



Solar System Science with the Zwicky Transient Facility

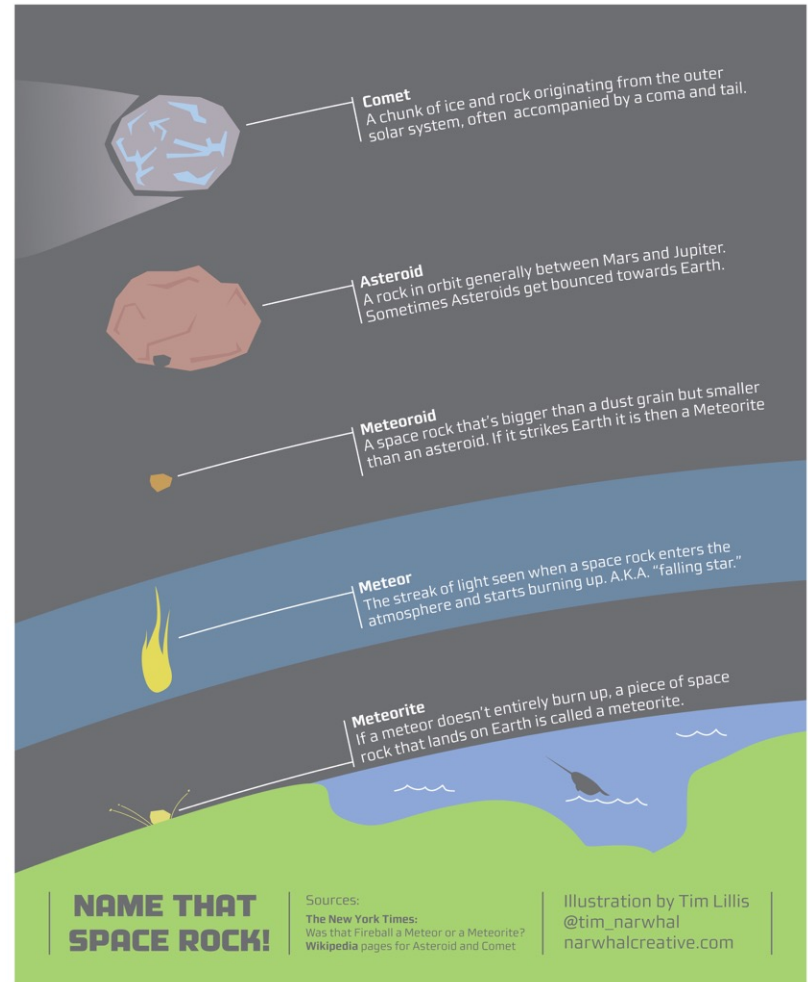
Tom Prince (Caltech)

Dennis Bodewits (U. Maryland), Quan-Zhi Ye (Caltech/IPAC), Rex Chang (NCU),
Gerbs Bauer (UMD), Bryce Bolin (UW), George Helou (Caltech/IPAC),
Wing Ip (NCU), Lynne Jones (UW), Mario Jurić (UW), Michael Kelley (UMD),
Emily Kramer (JPL), Zhong-Yi Lin (NCU), Frank Masci (Caltech/IPAC),
Joachim Moeyens (UW), Chow-Choong Ngeow (NCU)



ZTF Solar System Science

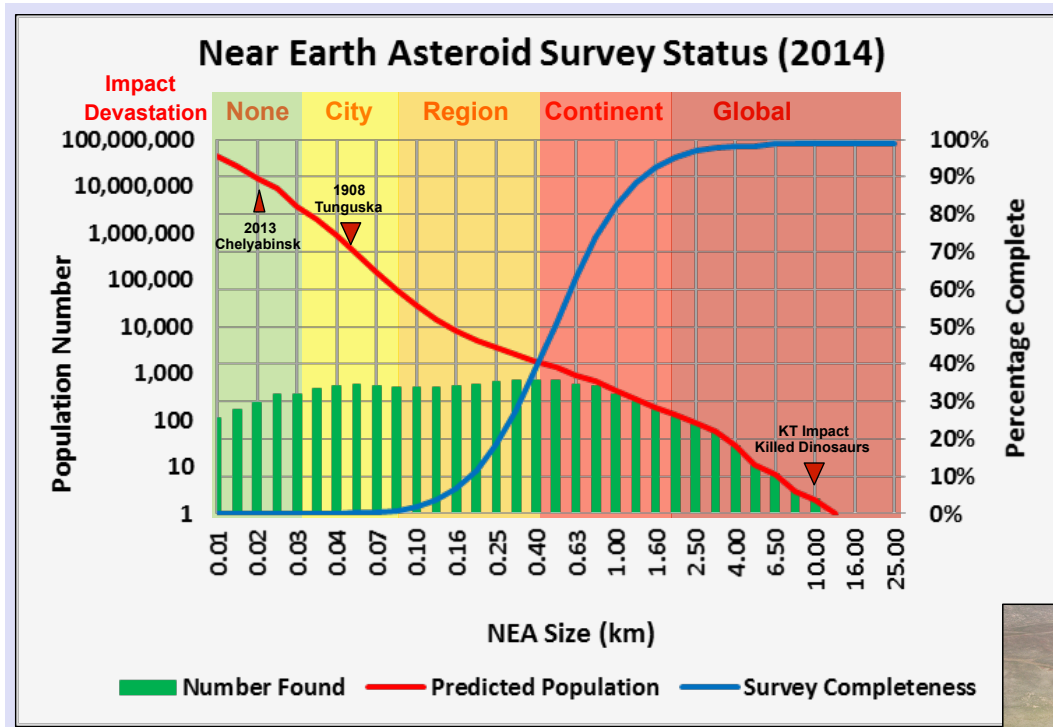
- **Discover, characterize, and monitor** small bodies in the solar system
 - Enable **rapid response** on transient events
- Comets
 - Main Belt Asteroids
 - Near Earth Asteroids
 - Centaurs
 - Interstellar objects



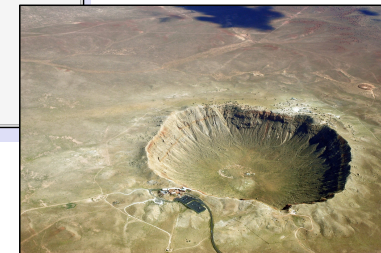
Topic: Near Earth Objects (NEOs)

Quan-Zhi Ye, Prince, +

Small Near Earth Asteroids ($d < 150$ meter): Hazardous population, but poorly characterized



