efforts will include extensive photometric and spectroscopic observing programs to eliminate false detections, and ultimately infrared radial-velocity measurements (using, for example, T-EDI on the Palomar Hale 5 m Telescope; Muirhead et al. 2008) to confirm the presence of planets.

3.12. RR Lyrae Stars

RR Lyrae are short-period, yellow or white giant pulsating variables. They are the most well-calibrated, near-field distance indicators known. With a mean magnitude of $M_R \approx 0.3 \pm 0.2$ mag for stars with $-2.6 < [\text{Fe/H}] < -1.6$ dex and a weak metallicity dependence, RR Lyrae have been used to measure distances throughout the Local Group. They have also been used to probe the kinematics and the global density distribution of the Galactic halo (Vivas & Zinn 2003; Ivezić et al. 2004; Kinman et al. 2007). Having many thousands of RR Lyrae stars over a significant fraction of the sky will enable us to better constrain not only the stellar density as a function of radius, but also the three-dimensional shape of the Galactic halo.

Another strong motivation for extending the sample of RR Lyrae variables is the mapping of substructures within the halo. It is still not completely clear whether the Galaxy formed primarily in a single, homogeneous collapse (Eggen et al. 1962), or the majority of stars were assimilated through the accretion of many smaller galaxies and galactic fragments (Searle & Zinn 1978). The distribution of RR Lyrae candidates in the SDSS is decidedly inhomogeneous, and a population of RR Lyrae stars associated with the Sagittarius tidal stream has been found (Ivezić et al. 2004). Since then, several other large tidal streams believed to be the remnants of accreted galaxies have been detected out to ~50 kpc (Yanny et al. 2003; Belokurov et al. 2006; Grillmair 2006a, 2006b, 2008; see Fig. 6). A large-area survey for RR Lyrae stars will allow much more accurate distances and orbital trajectories to be determined for these streams. Moreover, a clean sample of RR Lyrae stars selected through multi-epoch light-curve analysis would enable us to extend our reach well beyond the ≈ 50 kpc achieved to date using turn-off stars in the SDSS, and to detect additional debris streams out to ~ 100 kpc. Follow-up spectroscopy and proper-motion measurements of RR Lyrae stars in streams will put strong constraints not only on the global Galactic potential, but also on its lumpiness (Murali & Dubinski 1999).

Most known RR Lyrae stars are fundamental-mode pulsators with periods on the order of $\lesssim 1$ day. By virtue of its large areal coverage, the 5DC survey will be the most useful for detecting RR Lyrae stars throughout the Galactic halo. While the cadence is not particularly adapted to the detection of these stars on short time scales, the ~400 separate images field^{-1} over the course of the survey (half of which will be separated by ~60 minutes) will enable the identification of RR Lyrae stars and their mean magnitudes using standard time-series filtering techniques.

With a limiting magnitude per exposure of $R = 21.0$, PTF will be able to detect RR Lyrae stars at distances of 10–115 kpc. Kinman et al. (2007) found 26 RR Lyrae stars within 8 kpc in a $200\,\mathrm{deg}^2$ area centered on the north Galactic pole. Using this as a measure of the local volume density and adopting a radial density profile in the Galactic halo which falls as $\rho \propto R^{-2.7}$ (Siegel et al. 2002), an integration over the $10,000$ deg^2 area of the 5DC yields an expected total of 28,000 RR Lyrae stars. Changing the power-law index to -2.5 (Robin et al. 2000) or -3.3 (Sommer-Larsen & Zhen 1990) yields estimated totals of 38,000 and 14,000, respectively. These numbers are at least an order of magnitude larger than any previous RR Lyrae study; the final PTF database will clearly be a boon to

