Wesleyan University The Honors College

Monitoring Stellar Activity of Exoplanet Hosts with the Van Vleck Observatory 24-inch Telescope

by

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Abstract

The activity of exoplanet hosts has a significant impact on the atmospheres of close-in exoplanets and the observed transmission spectra. In particular, low-mass exoplanet hosts show frequent flares and spot modulation. The Sub-Neptune Planetary Atmosphere Characterization Experiment (SPACE) is a Cycle 30–31 *Hubble Space Telescope* program (GO 17192, 17414, PI: Kreidberg, Co-PI: Deming) that aims to study the planet atmospheres in eight exoplanetary systems. To mitigate the contamination of stellar activity and provide further insight into their connection with exoplanet atmospheres, I conduct multiyear photometry on the exoplanet hosts studied by the SPACE Program using the automated 24-inch telescope at Van Vleck Observatory. I create NewPORT, a customized photometry pipeline. With data at different wavelengths, I present a series of light curves and investigate the periodicity in the exoplanet host's brightness fluctuation. Long-term monitoring of exoplanet hosts may help constrain the spot structure, provide a statistical measure of stellar activity, or confirm no variability during the transit. Such knowledge could enhance the analysis of transmission spectra with greater detail and facilitate the characterization of planetary atmospheres.

"as for me, I am tormented with an everlasting itch for things remote."

—Herman Melville, *Moby-Dick; or, the Whale.*

Preface

In Rainer Maria Rilke's *Letters to the Young Poet,* he wrote, "Ask yourself in the most silent hour of your night: *must* I write? A work of art is good if it has arisen out of necessity. If one feels one could live without writing, then one shouldn't write at all." I attempt to be a young astronomer instead of a poet (most of the time), so the questions I ask myself are: *must* I look up at the stars? *Must* I process these data? *Must* I make these plots? And, *must* I write this thesis?

Let's face it, the answer is not always a solid yes. Much like my journey of studying astronomy, the process of writing this thesis went through a great amount of detours. In the darkest hour of my nights, I was so frightened by the mistakes I made, haunted by the chances I missed, and, to the utmost, ashamed by the fact that I might have not loved astronomy enough. Because if I did, why was it so hard for me to work on it? I hopelessly endured these long nights, before I made a painful realization: perhaps I could live a life without astronomy and graduate without this thesis, but from there on, every breath I take would be different. "A very, very important part of my soul would die."

I finally came to peace with myself, with my hope and my fear. It is okay that I don't love what I love one hundred percent all the time, and it doesn't make my love any faker or fainter. Because, after all, *love is love,* and if I dare say I *love* it, I am at my one hundred percent.

So, I wiped my tears and held onto it. I am relieved that I managed to finish this thesis, although I do want to warn potential readers who wish to continue, that this work is not of the quality I am satisfied with. I could have done a lot of things better than I did, but at this moment, I want to celebrate what I presently have.

I saw the previous quotation on the door to the rooftop observatory at Williams College. It is the most accurate depiction of astronomy to me. As long as I feel the itch, I will be tormented, willingly, forever.

"Power over sauce is power over all."

—Uday Narayanan

The author wishes to express his appreciation to Wesleyan University for the privileges of study accorded him at the Van Vleck Observatory.

—Thesis writers in the early years

I would like to thank my advisor Professor Seth Redfield. This work would not exist without your guidance and support. I am so fortunate to meet you and learn from you as your student. I am happy to say that I have grown so much in the past two years, not only as a researcher but also as a person. Thank you for making it happen.

Professor Ed Moran, your words gave me more hope than you could imagine. You lifted the imperfect student. You are always calming, caring, and spreading your everlasting passion for the things far, far away. He will miss being in your classroom and simply being around you.

I have said before that transferring to Wesleyan is the best decision in my life, particularly because of the cultivating environment at VVO. Thank you, Professor Wellons, Professor Hughes, Professor Kilgard, Stef, Azmain, Jonathan, Brianna, Alaina, Sara, Rewa, Lisseth, Katie, Cat, Kyle, Jamar, Owen, Elias, Caroline, Victoria, Junu, Carlos, Sofia, Max, Francesca, Aran, Aliya, and so many others. I cannot think of anything better than learning with and from all of you during this most wonderful and memorable period of my life.

To my fellow thesis writer Shuowen (Echo) Shen: I always believe that most people become friends because they happen to be, but we became friends because we *had* to be. Remember, we met under the great telescope's dome. For numerous reasons, you changed my life, and I'm nothing but heartfeltly grateful. Now, we both made it, and it is finally time for the champagne.

Uday Narayanan, you are the best, period. Thanks for being my greatest partner-in-crime. In astronomy and beyond, the connection we forged transcends my expectations for college friendship. We left marks on each other's lives, and I will forever cherish them. We've got to keep our dreams alive.

At last, I am forever indebted to my parents. Without your constant, unconditional love, I could not have arrived at where I am. Although there would never be any achievement in the world that is worth the time I lost with you, it is my tearful hope that this work brings it closer.

Contents

Chapter 1

Introduction

1.1 Overview of Exoplanet

Exoplanets, or, less and less commonly, extrasolar planets, refer to some objects orbiting stellar bodies other than the Sun. These objects' masses range from 0.02 Earth mass to 13 Jupiter masses (Wolszczan 1994; Lecavelier des Etangs & Lissauer 2022). Depending on the conditions, exoplanets can be rocky or gaseous. The detailed definition adopted by the International Astronomical Union (IAU) also ensures that exoplanets do not undergo thermonuclear fusion and are significantly less massive than their hosts (Lecavelier des Etangs & Lissauer 2022).