~50 meter



Barringer Crater, Arizona

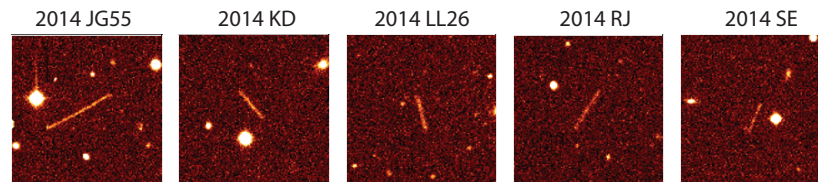
Johnson & Statler, SBAG 16

Detecting Small Asteroids with ZTF

Small asteroid: <100 meter diameter

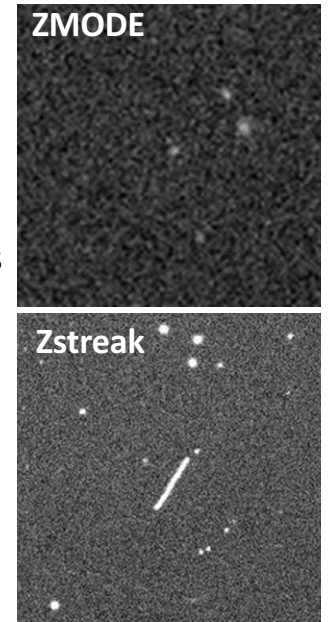
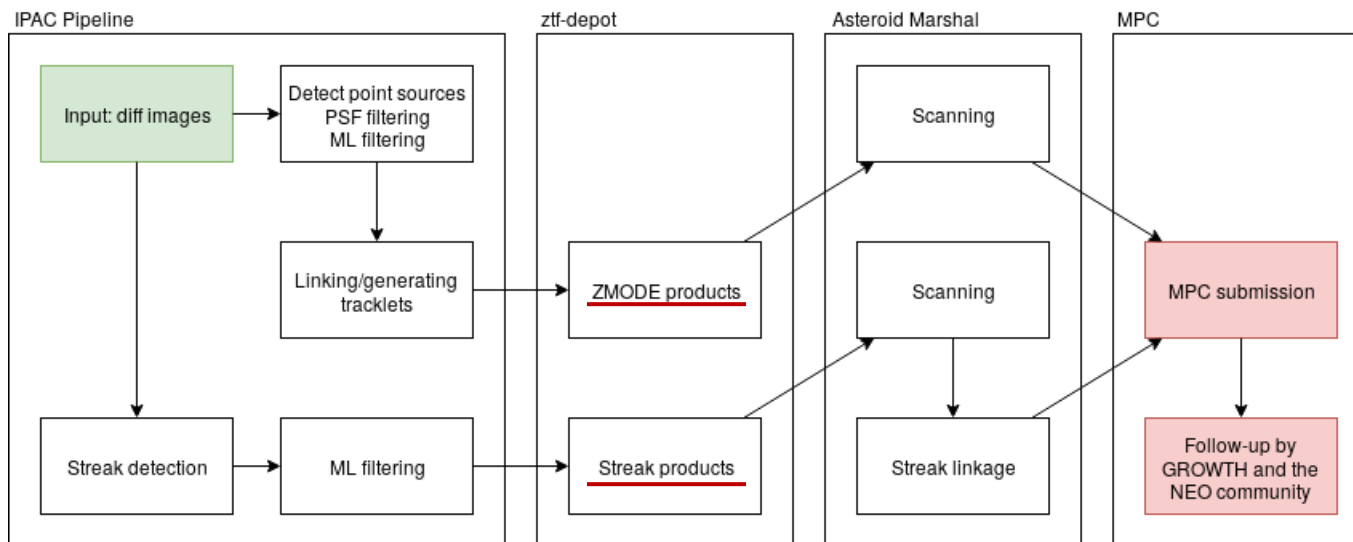
Small asteroids => dim => closer to earth at detection
=> higher angular rates => “trailed images” =>
STREAKS

Need to follow up quickly or they are “lost” due to orbital uncertainties (same ‘night’)



Discovery of Near-Earth Asteroids (NEAs)

- **ZMODE** : detecting point-like objects
 - Most detections are main-belt asteroids; approximately $\sim 0.1\%$ are far-away NEAs
- **Zstreak** : detecting trailed objects (streaks)
 - Asteroids will trail when less than 0.02 au from the Earth
 - Some “real” streaks are man-made objects (we do not know until orbital determination)



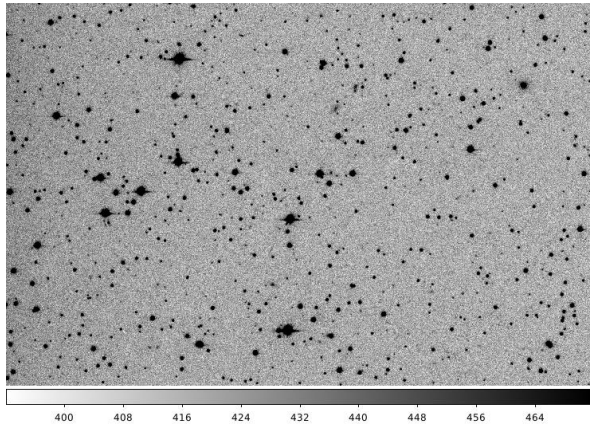
Status of ZMODE

- IPAC pipeline outputs ZMODE products by PT 9 am: sets of linked intra/inter-night tracklets (max 4 nights apart to match ZTF pattern)
- Review of ZMODE tracklets is done within 1-2 hours after they are reported
- As of Aug 1, 2018: ZMODE helps discover (with credit to ZTF) of ~500 new asteroids, including 3 NEAs, and recover 4 long-lost NEAs
- Work to do:
 - Characterize the completeness of ZMODE
 - Data “overflow” in the deep drilling fields
 - Improve response time (currently limited by available people_

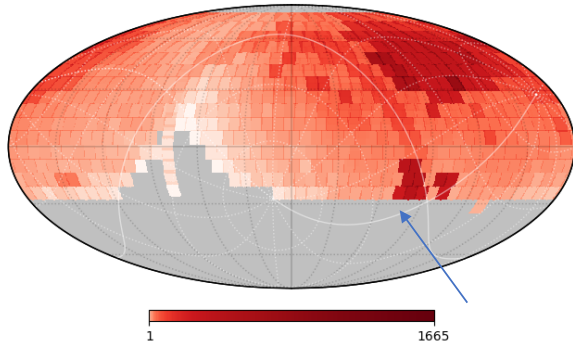
Status of ZStreak

- Update since the March meeting:
 - A more thorough characterization and optimization of the RF (random forest) model: the current model (implemented on June 7) now recovers ~99% of all <20 mag streaks falling fully on the chip
 - However, the false positive rate also goes up significantly: scanners need to go through 10,000 to 50,000 candidates daily (however, the efficiency still improves by 10-20x compared to the PTF era); looking for ways to improve, and working with the ML team to explore Deep Learning as a viable option to reduce the false positive rate
 - Marshal upgrade ongoing; now collecting streak products in real time
 - “Best-effort” real time scanning; scanning is usually done by noon the next day

ZTF ToO of 2018 MZ4



ZTF : R : Equatorial : All Programs : Thru 2018-07-30 (105/130 Nights)



Highlight of NEOZTF

- As of Aug 1, 2018:
 - 18 new NEAs
 - ~10 recoveries of known NEAs (most are long lost)
 - 7 of the 18 were found in July – we are doing better!
- ZTF is the first survey to submit in the new IAU ADES format: helping MPC with bug fixing, etc

International Asteroid Warning Network

Home ABOUT FEATURES TECHNICAL MEETINGS CLOSE APPROACHES

Minor Planet Close Approach Reports

Readers of this page will notice recent postings on close approaches of new minor planets. We expect to produce these reports automatically for each object passing closer than 1 lunar distance from the center of the Earth. These informational messages will eventually contain a bit more information on each object, including physical characteristics, where available. The main purpose of these messages will be to note that close approaches of this nature are commonplace. Further, providing some scale (the size of the Moon's orbit) for reference may assist readers in picturing the range and geometry of each approach. As the search capacity of the AAWN improves, we expect more objects to be found and reported on this page. Keeping track of these close approaches is one way to view, in real time, the improving efficiency of the worldwide search network.

Asteroid 2018 NX close approach

Asteroid designation: 2018 NX
 Discovery station: Palomar Mountain-ZTF
 Close approach date (UTC): 2018 07 07 79
 Close approach distance (* lunar distance): 0.35
[Discovery announcement](#)
[Latest orbit & observations](#)

Asteroid 2018 NW close approach

Asteroid designation: 2018 NW
 Discovery station: Palomar Mountain-ZTF
 Close approach date (UTC): 2018 07 08 13
 Close approach distance (* lunar distance): 0.33
[Discovery announcement](#)
[Latest orbit & observations](#)

Asteroid 2018 MZ4 close approach

Asteroid designation: 2018 MZ4
 Discovery station: Palomar Mountain-ZTF
 Close approach date (UTC): 2018 08 16 79
 Close approach distance (* lunar distance): 0.54
[Discovery announcement](#)
[Latest orbit & observations](#)