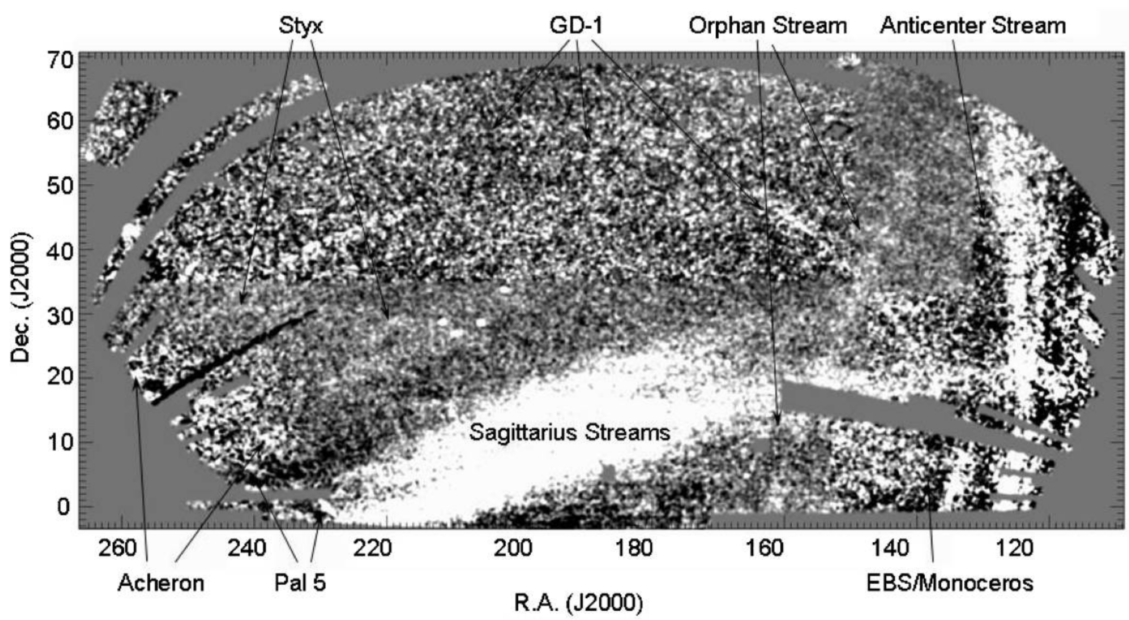

FIG. 6.—A composite, filtered surface density map of stars in the SDSS Data Release 5. Stars in DR5 have been filtered to select stellar populations at different distances with color-magnitude sequences similar to that of the globular cluster M13 (e.g., Grillmair 2008). Lighter shades indicate areas of enhanced surface density, and different portions of the field have been filtered for stars at different distances. Varying noise levels are a consequence of the very different levels of foreground contamination using these different filters. The distances of the streams range from 4 kpc for Acheron, to 9 kpc for GD-1 and the Anticenter Stream, to ~50 kpc for Sagittarius and Styx.

investigations of both the global structure of the Galactic halo and of the substructures within it.

3.13. Other Galactic Variables

Beside the already mentioned RR Lyrae stars, many more classes and subclasses of variables can be studied with PTF. In particular, the combination of PTF variability information and SDSS photometric colors can characterize stellar variability across the Hertzsprung-Russel diagram. Characterizing the detailed stellar variability is also imperative in the search of genuine transients.

Understanding the processes that lead to luminosity changes in stars is vital to decipher the stellar evolution. This 5DC survey with its wide-area coverage will enable the discovery of rare sources such as R CrB stars (Iben et al. 1996), the nonradial magnetic pulsating Ap stars (Shibahashi 1987), and SX Phe stars. The nature of the latter is uncertain, as they can be either stars evolving toward the white dwarf stage, or the result of stellar mergers (Cacciari & Clementini 1990).

R CrB stars are also linked to stellar mergers, specifically the merger of hydrogen-deficient stars, or of a neutron star with a helium-rich star. The birthrate of R CrB stars is estimated to be 0.004–0.1 yr^{-1} in the Milky Way (Iben et al. 1996) and the predicted short lifetime leads to estimates that approximately 1000 sources currently exist in our galaxy. Using their space and velocity distribution, PTF may able to resolve the fundamental question: to which population (e.g., thick disk) do they belong.

We will construct light curves for all stars in the PTF footprint in the range 14 mag $< R <$ 21 mag. Each of these data sets will consist of approximately 200–400 data points over all time scales from about one hour (and in some cases minutes) to several years.

3.14. Microlensing

Microlensing events occur when a large stellar-mass object passes in front of a background star. They take the form of a magnification of the background star and last on the order of several weeks, depending on the lensing geometry and lens mass. Lensing light curves having high temporal resolution offer the opportunity to detect planets around the lensing stars, while low-mass brown dwarfs and other faint nearby objects can be found by the lensing they induce without an obvious lens star. Current microlensing surveys such as OGLE (e.g., Pont et al. 2008) and MOA (e.g., Bennett et al. 2008) find ~1000 events yr^{-1}.

Microlensing surveys are usually targeted toward highly crowded stellar fields to maximize the event probability. PTF plans to avoid these fields to minimize stellar contamination to extragalactic transients. However, PTF's much larger field of view (FOV) allows coverage of many more high Galactic latitude stars than current microlensing projects can provide. On the other hand, at high Galactic latitude the number of suitable distant stars to be lensed is lower.

Han (2008) has performed detailed simulations of the expected event rate for a PTF-like survey. With a limiting magnitude of $V = 18$ mag an all-sky event rate of ~23 yr^{-1} is expected (for events with magnification >1.34). Approximately half of those events will occur at $|b| > 30^{\circ}$. Extrapolating the Han (2008) results to $R = 21$ mag suggests 200–300 events yr^{-1} throughout the sky.

With a typical time scale of about 20 days, these events can be detected in the 5DC with sufficient time to organize follow-up observations with high temporal resolution for the later parts of the light curve, to search for planets. Taking into account the PTF footprint, we expect the 5DC to find about 5 stellar-stellar events yr^{-1}. In addition, PTF will be sensitive to microlensing events caused by other optically faint, massive objects.

3.15. Solar System Objects

PTF will detect and measure orbits for many solar system bodies. In particular, asteroids will form the dominant variable foreground population. Depending on ecliptic latitude, the predicted number of known asteroids brighter than $R = 20.5$ mag ranges from ~30 deg^{-1} ($\beta = 0$ deg) to ~0.01 deg^{-1} ($\beta > 50$ deg).

