A New Ultra-fast Moving Object Discovery Engine for *iPTF*, *ZTF* and beyond

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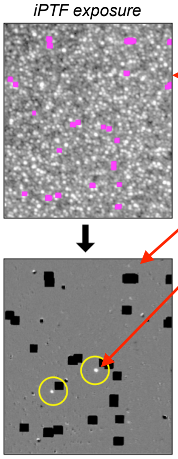
Goals / Overview

- A goal of the *intermediate* Palomar Transient Factory (iPTF; currently in progress), and its successor survey -- the Zwicky Transient Facility (ZTF; planned for 2017), is the discovery of near-Earth objects (NEOs).
- This will enhance our understanding of poorly-studied subsets of NEOs and enable a more complete census of the asteroid and comet population.
- We have developed an efficient, industrial-strength discovery pipeline: the "Moving Object Discovery Engine" (MODE).
- MODE utilizes transient candidates extracted from the nightly image-subtraction pipeline (PTFIDE: PTF Image-Differencing & Extraction).
- The use of difference-image extractions gives us an enormous advantage: the suppression of static (inertial) sources that would otherwise confuse and confound the source-linking process used to discover moving objects.
- This is unlike existing NEO surveys that attempt to remove stationary sources using prior catalog matching across image epochs. This can be expensive and ambiguous, leading to missed tracklets.
- Difference imaging has huge returns in the galactic plane and regions with complex backgrounds (see example below).
- MODE is optimized to discover *non-streaking* objects in single exposures, i.e., that move slower than the typical FWHM in a single exposure; for iPTF, this speed is <~ 3 arcsec / min. This is because transient candidates from image-subtractions are detected and characterized using PSF-fitting.
- The iPTF nightly processing pipeline also includes a streak-detection module to find "fast" moving objects on a per-image-exposure basis. This module is not part of the MODE design.
- MODE can report moving-object *candidates* within a few minutes from a bulk run of two-night's worth of iPTF data – consisting of typically a few thousand exposure images with several-thousand transient candidates extracted from difference images.
- MODE is normally executed on a single machine with 12 x 2.4 GHz Intel Xeon® processor cores. More cores, the better (of course).
- iPTF continues to serve as a testbed, paving the way to ZTF and beyond.

Processing Flow

iPTF exposure



Difference Image

Nightly pre-processing pipeline: astrometrically and instrumentally calibrated image exposures

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PTFIDE module: PTF Image Differencing & Extraction with PSF-characterized transient candidates (available <~ 20 min)

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Machine-learned (*real-bogus*) vetting of transient candidates (in progress)
Currently: simple filtering using many source-features/QA metrics

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MODE module: Moving Object Discovery Engine: find moving object tracklet candidates and generate metadata/QA metrics per tracklet

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Machine-learned vetting of tracklet candidates (in progress)

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Cross-match against database of known-moving objects using orbit-fit solution

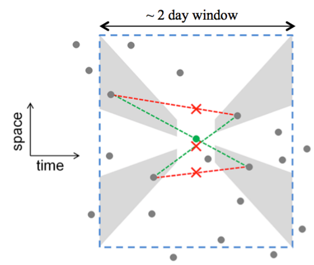
↓

Marshall: human vetting and follow-up new objects; delivery to Minor Planet Center

iPTF *ZTF*

Tracklet Finding Algorithm and Implementation

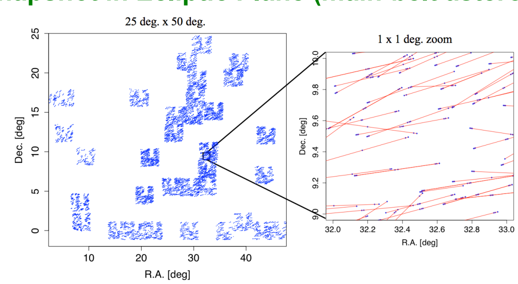
- A challenging computer science problem that makes using of tree-search algorithms: *kd-trees* and *quad-tree* partitioning on the sky.
- Basic idea is from Waszczak et al., 2013, MNRAS, 433, 3115 then optimized
- Implemented exclusively in Perl, utilizing methods from the object-oriented Perl Data Language (PDL) library with functions implemented in C/C++.
- PDL library provides a high level of parallelism for computations: multi-threaded vector/matrix methods optimized for multi-core architectures.
- Two step process to find tracklet candidates:
  1. *Find all triplet-transient-tracklets (TTTs) within min/max velocity cone centered on every transient by matching relative velocities & fluxes.*
  2. *Bin the 2D velocity vectors and merge all TTTs potentially belonging to same object to build final tracklets. See Masci et al. 2015 (in prep.)*



E.G: to match two lists containing past (v1) and future (v2) relative velocities using PDL:

```
$Dv = abs(zeroes($n1,$n2) +
              $v1 – $v2->transpose);
$indices = whichND($Dv <  $tolerance);
$matched_vels = $vdiff->$indices;
```

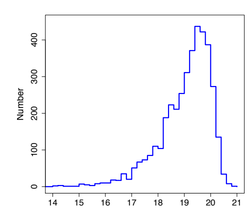
Snapshot in Ecliptic Plane (main-belt asteroids)



Performance

- We explored the recovery fraction (completeness) and reliability of MODE-detected tracklets from data spanning three nights over a 1500 deg^2 region.
- Applied filters to extracted transients: S/N > 5, > 2" from bright static sources
- Truth set: from predicted occurrences of known asteroids in iPTF exposures
- Overall, 3437 candidate tracklets with ≥ 4 detections/tracklet were reported by MODE to R_{PTF} ~ 20 from this run. Table below shows cumulative statistics

R mag limit	Completeness %	Reliability %	# Recovered (matched to truth)
16	74.13	100	43
17	82.66	100	143
18	88.46	100	529
19	93.09	100	1509
20	88.09	97.73	3359



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