ZTF discoveries

ZTF Small Asteroid Discoveries

		H			
2018 NX	7/9/18	27.7	←	Aten	Recent small (<20m) NEO discoveries inside orbit of moon
2018 NW	7/8/18	27.8	←	Apollo	
2018 NU	7/8/18	25.7	←	Amor	Potentially Hazardous Asteroids
2018 NQ	7/6/18	22.2		Apollo	
2018 MZ4	19-Jun	28.8	←	Apollo	
2018 LM15	19-Jun	25.5	←	Aten	
2018 LB	17-Jun	26	←	Aten	
2018 LU2	9-Jun	26.7	←	Apollo	
2018 JA	25-May	20.4		Apollo	
2018 HX1	24-Apr	24.5	←	Apollo	
2018 HL1	24-Apr	23.9	←	Apollo	
2018 GE2	13-Apr	27	←	Apollo	
2018 GN1	12-Apr	27.4	←	Apollo	
2018 CZ2	12-Feb	21.3		Apollo	
2018 CL	2-Feb	25.5	←	Aten	

H=22.7 (for 150m)
H=23.5 (for 100m)
H=27.0 (for 20m)

TECH & SCIENCE

TWO ASTEROIDS SLIPPED PAST EARTH UNDETECTED LAST WEEKEND

BY **KATHERINE HIGNETT** ON 7/12/18 AT 6:00 AM

TECH & SCIENCE

ASTEROID

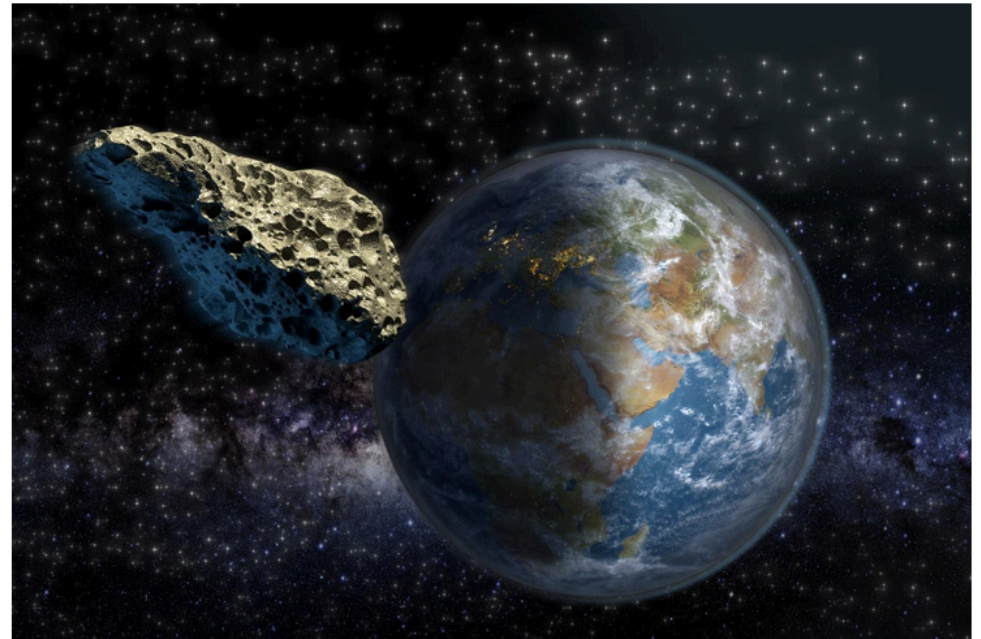
METEOR

EARTH

Two tiny asteroids sneaked safely past Earth last weekend, only to be discovered hours after they'd buzzed our planet. Asteroids [2018 NX](#) and [2018 NW](#) zipped past our blue-green orb at distances of just 72,000 miles and 76,000 miles, respectively. That's about one-third of the distance from the Earth to the moon.

Scientists think the asteroids both stretched between about 16 feet and 50 feet in diameter. That's relatively small for [near-Earth asteroids](#).

Astronomers at an observatory on the Palomar Mountain range in California spotted both [space rocks](#) on Sunday, according to the International Astronomical Union's Minor Planet Center.



ZTF Fast Moving Object: General Review Page

≤ UT 2018-07-30 ≥

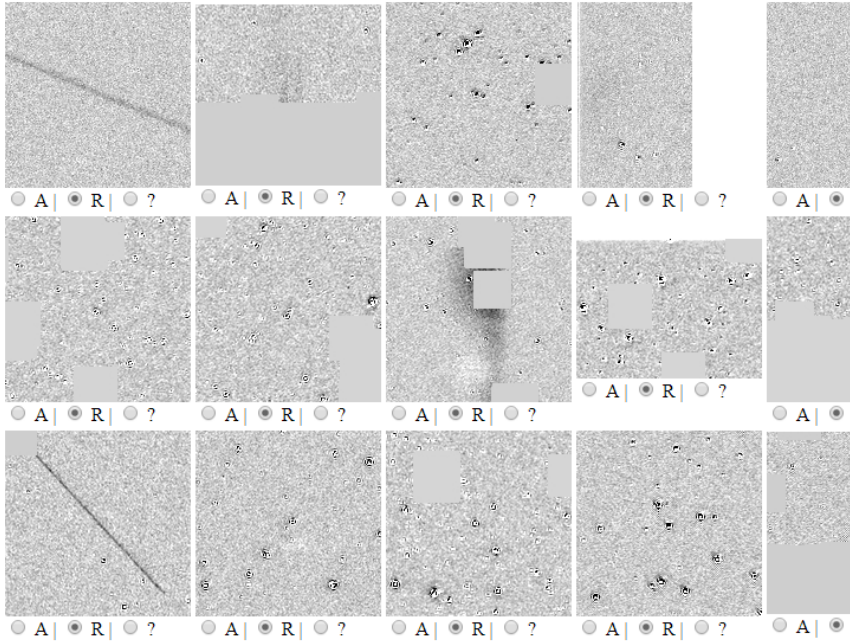
Database last updated at UT 2018-07-30 19:29.

Displaying 3146 of 45481 streak candidates between ML score of 5 and 100 that are not yet classified.

A to declare real, R to declare bogus, ? to skip | All ? are set to R by default. [Tutorial with examples](#)

Number of streak candidates that have been classified as real: 1 | [Information Page of Real Candidates](#)

[ML score 5-100, unclassified \(default\)](#) | [All unclassified](#) | [Everything with ML score above 5](#) | [Everything with ML score below 5](#)



ZTF Fast Moving Object: Information Page of Real Candidates

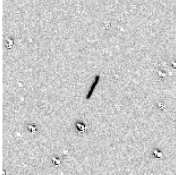
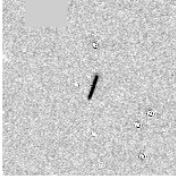
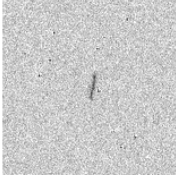
≤ UT 2018-07-26 ≥

Database last updated at UT 2018-07-26 18:42.

Displaying 6 streak candidates that have been labeled as real.

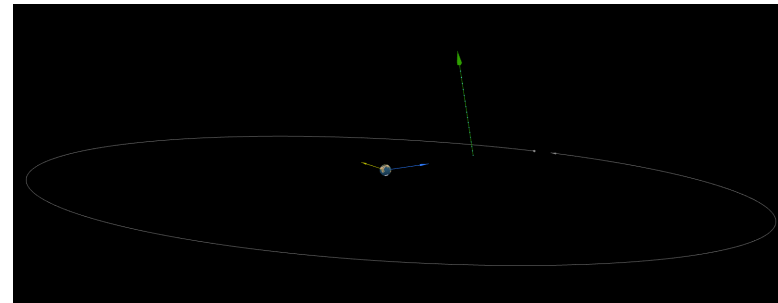
[Going back to General Review Page](#)

[Reals \(default\)](#) | [Unclassified](#)