Near-Earth objects (NEOs) are a subgroup of asteroids and comets that have been nudged by the gravitational attraction of nearby planets into orbits that allow them to enter the Earth's neighborhood. They are of astronomical interest as nearby samples of planetesimals left over from the formation of the solar system. The Earth was built from such planetesimals, and the outer layers of Earth, including the biosphere, have been strongly effected by asteroids and comets that impacted the early planet after it had solidified.

NEO discovery and characterization is also critical to assessing the impact risk hazard, as objects of size 1 km could have catastrophic planet-wide consequences. Here, PTF will contribute to NEO discovery and orbit determination by delivering astrometric and photometric measurements comparable (or even superior) to the those of the best currently-operating surveys (Table 5). In this way, PTF will provide a valuable testing ground for NEO searches with Pan-STARRS and LSST. The PTF NEO survey will be performed using the database of source extractions obtained by the main image-reduction pipeline. Nonstationary objects will be separated from the stationary objects detected in the 5DC.

Based on the estimated population of kilometer-size near-Earth asteroids (Bottke et al. 2002), discovery statistics (Moon et al. 2008), and the PTF observing strategy (which avoids the ecliptic plane), approximately 75 discoveries yr^{-1} are within reach of the PTF; in practice, the highly experienced Catalina and LINEAR surveys are likely to report most of these discoveries first, so the main PTF contribution will be confirmation and astrometry.

TABLE 5
COMPARISON OF PTF WITH OTHER NEO SURVEYS

Survey	D[a] (m)	Scale (arcsec pixel^{-1}	FOV (deg^2)	Exposure (s)	Magnitude Limit (mag)	Coverage (deg^2 hr^{-1})
PTF	1.2	1.0	7.78	60	21.0	300
LINEAR[b]	1.0	2.3	2.0	5	19.2	1050
Spacewatch[c]	1.8	1.0	0.3	150	22.6	7.2
Spacewatch	0.9	1.0	2.9	120	21.7	70
CSS[d]	1.5	1.0	1.2	60	21.5	600
CSS	0.7	2.5	8.1	30	19.5	420
CSS	0.5	1.8	4.2	60	19.0	92
Pan-STARRS1	1.8	0.3	3.0	30	24.0	360

[a] Telescope diameter.
[b] Lincoln Laboratories Near Earth Asteroid Research.
[c] At http://spacewatch.lpl.arizona.edu/.
[d] Catalina Sky Survey; http://www.lpl.arizona.edu/css/.

3.16. Transients Discovered Outside the Optical Band

Most of the time, PTF will operate in survey mode (see § 2.2). However, the $7.9\,\mathrm{deg}^2$ FOV is also ideal to search for optical counterparts to transients discovered at other wavelengths (e.g., radio, gamma rays) or by other means than electromagnetic radiation (e.g., gravitational waves, neutrinos, ultrahigh-energy cosmic-rays). The first direct detection of gravitational waves is expected to come from the Laser Interferometer Gravitational-Wave Observatory (LIGO) in its enhanced (start ~2009) and advanced (~2013) stages. A variety of sources, including nearby supernovae and merging compact objects, will be found in this way. With typical positional uncertainties of a few degrees, only wide-field instruments like PTF will be able to search for optical counterparts, provide arcsecond localizations, and allow estimates of distance.

Theory suggests that a few percent of all stellar collapses to neutron stars and black holes will result in strong gravitational waves (Dimmelmeier et al. 2007). Models include accretion-induced collapse leading to bar-unstable neutron stars (Liu 2002), and stars that collapse to black holes with very rapidly rotating cores (Janka et al. 2007). These events will likely be optically faint compared to standard supernovae, but still detectable in the nearby universe with PTF. Once identified, the light curves will provide insight into the explosion physics as well as into the fraction of radioactive material advected into the black hole. Similarly, observations of the expected dim supernovae (Li & Paczyński 1998) or macronovae (Kulkarni 2005) associated with LIGO-detected merging compact objects will immediately lead to a trove of results. In particular, the ejected mass is sensitive to the equation of state of dense matter and the type of binary (double neutron star vs. neutron star/black hole).

The IceCube Neutrino Observatory (Klein et al. 2008) will soon deliver automated alerts to follow-up observations of detections of pairs of neutrinos. With typical positional uncertainties of these events of 1°–2°, PTF can help to find the optical counterparts.

PTF will also advance our understanding of the new class of mysterious radio transients that has materialized in recent years (e.g., Levinson et al. 2002; Gal-Yam et al. 2006b; Bower et al. 2007). These events were discovered in archival data; thus, nothing is known about their transient appearance at other wavelengths. Furthermore, no quiescent X-ray, optical, near-infrared, or radio counterparts have been found. The event rate is overwhelming and estimated to be between 100 and $13,000$ deg^{-2} yr^{-1} with typical time scales of ~0.1–1 day. Within the framework of the dynamic cadence experiments, and in combination with new radio observations, PTF will attempt to resolve the nature of these events and probe their possible association with the elusive Galactic population of isolated-old neutron stars (Ofek et al. 2009, in preparation).

3.17. Science with Coadded Broadband and Narrowband Images

By the end of 2012, PTF will have observed each pointing in the 5DC footprint (i.e., ~$10,000\,\mathrm{deg}^2$) about 60 times. The combined R-band images will be deeper than the SDSS r band images by about 1–2 mag. Although the typical image quality will be 2″, these data will provide an excellent deep fiducial sky for many astronomical projects and can be mined for a variety of large-scale science applications.

