HIGHLIGHTS OF THE LINEAR SURVEY

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Abstract. Lincoln Near-Earth Asteroid Research asteroid survey (LINEAR) observed approximately 10,000 deg$^2$ of the northern sky in the period roughly from 1998 to 2013. Long baseline of observations combined with good cadence and depth ($14.5 < r_{SDSS} < 17.5$) provides excellent basis for investigation of variable and transient objects in this relatively faint and underexplored part of the sky. Details covering the repurposing of this survey for use in time domain astronomy, creation of a highly reliable catalogue of approximately 7,200 periodically variable stars (RR Lyrae, eclipsing binaries, SX Phe stars and LPVs) as well as search for optical signatures of exotic transient events (such as tidal disruption event candidates), are presented.

1 Introduction

The MIT Lincoln Laboratory has operated the Lincoln Near-Earth Asteroid Research (LINEAR) program since 1998 (Stokes et al., 2000). Unfiltered observations were performed with two telescopes at the Experimental Test Site located within the US Army White Sands Missile Range in central New Mexico at an altitude of 1506 m. The program used two essentially identical equatorially mounted, folded design telescopes with 1m diameter, f/2.5 primary mirrors equipped with 2560 × 1960 pixel back-illuminated, frame transfer CCD cameras mounted in the prime focus. Cameras had no spectral filters and in combination with the telescopes produced 1°.60 × 1°.23 ($\approx$ 2 deg$^2$) field of view with a resolution 2.25′′/pix.

In 2013, this setup was replaced by the 3.5m Space Surveillance Telescope. First in the series of LINEAR papers (Sesar et al., 2011), henceforth Paper I) describes the LINEAR survey and photometric recalibration of acquired data (covering the period from 2002 to 2008), with the SDSS acting as a dense grid of photometric standards. In the overlapping 10,000 deg$^2$ of sky between LINEAR and SDSS, a total of $5 \times 10^9$ observations of $25 \times 10^6$ objects were made. Photometric
errors range from 0.03 mag for sources not limited by photon statistics to 0.20 mag at $r_{SDSS} = 18$ (Figure 1). In this six-year period objects along the ecliptic were observed 400 times on average, and elsewhere approximately 250 times (Figure 1).

![Graph](image)

**Fig. 1:** Photometric errors of the recalibrated LINEAR data (left) and average number of observations per object (right). Color-coding is according to the color bar, with the objects along the ecliptic saturating in red.

## 2 The Periodic LINEAR Variables Catalog (PLV)

Periodic LINEAR variables catalog (PLV) contains 7,194 variable stars classified with high reliability. Majority of these are new discoveries. The sample is dominated by RR Lyrae and eclipsing binaries, which account for more than 90% of the entire catalog (see Table 1).

| Type            | F [%] | N   |
|-----------------|-------|-----|
| RRAB            | 41    | 2923|
| RRC             | 14    | 990 |
| EA              | 5     | 357 |
| EB/ EW          | 33    | 2385|
| SXP/DSCT        | 2     | 112 |
| LPV             | 1     | 77  |
| Other           | <5    | 350 |
| **Total**       | 100   | 7194|

In order to create an exceedingly pure and complete catalog of variable stars visual check of all of the variable star candidates had to be performed. Since the initial $25 \times 10^6$ object catalog was too large for human classification, simple statistical cuts were applied in order to bring the variable star candidate sample to a level manageable on human scale. Application of cuts on brightness ($14.5 < m_{LINEAR} < 17.5$), likely variability ($\chi^2_{dof} > 3$) and variability amplitude ($\sigma > 0.1$ mag) produced a subsample of 200,000 variable star candidates. The
resulting subsample was phase-folded, crossmatched with 2MASS and WISE catalogs and classified. Reliability of the classification was checked against AAVSO Variable Star Catalog (VSX), General Catalog of Variable Stars (GCVS), SDSS Stripe 82 catalog of variable stars and CSDR2 catalog of RR Lyrae. Based on these comparisons it is estimated that the purity of the catalog is in the 98% and completeness in the 55%-75% range. Distribution of classified variable stars in color-period diagram, color coded with amplitude is plotted in Figure 2.

Further details regarding the creation of the catalog can be found in Palaversa et al. (2013) (Paper III). PLV catalog is available online from Vizier and also from a web page maintained by the authors of Paper III.

In the age of vast astronomical surveys such as Gaia (Eyer et al., 2012) and LSST (Ivezić et al., 2008) automated classification becomes increasingly more important. Particularly, in the case of time-resolved astronomical phenomena, a need exists for reliable machine learning training samples that will allow use of automated machine learning methods.

Periodic LINEAR variables catalog (PLV) addresses these needs: it covers a sufficiently large area of the sky, has no target selection criteria (i.e. it is unbiased), goes sufficiently deep to overlap with the current (2MASS, GALEX, SDSS, WISE) and future large surveys (Gaia, LSST) and furthermore has high reliability and completeness.

With this in mind, several popular automated classification models are described in the Paper III. Machine learning and data mining python package astroML was extensively used in the process.
3 Periodic variables and transients from recalibrated LINEAR data

PLV catalog contains several interesting variable star subsamples, some of which have already been subject of research. In particular, Sesar et al. (2013) used the ab type RR Lyrae stars to explore halo structure and substructure and confirm the existence of the Oosterhoff dichotomy in the halo.

Furthermore, Paper III describes 112 candidate SX Phoenicis short period variable stars outside globular clusters and reproduces the color-period relation for EW-type eclipsing binaries (Figure 3). If SDSS g-i color is taken as proxy for temperature of these mostly main sequence binaries, relationship between the decreasing temperature and shortening of the orbital period is observed. Furthermore, some of the identified short period dM+dM type binary candidates are found to be below the established 0.2 day period limit.

![Color-period relation of EW-type binaries. EW type binaries are marked with green circles and EB type binaries with blue triangles.](image)

Fig. 3: Color-period relation of EW-type binaries. EW type binaries are marked with green circles and EB type binaries with blue triangles.

Long baseline of recalibrated LINEAR data can also be useful in identification and analysis of transients. One such example is the extreme coronal-line emitter SDSS J095209.56+214313.3 (Palaversa et al., in prep.). Combining the LINEAR light curve with archived spectroscopic and multi-wavelength observations allows for precise timing and light curve modelling of this event which occurred in late 2004, while difference imaging constrains the location of the transient with respect to the host galaxy core.

4 Conclusion

Recalibrated LINEAR observations represent a faint and wide time resolved data set. Well characterized, clean and complete catalogue of LINEAR periodic variables provides a necessary machine learning training sample for the large ongoing and upcoming surveys such as Gaia and LSST. Surveys issuing large numbers of transient event alerts can also benefit from the classification provided by the PLV and the complete LINEAR light curve database to which their more current observations can be compared to. LINEAR data can also be used in the studies of Galactic structure and physics of binary and eclipsing stars. Finally, LINEAR data is available on-line via SkyDOT and Vizier.
References

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