Discovering Near Earth Asteroids with the Zwicky Transient Facility (ZTF)

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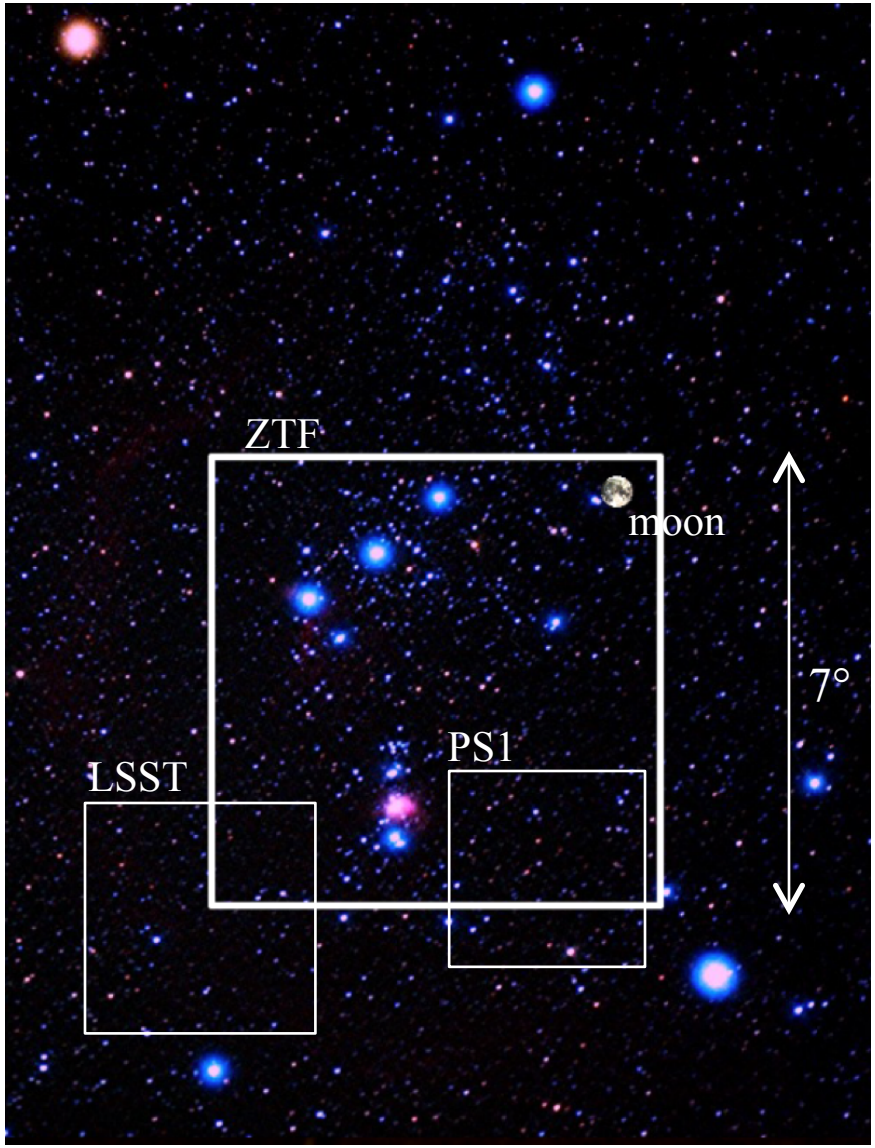
ZTF at a glance



- A fast, wide-area time-domain survey using the Palomar 48-inch Schmidt telescope.
- Active detector area: ~ 47 deg^2 (576M pixels).
- Areal survey rate: 3760 deg^2 / hour.
- Single exposure depth (5σ): r ~ 20.6 mag.
- Nominal survey duration: 3yr (start: Mar 2018).
- Survey entire Northern visible sky to Dec ~ –28°.
- Visit cadence is ~ minutes to days.
- Data stream serves many science programs.
- We leverage this data stream to search for NEAs.
  - ➢ Given large area-coverage; ZTF is ideal!

- Data processing and archiving occurs at IPAC.
- Public DR1 was in May 2019; DR2 in Dec 2019.
  - ➢ Public transient-alert stream is continuous.

Asteroid Discovery & Vetting Methodology
Method 1: ZMODE

Palomar 48-inch

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Realtime processing at IPAC: image differencing

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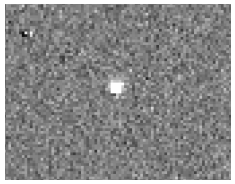
point-source transient extraction with machine-learned vetting to serve all science programs



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link sources into tracks using ZMODE: ZTF Moving Object Discovery Engine: <~ 2°/day

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preliminary orbit fit / quality thresholding

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cross-match to known objects and label

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more QA metrics, image cutouts, reports

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human scanning

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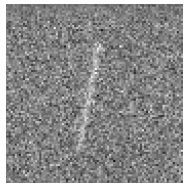
IAU Minor Planet Center, NEOCP

- Objects moving at >~ 2°/day => streaked!
- Input is ~ 10^6 point sources/night from four previous consecutive nights to make tracks.
- Executed at end of each night.
- Results submitted within ~ 8hrs of observation.
- Typically recover ~ 5-10k known objects per night (mostly MBAs)
- Few 100 potentially new objects (unmatched).
- Sensitive to fainter, further, and slower objects.