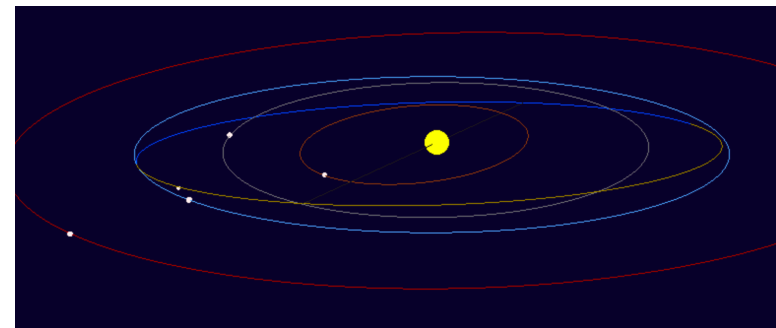
	<p>5714719562150009 ADES</p> <p>Times: 2018-07-26T11:19:36.998Z 2018-07-26T11:20:06.996Z End point 1: RA=329.8240657 Dec= 57.0812683 End point 2: RA=329.8199342 Dec= 57.0756985 mag: 16.37 R seeing: 2.6" score: 13 released: UT 2018-07-26 06:20 classified as real by Avery Nielsen at UT 2018-07-26 18:19</p>
	<p>5714710151150013 ADES</p> <p>Times: 2018-07-26T11:18:15.998Z 2018-07-26T11:18:45.996Z End point 1: RA=329.8119263 Dec= 57.0665695 End point 2: RA=329.8075664 Dec= 57.0611174 mag: 16.47 R seeing: 2.6" score: 10 released: UT 2018-07-26 06:20 classified as real by Avery Nielsen at UT 2018-07-26 18:19</p>
	<p>5714247333150001 ADES</p> <p>Times: 2018-07-26T10:11:37.000Z 2018-07-26T10:12:06.998Z End point 1: RA=329.3308399 Dec= 56.2895715 End point 2: RA=329.3279600 Dec= 56.2832481 mag: 17.30 g seeing: 2.7" score: 17 released: UT 2018-07-26 06:20 classified as real by Avery Nielsen at UT 2018-07-26 18:19</p>

Discovering Near Earth Objects

- *Interesting, fun, and exciting*
- *Opportunity for student involvement*
 - Get credit for discovery of new solar system bodies: *find an asteroid that may impact the earth?*
 - See how discovery triggers observations by worldwide network of observatories
- *Scanners actively sought from Europe and Asia*
 - Near real-time detection of small asteroids (while California sleeps)
- Send names to prince@caltech.edu



Minor Planet Center plot of ZTF asteroid passing within moon's orbit



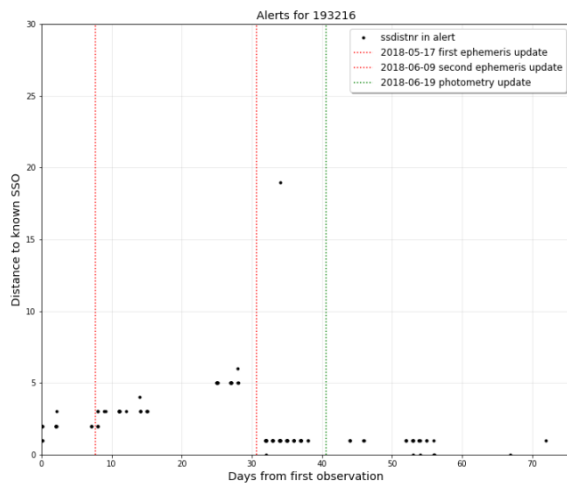
Topic: Solar System Objects in Alert Stream

Lynne Jones

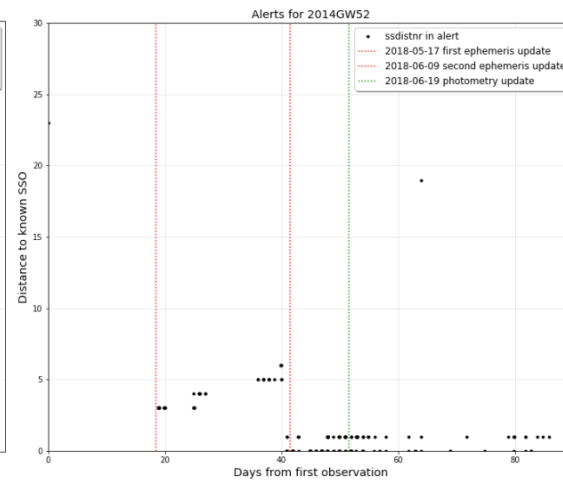
Identifying Solar System Objects in Alerts

- Identified in alerts with SSO relevant information:
 - **ssnamnr** (name of object as reported in current MPCORB file),
 - **ssdistnr** ($0'' < \text{ssdistnr} < 30''$) for successful matches,
 - **ssmagnr** (the predicted V band magnitude for the known object).
 - 4/8/2018 – 8/1/2018 : 42327 alerts on 13327 different SSOs
- Identified by matching against predicted positions - **ssdistnr**
 - Improvements on predicted positions : updates on 5/17 and 6/9
 - In current pipeline, ephemeris accuracy depends on the type of orbit/object
 - Photometry measurement has also been improved: update on 6/19
- After these updates there are 39331 alerts on 9518 different SSOs

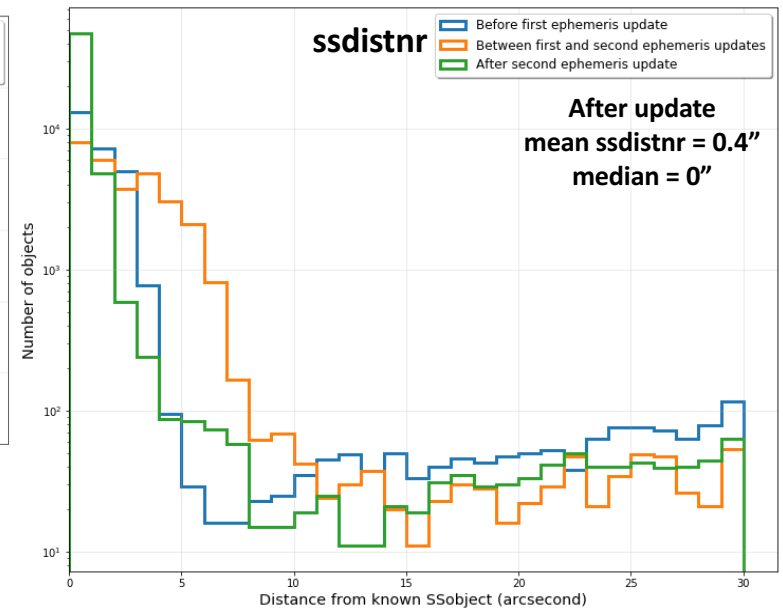
Improvement on ephemeris accuracy / ssdistnr



May 17 June 9 June 19



May 17 June 9 June 19

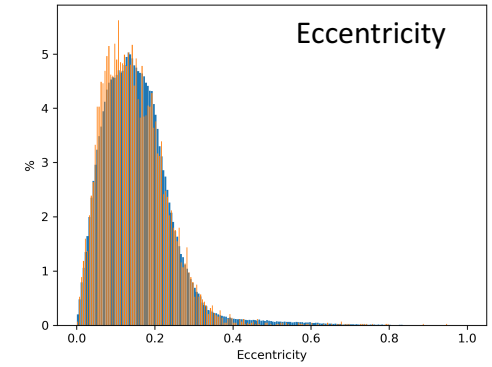
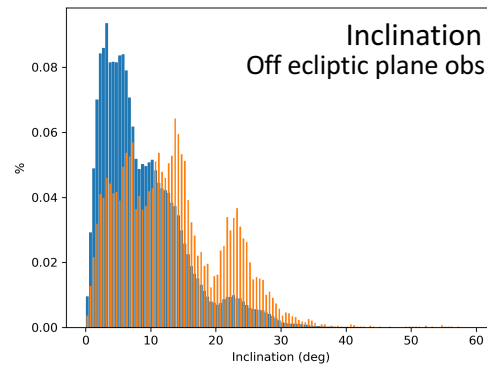
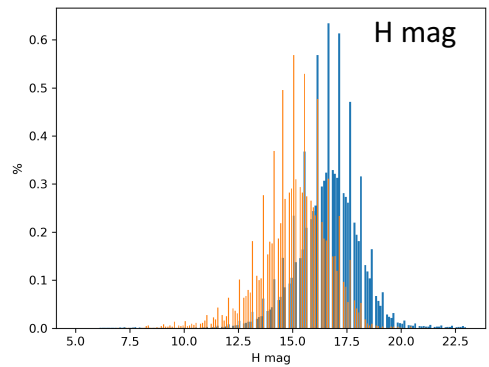
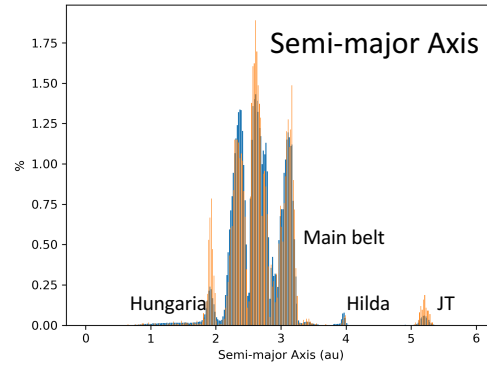
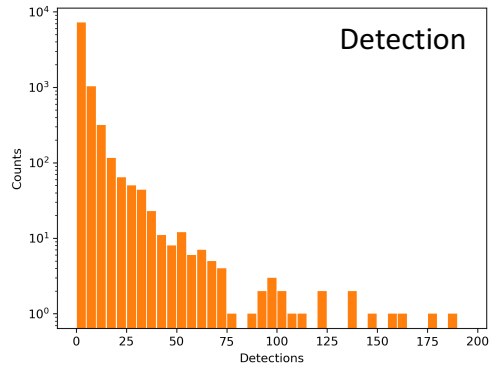