Since the first detection in the 1980s and 1990s, astronomers have been discovering new exoplanets with various methods (Seager & Lissauer 2010). The majority of exoplanets are discovered by the transit method, the phenomenon when an exoplanet passes by in front of its host star and temporarily dims its observed brightness. Other methods include observing the wobble of the host star in response to the planet's orbital movement, either by spectroscopically measuring the radial velocity or by astrometrically determining the star's position. In addition, exoplanets can also be discovered when it is directly imaged, when the system passes by a background star and undergoes gravitational microlensing, and in a number of other ways. In 2022, there was roughly one new exoplanet discovered every two days. According to the `exoplanet.eu` portal, there have been 5660 exoplanets discovered as of April 2024, among which 3903 ones are discovered through the transit method.

1.2 The Transit Method

An astronomical transit describes the phenomenon when a celestial body of interest passes in between another body and the observer. In the context of exoplanets, an exoplanet transit usually refers to the event in which the planetary object passes in front of a star and along the line of sight of the observer. Since the planetary object obstructs the star in part during the transit, changes in the star's flux can be observed.

There is a long list of facilities dedicated to discovering exoplanets with the transit method. Notable examples include the Trans-Atlantic Exoplanet Survey (TrES), the MEarth project, and the Wide Angle Search for Planets (WASP) from the ground, and the CoRoT satellite, the Kepler space telescope, and the Transiting Exoplanet Survey Satellite (TESS) in the space (Perryman 2011). Since photometry is relatively easy and there is an abundant amount of sufficiently bright stars, a lot of efforts are conducted on small telescopes with apertures of 0.4 m or even lower.

Using the transit method makes it possible to measure the planet's size, particularly, transit depth is given by (Perryman 2011)

$$\Delta F = \left(\frac{R_p}{R_\star}\right)^2, \tag{1.1}$$

while the transit probability is (Perryman 2011; Winn 2010)

$$p = \frac{R_\star \pm R_p}{a} \cdot \frac{1}{1 - e^2}. \tag{1.2}$$

1.3 Exoplanet Transmission Spectroscopy

If an exoplanet has an atmosphere, starlight goes through the atmosphere when the exoplanet is in transit. Since exoplanet atmospheres consist of various compositions of gases, absorption features are imprinted into the starlight during transits. Transmission spectroscopy aims to extract such information by taking observing exoplanet transits at different wavelengths.

The first successful exoplanet transmission spectroscopic studies are on hot Jupiters in the early 2000s because of their high transit depth, loose atoms, and hot and extended atmospheres. The examples include HD 209458 b and HD 189733 b. Since then, both space and ground efforts have been made. Astronomers are pushing the technique to apply to smaller planets, with rocky planets within the horizon with the next generation of telescopes.

1.3.1 SPACE Program

The Sub-Neptune Planetary Atmosphere Characterization Experiment (SPACE) is a large *Hubble Space Telescope (HST)* Cycle 30–31 program (GO 17192) under the HST-TESS Exoplanet Initiative (HTEI) (Kreidberg et al. 2022). The program combines UV stellar characterization and near-infrared transmission spectroscopy, seeking to answer open questions about how sub-Neptunes form and evolve. The program's targets span a physically-motivated grid, ranging from 2–3.5 $R_\oplus$ and 300–1400 K.

The program surveys eight targets with the Space Telescope Imaging Spectrograph (STIS) and Wide Field Camera 3 (WFC3), as detailed in Table 1.1.

	Planet	R_p [$R_\oplus$]	M_p [$M_\oplus$]	T_{eq} [K]	P_{orb} [day]
Cycle 30	HD 191939 b	3.4	9.3	810	8.88
	HD 86226 c	2.2	7.3	1304	3.98
	TOI-431 d	3.3	8.8	580	12.46
	TOI-561 c	2.9	5.4	810	10.80
	TOI-1201 b	2.4	6.3	703	2.49
Cycle 31	TOI-1759 b	3.1	8.3	320	18.80
	TOI-178 g	2.9	3.9	470	20.71
	TOI-1410 b	3.2	10.6	1181	1.22

Table 1.1: The SPACE Program Target Physical Properties

1.4 Stellar Activity

Contrary to the popular view, stars are not uniformly glowing fireballs that always show the same brightness. Stellar activity come in multiple forms, including star spots, faculae, and flares. They occur on different time scales and change the star's brightness by greatly different amounts, and exhibit different spectroscopic characteristics. For example, rotational features on the stars might show periodicity in cycles of tens of days. M-dwarfs are especially susceptible to variations, some with variations larger than 10%, but the effect extends to nearly all types of stars (Goulding et al. 2012).

1.5 Transit Light Source Effect

Exoplanet transmission spectroscopy is an act of a shadow play. The host star of the exoplanetary system serves as a light source, illuminating the atmosphere of the exoplanets we study, which, in turn, creates absorption features that can be extracted from spectroscopic observations of the system. In an ideal case, one would presume the "light source" to be constant and homogeneous. However, flares, starspots, faculae, and other rotational features on exoplanet hosts alter their fluxes. It is also worth noting that the later-type stars are preferred targets in exoplanet transmission spectroscopy because they yield a better signal-to-noise ratio given the same planet size, but they also have larger variations than early-type stars, as discussed above. Stellar variability negatively affects the accuracy of transmission spectroscopy and poses a challenge to combining data from multiple transits. This effect has been referred to as the transit light source effect (Rackham et al. 2018, 2019).

1.6 Photometric Monitoring

Photometric monitoring has been used by various groups studying exoplanets around active stars, including Demory et al. (2007), Pont et al. (2007, 2008, 2013), Henry & Winn (2008), Bentley et al. (2009), Dittmann et al. (2009), Rabus et al. (2009), Winn et al. (2010), Berta et al. (2011), Carter et al. (2011), Désert et al. (2011), Knutson et al. (2011), Sing et al. (2011), Narita et al. (2013), Nascimbeni et al. (2015), and Zellem et al. (2015).

Chapter 2

Observations

2.1 Objective and Setup

To detect and characterize potential stellar activity signals in the SPACE Program exoplanet hosts, a photometric monitoring campaign is carried out. As discussed in Section 1.4, stellar activity signals are present on different timescales. With starspots and faculae, the stellar surface is inhomogeneous. If the star's rotational period is longer than the timescale of the evolution of the inhomogeneity, it exhibits periodical flux changes. Although stellar flares also provide crucial information, they happen on a much shorter timescale of minutes and hours, thus requiring constant staring observation, which is impossible given that the program has eight targets and a limited telescope time. Therefore, the photometric monitoring campaign focuses on the stars' brightness variation caused by their rotation.