Asteroid Discovery & Vetting Methodology
Method 2: ZSTREAK

- Speed limit (>~ 8°/day) is constrained by shortest detectable streaks such that not overwhelmed by false positives (artifacts); goal is to reduce this.
- We detect ~ 10^5 *raw* streaks/night.
- Executed close to realtime (~ 20 min following observation).
- Results submitted within ~ 1hr of observation.
- Typically report ~ few to several candidates/night.



Palomar 48-inch

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Realtime processing at IPAC: image differencing

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streak detection: sensitive to "fast" and close moving objects: >~ 8°/day

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streak PSF (x) line fitting: metadata

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machine-learned vetting & scoring; see *DeepStreaks* talk by D. Duev (Friday)

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intra-night linking of streaks / orbit fit

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filter artificial objects

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human scanning

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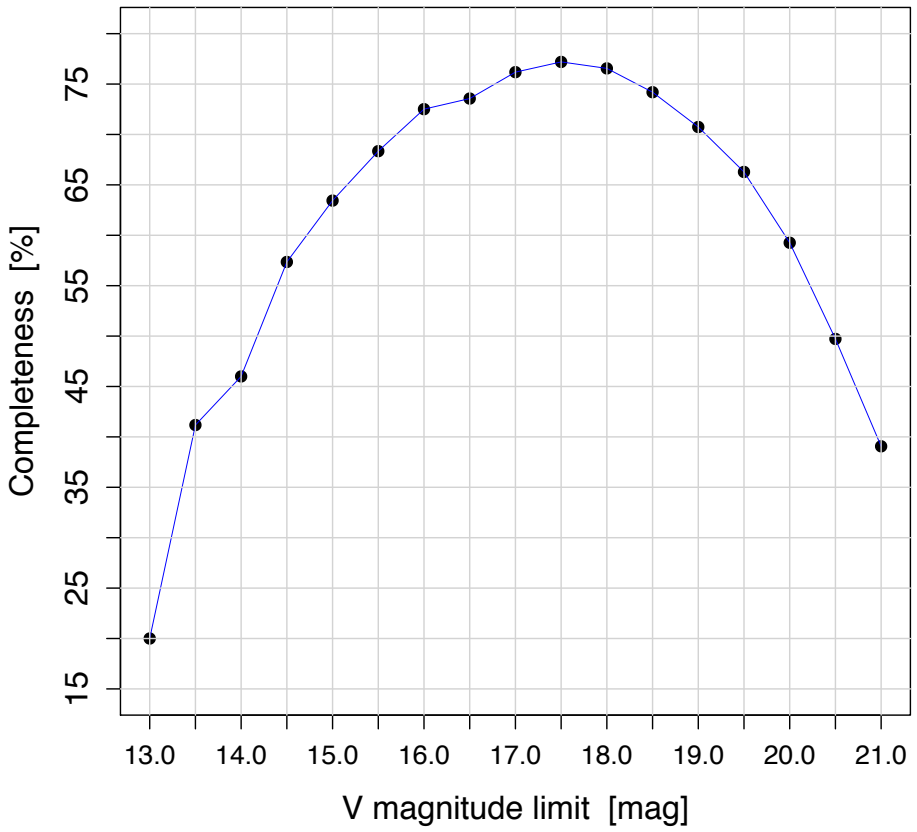
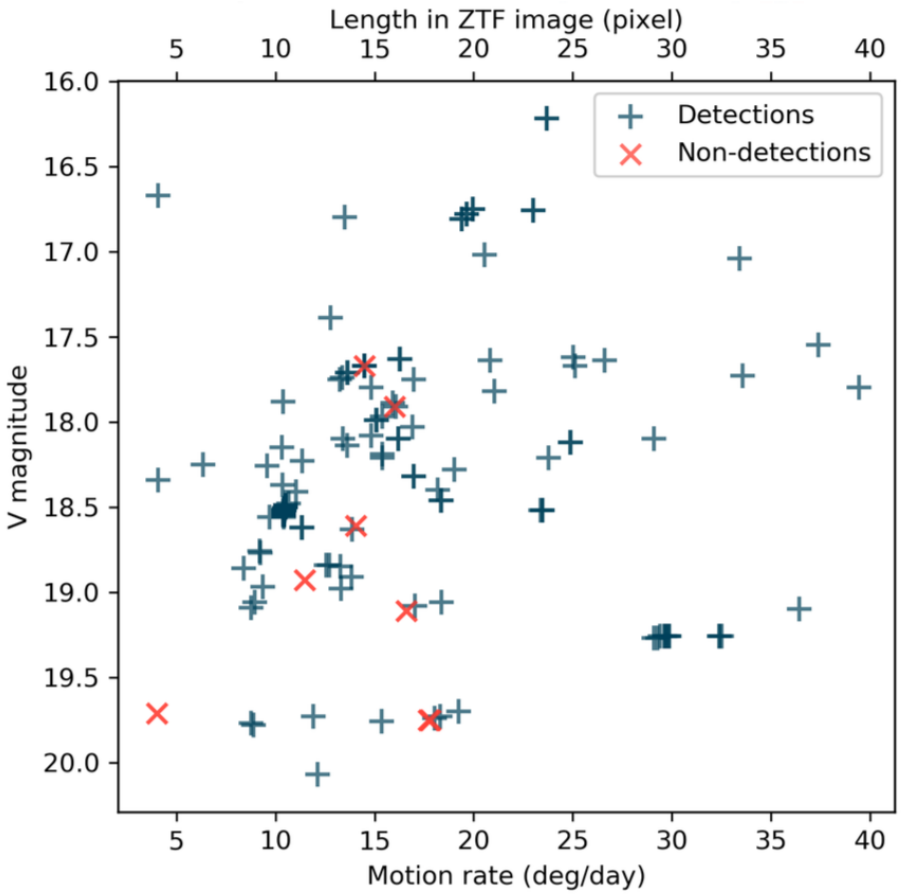
Performance: efficiency at recovering known objects
ZMODE (point source linking)