May 17: 1st position update
June 09: 2nd position update
June 19: photometric improvement

Asteroids in Alert Stream (June 19 – Aug 1, ssdistnr <=4)

**35454 detections of 8957 known asteroids,
94 asteroids have detections > 20 in g or r band**

ZTF ~9k
MPC ~750k

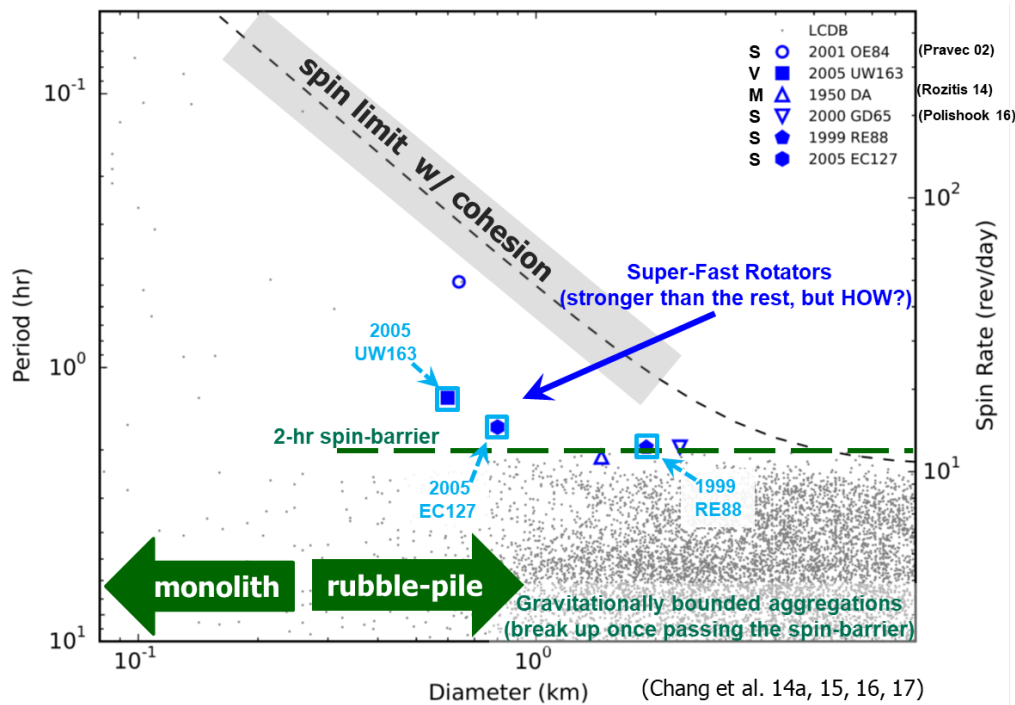


Topic: Asteroid light curves

Rex Chang

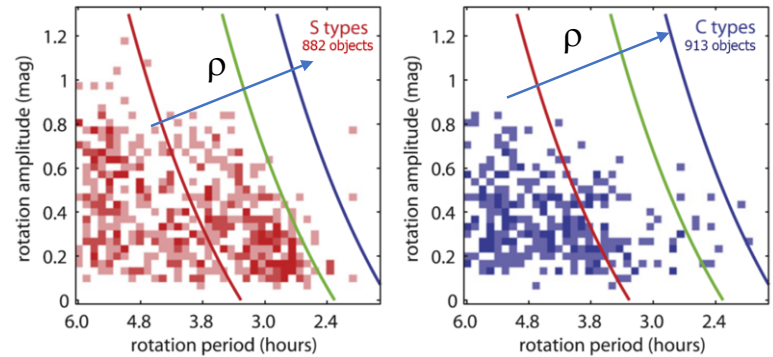
Characterization of Asteroids

Spin rate reveals asteroid strength, interior structure, and evolution



- ZTF will measure over 100,000 asteroid light curves per year
- As of May 2018 over 600,000 measurements have been reported to MPC

Taxonomic dependence of spin rate and amplitude

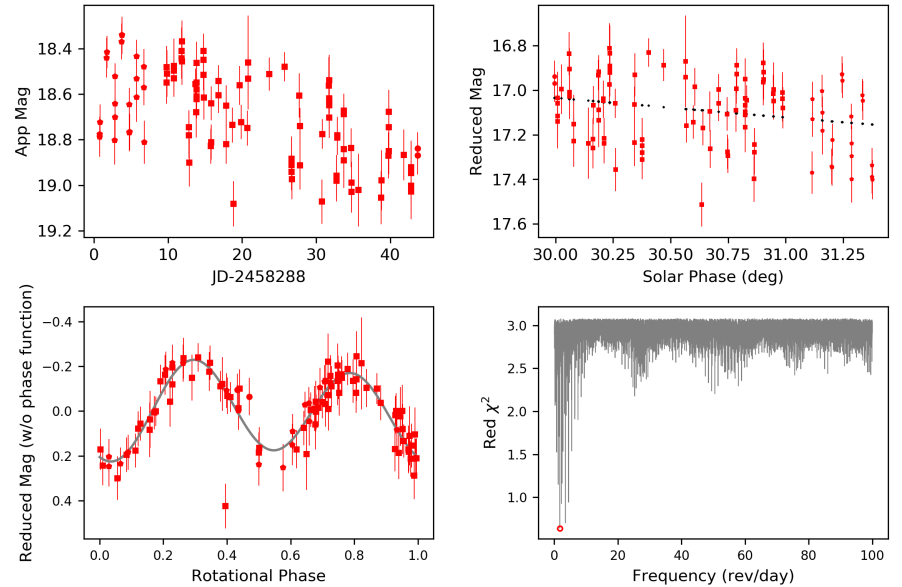
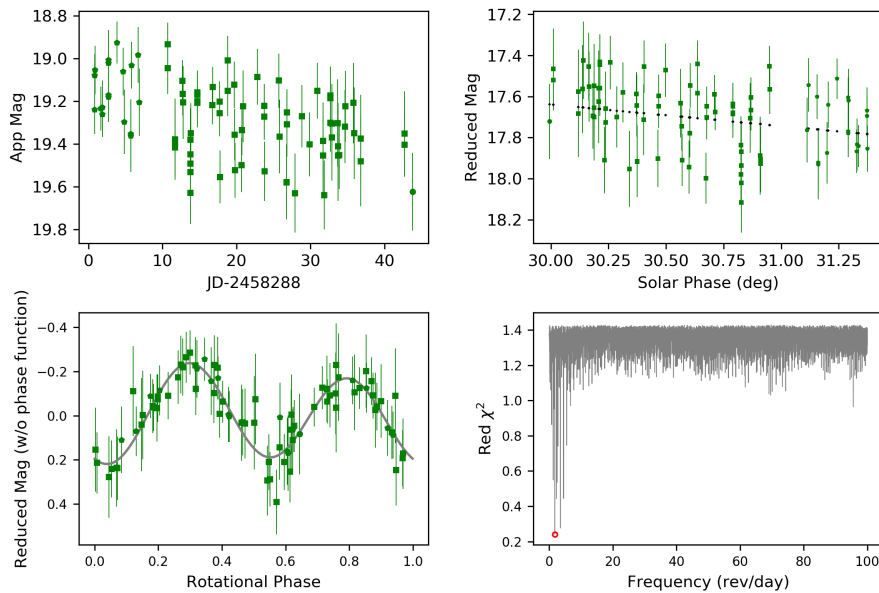