Table 2.1 outlines the estimated stellar variability information derived from TESS data by the SPACE Program. As discussed in Section 1.4, stellar activity is closely related to the spectral type of the star, Table 2.1 also includes such information, along with the effective temperature of the stars, as it provides more numerical and continuous information about the stars' position on the H-R diagram than the categorized spectral types. As the table shows, there are two

Star	Spec. Type	T_{eff} [K]	TESS Variability [ppm]	TESS Var. Period [d]
HD 191939	G8	5427	44	14
HD 86226	G2	5863	79	6.4
TOI-431	K3	4850	500	N/a
TOI-561	G9	5326	Not detected	Not detected
TOI-1201	M2	3476	6700	21
TOI-1759	M0	3930	N/a	N/a
TOI-178	K7	4316	N/a	N/a
TOI-1410	K4	4507	N/a	N/a

Table 2.1: Known Variability of the SPACE Program Host Stars (Credit: the SPACE Program)

M-dwarf hosts that are most likely to show a greater amount of stellar activities, and the TESS data confirms that TOI-1201 exhibits significant variability, which is also expected for the other M-dwarf, TOI-1759, albeit the lack of data coverage.

In line with the above information and general knowledge of stellar activities discussed in Section 1.4, rotational stellar variation is most significant on the timescale of days or tens of days. Therefore, photometric monitoring should occur on a daily basis for it to be adequate to recover the variability period and amplitude. Instead of conduction photometry on a single image, multiple frames, at least five, should be taken to improve the signal-to-noise ratio (SNR). Furthermore, M-dwarf should be given priority as they are more likely to produce large variations. Additionally, since the goal is to aid the SPACE Program in determining the potential influence of stellar variability on the transmission spectra, it is more important to obtain the stellar variation information around the SPACE Program's *HST* visits.

2.2 The Van Vleck Observatory 24-inch Telescope

To achieve the goal of daily photometric monitoring with the preference of M-dwarf targets and around *HST* visits outlined in the above section, a lot of telescope time is required every day. However, since the observation only involves photometry and the targets are relatively bright, a small telescope could suffice. A non-professional telescope that allows relatively unrestricted access is the best choice.

Fortunately, the Astronomy Department and Van Vleck Observatory (VVO) at Wesleyan University recently commissioned a new 24-inch telescope. The telescope, located on top of the attic of VVO, replaces the aging Perkin Telescope, serving multiple purposes in student research, public outreach, and class instruction.

Figure 2.1: The New Van Vleck Observatory 24-inch Telescope

2.2.1 Technical Specification

The new Van Vleck Observatory 24-inch Telescope is manufactured by PlaneWave Instruments. It has a 0.61-m primary mirror in PlaneWave's Corrected Dall-Kirkham (CDK) optical design. The telescope's focal length is 3974 mm, and the f-ratio is f/6.5. The telescope is mounted on a PlaneWave L600 direct drive altazimuth (alt-az) platform, allowing smooth and fast slews.

On the instrument side of the telescope, a PlaneWave focuser-rotator is installed because of the alt-az mount. A Perseus 4-port instrument selector connects to the focuser-rotator, allowing an easy switch between scientific imaging and eyepiece observing since the telescope also serves public outreach. The imaging capability is provided by an FLI filter wheel and an FLI Proline CCD42-40 camera mounted onto the main port on the instrument selector. The CCD detector has a 2K by 2K resolution and 13.5 μm pixel size, giving an approximately 23-arcsecond field of view and a 0.7 arcsecond per pixel scale. The filter wheel is currently equipped with $BVRI$ filters, a luminance filter, an H-α filter, and a clear channel.

The telescope is housed in a rotating dome, controlled by the Maestro software. The dome features a home sensor and is able to slew to any given azimuth or be "slaved" to the telescope's pointing. The dome has a sliding upper shutter and a lower shutter.

The new Van Vleck Observatory 24-inch Telescope has delivered successful exoplanet transit and minor planet occultation observations among many attempts (Pereira et al. 2023), as well as satisfying eyepiece viewing experiences.

2.3 Automation

As the goal of the photometric monitoring campaign is daily observations, the telescope has to be operated every day. It would be a huge amount of labor if the observation was carried out manually. Luckily, the telescope is featured with a suite of automation designs and is capable of unsupervised night-to-night running.

A crucial piece of hardware for an automated telescope running without supervision, or a robotic telescope, is a weather station. A Lunatico Astronomia weather station is installed on the roof of Van Vleck Observatory. It consists of an infrared cloud sensor, a rain sensor, an anemometer, and a brightness sensor. It also measures the ambient temperature and relative humidity, allowing the dew point to be determined.

The weather station feeds information to ACP[1], a remote observation software that controls the telescope, camera, and other peripheral equipment like the focuser-rotator. ACP offers the Scheduler, which works in tandem to perform dusk-to-dawn operations and observe planned targets. The workflow of the Scheduler can be outlined as:

1. Start up the telescope and instruments at dusk;
2. Open the dome;
3. Take dusk twilight flat frames;
4. Slew to an available target specified by a “plan;”
5. Take exposures according to the plan;

[1] https://acpx.dc3.com

6. Repeat 4. and 5. multiple times until dawn; (If targets run out, enter a "sleep." Exit the sleep if any target becomes available.)

7. Take dawn twilight flat frames (optional);

8. Close the dome;

9. Take bias and dark frames;

10. Shut down the telescope and instruments.

An observing plan contains information needed for ACP to carry out the observation. It usually includes RA/Dec coordinates of the target, numbers of images and exposure times in different filters, observing constraints (for example, a maximum airmass at which this target is to be observed), etc. Before I started working the project, Kyle McGregor played an important role in setting up the ACP plans for the SPACE Program targets. Figure 2.2 shows the ACP plan of HD 191939's target and *B*-band exposure setup pages. A complete list of the RA/Dec coordinates and exposure times of the SPACE Program targets in the ACP plans can be found in Table 2.2.

