DIFFERENCE IMAGING OF STAR CLUSTERS AT LOW GALACTIC LATITUDE

1 Scientific Motivation

Each of the ∼1000 star clusters of the Milky Way is a gift to astrophysics, providing a sample of stars that vary widely in mass but all have approximately the same age and composition. Time-series photometry of clusters[1] has numerous applications. By measuring rotation periods over a range of ages, we can study the angular momentum evolution of stars and improve our ability to determine stellar ages through "gyrochronology." By measuring eccenticities as a function age, we can study the tidal evolution of binaries. The detection of eclipsing binaries can lead to the precise determination of the absolute dimensions of the stars and stringent tests of stellar-evolutionary models. Circumstellar material can also be studied by finding the rare cases in which the material produces eclipses.

The detection of transiting planets — our main motivation for the proposed work — will shed light on the timescales for processes in planet formation, evolution, and migration, and on the effects of metallicity. With a larger sample of transiting planets in clusters of varying ages, we could see the evolution of the radius distribution of giant planets as they contract (Fortney et al., 2017), and watch as the closest-in planets lose mass to photo-evaporation (Owen and Wu, 2017; Fulton et al., 2017). The Hyades planet K2-25b (Mann et al., 2016a), for example, appears to be oversized compared to mature planets of the same mass and irradiation. By searching for hot Jupiters in clusters we can determine when they begin to appear, thereby constraining theories for their formation. The discovery of K2-33b has already showed that in at least one case the process required fewer than 10 Myr (David et al., 2016; Mann et al., 2016b). Detecting planets in dense clusters ($\gtrsim 1000\,\mathrm{pc}^{-3}$) may also reveal how the stellar environment affects planetary system architecture (Meibom et al., 2013). Yet most of this work remains for the future: only about 10 of the currently known transiting planets are in clusters.

The Transiting Exoplanet Survey Satellite (*TESS*) holds the promise to deliver the most homogeneous and comprehensive cluster photometric survey in history. Based on the cluster membership database of Kharchenko et al. (2013) and the *TESS* apparent magnitude calculator of Jaffe and Barclay (2017), we estimate that 10^5 cluster members brighter than $T = 16$ will be observed in the southern ecliptic hemisphere's full-frame images.

However, there will be formidable obstacles to deriving precise photometry from the *TESS* images because of the relatively poor angular resolution. Almost all of the clusters are within 10 degrees of the Galactic plane (see Figure 1), where the problems with crowding and complex backgrounds are so severe that the *TESS* Science Team has neglected that portion of the sky in their planet simulations (Sullivan et al., 2015). Similarly, the *TESS* Candidate Target List deprioritizes all objects within 15° of the galactic plane (Stassun et al., 2017), which includes 90% of all star clusters. The large pixel size and the high stellar surface density will make aperture photometry unreliable (see Figure 2). Yet, aperture photometry is the basis of the official *TESS* data reduction pipeline and almost all reduction methods that have been applied to *Kepler* and *K2* data.

These challenges are substantial — and surmountable, with the tools we are already building for the analysis of ground-based images with very similar characterstics to those of *TESS* images. **We propose to produce light curves of star cluster members by applying difference-imaging methods to the *TESS* full-frame images.** Our own motivation is to search for transiting giant planets, but we will deliver these light curves promptly to the MAST public archive for the entire community to perform a wide range of scientific investigations.

[1] For brevity, we use this term to refer to open clusters, moving groups, associations, and star-forming regions.