Waszczak et al. 2015

The Most Densely Covered Sparse Light Curves

445370, P= 13.83 $\alpha=[30.0, 31.4]$, det=84

445370, P= 13.83 $\alpha=[30.0, 31.4]$, det=103

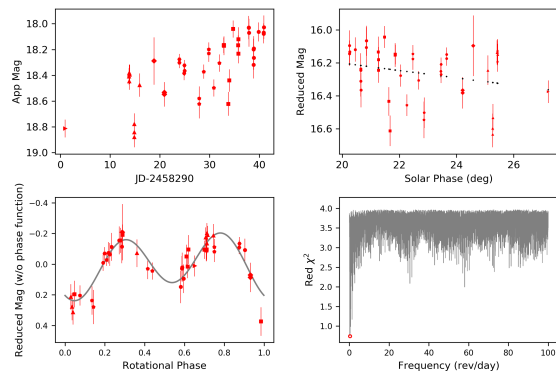


17 have reliable measurements of rotation periods.

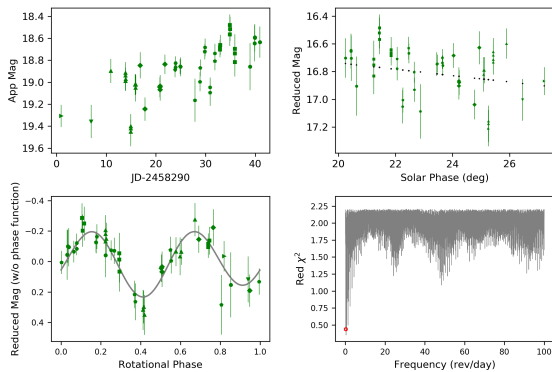
Difficulty

Inconsistent Rotation Periods in g/r

21260, $P = 76.19$ $\alpha = [20.3, 27.2]$, $\det = 46$

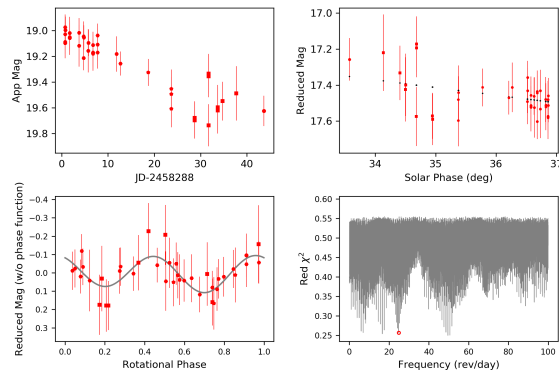


21260, $P = 129.73$ $\alpha = [20.2, 27.2]$, $\det = 48$

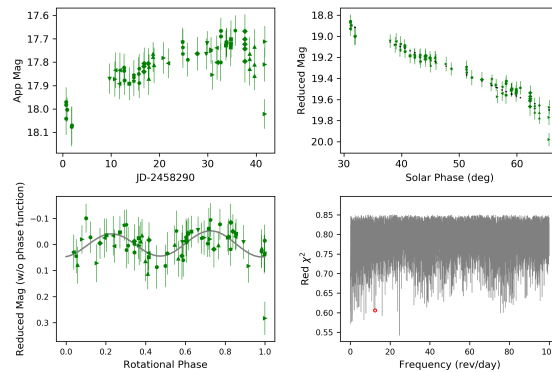


Ambiguous Rotation Period (SFR??)

6564, $P = 0.97$ $\alpha = [33.6, 36.9]$, $\det = 39$

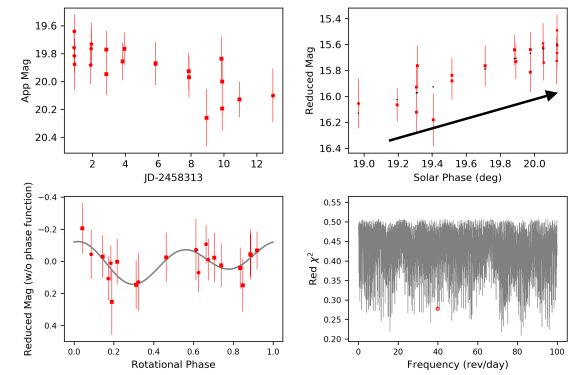


45550, $P = 1.94$ $\alpha = [31.1, 65.6]$, $\det = 70$



Weird Phase Curve

169979, $P = 0.60$ $\alpha = [19.0, 20.1]$, $\det = 21$



Topic: Cometary Outbursts

Michael Kelley, Dennis Bodewits, +

Cometary Outbursts

Rapid rise in brightness and mass-loss rate (<1 hr).

Long decay in activity as volatiles sublimate and dust slowly drifts away (days to weeks).

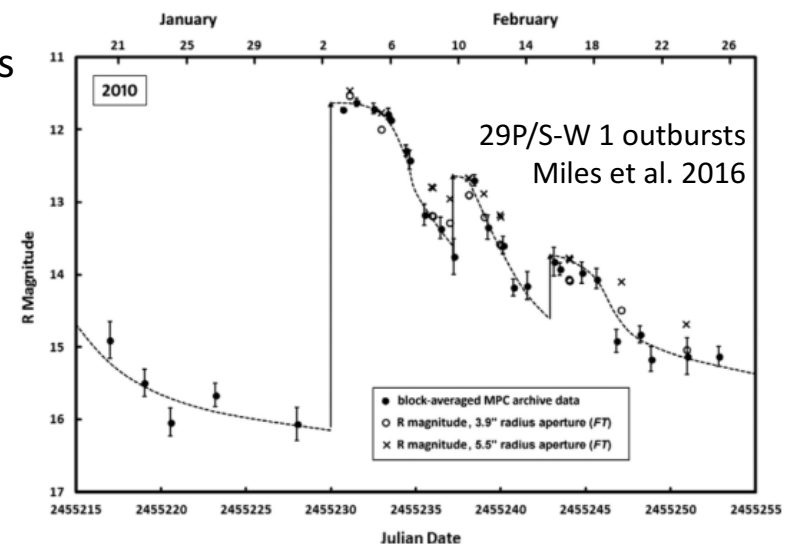
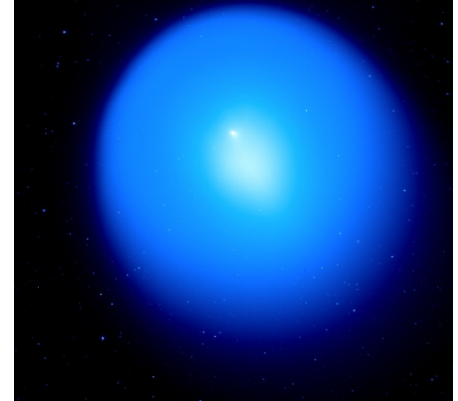
A variety of causes, some hypothesized:

- Rotational break up.
- Catastrophic fragmentation.
- Exothermic transition of water ice from amorphous to crystalline states.
- Gas pressure build up and catastrophic release.

More Observations, more chances to find comet outbursts.