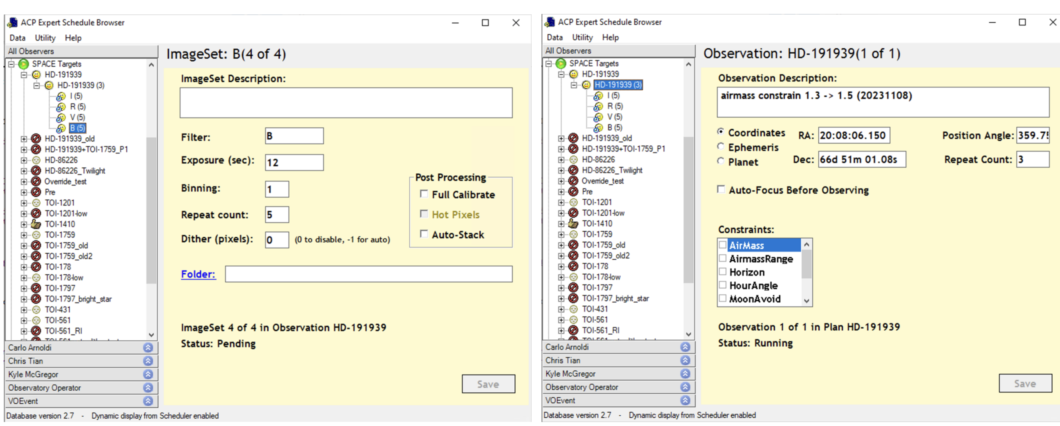

Figure 2.2: ACP Plan of the SPACE Program Target HD 191939

Target	RA	Dec	t_B [s]	t_V [s]	t_R [s]	t_I [s]
HD 191939	20h 08m 06s	+66° 51' 01"	12.0	5.0	2.0	2.5
HD 86226	20h 08m 06s	−24° 05' 57"	6.0	5.0	2.0	1.5
TOI-431	05h 33m 05s	−26° 43' 26"	10.0	10.0	5.0	5.0
TOI-561	09h 52m 44s	+06° 12' 58"	10.0	10.0	8.0	7.0
TOI-1201	02h 48m 59s	−14° 32' 14"	15.0	15.0	8.0	8.0
TOI-1759	21h 47m 24s	+62° 45' 14"	40.0	30.0	15.0	10.0
TOI-178	00h 29m 12s	−30° 27' 15"	60.0	50.0	40.0	30.0
TOI-1410	22h 19m 32s	+42° 33' 37"	110.0	38.0	15.0	13.0

Table 2.2: RA/Dec Coordinates and Exposure Times of the SPACE Program Targets

2.4 Operation Summary

Since the project is ongoing, data is actively being taken every night. Existing observations up to April 2024, with *HST* visit times, are shown in Figure 2.3.