As discussed in § 2.2, PTF will perform deep 3π sr surveys in several narrowband filters, including Hα. The resulting sky map will provide an unprecedented high-resolution view on the structure of the diffuse, ionized component of the interstellar medium in the Milky Way. This information will be vital for understanding the dynamics and evolutionary history of the interstellar gas. Next, new structures, such as stellar wind bubbles, supernova remnants, bow-shock nebulae, shells around old novae (Shara et al. 2007), and planetary nebula shells with large angular extent are anticipated to be found.

Furthermore, we will find low-surface brightness star-forming galaxies in the local universe, and based on the Hα emission strength we will be able to estimate the star-formation rate (e.g., Kennicutt 1998) of the galaxies within about 40 Mpc in our survey footprint (except for galaxies in the zone of avoidance).

4. CONCLUSION AND OUTLOOK

The Palomar Transient Factory is a wide-field ($7.9\,\mathrm{deg}^2$) imaging facility at the Palomar 48 inch Oschin Schmidt telescope, dedicated to mining the optical sky for transients and variables. Its main strengths are the exceptionally large sky coverage to a depth of $R \approx 21.0$ mag and the almost full-time operation (80%). Nearly real-time discovery of transient candidates will allow rapid follow-up observations with a wide range of committed telescopes, including optical and near-infrared photometry as well as spectroscopy.

PTF is expected to uncover numerous new members of a variety of source populations (see Table 4), ranging from distant supernovae to nearby cataclysmic variables. Furthermore, the exploration of new regions in phase space (e.g., cadence, environment) often yields unexpected discoveries. Thus, PTF is poised to provide an important contribution to filling the existing gaps in the transient phase space (Fig. 1), paving the path for future synoptic surveys, such as LSST.

This paper is based on observations obtained with the Samuel Oschin Telescope and the 60 inch telescope at the Palomar Observatory as part of the Palomar Transient Factory project, a scientific collaboration between the California Institute of Technology, Columbia University, Las Cumbres Observatory, the Lawrence Berkeley National Laboratory, the National Energy Research Scientific Computing Center, the University of Oxford, and the Weizmann Institute of Science. S. R. K. and his group were partially supported by NSF grant AST-0507734. J. S. B. and his group were partially supported by a Hellman Family Grant, a Sloan Foundation Fellowship, NSF/DDDAS-TNRP grant CNS-0540352, and a continuing grant from DOE/SciDAC. The Weizmann Institute PTF partnership is supported by an ISF equipment grant to A. G., whose activity is further supported by a Marie Curie IRG grant from the EU, and by the Minerva Foundation, the Benoziyo Center for Astrophysics, a research grant from Peter and Patricia Gruber Awards, and the William Z. and Eda Bess Novick New Scientists Fund at the Weizmann Institute. E. O. O. thanks NASA for partial support through grants HST-GO-11104.01-A, NNX08AM04G, 07-GLAST1-0023, and HST-AR-11766.01-A. A. V. F. and his group are grateful for funding from NSF grant AST-0607485, DOE/SciDAC grant DE-FC02-06ER41453, DOE grant DE-FG02-08ER41563, the TABASGO Foundation, Gary and Cynthia Bengier, the Sylvia and Jim Katzman Foundation, and the Richard and Rhoda Goldman Fund. S. G. D. and A. A. M. were supported in part by NSF grants AST-0407448 and CNS-0540369, and also by the Ajax Foundation. The National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231, has provided resources for this project by supporting staff and providing computational resources and data storage. L. B.'s research is supported by the NSF via grants PHY 05-51164 and AST 07-07633. M. S. acknowledges support from the Royal Society and the University of Oxford Fell Fund.

REFERENCES

Afşar, M., & Bond, H. E. 2007, AJ, 133, 387

Aigrain, S., et al. 2007, MNRAS, 375, 29

Aldering, G., Adam, G., Antilogus, P., Astier, P., & Bacon, R., et al. 2002, in Proc. SPIE, ed. J. A. Tyson, & S. Wolff, 4836, 61

Arbour, R., & Boles, T. 2008, CBET, 1234, 1

Astier, P., Guy, J., Regnault, N., Pain, R., & Aubourg, E., et al. 2006, A&A, 447, 31

Bakos, G. Á., Pál, A., Latham, D. W., Noyes, R. W., & Stefanik, R. P. 2006, ApJ, 641, L57

Baltay, C., Snyder, J. A., Andrews, P., Emmet, W., & Schaefer, B., et al. 2002, PASP, 114, 780

Baraffe, I., Chabrier, G., Barman, T. S., Allard, F., & Hauschildt, P. H. 2003, A&A, 402, 701

Barkat, Z., Rakavy, G., & Sack, N. 1967, Phys. Rev. Lett., 18, 379

Bath, G. T., Clarke, C. J., & Mantle, V. J. 1986, MNRAS, 221, 269

Becker, A. C., Wittman, D. M., Boeshaar, P. C., Clocchiatti, A., & Dell'Antonio, I. P., et al. 2004, ApJ, 611, 418

