A search for astrophysical transients and exoplanets with small-aperture telescopes

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1 Introduction

Over the past decade the use of time-series photometry has become a powerful tool to study many astrophysical phenomena. Uninterrupted, high-cadence observations of the night sky provide unprecedented access to the understanding of stellar variability, the detection of exoplanets and the discovery of transient objects. Small aperture telescopes (< 20 cm) are relatively inexpensive, highly reproducible equipment capable of producing high quality photometry.

2 Current Research

One such telescope was the Chinese Small Telescope ARray (CSTAR). CSTAR was designed to test the feasibility and quality of an observatory stationed at Dome A on the Antarctic Plateau. CSTAR was comprised of 4×145 mm aperture telescopes with SDSS gri filters and a clear pane of glass (N). Dome A is considered to be one of the most promising observing sites on Earth with low temperature, high altitude (4200 m), extremely stable atmospheric conditions (< 0.4 mag extinction for 70% of dark time) and dark conditions for nearly 6 months.

Previous studies of CSTAR data were reduced using aperture photometry. Aperture photometry involves the placing of an aperture with fixed radius around the centroid of a target star and summing the flux within the radius to determine the magnitude. Aperture photometry only works well if the PSF is well defined and the target field is not heavily blended or crowded. The 2009 CSTAR data did not meet these standards because the telescope was defocused, greatly exaggerating blending and crowding effects. We employed a novel version of difference image analysis in order to compensate for these effects.

Difference imaging "blurs" a high quality reference frame to match the observing conditions of a lower quality science frame. The two images are then subtracted and the change in flux is measured on the residual. Most versions of difference imaging use a convolution kernel comprised of multiple gaussians to match the shape of the point spread function (PSF) in each image. A gaussian kernel has difficulty successfully matching PSF shapes which are not circular, such as the oblong torus-shaped PSF of the 2009 CSTAR data. We implemented a version of difference imaging using a delta-function kernel that allows all types of PSFs to be matched. While not implemented on the CSTAR data, we also have developed a difference imaging code which exploits the convolution theorem to speed up data processing. We have begun implementing this routine on the data for the AggieCam.

Using difference imaging we successfully reduced $\sim 8 \times 10^5$ images taken during the Antarctic winter of 2009. We were able to successfully recover more than 100 variables in gNr and discovered 17 new possible variables. The photometric dispersion in each band and light curves for 6 recovered variable stars have been plotted in Figure 1.

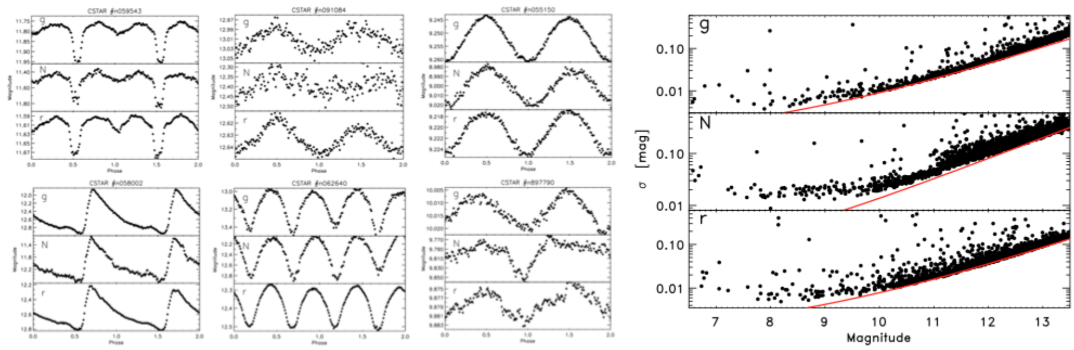

Figure 1: [left] Light curves for 6 variable stars from the 2009 defocused data in g (top panels), N (middle panels) and r (bottom panels). The light curves have been phased and binned into 200 data points. [right] Typical dispersions for the 2009 CSTAR data. The red line is a simple model for the noise based on the photon noise from the star and sky.

3 Proposed Thesis Topic

There are many young ($<$ 100 Myr old) stellar associations within 200 pc of the Sun. Observing these young stellar associations can provide much needed information about the creation and evolution of solar systems. Particularly important is the migration timescale of "Hot Jupiters" (HJs). HJs are gas giant planets with similar mass to Jupiter, $\sim 300 M_{\oplus}$, orbiting their host star at separations closer than Mercury and the Sun, $<$ 0.1 AU. The leading hypothesis to explain their existence is that these planets formed outside the frost line before migrating inwards, but the timescale for this process has yet to be fully explained theoretically or confirmed observationally.