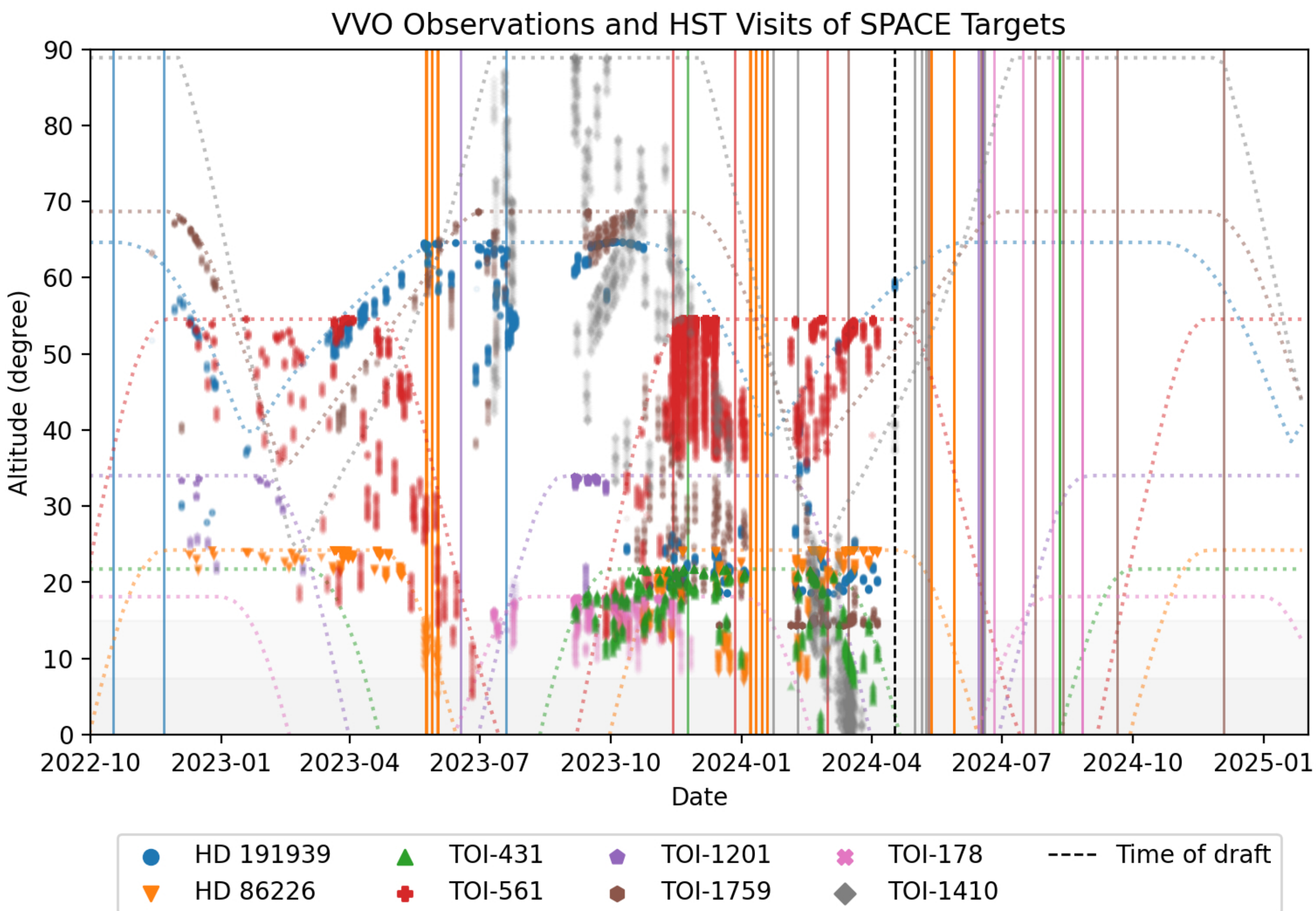

Figure 2.3: Archived observations of the SPACE Program targets (markers), nightly maximum altitude envelopes (dotted lines), and times of *HST* visits (vertical stripes).

Chapter 3

Data Reduction with NewPORT

Observation is only the first step of photometric monitoring. The images taken with the telescope and camera undergo a rigorous procedure of calibration, measurement, and visualization before they turn into meaningful photometry data that can be interpreted. This process of processing scientific is generally referred to as data reduction.

The key goal of the data reduction of the photometric monitoring campaign is self-evidently photometry. Traditionally, astronomers rely on general-purpose software packages to conduct photometry. Examples of these softwares include *IRAF* (Tody 1986, 1993), *DAOPHOT* (Stetson 1987), *DoPHOT* (Schechter et al. 1993), etc. The exoplanet community prefers *AstroImageJ* because of its numerous features that are useful for reducing transit observations (Collins et al. 2017). Large astronomy missions usually make an effort to write data reduction pipelines specific to their programs, like the TESS Science Processing Operations Center (SPOC) pipeline of the *TESS* mission (Jenkins et al. 2016). It is also common for individual researchers to create their own data reduction software tailored to their needs. Relevant examples are *eleanor* (Feinstein et al. 2019), *lightkurve* (Lightkurve Collaboration et al. 2018), and *prose* (Garcia et al. 2022). Notably, these software usually integrate appealing features, like data detrending and fancy visualizations, making data reduction easier and sparing users the need to switch between various tools.

After an initial period of reducing data with *AstroImageJ*, I determine that it is not sufficient for the photometric monitoring campaign. The key issue is that *AstroImageJ* cannot be easily automated. The campaign is carefully designed to utilize the automatic nature of the telescope to maximize efficiency, considering the fact that no single person can manually process eight targets' data every day. A data reduction software that is not automated undoes the advantage of automated observation.

In this chapter, I present the workflow of a customized data reduction pipeline I created for daily photometric data from an automated telescope, the New Pipeline for Optical Robotic Telescopes (NewPORT)[1]. The pipeline is written in Python and heavily relies on Astropy (Astropy Collaboration et al. 2013, 2018, 2022).

3.1 Plate Solving

After the images taken by the telescope are transferred into data storage with another customized script[2], the first task performed on these images is plate solving. Plate solving refers to astrometrically resolving the images, that is, finding out the pointing of the telescope when the image is taken through astrometrical means. In other words, the process is to map pixel coordinates to sky coordinates, so that it can be known the star located on pixel $(1023, 1025)$ is in fact located at (α = 20h 08m 06s, δ = +66° 51' 01") on the sky, and therefore it is also known with certainty that the star is HD 191939. Plate solving programs achieve that by comparing the topographic relations of groups of stars in the image to the position of the stars in the archive. In simpler words, if three stars form a triangle, the

[1] `https://github.com/qiushitian/newport`
[2] `https://github.com/qiushitian/schcopy`

size, portion, and direction of the triangle allow the programs to determine which three stars they are.

Plate solving in the NewPORT procedure serves a dual purpose. Performing photometry relies on the sky coordinates on the images, as explained in Section 3.3. Plate solving also filters out images of bad quality, such as an image taken through clouds that do not have enough stars, as those images are not possible to be plate solved.

NewPORT's plate solving function relies on ASTAP, the Astrometric STAcking Program[3], which uses *Gaia* mission data as the archival positions of stars (Gaia Collaboration et al. 2016, 2023). Compared with the most popular plate solving service `Astrometry.net`, ASTAP can run entirely locally. For a photometric observing campaign that deals with tens of thousands of images, running locally saves a considerable amount of time simply by avoiding uploading those files.

A command line version of ASTAP is called through the Python environment in which NewPORT runs. If the plate solving is successful, ASTAP outputs a .ini file that contains the astrometric mapping of the image, which is then interpreted by NewPORT as an World Coordinate System (WCS) object in Astropy and integrated with the original image. As mentioned above, images that do not yield plate solving results by ASTAP are disregarded. An exemplar .ini file is shown in Figure 3.1.

[3] `https://www.hnsky.org/astap`

```
PLTSOLVD=T
CRPIX1= 1.0745000000000000E+003
CRPIX2= 1.0265000000000000E+003
CRVAL1= 4.2247621644205338E+001
CRVAL2=-1.4535538524898604E+001
CDELT1=-1.9425619741979665E-004
CDELT2= 1.9455938185636949E-004
CROTA1= 1.7992924379044280E+002
CROTA2= 1.7989825352654216E+002
CD1_1= 1.9425604929468646E-004
CD1_2=-3.4550050188567150E-007
CD2_1=-2.3989251626627792E-007
CD2_2=-1.9455907508449918E-004
CMDLINE=[executable_path] -f [input_path] -o [output_path] -ra 2.8165138888888888 -spd 75.46272222222223
DIMENSIONS=2148 x 2052

```

Figure 3.1: A .ini File

3.2 Bias, Dark, and Flat Calibration

Images taken with scientific astronomy cameras usually undergo bias subtraction, dark current subtraction, and flat-field correction. These calibrations ensure the image is free from systematic noise patterns.

