National Aeronautics and Space Administration

Multiply-Imaged Distant Supernovae in Strong Gravitational Lenses with the Zwicky Transient Facility

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Objectives

This Spontaneous Project's Objective was to discover and analyze multiply-imaged supernovae in known strong gravitational lenses, that can be used to measure the local cosmological expansion rate, the Hubble Constant, using multi-year time-domain data from the Zwicky Transient Facility. As part of this goal, we aimed to deliver sophisticated and flexible processing and analysis code that can be built on in future work, including NASA ROSES, *Hubble* and *James Webb* Space Telescope proposals, and for opportunities with the *Nancy Grace Roman* Flagship mission which launches in 2025.

Background

Knowing the local cosmological expansion rate, the Hubble Constant (H0), is fundamental to cosmology. Long-established methods use the Universe-scale Cosmic Microwave Background (CMB); and "local distance ladder"-scale Cepheid variable stars. These produce what appear to be statistically-significant differences in H0. Is there new physics lurking? Or are there unresolved issues such as with the error budgets?

Independent H0 measurements can be made at intermediate cosmological distances using strong gravitational lenses (**Fig. 1**), which may help bridge that gap and deepen our understanding. This is what we're after! Our project focuses on leveraging the discovery and characterization of supernovae that are multiply-imaged by strong lenses (**Fig. 2**).

A supernova is an exploding star with well-characterized flux-variations. A supernova behind a strong lens will leave a tell-tale signature – as long as we have the monitoring data to see it. The Zwicky Transient Facility (ZTF [1]) on Palomar has years of nightly observations of the sky in three optical bands. Based on the data volume and coverage, there may be 1-5 lensed supernovae to be mined – hence "PastWatch!" The search is essential for improving our understanding the astrophysical rates; and for testing and advancing future techniques for seeking them in real-time data.

Approach and Results

We worked with ZTF Data Release 6, which contains 2.5 years of optical imaging covering 20,000 square degrees every three nights. Our approach involved analyzing observations at the specific positions of 5168 objects published candidate or confirmed strong gravitational lenses that we drew from the full catalog of 8500 lenses from the Main Lens Catalog [2].

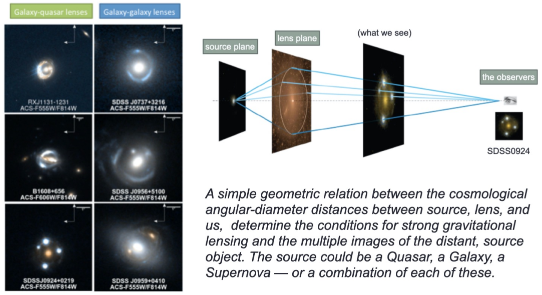
Software was developed with attention paid to best practices, with an agile software development approach . We used the FN-accessible JPL GitHub system for version and branch control. This pipeline architecture will be the basis from which future capabilities and analyses are added in the future, including for anticipated NASA funding competitions.

The background objects in strong lenses are generally either **galaxies**, or galaxies hosting Active Galactic Nuclei (AGN), which are time-varying accreting supermassive black holes. The brightest AGN are called **quasars** and can outshine their host galaxy. Lensed quasars are distinctive in morphology, and have distinctive and dramatic flux variability. Many lenses may have lower-luminosity, and lower-variability AGN compared to quasars, which could mimic a supernova-type signal in ZTF data.

To classify the variability properties of each target, and to look for statistically meaningful supernova-type outlier behaviors, we adopted a classic approach that allows us to use all photometric and photometric uncertainty information across the full time-span of irregularly-sampled data.

The **Gaussian Process** (GP) formalism [3] compares the covariance behaviors of the actual dataset against a specified assumed behavior, encoded in a reference covariance matrix, the kernel. Our needs led to two natural models: a white-noise kernel for demonstrating how consistent a dataset is with no statistically meaningful variations; and a Damped Random Walk kernel [4] which represents typical optical quasar variability.

Our pipeline combines ZTF data with the parent Main Lens Database, and multiple external catalogs ("Million Quasars" catalog [5], Gaia Data Release 2 [6], etc), multi-wavelength cutout images from ZTF and PanSTARRS1 [7], and the GP-derived classification parameters. For each individual target, the key data, matching, and analysis information is gathered in a dashboard view, which is used for review and follow-up. Examples of a densely-sampled quasar lens (Fig 3), a quiescent galaxy lens (Fig 4), and a representative object for more detailed follow-up (Fig 5) show the status of the project, and the potential for future work.



