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The Visual Survey Group: A Decade of Hunting Exoplanets and Unusual Stellar Events with Space-based Telescopes

Martti H. K. Kristiansen[1], Saul A. Rappaport[2], Andrew M. Vanderburg[2], Thomas L. Jacobs[3], Hans Martin Schwengeler[4], Robert Gagliano[5], Ivan A. Terentev[6], Daryll M. LaCourse[7], Mark R. Omohundro[4], Allan R. Schmitt[8], Brian P. Powell[9], and Veselin B. Kostov[9,10,11]

[1] Brorfelde Observatory, Observator Gyldenkernes Vej 7, DK-4340 Tølløse, Denmark; martti@outinto.space, marki@holb.dk
[2] Department of Physics, and Kavli Institute for Astrophysics and Space Research, M.I.T., Cambridge, MA 02139, USA
[3] Amateur Astronomer, 12812 SE 69th Place, Bellevue, WA 98006, USA
[4] Citizen scientist, c/o Zooniverse, Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK
[5] Amateur Astronomer, Glendale, AZ, USA
[6] Citizen Scientist, Petrozavodsk, Russia
[7] Amateur Astronomer, 7507 52nd Pl NE, Marysville, WA 98270, USA
[8] Citizen Scientist, 616 W. 53rd. St., Apt. 101, Minneapolis, MN 55419, USA
[9] NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA
[10] SETI Institute, 189 Bernardo Ave, Suite 200, Mountain View, CA 94043, USA
[11] GSFC Sellers Exoplanet Environments Collaboration
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Abstract

This article presents the history of the Visual Survey Group (VSG)—a Professional-Amateur (Pro-Am) collaboration within the field of astronomy working on data from several space missions (Kepler, K2 and Transiting Exoplanet Survey Satellite). This paper covers the formation of the VSG, its survey-methods including the most common tools used and its discoveries made over the past decade. So far, the group has visually surveyed nearly 10 million light curves and authored 69 peer-reviewed papers which mainly focus on exoplanets and discoveries involving multistellar systems. The preferred manual search-method carried out by the VSG has revealed its strength by detecting numerous objects which were overlooked or discarded by automated search programs, uncovering some of the most rare stars in our galaxy, and leading to several serendipitous discoveries of unprecedented astrophysical phenomena. The main purpose of the VSG is to assist in the exploration of our local universe, and we therefore advocate continued crowd-sourced examination of time-domain data sets, and invite other research teams to reach out in order to establish collaborating projects.

Unified Astronomy Thesaurus concepts: Exoplanet detection methods (489); Exoplanets (498); Transit photometry (1709); Astronomy data visualization (1968); History of astronomy (1868); Amateur astronomy (35); Eclipsing binary stars (444); Multiple stars (1081); Stellar phenomena (1619); Young stellar objects (1834)

1. Introduction

The field of astronomy has a long history of collaboration between professional and amateur astronomers dating back centuries (see e.g., Boyd 2011; Lintott 2020). In recent times, largescale projects such as MilkyWay@Home (Newberg et al. 2013), SETI@home (Anderson et al. 2000), Stardust@home (Westphal et al. 2005) and Galaxy Zoo (Lintott et al. 2008) became widespread, counting millions of participant volunteers to date. The popularity of Galaxy Zoo evolved into the citizen science platform Zooniverse which at the time of writing has 2.455.914 registered users alone.[12] One particular project from this platform, Planet Hunters (PH, Fischer et al. 2012), was created on 2010 December 16 alongside the launch of the Kepler spacecraft and its wonderful photometric data stream (Koch et al. 2010). In the PH-project, citizen scientists were given an optional tutorial and shown light curves in which they were asked to identify exoplanetary transits (Lintott et al. 2013). This effort was intended to serve as an aid to the Transiting Planet Search algorithm developed by the Kepler team (TPS, Jenkins et al. 2010a, 2010b). Initially, in order for a suspected Planet Candidate (PC) to be upgraded to a Threshold Crossing Event (TCE), the TPS-algorithm needed at least three consistent transits with a statistical significance $\geqslant 7.1\sigma$ (Jenkins et al. 2002). Consequently, these criteria left a large portion of parameter space initially unexplored, but at the same time, an open door for focused visual surveying by citizen scientists. Those collective efforts quickly proved to be particularly effective with respect to the dearth of long-period exoplanet

[12] https://www.zooniverse.org/

detections, the improvement of which betters the census of planet occurrence rates.[13] In the primary Kepler mission (Borucki et al. 2010), few long-period exoplanets (i.e., planets with <3 transits) were identified by professional astronomers (see e.g., Batalha et al. 2013; Foreman-Mackey et al. 2016; Uehara et al. 2016; Schmitt et al. 2017). Similar circumstances emerged for the K2-mission (Howell et al. 2014). Although the presence of more single transits was expected for K2, due to its 80-day observation campaigns, few were detected (see e.g., Osborn et al. 2016). In the Transiting Exoplanet Survey Satellite mission (TESS, Ricker et al. 2014), the estimated single transit harvest exceeds that of K2 (Cooke et al. 2018; Villanueva et al. 2019), partly due to even shorter observation intervals (≈27 days).