Belokurov, V., Zucker, D. B., Evans, N. W., Gilmore, G., & Vidrih, S., et al. 2006, ApJ, 642, L137

Bennett, D. P., Bond, I. A., Udalski, A., Sumi, T., & Abe, F., et al. 2008, ApJ, 684, 663

Bildsten, L., Shen, K. J., Weinberg, N. N., & Nelemans, G. 2007, ApJ, 662, L95

Bloom, J. S., Starr, D. L., Blake, C. H., Skrutskie, M. F., & Falco, E. E. 2006, in ASP Conf. Ser. 351, Astronomical Data Analysis and Software System XV, ed. C. Gabriel, C. Arviset, D. Ponz, & S. Enrique, 751

Bottke, W. F., Morbidelli, A., Jedicke, R., Petit, J.-M., & Levison, H. F., et al. 2002, Icarus, 156, 399

Bower, G. C., Saul, D., Bloom, J. S., Bolatto, A., & Filippenko, A. V., et al. 2007, ApJ, 666, 346

Brown, N. J., Waagen, E. O., Scovil, C., Nelson, P., & Oksanen, A., et al. 2002, IAU Circ., 7785, 1

Burrows, A., Guillot, T., Hubbard, W. B., Marley, M. S., & Saumon, D., et al. 2000, ApJ, 534, L97

Cacciari, C., & Clementini, G., eds. 1990, ASP Conf. Ser. 11, Confrontation Between Stellar Pulsation and Evolution

Cameron, A. C., Bouchy, F., Hébrard, G., Maxted, P., & Pollacco, D., et al. 2007, MNRAS, 375, 951

Cappellaro, E., Evans, R., & Turatto, M. 1999, A&A, 351, 459

Carini, M. T. 2004, New Astron. Rev., 48, 559

Carpenter, J. M., Hillenbrand, L. A., & Skrutskie, M. F. 2001, AJ, 121, 3160

Cenko, S. B., Fox, D. B., Moon, D.-S., Harrison, F. A., & Kulkarni, S. R., et al. 2006, PASP, 118, 1396