NewPORT performs bias, dark, and flat calibrations with Astropy's `ccdproc` package (Craig et al. 2017).

3.2.1 Creating Master Calibration Frames

More than one bias, dark, and flat frames each are usually taken during an observing night to reduce random noise, sky imperfection, and star contamination in flat frames. NewPORT combines the multiple bias, dark, and flat frames into master bias, dark, and flat frames with the `ccdproc.combine` method. The method's integrated sigma-clipping algorithm is used to filter out outlying values, with the clipping threshold set to five times the standard deviation from the median value on either side. A comparison view of a single raw bias frame and a master bias frame made by combining 30 frames is shown in Figure 3.2.

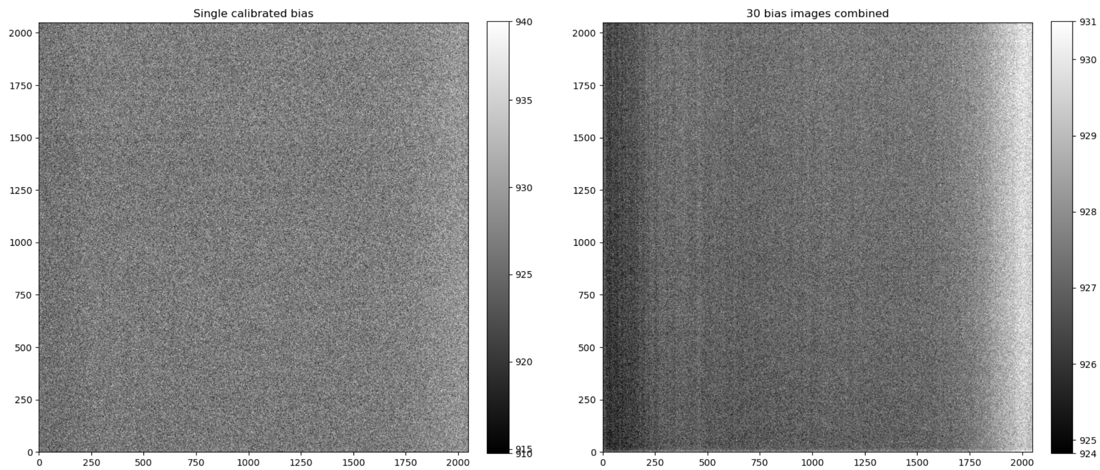

Figure 3.2: Single and Master Bias Frames

3.2.2 Calibration Science Frames with Master Calibration Frames

After a science frame's WCS object is integrated with the original image, NewPORT uses `ccdproc`'s `subtract_bias`, `subtract_dark`, and `flat_correct` methods to calibrate the science image with the master bias, dark, and flat frames.

At the stage of the draft of this thesis, bias, dark, and flat calibration is not performed on the data from the photometric monitoring campaign. In the earlier stage of the photometric monitoring campaign, calibration frames are not consistently taken. NewPORT has the capability to carry out bias, dark, and flat calibration.

3.3 Aperture Photometry

Aperture photometry is realized with the help of Astropy's `photutils` package (Bradley et al. 2023). After the science image is calibrated, NewPORT performs aperture photometry with a preset list of RA/Dec coordinates of the target and comparison stars, specific to each SPACE Program target. Figure 3.3 is the aperture list file for HD 86226.

```
#Dec in decimal or sexagesimal DEGREES
#Ref Star=0,1,missing (0=target star, 1=ref star, missing->first ap=target, others=ref)
#Centroid=0,1,missing (0=do not centroid, 1=centroid, missing=centroid)
#Apparent Magnitude or missing (value = apparent magnitude, or value > 99 or missing = no mag info)
#Add one comma separated line per aperture in the following format:
#RA, Dec, Ref Star, Centroid, Magnitude
09:56:29.591, -24:05:57.11, 0, 1, 99.999
09:55:56.308, -24:03:07.38, 1, 1, 99.999
09:56:01.472, -24:01:30.67, 1, 1, 99.999
09:56:19.900, -23:59:36.90, 1, 1, 99.999
09:56:42.442, -24:01:56.40, 1, 1, 99.999
09:56:45.595, -24:01:43.57, 1, 1, 99.999
09:56:34.385, -24:14:16.00, 1, 1, 99.999
09:56:41.802, -24:11:28.35, 1, 1, 99.999
09:56:40.865, -24:16:51.87, 1, 1, 99.999
09:56:27.900, -24:16:24.81, 1, 1, 99.999
09:55:52.932, -24:06:31.41, 1, 1, 99.999
09:55:53.009, -24:08:35.90, 1, 1, 99.999
09:55:45.377, -24:09:35.98, 1, 1, 99.999
09:56:06.109, -24:08:52.08, 1, 1, 99.999
09:57:15.357, -24:07:17.67, 1, 1, 99.999
09:57:08.754, -24:07:22.43, 1, 1, 99.999
09:57:00.795, -23:59:48.25, 1, 1, 99.999
```

Figure 3.3: Photometry Apertures for HD 86226

The coordinates in the aperture list file are first interpreted as Astropy's `Angle` objects, which then are used to create `SkyCoord` objects, and eventually `photutils`'s `SkyCircularAperture` and `SkyCircularAnnulus` objects, which are ready to be placed on a science frame. A science frame of HD 86226 with apertures listed in Figure 3.3 is shown in Figure 3.4.

