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Odysseus: AAVSOnet Data and Photometric Reductions

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1. INTRODUCTION

Odysseus is a multi-wavelength program aimed at understanding the variability of accreting pre-main sequence (PMS) stars, including T Tauri stars. This is a subset of the ULYSSES program, which focusses on obtaining legacy far-UV spectra or a representative sample of targets while the Hubble Space Telescope (HST) still has UV capabilities. The 13 Northern PMS targets, all in the Orion OB1b star forming region, were observed between 19 November and 17 December 2020, while the TESS satellite monitored this part of the sky.

The aim of the ground-based program is to obtain supporting optical and near-IR photometry and spectroscopy. TESS will return light curves with a 10 minute cadence nearly continuously for 27 days. The ground-based photometry will not be able to beat this, either for cadence or S/N, but will provide colors that will be indispensable for interpreting the TESS light curves (TESS operates in a single band, from approximately 600 to 1000 nm). We can also use calibrated R and I data from the ground to "calibrate" the TESS fluxes.

The photometry presented here was obtained in response to an AAVSOnet proposal. The AAVSOnet (www.aavso.org/aavsonet) is a set of robotic telescopes operated by volunteers for the AAVSO.

The five telescopes used for this project are listed in Table 1. Most of the images were obtained with the BSM systems. On most nights sets of three exposures were obtained in each band. We shifted and coadded these using a median filter to improve the S/N and to remove satellite and airplane trails. Exposure times were typically 3 minutes per image in Vri and 5 minutes in B. The scheduling algorithm was generally set to observe only within 2 hours of the meridian, to minimize the airmass.

There are significant gaps in the coverage due to inclement weather. In some cases nearly simultaneous observations from different sites provide a check on the photometric calibrations. We aimed to get occasional observations during the 27-day long TESS observation, with denser coverage around the time of the HST observations. The former goal was was met; the latter often succumbed to cloudy skies. A few

Table 1. Telescopes utilized for this program

Telescope	Location	Aperture (cm)	Plate Scale (arcec/px)
BSM_NH	New Hampshire	6	4.97
BSM_NM	New Mexico	6	4.97
OC61	New Zealand	61	0.55
SRO	Arizona	50	0.92
TMO61	New Mexico	61	0.32

targets were observed significantly less frequently than others. Since the scheduling algorithms start with the westernmost targets, they often failed to get to the easternmost targets while satisfying hour angle constraints (and pressure from other programs).

2. OBSERVATIONS, DATA REDUCTIONS AND CALIBRATION

The thirteen targets were submitted to AAVSO, who scheduled observations. In Table 2 I summarize the number of successful observations of each target. Some targets appear in multiple fields, facilitating multiple observations in a single night. Images are flattened and in most cases an astrometric solution is computed prior to delivery. I did not reduce those images that lacked astrometric solutions; many were blank (clouds); others were far off the target and not useful. The number of unusable images is small.

Data were extracted using aperture photometry. The extraction aperture is circular. The background is the median sky value in a torus of radius twice the extraction aperture. There is a 5 pixel-wide gap between the extraction aperture and the background torus. Taking the median of the sky values in the background torus effectively removes any stars, and is appropriate so long as the spatial variations in the sky brightness are approximately planar near the target.

First a bright (but unsaturated) star is extracted using a series of apertures to determine the aperture that contains 90% of the flux. This is the extraction radius. Then I extract the target counts with a similar series of apertures to determine the radius that maximizes the signal-to-noise ratio. This radius is generally smaller than the extraction radius, because the target noise may be dominated by the sky. This is

Table 2. Target

Target	Nights Observed	Observations Collected	AAVSO Points
CVSO 17	30	39	39
CVSO 36	20	23	64
CVSO 58	27	35	89
CVSO 90	29	70	56
CVSO 104	28	66	81
CVSO 107	22	35	66
CVSO 109	29	66	82
CVSO 146	10	11	65
CVSO 165	5	6	75
CVSO 176	8	10	31
TX Ori	20	44	553
V505 Ori	20	44	428
V510 Ori	20	37	419

only used for determining the S/N of the source detection. For calibration purposes it is important that the target and the calibration stars be extracted using the same aperture.