Cortini, G., Antonellini, S., Kehusmaa, P., et al. 2009, CBET, 1707

della Valle, M., & Livio, M. 1995, ApJ, 452, 704
della Valle, M., Rosino, L., Bianchini, A., & Livio, M. 1994, A&A, 287, 403
Dennison, B., Simonetti, J. H., & Topasna, G. A. 1998, PASA, 15, 147
Dermer, C. D. 2007, preprint (astro-ph/0711.2804)
Dilday, B., Kessler, R., Frieman, J. A., Holtzman, J., & Marriner, J., et al. 2008, ApJ, 682, 262
Dimmelmeier, H., Ott, C. D., Janka, H.-T., Marek, A., & Müller, E. 2007, Phys. Rev. Lett., 98, 251101
Djorgovski, S. G., Baltay, C., Mahabal, A. A., Drake, A. J., & Williams, R., et al. 2008, Astron. Nachr., 329, 263
Drake, A. J., Djorgovski, S. G., Mahabal, A., Beshore, E., & Larson, S., et al. 2009, ApJ, 696, 870
Eggen, O. J., Lynden-Bell, D., & Sandage, A. R. 1962, ApJ, 136, 748
Endl, M., Cochran, W. D., Kürster, M., Paulson, D. B., & Wittenmyer, R. A., et al. 2006, ApJ, 649, 436
Feldmeier, J. J., Ciardullo, R., Jacoby, G. H., & Durrell, P. R. 2004, ApJ, 615, 196
Ferrarese, L., Côté, P., & Jordán, A. 2003, ApJ, 599, 1302
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Filippenko, A. V., Li, W. D., Treffers, R. R., & Modjaz, M. 2001, in IAU Colloq. 183, Small Telescope Astronomy on Global Scales, ed. B. Paczynski, W.-P. Chen, & C. Lemme (ASP Conf. Ser. 246; San Francisco: ASP) , 121
Foley, R. J., Chornock, R., Filippenko, A. V., Ganeshalingam, M., & Kirshner, R. P., et al. 2009, AJ, 138, 376
Fox, D. B., Frail, D. A., Price, P. A., Kulkarni, S. R., & Berger, E., et al. 2005, Nature, 437, 845
Fox, D. W., Price, P. A., Soderberg, A. M., Berger, E., & Kulkarni, S. R., et al. 2003, ApJ, 586, L5
Frail, D. A., Kulkarni, S. R., Sari, R., Djorgovski, S. G., & Bloom, J. S., et al. 2001, ApJ, 562, L55
Frail, D. A., Waxman, E., & Kulkarni, S. R. 2000, ApJ, 537, 191
Frieman, J. A., Bassett, B., Becker, A., Choi, C., & Cinabro, D., et al. 2008, AJ, 135, 338
Frieman, J. A., Turner, M. S., & Huterer, D. 2008, ARA&A, 46, 385
Fryer, C. L., Mazzali, P. A., Prochaska, J., Cappellaro, E., & Panaitescu, A., et al. 2007, PASP, 119, 1211
Gal-Yam, A., Cenko, S. B., Fox, D. B., Leonard, D. C., & Moon, D.-S., et al. 2007, in AIP Conf. Ser. 924, The Multicolored Landscape of Compact Objects and Their Explosive Origins, 297
Gal-Yam, A., Fox, D. B., Price, P. A., Ofek, E. O., & Davis, M. R., et al. 2006a, Nature, 444, 1053
Gal-Yam, A., Maoz, D., Guhathakurta, P., & Filippenko, A. V. 2003, AJ, 125, 1087
Gal-Yam, A., Ofek, E. O., Poznanski, D., Levinson, A., & Waxman, E., et al. 2006b, ApJ, 639, 331
Gaustad, J. E., McCullough, P. R., Rosing, W., & Van Buren, D. 2001, PASP, 113, 1326
Gebhardt, K., Bender, R., Bower, G., Dressler, A., & Faber, S. M., et al. 2000, ApJ, 539, L13
Gezari, S., Basa, S., Martin, D. C., Bazin, G., & Forster, K., et al. 2008, ApJ, 676, 944
Gezari, S., Martin, D. C., Milliard, B., Basa, S., & Halpern, J. P., et al. 2006, ApJ, 653, L25
Giommi, P., Capalbi, M., Cavazzuti, E., Colafrancesco, S., & Cutini, S., et al. 2007, in AIP Conf. Ser. 921, The First GLAST Symposium, ed. Ritz, S., Michelson, P., & Meegan, C. A., 32
Giommi, P., Colafrancesco, S., Cavazzuti, E., Perri, M., & Pittori, C. 2006, A&A, 445, 843
Grillmair, C. J. 2006a, ApJ, 645, L37
———. 2006b, ApJ, 651, L29
———. 2009, ApJ, in press
Guetta, D., Granot, J., & Begelman, M. C. 2005a, ApJ, 622, 482
Guetta, D., Piran, T., & Waxman, E. 2005b, ApJ, 619, 412
Hamuy, M., & Pinto, P. A. 2002, ApJ, 566, L63
Han, C. 2008, ApJ, 681, 806
Harrison, F. A., Bloom, J. S., Frail, D. A., Sari, R., & Kulkarni, S. R., et al. 1999, ApJ, 523, L121
Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532
Hills, J. G. 1975, Nature, 254, 295
Horan, D., & Weekes, T. C. 2004, New Astron. Rev., 48, 527
Horns, D. 2008, preprint (astro-ph/0808.3744)
Howell, D. A., Conley, A., Della Valle, M., Nugent, P. E., & Perlmutter, S., et al. 2009, preprint (astro-ph/0903.1086)
Iben, I., Jr., & Tutukov, A. V. 1984, ApJS, 54, 335
Iben, I. J., & Tutukov, A. V. 1992, ApJ, 389, 369
Iben, I., Tutukov, A. V., & Yungelson, L. R. 1996, in ASP Conf. Ser. 96, ed. C. S. Jeffery, & U. Heber, 409
Ida, S., & Lin, D. N. C. 2005, ApJ, 626, 1045
Irwin, J., Charbonneau, D., Nutzman, P., & Falco, E. 2009, in IAU Symp. Proc. 253, 37
Ivezić, Ž., Lupton, R., Schlegel, D., Smolčić, V., & Johnston, D., et al. 2004, in ASP Conf. Ser. 327, Satellites and Tidal Streams, ed. Prada, F., Martinez Delgado, D., & Mahoney, T. J., 104
Ivezic, Z., Tyson, J. A., Allsman, R., Andrew, J., & Angel, R., et al. 2008, preprint (astro-ph/0805.2366)
Janka, H.-T., Langanke, K., Marek, A., Martínez-Pinedo, G., & Müller, B. 2007, Phys. Rep., 442, 38
Jha, S., Kirshner, R. P., Challis, P., Garnavich, P. M., & Matheson, T., et al. 2006, AJ, 131, 527
Johnson, J. A., Butler, R. P., Marcy, G. W., Fischer, D. A., & Vogt, S. S., et al. 2007, ApJ, 670, 833
Kann, D. A., Klose, S., Zhang, B., Wilson, A. C., & Butler, N. R., et al. 2008, preprint (arXiv.org 0804.1959)
Kennedy, G. M., & Kenyon, S. J. 2008, ApJ, 682, 1264
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Kinman, T. D., Cacciari, C., Bragaglia, A., Buzzoni, A., & Spagna, A. 2007, MNRAS, 375, 1381
Klein, S. R. for the IceCube Collaboration 2008, preprint (astro-ph/0807.0034)
Kolb, U. 1993, A&A, 271, 149
Komossa, S., & Bade, N. 1999, A&A, 343, 775
Komossa, S., & Greiner, J. 1999, A&A, 349, L45
Kulkarni, S. R. 2005, preprint (astro-ph/0510256)
Kulkarni, S. R., Ofek, E. O., Rau, A., Cenko, S. B., & Soderberg, A. M., et al. 2007, Nature, 447, 458
Kulkarni, S. R., Law, N., Kasliwal, M. M., Quimby, R., & Ofek, E. O., et al. 2009, ATel, 1964
Kulkarni, S. R., & Rau, A. 2006, ApJ, 644, L63
Law, N., et al. 2009, PASP preprint (astro-ph/0906.5350)
Léger, A., et al. 2009, A&A submitted