In this paper, we describe the efforts of a Professional-Amateur (Pro-Am) collaboration called the Visual Survey Group (VSG) with the goal of searching for long-period planets and other unusual astrophysical phenomena. Even though astronomers have developed new methods (e.g., Cui et al. 2021; Olmschenk et al. 2021; Osborn 2021), the hunt for single transits is time consuming and incomplete. Visual surveying therefore continues to be a viable detection method for these signals. Moreover, some of the new automated methods designed to detect irregular light curve features (The Weird Detector, Wheeler & Kipping 2019) and exocomets (Kennedy et al. 2019) were inspired by discoveries made by the VSG. Therefore, in spite of significant advances in automated search approaches over the last decade, the pattern recognition ability of the human mind and the steadfast participation of amateurs is far from being rendered a useless or frivolous endeavor.

In this work, we describe the history of the VSG (Section 2), while Section 3 covers the manual and visual search approach primarily undertaken by the VSG and tools used. Section 4 discusses the scientific discoveries made by the VSG which among others consist of exoplanets, light curve anomalies which have turned out to be all manner of dusty occultations, including exocomets, and eclipsing binaries which we have found to be part of triply eclipsing triples, and higher-order stellar systems. In Section 5 we carry out a discussion and our conclusion.

2. The Visual Survey Group

The Visual Survey Group (hereafter, VSG) consists of seven citizen scientists (TLJ, RG, MRO, DML, IAT, HMS and MHK) from four countries (USA, Russia, Switzerland and Denmark). Their professions (or former employment in the case of retirement) range over the fields of business, medicine, programming, aerospace engineering, information technology, mathematics and astronomy. Three group members are formally retired. In addition, two professional astronomers situated at the Massachusetts Institute of Technology (MIT; SAR and AV) and two at NASA's Goddard Space Flight Center (NASA GSFC; BPP and VBK) complete the VSG-collaboration.

The establishment of the VSG is outlined in the following subsection but for the purpose of historical record-keeping, we here mention three individuals who no longer are affiliated with the VSG but nonetheless made important contributions in the earlier stages: Troy Winarski, Alexander Venner and Kian J. Jek (see references in Section 4 and Venner et al. 2021). Kian J. Jek received the American Astronomical Society Chambliss Amateur Achievement Award in 2012 which also was awarded to a VSG-member (DML) in 2016.[14]

2.1. Common Grounds

All members met on the Zooniverse platform at the now defunct, original Planet Hunters project led by Yale University between 2010 and 2013. For each individual, the exact pathway toward the VSG-collaboration varies and is therefore summarized in a timeline in Figure 1. At the outset, the hunt for exoplanets was done using ingested data from the Kepler mission (Borucki et al. 2010), which were shown in light curve snips (light curves from single Kepler-Quarters were divided in smaller portions) followed by the question: "Does the star have any transit features?" (Figure 1, Lintott et al. 2013). Subsequently, the users could either continue to the next classification or get involved in a discussion concerning the most recently classified star ("Talk-section"). The Talk-section connected the VSG-members and was also heavily used by other so-called "superusers" (see Section 2 in Schwamb et al. 2013).

By the time of Kepler's repurposed two-wheel mission, K2 (Howell et al. 2014), the PH-website was redesigned. It was during the K2-revival that AV joined PH as an official Science Team member and TLJ, DML and MHK made contact with SAR on a more informal basis. All seven citizen scientists made the transition to the new PH-website, however a lack of certain improvements of the interface backend, specifically common to how potential targets of interest were tracked, tallied and subsequently analyzed, resulted in this being a limited visit for some individuals (first TLJ, DML and later MHK). This said, connections to the PH-science team were maintained, and some of the VSG-members were engaged in public outreach (see e.g., the PH-science team's Reddit science "Ask me anything,"[15] PH-interviews[16] and earlier PH-blog posts[17]).