- From a typical 4-night survey run of ZMODE from early Aug 2019.
- 16,457 length ≥ 4 tracks were constructed from a highly non-uniform cadence and survey area.
- Purity of these ZMODE tracks is > 99.9%
- All imaging covered 29,621 known SSOs to Vmag = 21.

Performance: efficiency at recovering known objects
ZSTREAK (streak detection)



- Used streaks associated with 210 known NEAs observed by ZTF ~ Oct/18 - Jan/19.
- Completeness (true positive rate) following automated classification: ~ 96 - 98%
- Only a measure of classifier performance, not efficiency of initial *raw* streak detection.
- Courtesy: Duev et al. 2019, MNRAS.

Discovery Statistics (~ Feb 2018 to Sep 2019)

NEAs as of Sep 10, 2019:
Spanning ~ 3548 hours of on-sky survey time (equivalent to ~ 417 nominal "full" 8.5hr observing nights)

- 133 new near-Earth asteroids
  - 22 Atens; 82 Apollos; 26 Amors; 3 Atiras
- 3 of these are potentially hazardous asteroids (MOID $\leq$ 0.05AU, $H \leq 22$)
- ZTF discovered 2 of the 4 new 1km sized asteroids found so far in 2019

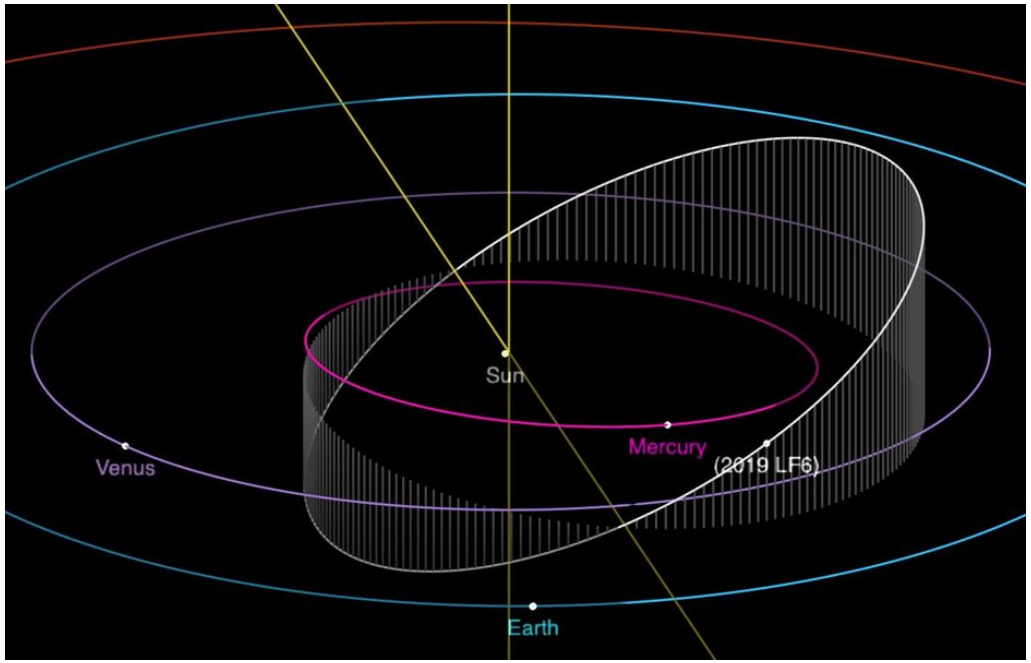
- In general, ZTF is discovering smaller asteroids (<~100m) & objects with smaller MOIDs (<~0.03AU)
  - $H \sim 26.2 \pm 1.7$ compared to other current surveys: $H \sim 23.3 \pm 2.6$