A simple geometric relation between the cosmological angular-diameter distances between source, lens, and us, determine the conditions for strong gravitational lensing and the multiple images of the distant, source object. The source could be a Quasar, a Galaxy, a Supernova — or a combination of each of these.

Figure 1. There are thousands of strong gravitational lenses discovered to date, and the left panel shows representative examples of galaxy-scale ones. These are typically one to a few arc-seconds in size. The geometry that leads to the strong gravitational lensing phenomenon is shown on the right panel.

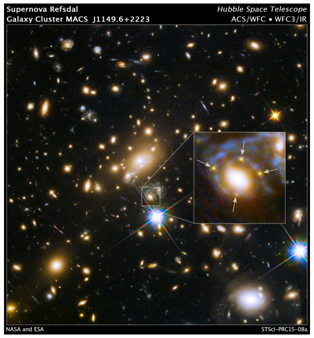
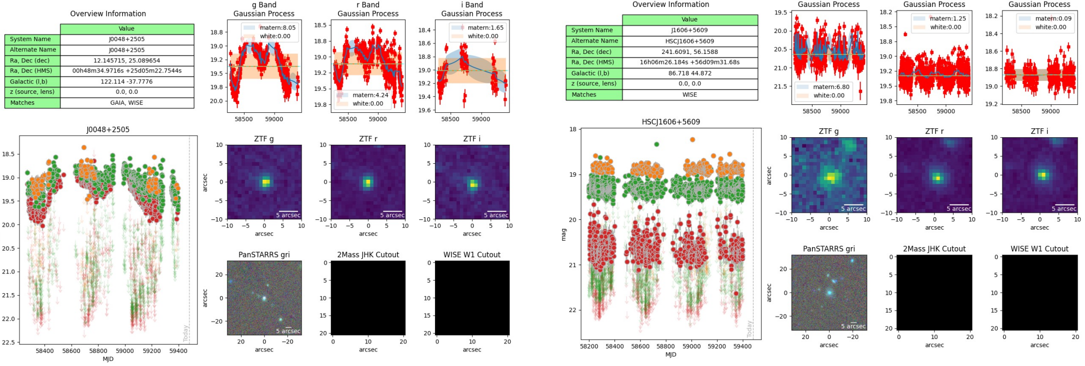


Figure 2. The first multiply-imaged, gravitationally lensed supernova was discovered in 2015, lensed by a galaxy embedded within an extremely massive cluster of galaxies which is at a distance of more than 5 billion light years. This supernova, dubbed "Refsdal," is some 9.3 billion light years away. All data shown come from the Hubble Space Telescope.

Credit:
https://hubblesite.org/contents/news-releases/2015/news-2015-08.html



Overview Information

	Value
System Name	J0048+2505
Alternate Name	J0048+2505
Ra, Dec (dec)	12.145715, 25.089654
Ra, Dec (HMS)	00h48m34.9716s +25d05m22.7544s
Galactic (l,b)	122.114 -37.7776
z (source, lens)	0.0, 0.0
Matches	GAIA, WISE

Overview Information

	Value
System Name	J1606+5609
Alternate Name	HSCJ1606+5609
Ra, Dec (dec)	241.6091, 56.1588
Ra, Dec (HMS)	16h06m26.184s +56d09m31.68s
Galactic (l,b)	86.718 44.872
z (source, lens)	0.0, 0.0
Matches	WISE

Figure 3. Two PastWatch Dashboard views of a quasar strong gravitational lens (**left**) and a quiescent galaxy strong gravitational lens (**right**) . Basic information including catalog matches are captured in the overview table. ZTF light curve data are shown in the bottom left, where red, green, and orange dots are the g-, r-, and i-bands, respectively, with detection-limits shown as arrows. The results of the Gaussian Process analysis in each band are shown in the top right trio of plots, with "white"-noise and a "matern" damped random walk (quasar-type) kernels. The middle trio shows ZTF reference-image cutouts, and the bottom row has a PanSTARRS three-color gri image. Currently, the 2MASS and WISE cutouts are not populated.

Significance/Benefits to JPL and NASA

Time-domain astrophysics is going to be profoundly important this decade. It is already a focus for the Nancy Grace Roman Flagship mission, launching in 2025. Between tension in cosmological parameter measurements, and the need to exhaustively study transient objects such as supernovae, extreme stellar phenomena, or gravitational wave events' electromagnetic counterparts, the infrastructure from this project lays a solid foundation for future NASA work.

References

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