[13] https://blog.planethunters.org/2014/09/11/planet-occurrence-rates-2/

[14] https://aas.org/grants-and-prizes/chambliss-amateur-achievement-award

[15] https://www.reddit.com/r/science/comments/3ebavu/science_ama_series_were_the_planet_hunters_team/

[16] https://blog.planethunters.org/2018/01/07/without-planet-hunters-none-of-the-subsequent-discoveries-would-have-been-possible/

[17] https://blog.planethunters.org/2011/12/

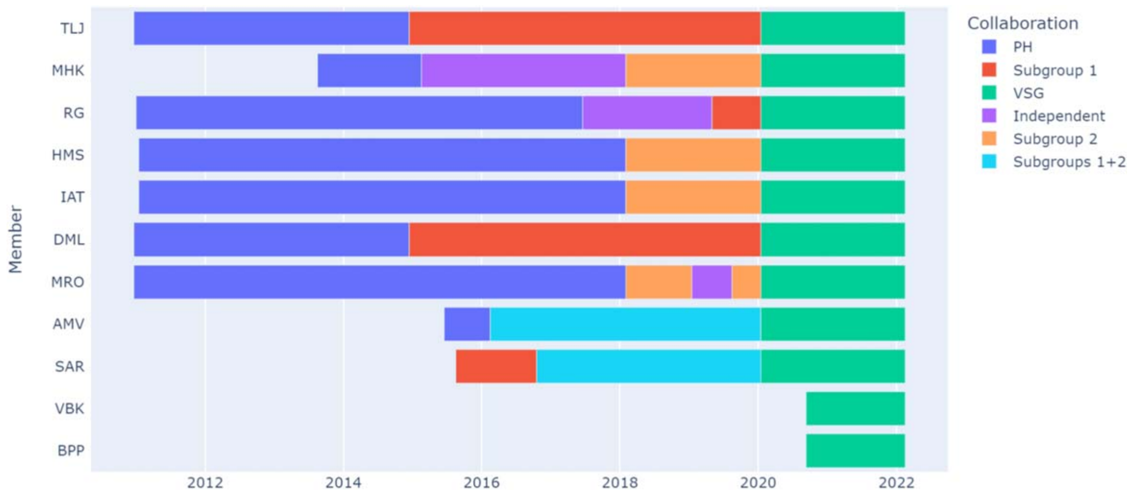

Figure 1. Timeline of the individual members. The different collaborations include Planet Hunters (PH, blue), Subgroup 1 and 2 (red, orange and cyan), independent activities (purple) all leading toward the VSG-collaboration (VSG, green).

Meanwhile, a new Zooniverse project arose which also dealt with data from K2, the Exoplanet Explorers[18] (Christiansen et al. 2018), and later a third project, Planet Hunters TESS[19] (Eisner et al. 2020) working on TESS-data. From the VSG, HMS and IAT participated in both projects.

Instead of running several parallel surveys of similar nature, the subteams joined forces in 2020 January and once again found common ground. In doing so, the workflow was streamlined in both light curve surveying and vetting. Two years later, in 2022 January, BPP and VBK formally joined the VSG, adding two more professional colleagues to the collaboration which had begun in 2020 September.

3. Approach, Tools and Data

The VSG operates on Linux, Macintosh, and Windows systems. The primary approach has since the beginning been visual and manual surveying, which still has many advantages compared to state-of-the-art computer software. All communications about potential discoveries are made within a day via e-mail contact to all members. When members find potentially interesting new objects they are immediately shared among the entire VSG via e-mail. Discussions about the viability of each discovery is then continued via a continuous e-mail stream.

3.1. The LcTools Approach

Since 2012, the VSG-members have worked closely with the `LcTools` project (Kipping et al. 2015; Schmitt et al. 2019; Schmitt & Vanderburg 2021) whose purpose is to provide citizen scientists, students, and universities worldwide with custom applications, data, and consulting services for viewing and analyzing light curves from NASA space missions. Based on their research needs and objectives, the VSG members have contributed many ideas for improvement in the product and have assisted in testing the product prior to public release.

`LcTools` has revolutionized visual surveying of stellar light curves. Since becoming available in 2012, the product has been gradually upgraded with sophisticated packages such as `VARTOOLS` (Hartman 2012). However, its manual and visual features should undoubtedly be credited with the underlying success of the VSG. This Windows-based software allows its users to efficiently scan light curves in a matter of seconds. For instance, upon release of a K2-campaign consisting of ≈20,000 light curves, a VSG-member could normally survey the entire data set within a day.