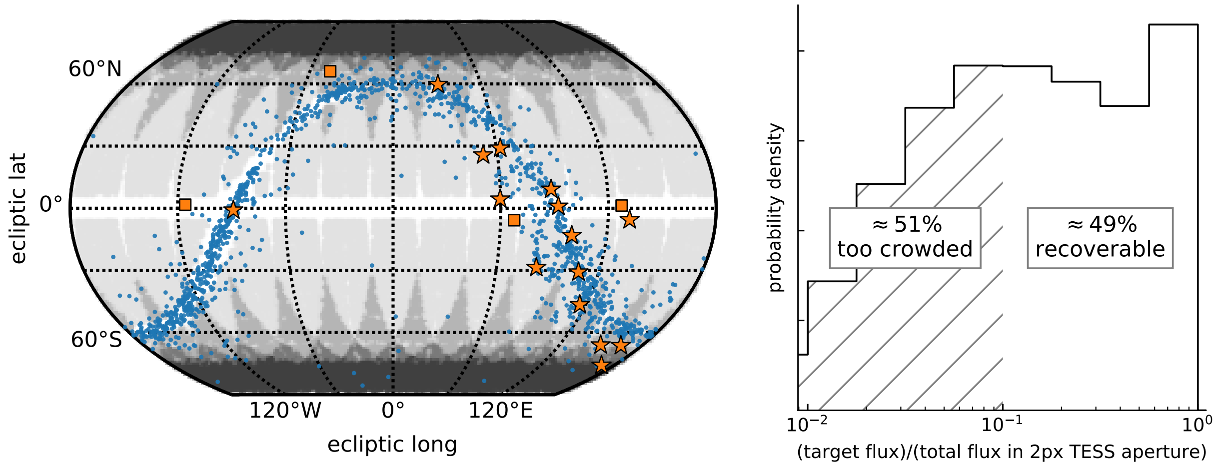

Figure 1: *Left:* Clusters are at low galactic latitudes. The southern ecliptic hemisphere has about 10^5 cluster stars with $T < 16$ and $d < 2\,\mathrm{kpc}$. Blue circles show the 885 documented clusters (Kharchenko et al., 2013). Orange stars are the clusters that have been monitored previously with ground-based telescopes. *TESS* will provide more homogeneous and continuous data for these clusters. Orange squares are clusters that were surveyed by *Kepler* and *K2*.
Right: The dilution problem. Within a standard aperture, a single cluster star usually contributes only a small fraction of the total flux. Shown here is the histogram of this flux fraction for cluster stars with $T < 16$ and $d < 2\,\mathrm{kpc}$. Almost none are well suited to aperture photometry. About half have flux fractions > 0.1 and will be amenable to difference imaging.

2 Data Reduction Plan

Our group has extensive experience with precise time-series photometry, including difference imaging and cluster photometry, through our leadership of the HATNet and HATSouth transiting planet surveys as well as deep surveys of crowded fields in M37 and M33 (Hartman et al. 2006, 2009). We are commissioning a new multi-telescope observatory called HATPI, at Las Campanas Observatory, employing 63 wide-field 10 cm lenses that have a pixel scale similar to the *TESS* cameras. We have an existing software pipeline for difference imaging, photometry, and detrending.

The concept of difference imaging (also called image subtraction) is to isolate variable sources from within blends and complex backgrounds, by subtracting each image from an appropriate convolution of a master image (Alard and Lupton, 1998). Our implementation is a descendant of the code desribed by `fitsh` (Pál, 2012). Our light curve processing tools are based on `VARTOOLS` (Hartman and Bakos, 2016) and `astrobase`, developed by W. Bhatti. We also have modules to reduce systematic effects by removing correlations between the apparent variations of a star and the variations of ensembles of similar stars, as well as external parameters such as PSF width and pixel coordinates (Kovács et al., 2005; Bakos et al., 2010). We also have extensively tested tools for identification and vetting of candidate transit signals that have been honed over 15 years and more than 100 planet discoveries.

Figure 3 shows our image subtraction pipeline's successful reduction of HATPI images, which will be very similar to *TESS* full-frame images. We have also successfully applied our pipeline to *K2* data. Soares-Furtado et al. (2017) performed difference imaging on a *K2* "superstamp" covering the open clusters M 35 and NGC 2158, leading to the most precise time-series photometry that is currently available for those fields.

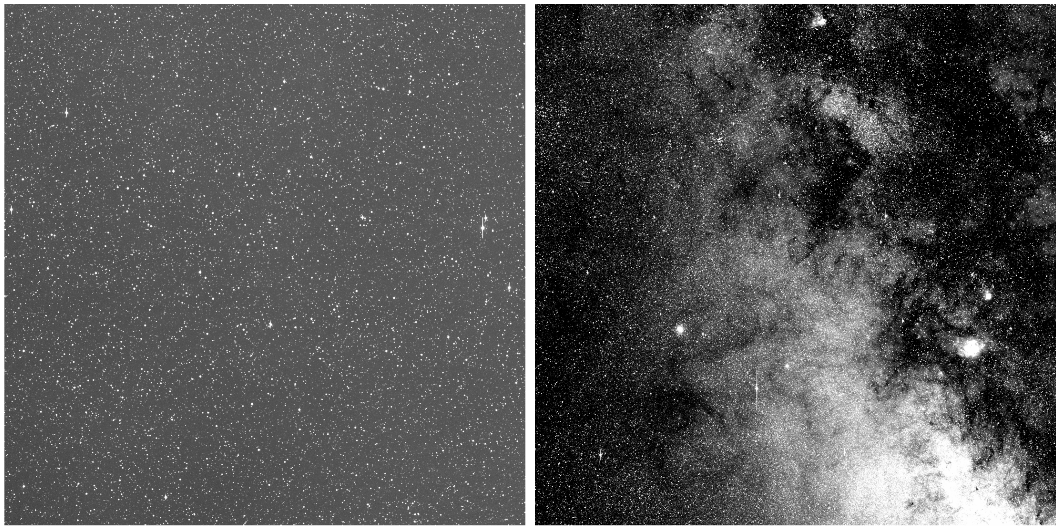

Figure 2: The problem of crowding. Each field is a real 13° image from HATPI, which has nearly the same pixel scale as *TESS*. On the left is a typical field, for which aperture photometry will be adequate. On the right is a typical *cluster* field, for which aperture photometry cannot be relied upon. Difference imaging is required to isolate sources of photometric variability.