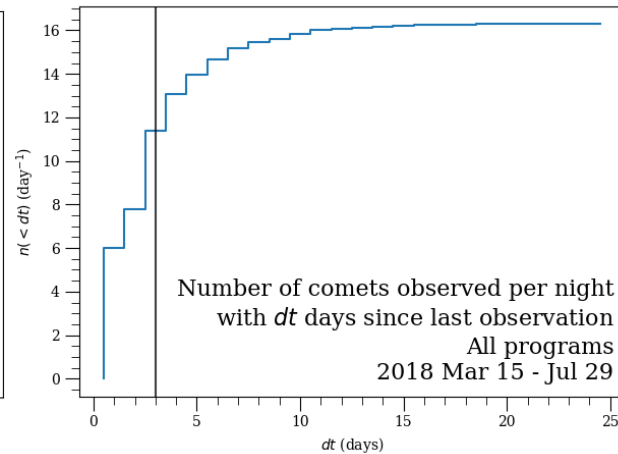
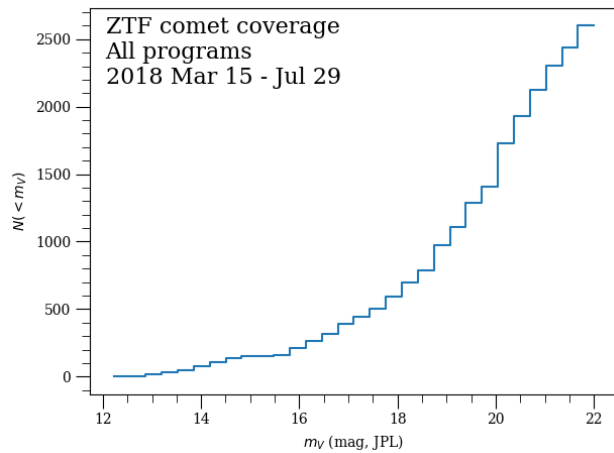
- On average, we observe 11 to 12 comets within 1 to 3 days of its last observation.

Outburst of comet 17P/Holmes
(Stevenson et al. 2010)

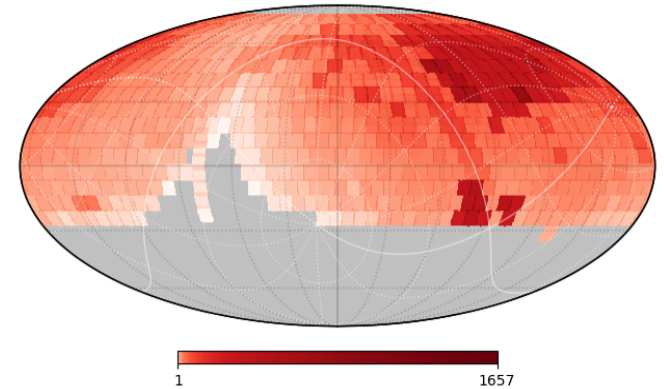


ZTF Comet Coverage

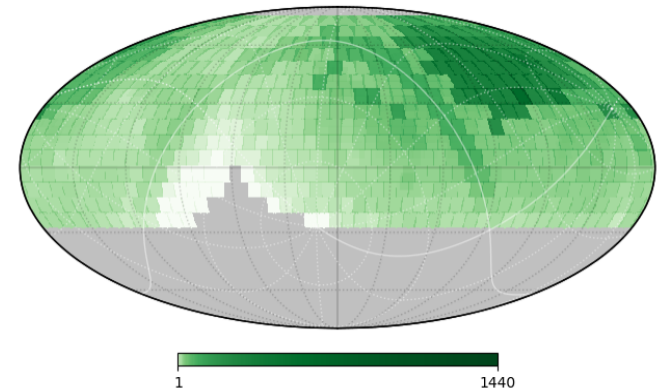
- Examined ZTF sky coverage, $g'r'i''$, for all comets with $V < 22$ mag.
- 2600 comet observations since Mar 15, 2017.
- On average, we observe 11 to 12 comets within 1 to 3 days of its last observation



ZTF : R : Equatorial : All Programs : Thru 2018-07-29 (104/129 Nights)



ZTF : G : Equatorial : All Programs : Thru 2018-07-29 (107/129 Nights)



Identifying Known Comets in the Alert Stream

The alert stream provides access to transients in the Public Survey.

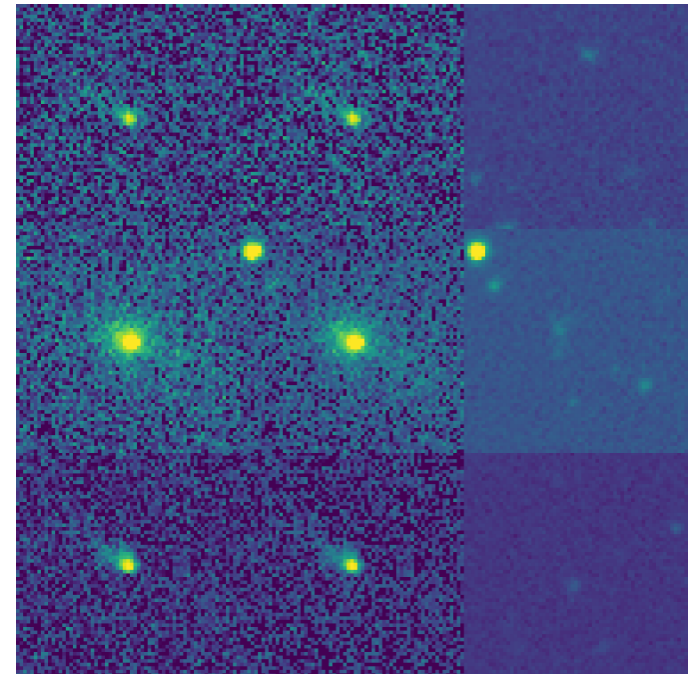
For `ssnamer == [comet]` and `ssdistnr < 30"`:

- **61 comet observations** are near a transient since 1 June.
- To verify, we independently examined the position of each transient for nearby comets: **71 total cometary alerts**.
- Compare with **268 comets with $V < 20.5$** from our coverage analysis.

One issue is the ephemeris predictions by the pipeline:

- *We have developed a fix and it is being considered.*

If Solar System objects can be reliably ID'ed in alerts, then we will propose all Solar System related alerts bypass alert filtering to enhance our outburst searches.



Alert stream comets

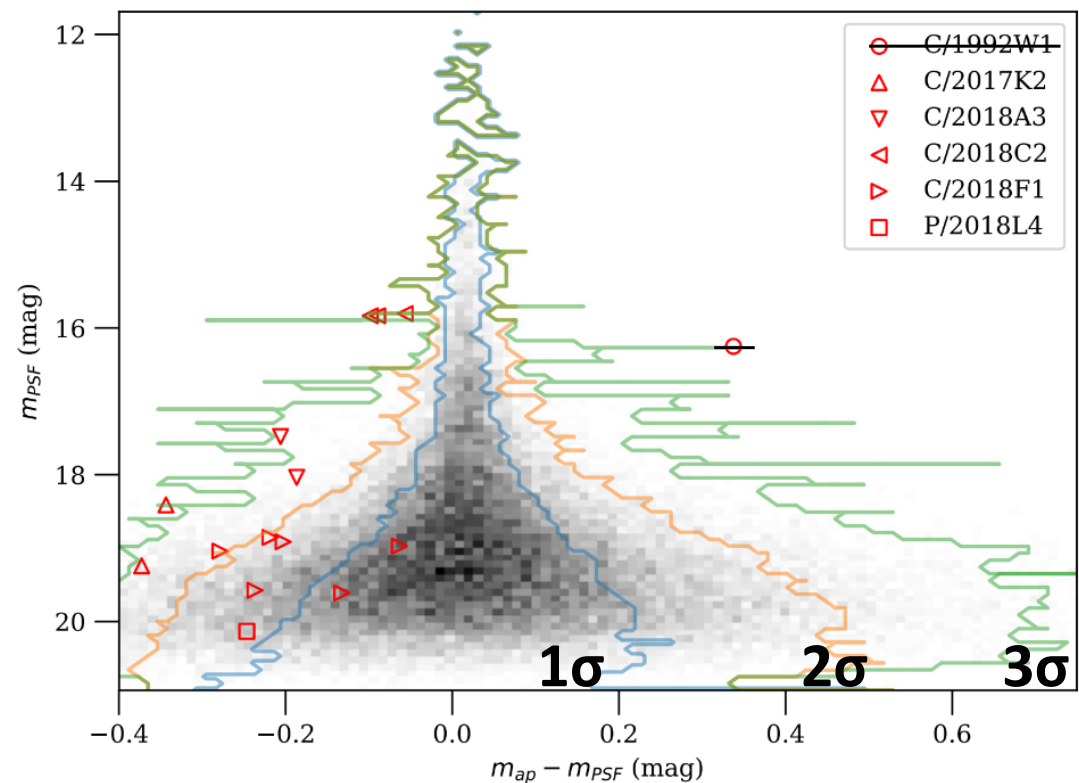
Finding Dust Around Solar System Transients

Asteroids can also produce dust, either through sublimation-driven activity or impacts.