`LcTools` provides many user-friendly custom-designed features, some not found in any other publicly available product. These include, but not limited to (1) a near instantaneous display of light curves using a simple one-button click to rapidly scan through a large list of light curve files in a directory, (2) optimized light curve presentation to facilitate the visual detection of signals, (3) fast and efficient light curve navigation operations such as panning and zooming, (4) real-time tracking of time and flux at the cursor, (5) ability to measure signals and time/flux intervals using the mouse, (6) display of mission-based and community-based signals such as TCEs, Kepler Objects of Interest (KOIs), K2 Objects of Interest (K2OIs), Community TESS Objects of Interest (CTOIs) and TESS Objects of Interest (TOIs) to avoid known signals being re-discovered, (7) automatic detection of periodic signals and single events using the QuickFind and Box Least Squares (BLS) signal detection methods, (8) recording and display of user defined signals, (9) ability to phase-fold periodic signals over different time domains, (10) manual detrending of light

[18] https://www.zooniverse.org/projects/ianc2/exoplanet-explorers/
[19] https://www.zooniverse.org/projects/nora-dot-eisner/planet-hunters-tess

Table 1
Overview of Data Sources and the Number of Light Curves Manually Surveyed by the VSG

Data Source	Quarter/Campaign/Sector	Light Curves
Kepler	Q1-17	181,300
K2 SFF	ET—C19	421,600
TIC CTL	S1-48	907,200
QLP	S2-3, S13, S17-21, S16-27	5,914,000
OELKER	S1-5	543,300
CDIPS	S6-13	67,200
PATHOS	S4-14	31,800
SPOC	S22, S30	31,200
TICA	S35	2,200
GSFC	S1-40	1,573,000
Total		9,672,800

Note. Entries do not correspond to unique stars due to overlaps between data sources and missions.

curves based on easy-to-use flattening levels, (11) display of the host star properties for a light curve, (12) creation of signal based property reports in Excel, (13) building of light curve files (individually or bulk) for the Kepler, K2 and TESS missions and associated High Level Science Products (HLSPs) using the source data from the Mikulski Archive for Space Telescopes (MAST).[20]

At present, light curve files are obtained in a .txt-format from the `LcTools` website[21] if available or built using the LcGenerator application in `LcTools`. Otherwise, data are directly obtained at the source (see Table 1). Most of the discoveries made by the VSG (Section 4) were initially flagged using the LcViewer application in `LcTools`. Figure 2 shows the Quick Look Pipeline (QLP) light curve for TIC 123738465 in LcViewer and the accompanying user interface for finding signals automatically using the QuickFind signal detection method.

3.2. Additional Survey Tools

During the Kepler mission (Borucki et al. 2010), and prior to the first release of `LcTools`, the seven citizen scientists primarily made use of the PH-interface for light curve classification and the MAST for data acquisition. This was accompanied by services such as Tool for OPerations on Catalogues And Tables (`TOPCAT`, Taylor 2011) and `Fv` (Pence & Chai 2012) used for light curve files and Target Pixel Files (TPFs), the SkyView Query Form[22] to identify the stellar vicinity of a target star, and the Amateur Kepler Observer (`AKO`, T. Winarski 2012, private software) to search for Transit Timing Variations (TTVs), i.e., in order to produce "Winarski-plots" which now are commonly known as river-plots (see e.g., Figure 4 in Agol & Fabrycky 2018).

In the K2-era (Howell et al. 2014), VSG also made use of `VESPA` to statistically validate transiting exoplanets (Morton 2015), and `Kadenza` (Barentsen & Cardoso 2018) in order to obtain raw cadence pixel files for quick-views of targets of interest, and other light curve extraction software for operating TPFs (`PyKE`, Still & Barclay 2012; `AKO-TPF`, (T. Winarski 2012, private software)). The latter is comparable to the interactive features of `Lightkurve` (Lightkurve Collaboration et al. 2018), which now is a standard ingredient in the VSG-vetting process for TESS data. In the VSG, `Lightkurve` is mostly used to look for contamination, e.g., EBs mimicking PCs, and Solar System Objects (SSOs) mimicking PCs or stellar flares/outbursts. These SSOs are identified using the Sky Body Tracker (`SkyBoT`, Berthier et al. 2006, 2016). Furthermore, `Lightkurve` has been proven extremely useful when assessing hierarchical eclipsing candidates due to the large pixel size (21″) of TESS as illustrated in Figure 3. During the TESS-mission, TPFs have also been obtained using `TESScut`[23] (Brasseur et al. 2019).