3 Necessity and Feasibility

For almost all the clusters *TESS* will observe, image subtraction is necessary to produce reliable light curves. One way to quantify the blending problem is to ask what fraction of the total flux in a photometric aperture is contributed by a particular target star. Aperture photometry is reliable when this fraction is close to unity. Difference imaging, in our experience, can produce reliable photometry even when this fraction is as low as 0.1. Based on the cluster membership data of Kharchenko et al. (2013), and the density of background stars, we find that the median dilution fraction of stars with $T < 16$ is 0.13 for an aperture radius of 2 pixels. Difference imaging is therefore essential, and feasible.

As noted above, the scope of scientific investigations that will be possible with cluster light curves is very broad. Since our own interest is in transiting planets, we have assessed the prospects for planet detection in the following manner. We used the *TESS* noise model of Sullivan et al. (2015), as implemented in the code of Jaffe and Barclay (2017), to to predict the achievable noise level for all $T < 16$ cluster members in the southern ecliptic hemisphere. Using the catalog values of the color and age of each star, we estimated the mass and radius with reference to the stellar-evolutionary models of Siess et al. (2000). We then calculated the number of stars for which a planet with a 10-day period could be detected with a signal-to-noise ratio exceeding 10, even in the face of the estimated flux dilution.

During Cycle 1 we find that 20,000 cluster stars can be searched for Jupiter-sized planets, and 3,200 stars can be searched for Neptune-sized planets. Taking into account the transit probability, and a typical occurrence of 0.5%, this would result in about 15 hot Jupiters and 5 hot Neptunes. To put this into perspective, there are currently only 13 transiting cluster planets known, and only one transiting hot Jupiter (David et al., 2016; Mann et al., 2017). Planet candidates will be followed up through our participation in the *TESS* Follow-up Observing Program and the international KESPRINT consortium. We also have 100% of the observing time on the newly deployed CHAT 0.7m automated photometric telescope at Las Campanas Observatory, Chile, which will allow us

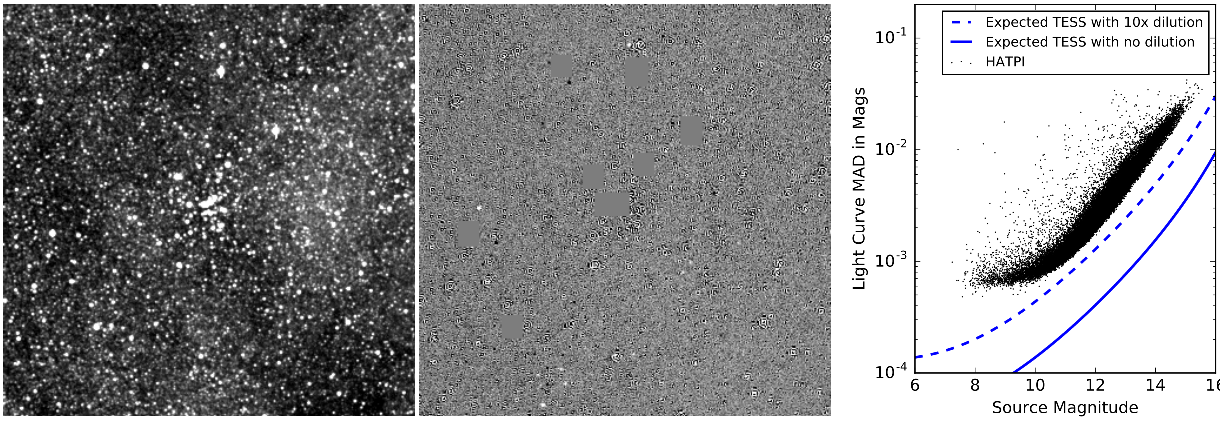

Figure 3: Successful application of difference imaging to the field shown in the right panel of Figure 2. *Left*: The 2.2° region surrounding the cluster M 25. *Middle:* Typical difference image. Variable stars are black or white; saturated stars are masked; other artifacts are PSF residuals. *Right:* Light curve scatter at 30 minutes versus apparent magnitude for thousands of stars in this crowded field. The expected performance for *TESS* is also shown, both without dilution, and accounting for typical dilution in clusters.

to obtain images with better angular resolution and more precise light curves than the *TESS* data.

4 Impact

The *TESS* full-frame images of star clusters are a gold mine for stellar astrophysics and exoplanetary science. However the gold will remain in the ground without a dedicated effort to solve the problem of achieving high photometric precision in crowded images. With funding from the GI program we will adapt our codes for difference imaging to the *TESS* full-frame images. We will make the light curves available through MAST, and we will make the source code for image subtraction, photometry, and detrending available on github. We will also search the light curves of suitable stars for transiting planets, which we intend to validate and follow up. Through this effort we can expect to triple the number of known transiting planets in clusters, and provide a glimpse of the evolving physical and dynamical properties of giant planets.

5 Budget Justification

Most of the budget will be used to fund a Research Assistantship for Ph.D. student Luke Bouma. Mr. Bouma will play a crucial role in the project, with primary responsibility for image processing and light curve production, under the supervision of Dr. Joel Hartman and Prof. Joshua Winn. Funds will also be requested for publication charges, a server to perform the analysis, and a modest travel budget to attend *TESS* meetings and related conferences.

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