The photometry apertures' positions are fine-tuned with the actual position of the star within the aperture in a process called centroiding. The graphical center of the star, the centroid, is found with the `photutils`'s `ApertureStats.centroid`

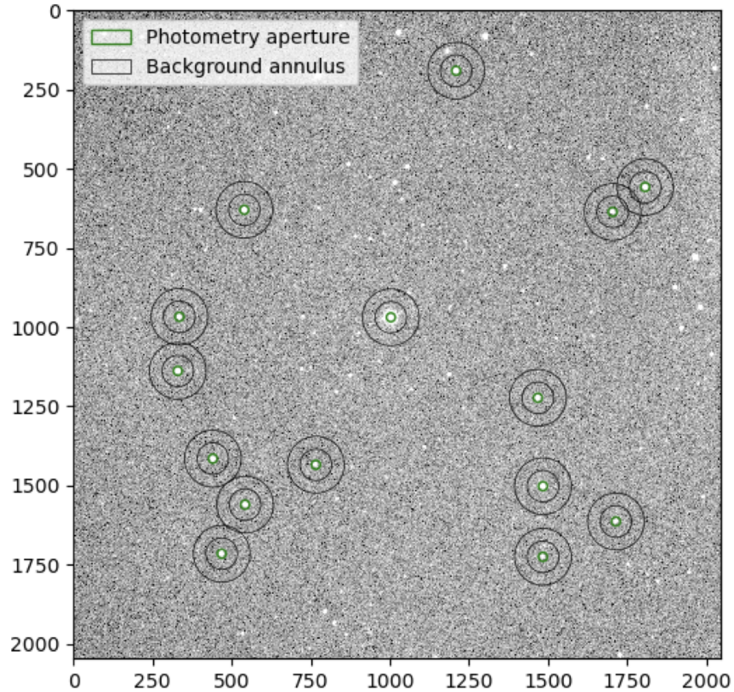

Figure 3.4: HD 86226 Science Frame with Photometry Apertures

method, replacing the original aperture position based on each frame. Then, the brightness of the star and the background are measured respectively, by summing up the pixel values within the circular apertures and annuli. The photometry result is obtained by subtracting the background from the stars' measured fluxes. Finally, NewPORT checks for saturation by discarding frames with any pixel value greater than 64000 ADU in an aperture. The number is determined based on the maximum value of the 16-bit CCD camera can record 65535 ADU and an average background level of around 1500 ADU. In this way, only photometry results from frames without any saturated star are kept in the final output.

3.4 Data Visualization

A few basic tools that make the photometric monitoring campaign's data easier to interpret and analyze are integrated into NewPORT.

3.4.1 Light Curve Plotting

NewPORT uses matplotlib's `pyplot` package to render scientific plots. A light curve is photometry data plotted against time, showcasing brightness changes at over time. Therefore, it is the best way to present photometric monitoring data.

3.4.2 Binning

As explained in Section 2.1, at least five frames of each target are taken on an observing night when the target is observed. To achieve the effect of improving SNR, data from different frames should be combined. Therefore, when producing a light curve with a multiple-day view, NewPORT takes the arithmetic mean of the photometric results of a given band from a given observing night, and reports the mean value as the photometry result of the observing night. The original unbinned data are also preserved.

3.4.3 Lomb–Scargle Periodogram

A periodogram is an illustrative way to identify periodic signals hidden in the data. NewPORT utilizes the `LombScargle` class in Astropy to produce Lomb–Scargle periodograms (VanderPlas & Ivezić 2015).

Chapter 4

Results and Analyses

The SPACE Program studies eight exoplanets, and here I present the photometric monitoring results of TOI-1201.

TOI-1201 is an M-dwarf and the latest-type host among the SAPCE Program targets, so a certain level of stellar activity is expected. Figures 4.1–5 are light curves of TOI-1201. Figure 4.6 shows the Lomb–Scargle periodogram of TOI-1201's V-band photometry.