Information concerning stellar parameters can be found at the Exoplanet Follow-up Observing Program (ExoFOP),[24] the Gaia-collaboration[25] (Gaia Collaboration et al. 2016; Brown et al. 2021), the Aladin Lite finding charts at Swarthmore,[26] the MAST or at databases operated by the Strasbourg astronomical Data Center (CDS)[27]—SIMBAD (Wenger et al. 2000) and ViZieR (Genova et al. 2000). In addition, while evaluating dipper candidates (Section 4.4), the online search engine[28] of the Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010) is used to search for IR-excess. Moreover, custom programs written in python, C, Fortran, and JavaScript languages have been created by the VSG over the years.

In addition to this work, the analysis, expertise and guidance from the members at MIT and NASA help ensure the prospects of follow-up observations at suitable facilities. Follow-up also includes searching for archival photometry at the Digital Access to a Sky Century @ Harvard (DASCH, Grindlay et al. 2009), the All Sky Automated Survey (ASAS, Pojmanski 1997), the All Sky Automated Survey for Supernovae (ASAS-SN, Shappee et al. 2014) and the Asteroid Terrestrial-impact Last Alert System (ATLAS, Tonry et al. 2018).

When validating a target, several steps are taken into consideration: For each source that looks potentially interesting, the VSG-team, usually starting with the person who initially found the source, checks such archival resources as (i)

[20] https://archive.stsci.edu/prepds/index.html/
[21] https://sites.google.com/a/lctools.net/lctools/
[22] https://skyview.gsfc.nasa.gov/current/cgi/query.pl
[23] https://mast.stsci.edu/tesscut/
[24] https://exofop.ipac.caltech.edu/
[25] https://gea.esac.esa.int/archive/
[26] https://astro.swarthmore.edu/transits/aladin_finder.html
[27] http://cdsweb.u-strasbg.fr/about
[28] https://irsa.ipac.caltech.edu/applications/wise/

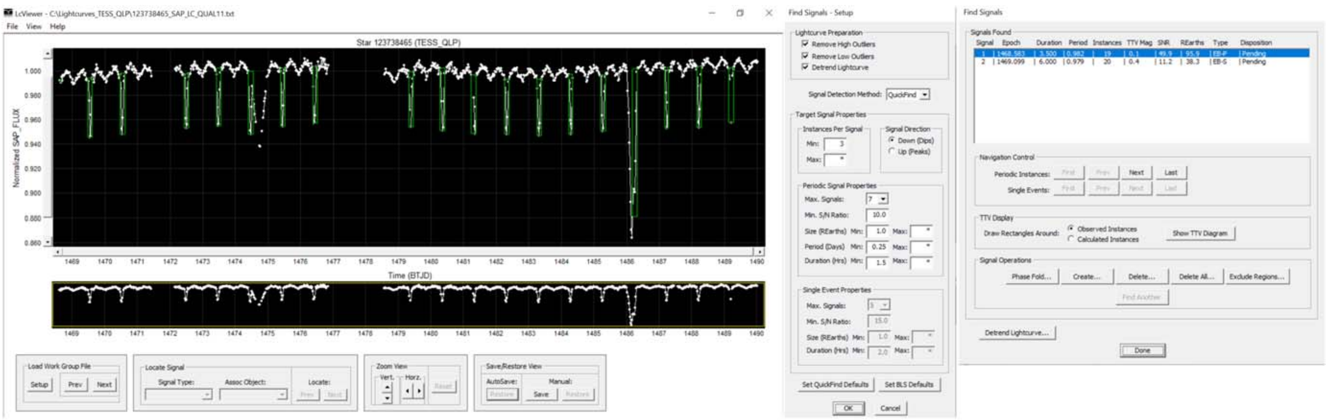

Figure 2. A TESS Quick Look Pipeline (QLP) light curve for TIC 123738465 showing a multistellar candidate signal. Highlighted in green, is the primary signal of the short-period eclipsing binary detected by LcViewer via its automated QuickFind search feature.