Our first step to developing a general dust detector is on the right.

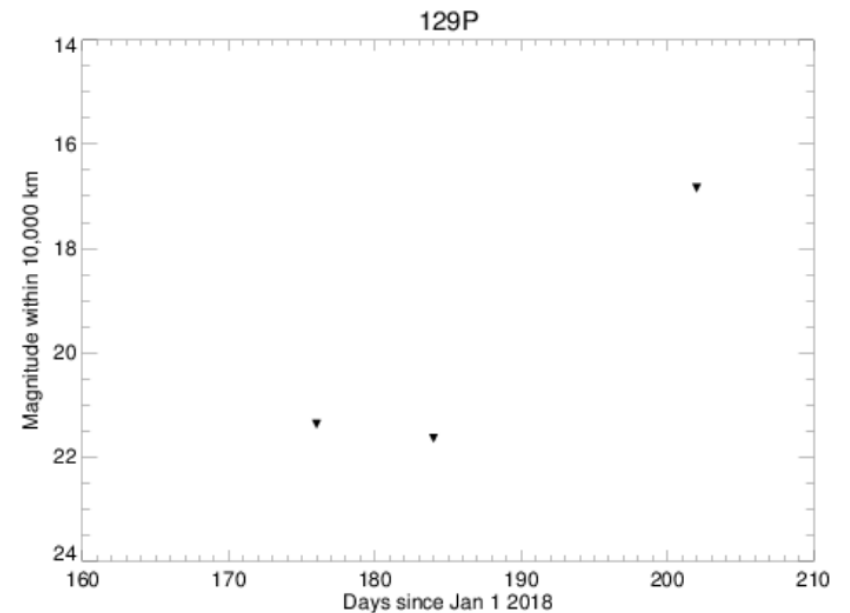
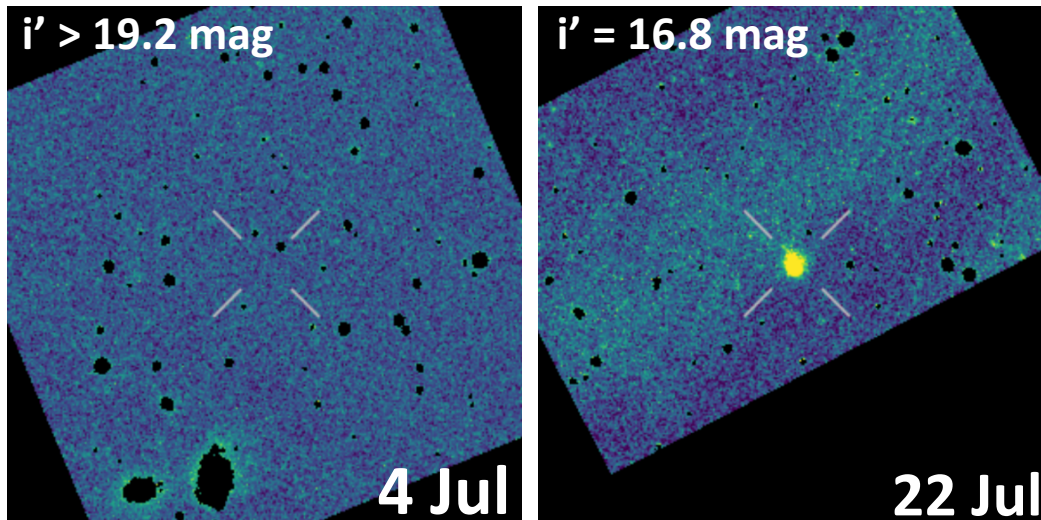
Comets tend to have **aperture magnitude < PSF magnitude** (due to coma).

Asteroids that repeatedly fall on the left-hand side might be considered active.



Outburst of 129P/Shoemaker-Levy 3

- ~5 mag outburst discovered by ATLAS on ~21 July (at aphelion, 4.6 au from the Sun)
- ZTF Partnership observations show outburst occurred between 4 Jul and 22 Jul.
- Public survey data on 5th, 8th, 12th, and 15th, but no alerts likely due to FWHM filtering.
- SEDM spectrum taken 25 Jul, and DDT Gemini-N GNIRS spectrum in the queue.

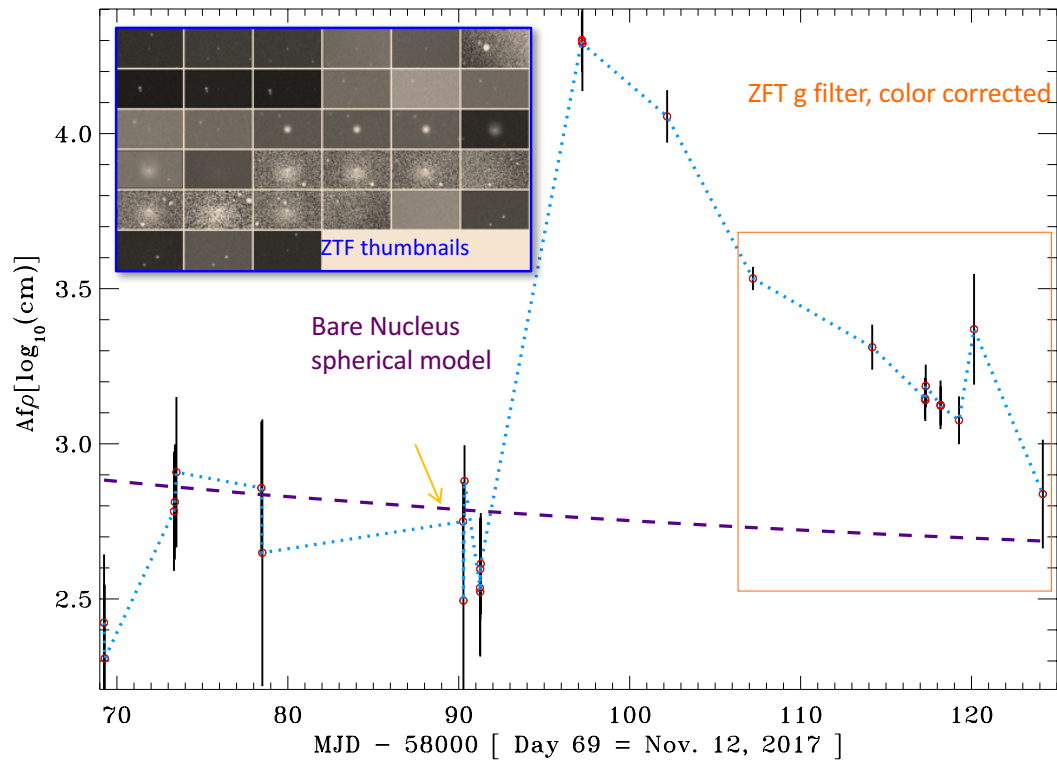


Topic: Centaurs

Gerbs Bauer

Centaur

Survey the number, rate, and amplitude of activity within the Centaur population
(Centaur's have semi-major axis between the giant planets => short lifetimes)



Echeclus Photometry:

- Periodic outbursts – intense and short-lived
- December 2017 intensity similar to December 2006 outburst.
- Weeks before activity onset observed in Aug. 2016, CO_2 production $\sim 2 \times 10^{26}$ molecules/sec

Summary

- Solar System Working Group is very active with several investigations
 - Near Earth Objects (NEOs)
 - Comet activity
 - Asteroid rotation curves
 - Centaurs and other specific asteroid classes
- Several topic well-matched to student research
 - In particular, NEOs