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ZChecker: Finding Cometary Outbursts with the Zwicky Transient Facility

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Abstract. ZChecker is new, automated software for finding, measuring, and visualizing known comets in the Zwicky Transient Facility time-domain survey. ZChecker uses on-line ephemeris generation and survey metadata to identify images of targets of interest in the archive. Photometry of each target is measured, and the images processed with temporal filtering to highlight morphological variations in time. Example outputs show outbursts of comets 29P/Schwassmann-Wachmann 1 and 64P/Swift-Gehrels, and an asymmetric coma at C/2017 M4 (ATLAS).

1. Overview

Cometary science benefits from wide-field, time-domain optical surveys. Aside from the discovery of new comets, they can provide a better description of known objects through brightness variation with heliocentric distance and season; estimates of dust-to-gas ratio and its variation with time; and identification of cometary outbursts or other

rapid identification of anomalous behavior and enable follow-up studies of discovered events.

The Zwicky Transient Facility (ZTF) is an optical system using the Palomar Observatory 48-in Schmidt telescope (Bellm et al., in press). ZTF's time-domain surveys target a wide range of astrophysical phenomena (Graham et al., submitted). Solar System science is mainly piggybacked onto these surveys. A wide-field camera delivers a 47 deg^2 field of view, and 5σ sensitivities near 20–21 mag in the g, r, and i filters. Images are processed and analyzed for transient sources and fed to an alert stream in near real time (Masci et al., in press; Patterson et al. 2019). All data are hosted at the Infrared Science Archive (IRSA).

The ZTF alert stream and ZTF Moving Object Discovery Engine (Masci et al., in press) regularly identify Solar System objects. However, these pipelines are optimized for point sources, and not guaranteed to find comets. As an alternative, we developed an ephemeris-based search tool, named ZChecker, custom designed for locating specific Solar System objects in the ZTF archive. Our primary goal is to promptly identify cometary outbursts for follow-up investigation. In the following sections we describe the search method and subsequent prompt cometary analyses.

2. Finding Solar System Objects

ZChecker is designed for daily searches for short ($\lesssim$1000) lists of objects. The basis for the search engine is a spatial index via SQLite's R*Tree module (Guttman 1984; Beckmann et al. 1990). Here, the R-Tree's "rectangles" are four-dimensional bounding boxes: three spatial dimensions and one time. Each box is defined using five sky coordinates (four corners and the center) to account for the curvature of the celestial sphere. The polar singularities and the Right Ascension discontinuity at $0/24^h$ are avoided by using Cartesian coordinates. A separate R-Tree similarly indexes the object ephemerides. Searching with the indexes is accurate, but imprecise. However, the goal is to narrow down the number of potential matches from millions to tens, at which point slower, precise methods can be executed. R-Trees were previously discussed in the context of astronomy by Baruffolo (1999), and are used to find Solar System objects at IRSA and in the Keck Observatory Archive (Yau et al. 2011; Berriman et al. 2016).

Ephemerides are retrieved from online tools, either Minor Planet Center's Minor Planet and Comet Ephemeris System (MPES) or Jet Propulsion Laboratory's Horizons (Giorgini et al. 1997), using astroquery v0.3.9 (Ginsburg et al. 2018). Given a list of targets, ZChecker requests ephemerides for Palomar Observatory with adaptable time steps. Object lists are updated four times per year, but individual targets are added and updated as needed.

Once per day, the ZTF database at IRSA is queried for new science image metadata. The metadata are stored and indexed with the unique science product ID, and the image bounding boxes spatially indexed. Next, the ephemeris R-tree is queried for all tracks defined over the previous night. For each track, the observation R-tree is searched for overlapping boxes. For every match, a more precise target position is computed via spherical interpolation of the ephemeris, and compared to the image boundaries. If a match is found, a high-precision ephemeris and detailed observation geometry is retrieved from the MPES or Horizons, and a $5' \times 5'$ cutout is downloaded.

Daily searches typically take ~5 s, identifying up to ~100 observations of comets in ~10,000–30,000 data products. A single-object search for comets 2P/Encke and C/2017 M4 (PanSTARRS) in the full ZTF Partnership data archive (6 million images) takes 1 and 23 s identifying 17 and 478 observations, respectively. A full search for 528 comets nominally brighter than 25th mag yields 37,300 observations in 2380 s.

3. Photometry and Morphological Variations

The ZTF pipeline calibrates images using a filtered Pan-STARRS DR1 catalog (Masci et al., in press). Comets are extended objects with sizes that depend on, e.g., distance to the Sun and observer, or instrument sensitivity and bandpass. We centroid on each comet, and then measure the total flux in a range of circular apertures. Automatic brightness plots using 10,000-km radius apertures are generated and inspected for anomalies. This fixed aperture size facilitates comet-to-comet comparisons.