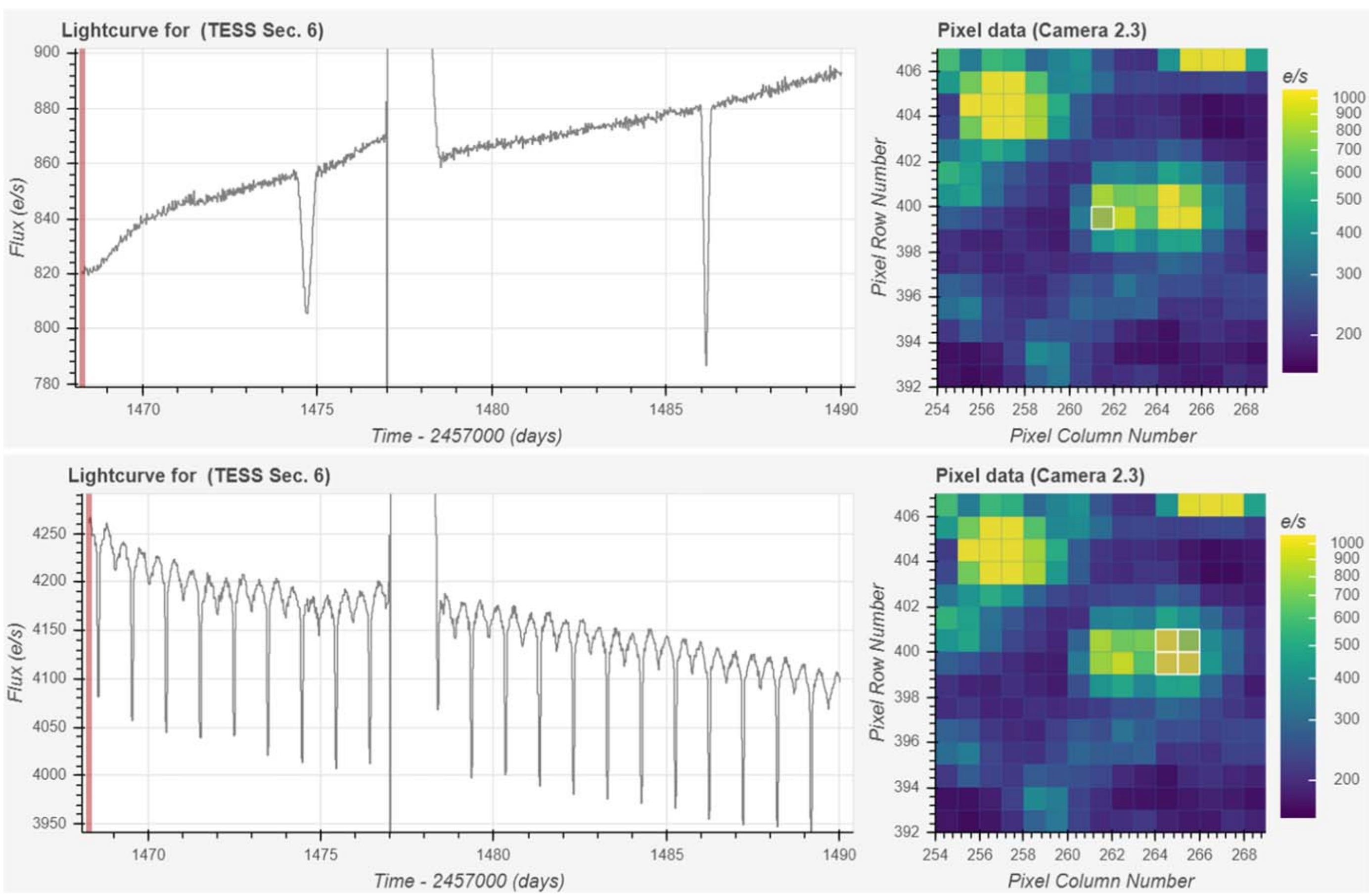

Figure 3. Target Pixel File analysis of TIC 123738465 using the interactive graphical user interface from the Lightkurve software showing that the multistellar candidate from Figure 2 is a false positive. The figure shows two light curves (left), for two stars with two different photometric aperture sizes (right) indicated with white bordered regions (1 × 1 pixel and 2 × 2 pixels, respectively).

SIMBAD, (ii) the WISE-images in four bands, (iii) Pan-STARRS-images (Chambers et al. 2016), (iv) the VizieR spectral energy distribution and (v) Gaia. These provide some immediate indication of (i) what is already known about the object and pointers to the literature, (ii) whether the object has any obvious near-infrared excess, (iii) if there are any nearby neighbors that might be contaminating the signal, (iv) what is known about the overall spectral shape of the source, and (v) to see if the star has any bound neighbors. This individual also checks for earlier *TESS* sectors in which the source might have been observed. Archival data from such publicly available resources as ASAS-SN, ATLAS, and DASCH are downloaded to investigate the source activity over intervals of six years to possibly a century. We also check with team members of ground-based surveys to determine if there is any archival data for these sources (see e.g., Rappaport et al. 2022 and references herein).