Previous exoplanet studies have shown there is a trend between host star mass and giant planet occurrence rate. However, there is a clear lack of HJs orbiting K dwarfs. While this trend may be a true physical phenomenon, it may be the result of an observation bias against K dwarfs. Current surveys tend to observe either G dwarfs, because our Sun is a G dwarf, or M dwarfs, because of the larger transit signature. These observational constraints have led to significantly less K dwarfs being targeted in transit surveys. Our proposed survey will not limit our search to planets around a single spectral type and can provide unbiased observations of all spectral types.

Eclipsing binaries (EB) provide the most efficient measure of stellar radii. Measurements of EB systems at different ages can provide information about how a star evolves in its lifetime. While many EBs have been measured during and post their main sequence lifetimes, only a handful of systems are know to be pre-main sequence eclipsing binaries (PMB). The detection of a PMB will provide critical information about stellar radii at the early stages of stellar evolution. Our survey will be sensitive to the detection of PMBs because our targeted fields have a ages less than 50 Myr.

Motivated by the above, the proposed thesis project will use wide-field, high cadence, optical time-series photometry to address the following goals:

1. Provide a statistically significant constraint on the formation and migration time scales of detected HJs. A null result can also provide a statistical lower limit to the migration and formation time scales.

2. Provide unbiased observations of K dwarfs to determine the authenticity of the lack of gas giant planets orbiting K dwarfs.

3. Search for pre-main sequence eclipsing binary pairs to constrain the stellar radii during the early stages of stellar evolution.

All photometric observations will be obtained at the Bosque Alegre Astrophysical Station (EABA, in Spanish) located in Cordoba, Argentina. A recent collaboration with the Institute of Theoretical and Experimental Astronomy of the University of Cordoba has led to the installation of a small aperture, wide field imager at EABA dubbed "AggieCam". While there will be subsequent trips to EABA to observe on site, the majority of exposures will be taken remotely from College Station, Texas. As of April 2014, the telescope has been successfully operated from College Station for 2 months on all clear nights.

In order to maximize our observations we will observe three known young stellar associations; Upper Scorpius, IC 2391 and η Chamaeleon. Data reduction will follow that of the 2009 CSTAR data with the addition of the differencing imaging routine now operating in Fourier space to save computation time.

After the photometry has been collected we will employ tests for both stellar variability and exoplanet transits. We will use the same variability statistics used for the 2009 CSTAR data set: Δ_{90}, *rms* and J-Stetson statistic. We will also subject all light curves to the Lomb-Scargle algorithm for periods and the Phase Dispersion Minimization technique to only select objects with significant periods that lie outside of aliased frequencies. Finally we subject each light curve to visual inspection to confirm the nature of the variability.

To search for exoplanet transits we will use the Box Least Squares (BLS) fitting algorithm. We will only test the BLS algorithm on stars which show consistent, stable dispersion levels from night to night. We will adopt a number of detection thresholds before selecting candidates for the next level of confirmation. These thresholds include at least 3 transit events, no brightening at the anti-transit, consistent odd and even transit depths and the S_{red} statistic of 7 or greater.

Candidates passing these tests will be subject to further photometric follow up on the 1.5-m telescope at EABA. These high precision photometric measurements of the transit will confirm the transit timing and investigate the anti-transit for small amplitude transits indicative of an eclipsing binary system. Stars will be investigated with initial spectroscopy up to rule out any significant radial velocity variations indicative of binary stars. These binary stars can still be followed up as candidates for our PMB search. Stars passing this cut will then be sent for m/s precision radial velocity measurements. This high precision radial velocity measurements will allow us to search for Lithium lines indicative of a young star ($\lesssim$ 10 Myr in age).

The data reduction toolset created for the 2009 CSTAR data is highly beneficial for our survey. Initial results for the *rms* in 30 minutes and 4 light curves of recovered variables stars are plotted in Figure 2. The precision is expected to be increased with better trend removal and more data. The higher scatter in the *rms* values for the Upper Scorpius region is still being investigated but is likely due to the substantial drift across pixels during initial site testing in July 2013. Given the constraints on data processing, weather and proposal writing we expect project completion and graduation no later than May 2016.