In addition to photometric outburst discovery, we use temporal filtering to show morphological variations with time (cf. Schleicher & Farnham 2004). All images of a comet are projected into the ephemeris reference frame, with the projected Sun vector along the image $+x$-axis. Images are photometrically scaled to a common heliocentric and geocentric distance, then median combined into nightly and two-week averages. The two-week average serves as the temporal reference for the nightly image. The difference or ratio two highlights morphological variations.

The default photometric scaling is designed for cometary comae: $r_{\rm h}^{-4}\Delta^{-1}$, where $r_{\rm h}$ is heliocentric distance and Δ is observer-comet distance. This scaling does not account for dust phase darkening, and comets follow a wide range of heliocentric distance slopes, but in practice it works for most cases as a quick-look tool.

Based on ZChecker-produced data products, we independently discovered an outburst of comet 64P/Swift-Geherls (Kelley et al. 2018), and confirmed or rejected a few others. Moreover, we have identified a dust feature in the coma of comet C/2017 M4 (ATLAS). Example data are provided in Fig. 1.

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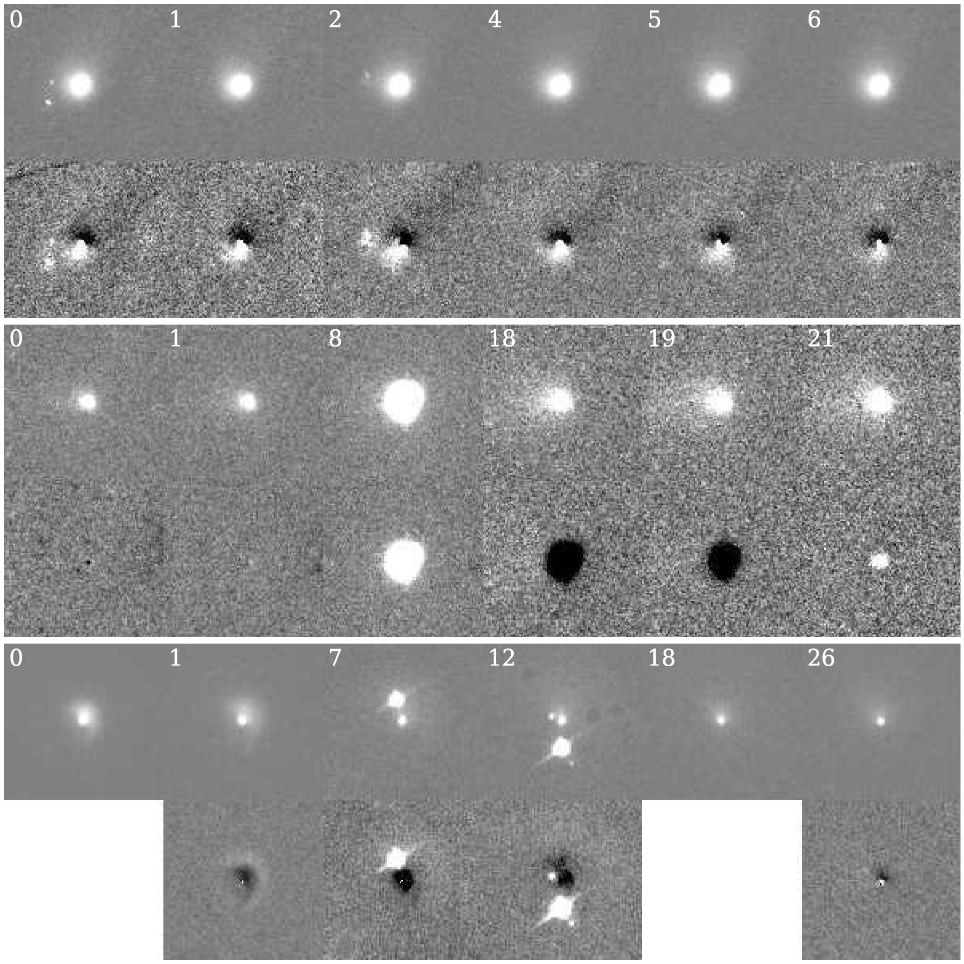

Figure 1. Time series and temporal filtered images of three comets. The time series is the first row and the reference subtracted data the second row. The sun direction is to the right. Images in each row are relatively scaled (linear scaling), and labeled with the relative time offset in days. (Top) C/2017 M4 (ATLAS), with residuals due to a strongly asymmetric coma and a rapid counter-clockwise rotation of the projected velocity vector. (Center) Outburst of 64P/Swift-Gehrels, the over-subtraction on days 18 and 19 caused by the outburst in the reference image. (Bottom) Outburst of 29P/Schwassmann-Wachmann 1 and propagating shell of dust.

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