There are a few members of the VSG-team who are expert in measuring the light centroid of the time varying part of the signal, and this is checked to be certain that the correct star has been identified. In cases where potential planet candidates have been found, initial checks of the folded light curve are made to inspect transit shapes and to check for odd–even effects. Our group also has access to many experts in various subfields of astronomy with whom we consult for opinions about classes of objects that are outside the immediate expertise of the professional astronomy members of the VSG-team. If necessary, we have access to astronomers who can take spectra or high-resolution images for us (speckle or adaptive optics).

3.3. Data Under the Bridge

Table 1 lists different data sources including numbers of light curves manually surveyed by the VSG. The estimated numbers do not refer to unique stars due to overlaps for the three missions, and for K2 and TESS, also overlapping campaign and sector targets. In cases where a light curve has been surveyed multiple times, or by additional surveyors, it only counts once. In this manner, the VSG has so far surveyed nearly 10 million distinct light curves.

On the PH-website, it is impossible to assess the number of Kepler-targets (Brown et al. 2011) surveyed by the individual VSG-members. However, it is fair to estimate that all seven citizen scientists have surveyed more than half of the stars in the primary Kepler mission, and the entire Kepler-data set was later fully scrutinized by TLJ twice using `LcTools`. All seven citizen scientists have individually surveyed the entire K2 Self Flat Fielding (SFF) data set from Vanderburg & Johnson (2014).

In the TESS-mission a number of data sources have been surveyed including the TESS Input Catalog Candidate Target List (TIC CTL, Stassun et al. 2018), the Science Processing Operations Center (SPOC, Caldwell et al. 2020), OELKER (Oelkers & Stassun 2018), the PSF-based Approach to TESS High quality data Of Stellar clusters (PATHOS, Nardiello et al. 2019), the Cluster Difference Imaging Photometric Survey (CDIPS, Bouma et al. 2019), the MIT Quick Look Pipeline (QLP, Huang et al. 2020a, 2020b), the TESS Image CAlibrator Full Frame Images (TICA, Fausnaugh et al. 2020) from which we generate custom light curves of one-orbit TESS-data previews that are available earlier than the standard mission products, and the Goddard Space Flight Center (GSFC, see Section 2, Powell et al. 2021a). For a combined, more detailed description of the various TESS data sources, we direct the reader to Section 2.1 of Capistrant et al. (in-review).

4. Scientific Impacts

The VSG has collectively authored 72 papers (69 peer-reviewed) distributed among six main topics: (I) exoplanets, (II) eclipsing binaries (EBs), (III) multistellar systems, including triply eclipsing triple stars (Figure 4), (IV) variable stars, including pulsators and stellar flares, (V) black swans, i.e., unanticipated, new, or rare events, and (VI) dipper stars, i.e., young stars which typically exhibit quasi-regular dipping-flux behavior, which is presumably due to orbiting dusty material (Figure 5). By far, most discoveries made by the VSG are found by several team members within a short time frame. However, there are a few exceptions, where only one VSG-member made the discovery. These cases can be explained by some of us having different personal interests, which thereby creates an intensified lookout for particular types of objects.

Usually, the papers are led by one of the four professional astronomers on the team, or a professional astronomer from outside the VSG with whom we regularly collaborate and/or who may be the appropriate expert on the type of source we are reporting. Table 2 gives an overview of research topics covered by the VSG including primary and secondary focus topics. The references mentioned from this section represent the VSG's prior and current collaborators in its entirety, and the group's participation in these discoveries is described in what follows.

4.1. Exoplanets

The effort to search for additional, previously undetected exoplanets naturally arose by virtue of the team's involvement in the PH-enterprise. At first, this pursuit was either directed toward single transiting exoplanets (Lintott et al. 2013; Wang et al. 2013b, 2013a, 2015; Schmitt et al. 2015) and/or multiplanet systems due to the main purpose of the PH-project (Schmitt et al. 2014a, 2014b). In addition, contributions were also made in the Exoplanet Explorers project (Zink et al. 2019). The pursuit of lone-signals continued past the close of the collaboration with the original PH science team (Osborn 2017; LaCourse & Jacobs 2018; Quinn et al. 2021) which led to the discovery of the longest period exoplanet found in K2 (Figure 4.1 and Giles et al. 2018) and several long-period planets found with TESS photometry (Eisner et al. 2020; Dalba et al. 2020, 2022a, 2022b).