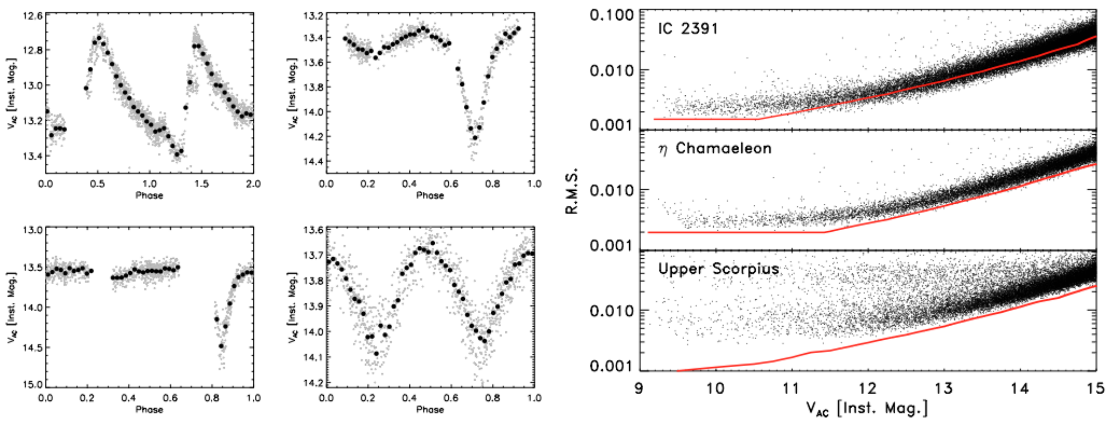

Figure 2: [left] Light curves for 4 previously known variable stars in the Upper Scorpius, η Chamaeleon and IC 2391 fields. The top left RR Lyrae is from Upper Scorpius; the top right is a semi-detached binary from IC 2391; the bottom left and right are a semi-detached and contact binaries from η Chamaeleon. Grey points show the raw 60 second exposures while the black points show the data binned on 30 min intervals. [right] *rms* for the Upper Scorpius, η Chamaeleon and IC 2391 fields from test observations of 20-50 hours per field. The red line is a model for the expected *rms* based on the photon noise from the star and the sky with an added error floor for scintillation.

4 Timeline for Completion

4.1 Spring 2014

AggieCam Observations - Observations of each stellar association begins, with remote observations being taken every clear night an observer is at Bosque Alegre.
Data Reduction - As data is collected it will be processed for bias subtraction, flat fielding, residual subtraction, alignment, difference imaging, flux measurement and position based trend removal.
Funding Proposals - Proposals will be submitted to the NASA exoplanet division (a similar proposal to the NSF was submitted last Fall). As a backup, a proposal will be submitted to the Mitchell Institute for Fundamental Physics and Astronomy.
Publications - The 2009 CSTAR data analysis paper is submitted to a referred journal.

4.2 Summer 2014

Observations and Data Reduction Continues
Travel - Travel to Cordoba, Argentina for a 3-week observing run and installation of a new computer for on-site data reduction.
Variability Testing - The resulting light curves will be subjected to initial statistical tests for variability. Visible inspections carried out for light curves and stellar images in the reference frame to spot obvious blending.
Transit Searches - The BLS routine will be run on each stable light curve. Candidate exoplanets will be selected according to the statistics above. Odd and even transits will be inspected to rule out significant variation.
Period Determination - Stars matching the criteria for binary pairs and transiting exoplanets will have their period and eclipse depths independently confirmed using the 1.5-m telescope at Bosque Alegre Observatory.

4.3 Fall 2014

Observations, Data Reduction, Variability Testing, Travel and Period Determination Continues
Funding Proposals - Proposals will be submitted to the NSF for continued funding for the 2015-2016 school year assuming the Fall 2013 NSF and Spring 2014 NASA proposals were not funded.
Spectroscopic Measurements - Any stars showing binary nature and no secondary transit will be submitted for spectroscopic follow up using a 1m class telescope with a stable spectroscope such as CHIRON on the CTIO SMARTS 1.5-m telescope.

4.4 Spring 2015

Observations, Data Reduction, Variability Testing, Travel and Period Determination Continues
Presentations - Preliminary photometric results will be presented at the winter meeting of the American Astronomical Society (AAS) in poster format.
Spectroscopic Measurements - Initial spectroscopic measurements taken. Candidates with no discernible variation are selected for further study.

4.5 Summer 2015

Observations, Data Reduction, Variability Testing, Period Determination and Spectroscopic Measurement Continue
Spectroscopic Measurements - Radial velocity curves with m/s precision are extracted.

4.6 Fall 2015

Observations, Data Reduction, Variability Testing, Period Determination and Spectroscopic Measurements Continue

4.7 Spring 2016

Observations, Data Reduction, Variability Testing, Period Determination and Spectroscopic Analysis Concludes
Presentations - Presentation of final results at AAS meeting in dissertation presentation format.
Publications - Final results are published in a referred journal.
Graduation