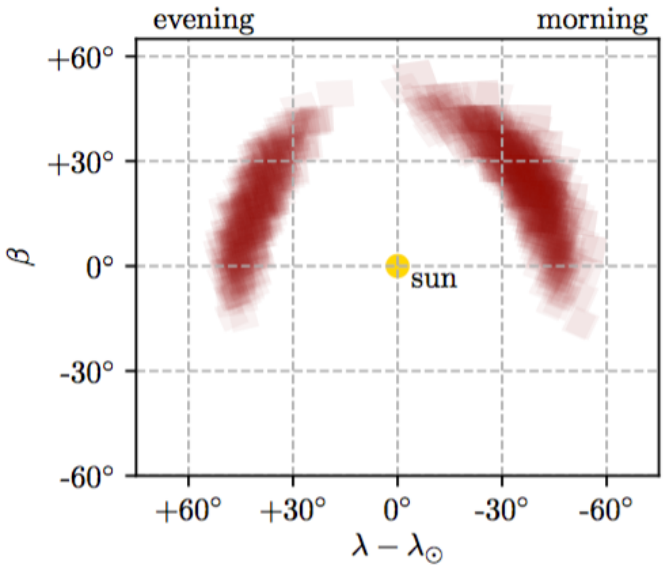
- Ratio of ZMODE (point source linked tracklets) to ZSTREAK discoveries: ~ 1 : 2

Other:
- ~ 2000 new main belt asteroids
- 2 new comets: C/2019 J2 (Palomar), C/2019 K4 (Ye)

ZTF Twilight Survey

- Conducted during Nov 2018 – Jun 2019 under partnership time (will resume soon)
- Goal: search for NEAs interior to Earth's orbit: Atiras, Vatiras, including Earth/Venus co-orbitals
- Detected 6 Atira class NEAs; 3 were ZTF discoveries
- Two discoveries made the headlines: broke records for shortest orbital period of any asteroid
  - 2019 AQ3 (Jan 2019) – 165 day period (~1km)
  - 2019 LF6 (Jun 2019) – 151 day period (~1.2km)





Summary

- ZTF is a time-domain survey that is serving a multitude of astrophysics programs.
  - not optimized to discover NEAs (aside from the intermittent Twilight Survey)
  - we are starting to scratch the surface and learning how to best utilize ZTF for this purpose

- ZTF is contributing ~ 5% to the current discovery of NEAs
  - average discovery (confirmation) rate is ~1.8 NEAs per week (highly non-uniform and seasonal)
  - 30 – 50% of candidates (mostly streaks) are lost due to inability to follow-up on short timescales

- Statistics are dominated by ~100m sized NEAs, small MOIDs; also sensitive to ~1km sized Atiras.

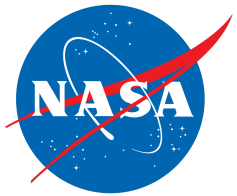
Near-term plans:

- Resume Twilight Survey to search for NEAs interior to Earth's orbit, including co-orbitals.
  - from our initial 7 month trial survey, models predict we detected only ~ 10% of all $H < 20$ Atiras

- Improve discovery efficiency: more aggressive searches by relaxing detection thresholds; optimize automated classifiers; more rapid follow-up of candidates.

Acknowledgment

This work (coined NEOZTF) is supported by NASA through the PDCO/NEOO program.



Back up slides

ZMODE: ZTF's Moving Object Discovery Engine

- Novel algorithm implemented for the *intermediate* Palomar Transient Factory (2013 – 2017).
- Input: all difference image detections from previous four consecutive nights at most.
- Uses a two step process to construct moving object tracks:
  1. Atomic building blocks: find triples of difference image detections ("stringlets") within min/max velocity cone centered on every detection by matching relative velocities.
  2. Bin the stringlet velocity vectors and merge all stringlets belonging to same object to build track.
- Includes optional iterative removal of MBAs to mitigate cross-track contamination.

For details, see Masci et al. 2019, PASP, vol. 131