3. PHOTOMETRIC CALIBRATION

We used stars in the AAVSO Photometric All-Sky Survey (APASS: www.aavso.org/apass) to calibrate our targets. Data are from APASS Data Release 10. The APASS lists B, V, r', and i' magnitudes, for V between about 7 and 17. We measured all stars in our images within ±500 pixels of the target using the same aperture radii as for the target. We fit the calibrated magnitudes as a function of the instrumental magnitude. We expect the relation to be linear, and indeed it is for unsaturated stars. We constrain the relation to be linear, and exclude stars that deviate by more than 5 σ from the fit. We then refit the relation.

There are typically a few hundred stars in the fit for the BSM images, and a few score stars in the TMO images.

The calibrated magnitude of the target is determined by plugging its instrumental magnitude into the calibration relation. The uncertainty on the calibration, which typically exceeds the formal uncertainty on the target detection, is added in quadrature to estimate the net uncertainty. These uncertainties of the target detection is given in the S/N column in the text output.

Because the standard stars are observed simultaneously with the target, no correction for atmospheric extinction is necessary. Likewise, a thin uniform cloud layer should have negligible impact on the magnitude determinations.

I convert the r, i magnitudes to R_C, I_C using the prescription given by Lupton (2005, quoted at www.sdss3.org/dr8/algorithms/sdssUBVRITransform.php). I also checked the Jordi *et al.* (2006, A&A **460** 339) transformations for population I stars, and those published by Chonis & Gaskell (2008, AJ **135**, 264). The 3 transformations give almost identical results in most cases. The Chonis & Gaskell prescription returns much larger (and perhaps more realistic) uncertainties.

3.1. **Concerns**

The APASS r', i' magnitudes are in the Sloan filter system. I ignore the small differences between the r, i and r', i' systems. The BSM and SRO telescopes use Cousins R_C and I_C filters. By calibrating these as though they were taken through the Sloan r' and i' filters, we undoubtably introduce small errors, especially for stars with extreme colors. But the targets do not have extreme colors, so we reduce them as though they were taken in the Sloan filters. Comparison to data from the TMO61 shows no obvious systematic offsets. Comparing our derived R_C, I_C magnitudes to the AAVSO data also shows no systematic offsets.

However, the photometric conversions are determined for normal stellar spectra. In a star like V510 Ori the Hα line has an equivalent with of order 100Å, which means it contributes about 10% of the flux in the r band, above the "normal" stellar continuum. This will certainly add a systematic offset to the color transformations. The proper way to compute the transformations would be to convolve the observed spectra with the filter+camera responses for each target.

CVSO-104 is a 2.4 arcsec binary of approximately equal magnitudes. The system is unresolved in the BSM images, but is clearly resolved on most nights in the telescopes with a smaller plate scale. The current aperture photometry includes both stars; we will use PSF fitting to separate the stars at a later date.

4. AAVSO OBSERVATIONS

Prior to requesting the AAVSOnet data, we issued AAVSO alert 725 (https://www.aavso.org/aavso-alert-notice-725), requesting that anyone who could also obtain images, and report them to the AAVSO. Response has been excellent. The number of data points obtained for each target from JD 9160 though JD 9205 is given in the rightmost column of Table 2. These data uploaded through 28 December are shown in the plots on the web pages, but I have not set about deriving colors from these data.

5. WEB PAGE FORMAT

The main page for each target has a link to "AAVSOnet Photometry" This leads to a page that has 2 links and 4 or 5 plots. The links are to the observed magnitudes, and to the derived colors. These are the AAVSOnet data only; the AAVSO data are accessible through the AAVSO data portal. Some preliminary discussion of the time-variability is included here.

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