Levinson, A., Ofek, E. O., Waxman, E., & Gal-Yam, A. 2002, ApJ, 576, 923
Li, L.-X., & Paczyński, B. 1998, ApJ, 507, L59
Li, W. D., Filippenko, A. V., Treffers, R. R., Friedman, A., & Halderson, E., et al. 2000, in AIP Conf. Ser. 522, ed. S. S. Holt, & W. W. Zhang, 103
Liu, Y. T. 2002, Phys. Rev. D, 65, 124003
Malacrino, F., Atteia, J.-L., Boër, M., Klotz, A., & Veillet, C., et al. 2007, A&A, 464, L29
Maoz, D., & Gal-Yam, A. 2004, MNRAS, 347, 951
Marcy, G. W., Butler, R. P., Fischer, D. A., & Vogt, S. S. 2004, in ASP Conf. Ser. 321, Extrasolar Planets: Today and Tomorrow, ed. J. Beaulieu, A. Lecavelier Des Etangs, & C. Terquem, 3
Martini, P., Wagner, R. M., Tomaney, A., Rich, R. M., & della Valle, M., et al. 1999, AJ, 118, 1034
Meyer, F., & Meyer-Hofmeister, E. 1981, A&A, 104, L10
Miknaitis, G., Pignata, G., Rest, A., Wood-Vasey, W. M., & Blondin, S., et al. 2007, ApJ, 666, 674
Modjaz, M., Kewley, L., Kirshner, R. P., Stanek, K. Z., & Challis, P., et al. 2008, AJ, 135, 1136
Monard, L. A. G. 2008, IAU Circ., 8946, 1
Moon, H.-K., Byun, Y.-I., Raymond, S. N., & Spahr, T. 2008, Icarus, 193, 53
Muirhead, P. S., Erskine, D. J., Edelstein, J., Barman, T. S., & Lloyd, J. P. 2008, in Precision Spectroscopy in Astrophysics, ed. Santos, N. C., Pasquini, L., Correia, A. C. M., & Romaniello, M. (Proc. ESO; Garching: Springer) 303
Murali, C., & Dubinski, J. 1999, AJ, 118, 911
Nakar, E., Gal-Yam, A., & Fox, D. B. 2006, ApJ, 650, 281
Narumoto, T., & Totani, T. 2006, ApJ, 643, 81
Neill, J. D., & Shara, M. M. 2004, AJ, 127, 816
Neill, J. D., Shara, M. M., & Oegerle, W. R. 2005, ApJ, 618, 692
Nugent, P., Sullivan, M., Ellis, R. S., Gal-Yam, A., & Leonard, D. C., et al. 2006, ApJ, 645, 841
Ofek, E. O., Cameron, P. B., Kasliwal, M. M., Gal-Yam, A., & Rau, A., et al. 2007, ApJ, 659, L13
Ofek, E. O., Kulkarni, S. R., Rau, A., Cenko, S. B., & Peng, E. W., et al. 2008, ApJ, 674, 447
Paciesas, W. S., Meegan, C. A., Pendleton, G. N., Briggs, M. S., & Kouveliotou, C., et al. 1999, ApJ, 122, 465
Park, H. S., Porrata, R. A., Williams, G. G., Ables, E., & Band, D. L., et al. 1999, A&AS, 138, 577
Pastorello, A., Della Valle, M., Smartt, S. J., Zampieri, L., & Benetti, S., et al. 2007, Nature, 449, 1
Pastorello, A., Zampieri, L., Turatto, M., Cappellaro, E., & Meikle, W. P. S., et al. 2004, MNRAS, 347, 74
Perets, H. B., Gal-Yam, A., Mazzali, P., Arnett, D., & Kagan, D., et al. 2009, Nature, preprint astro-ph/0906.2003
Perlmutter, S., Aldering, G., Goldhaber, G., Knop, R. A., & Nugent, P., et al. 1999, ApJ, 517, 565
Pont, F., Moutou, C., Gillon, M., Udalski, A., & Bouchy, F., et al. 2007, A&A, 465, 1069
Pont, F., Tamuz, O., Udalski, A., Mazeh, T., & Bouchy, F., et al. 2008, A&A, 487, 749
Poznanski, D., Butler, N., Filippenko, A. V., Ganeshalingam, M., & Li, W., et al. 2009, ApJ, 694, 1067
Prieto, J. L., Kistler, M. D., Thompson, T. A., Yüksel, H., & Kochanek, C. S., et al. 2008, ApJ, 681, L9
Quimby, R. M. 2006, Ph.D. thesis, Univ. Texas
Quimby, R. M., Aldering, G., Wheeler, J. C., Höflich, P., & Akerlof, C. W., et al. 2007, ApJ, 668, L99
Rahmer, G., Smith, R., Velur, V., Hale, D., & Law, N., et al. 2008, Proc. SPIE, 7014, 163
Rau, A., Greiner, J., & Schwarz, R. 2006, A&A, 449, 79
Rau, A., Kulkarni, S. R., Ofek, E. O., & Yan, L. 2007a, ApJ, 659, 1536
Rau, A., Schwarz, R., Kulkarni, S. R., Ofek, E. O., & Kasliwal, M. M., et al. 2007b, ApJ, 664, 474
Rees, M. J. 1988, Nature, 333, 523
Renzini, A., Greggio, L., di Serego-Alighieri, S., Cappellari, M., & Burstein, D., et al. 1995, Nature, 378, 39
Rhoads, J. E. 1999, ApJ, 525, 737
Rich, R. M., Mould, J., Picard, A., Frogel, J. A., & Davies, R. 1989, ApJ, 341, L51
Richardson, D., Branch, D., Casebeer, D., Millard, J., & Thomas, R. C., et al. 2002, AJ, 123, 745
Riess, A. G., Filippenko, A. V., Challis, P., Clocchiatti, A., & Diercks, A., et al. 1998, AJ, 116, 1009
Robin, A. C., Reylé, C., & Crézé, M. 2000, A&A, 359, 103
Roelofs, G. H. A., Nelemans, G., & Groot, P. J. 2007, MNRAS, 382, 685
Saffe, C., Gómez, M., & Chavero, C. 2005, A&A, 443, 609
Saumon, D., Hubbard, W. B., Burrows, A., Guillot, T., & Lunine, J. I., et al. 1996, ApJ, 460, 993
Scannapieco, E., Madau, P., Woosley, S., Heger, A., & Ferrara, A. 2005, ApJ, 633, 1031
Schwope, A. D., Brunner, H., Buckley, D., Greiner, J., & Heyden, K. v. d, et al. 2002, A&A, 396, 895
Searle, L., & Zinn, R. 1978, ApJ, 225, 357
Shafter, A. W., Rau, A., Quimby, R. M., Kasliwal, M. M., & Bode, M. F., et al. 2009, ApJ, 690, 1148
Shara, M. M. 2006, AJ, 131, 2980
Shara, M. M., Martin, C. D., Seibert, M., Rich, R. M., & Salim, S., et al. 2007, Nature, 446, 159
Sharon, K., Gal-Yam, A., Maoz, D., Filippenko, A. V., & Guhathakurta, P. 2007, ApJ, 660, 1165
Shibahashi, H. 1987, in Lecture Notes in Physics, ed. Cox, A. N., Sparks, W. M., & Starfield, S. G. (Berlin : Springer-Verlag), 274, 112
Siegel, M. H., Majewski, S. R., Reid, I. N., & Thompson, I. B. 2002, ApJ, 578, 151
Smith, N., Chornock, R., Li, W., Ganeshalingam, M., & Silverman, J. M., et al. 2008, ApJ, 868, 467
Smith, N., Li, W., Foley, R. J., Wheeler, J. C., & Pooley, D., et al. 2007, ApJ, 666, 1116
Soker, N., & Tylenda, R. 2003, ApJ, 582, L105
Sommer-Larsen, J., & Zhen, C. 1990, MNRAS, 242, 10
Stanek, K. Z., Garnavich, P. M., Kaluzny, J., Pych, W., & Thompson, I. 1999, ApJ, 522, L39
Stanek, K. Z., Gnedin, O. Y., Beacom, J. F., Gould, A. P., & Johnson, J. A., et al. 2006, Acta Astron., 56, 333
Sterken, C., & Jaschek, C. 2005, Light Curves of Variable Stars, ed. Sterken, C., & Jaschek, C. (Cambridge, UK: Cambridge University Press)
Strubbe, L., & Quataert, E. 2009, MNRAS preprint astro-ph/0905.3735
Thompson, T. A., Prieto, J. L., Stanek, K. Z., Kistler, M. D., & Beacom, J. F., et al. 2008, preprint (astro-ph/0809.0510)