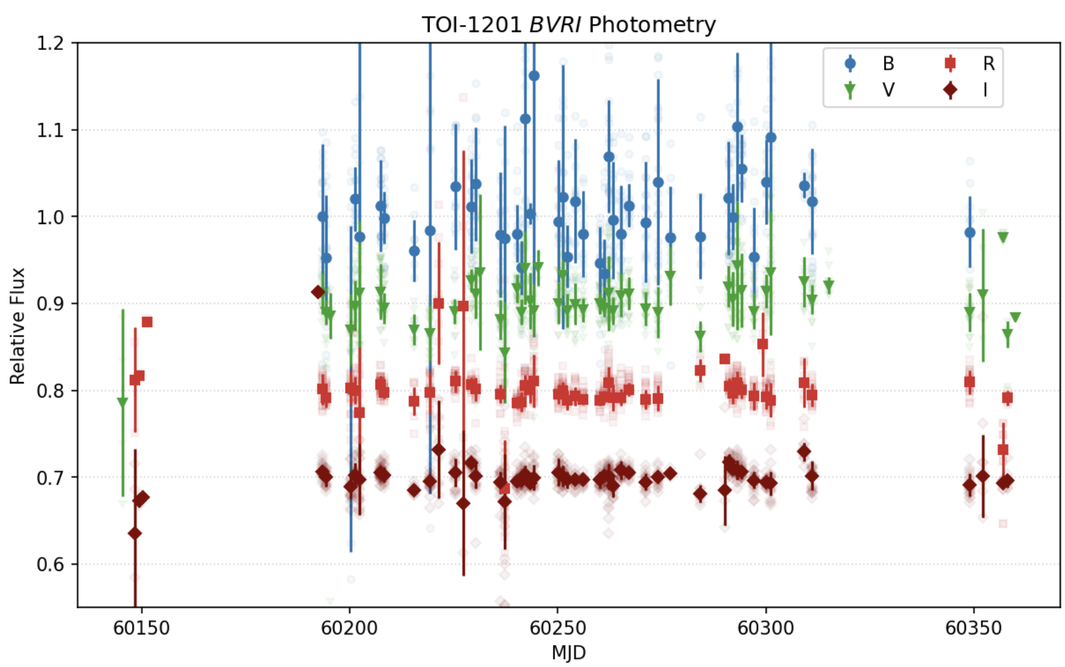

Figure 4.1: TOI-1201 *BVRI*-band Light Curve

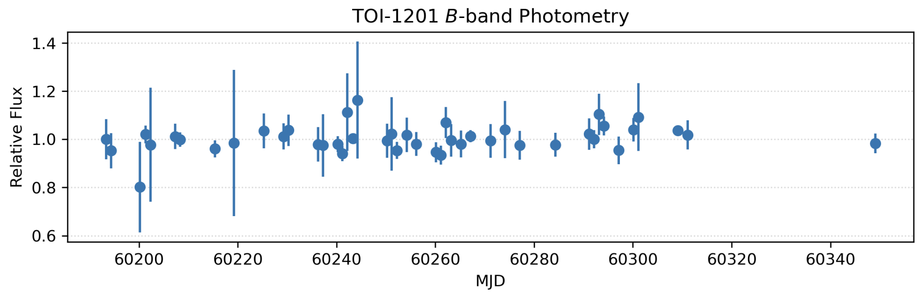

Figure 4.2: TOI-1201 *B*-band Light Curve

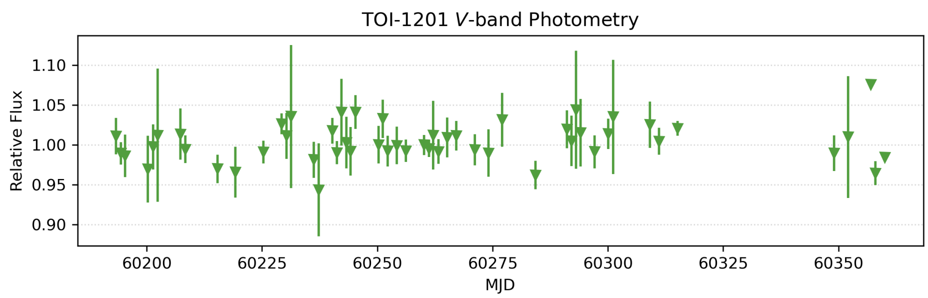

Figure 4.3: TOI-1201 *V*-band Light Curve

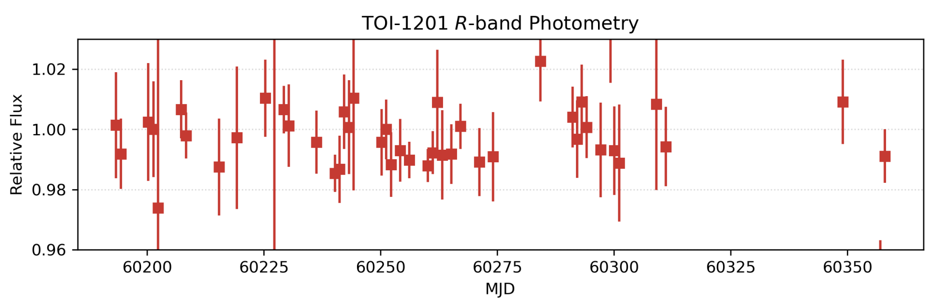

Figure 4.4: TOI-1201 *R*-band Light Curve

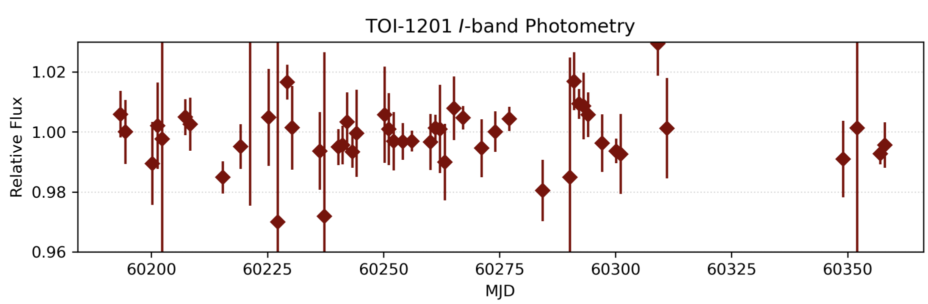

Figure 4.5: TOI-1201 *I*-band Light Curve

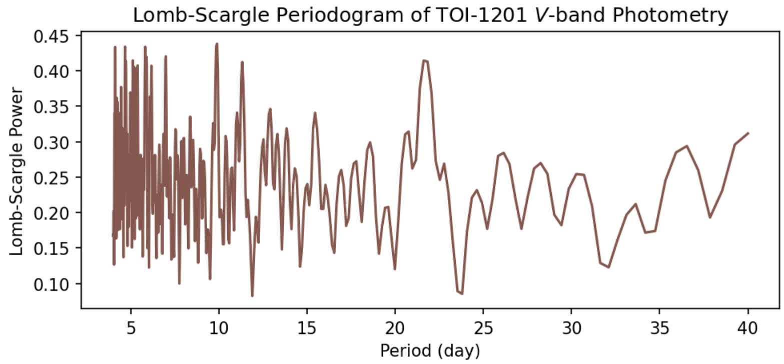

Figure 4.6: TOI-1201 V-band Lomb–Scargle Periodogram

The light curves demonstrate that the campaign is capable of monitoring the host star's brightness at the precision of a few percent over months at four different bands, which is useful for revealing stellar variation, using tools like the Lomb–Scargle periodogram.

Chapter 5

Summary

To counter the transit light source effect and the potential issue of combining spectra when the host star's flux varies, I conduct a photometric monitoring project to support the SPACE Program (Kreidberg et al. 2022). I observe the SPACE targets with the automated 24-inch telescope at Van Vleck Observatory and obtain $BVRI$-band photometry. I create the customized data reduction pipeline NewPORT, powered by ASTAP and Astropy, which performs astrometric plate solving and aperture photometry. I demonstrate the ability to find the star's rotational period by producing the Lomb–Scargle periodogram.

In the future, there is great potential for improvements and developments in the instrument, observation method, NewPORT, and data analysis techniques, including spot modeling and Gaussian processes. With more precise and accurate photometry, it is possible to determine the SPACE Program target's rotation, flux, and color changes, and shed light on their impact on the transmission spectra.

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This work makes use of ASTAP, Astropy and its affiliated packages `astroplan`, `ccdproc`, and `photutils`, matplotlib, NumPy, and CPython. This work has also made use of data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

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