Tremaine, S., Gebhardt, K., Bender, R., Bower, G., & Dressler, A., et al. 2002, ApJ, 574, 740
Tremonti, C. A., Heckman, T. M., Kauffmann, G., Brinchmann, J., & Charlot, S., et al. 2004, ApJ, 613, 898
Ulmer, A. 1999, ApJ, 514, 180
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Vivas, A. K., & Zinn, R. 2003, Mem. Soc. Astron. Italiana, 74, 928
Walton, N. A., Drew, J., Barlow, M. J., Corradi, R., & Drake, J., et al. 2004, in BAAS, 36, 1541
Warner, B. 1995, Cataclysmic Variable Stars, (Cambridge Astrophysics Ser.; Cambridge, New York: Cambridge Univ. Press)
———. 2008, in Classical Novae, 2nd ed., ed. Bode, M., & Evans, A. (Cambridge, New York: Cambridge Univ. Press), 16
Webbink, R. F. 1984, ApJ, 277, 355
Wood-Vasey, W. M., Aldering, G., Lee, B. C., Loken, S., & Nugent, P., et al. 2004, New Astron. ., 48, 637
Wright, E. L., Chen, X., Odegard, N., Bennett, C. L., & Hill, R. S., et al. 2009, ApJS, 180, 283
Yanny, B., Newberg, H. J., Grebel, E. K., Kent, S., & Odenkirchen, M., et al. 2003, ApJ, 588, 824
Young, D. R., Smartt, S. J., Mattila, S., Tanvir, N. R., & Bersier, D., et al. 2008, A&A, 489, 359