Additionally, the VSG has assisted in discovering several multiple planet systems, including a star hosting three planets (David et al. 2018), four planets (Daylan et al. 2021), five planets (Vanderburg et al. 2016; Becker et al. 2018;

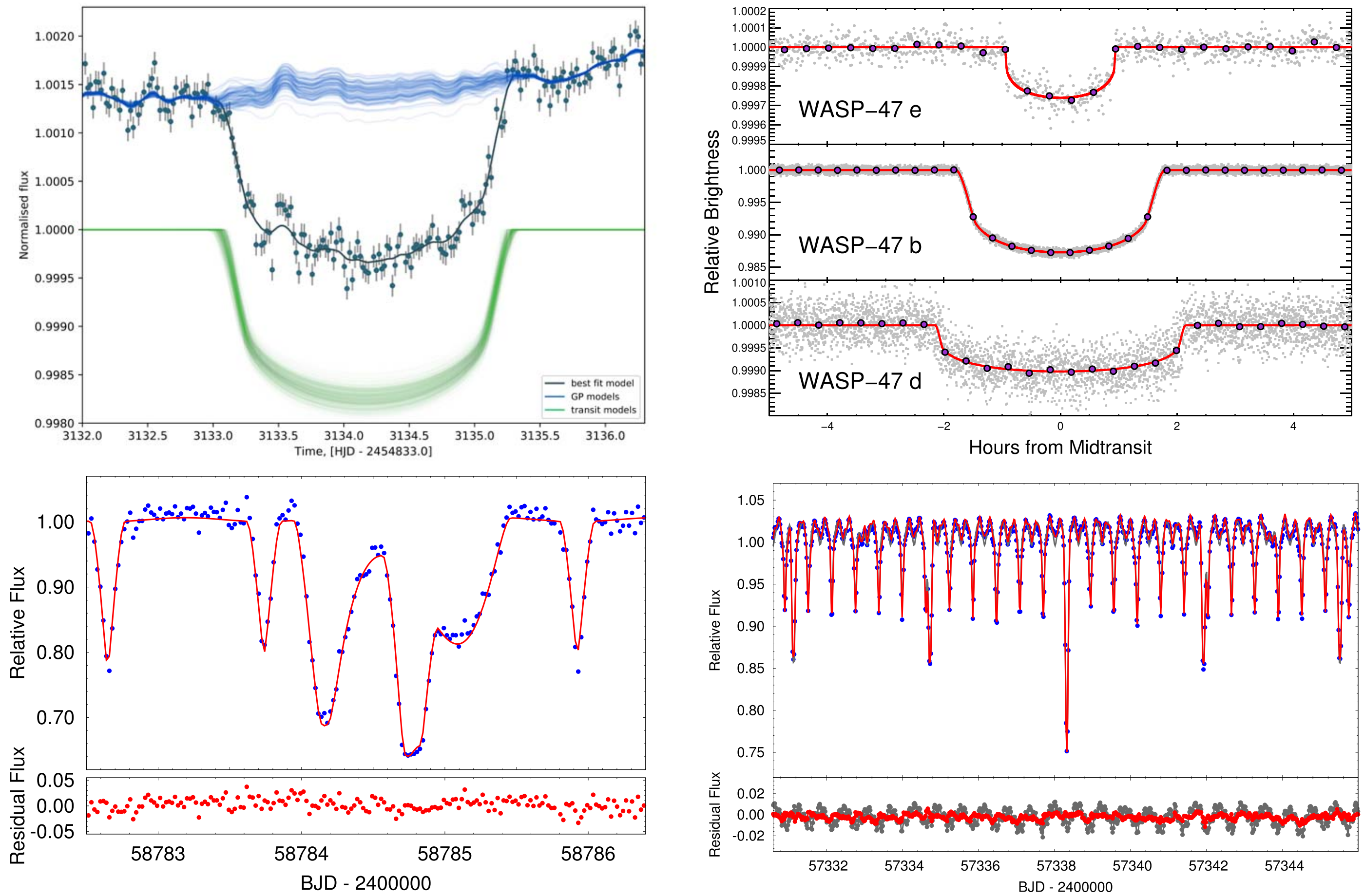

Figure 4. Snapshots of some VSG highlight results. Starting from the first row of panels, and working downward, these are: (4.1) a mono-transit of the longest period planet found with K2 (EPIC 248847494 b, Giles et al. 2018); (4.2) transit profiles of the inner three planets of WASP-47 (Becker et al. 2015); (4.3) an outer third-body eclipse of TIC 388459317 (Borkovits et al. 2022); (4.4) a quadruple system, EPIC 219217635 (Borkovits et al. 2018).

Quinn et al. 2019) and six planets (Christiansen et al. 2018; Rodriguez et al. 2018; Hardegree-Ullman et al. 2021; Leleu et al. 2021).

In addition, multistellar systems with orbiting planets were found including a quadruple with a circumbinary planet (Schwamb et al. 2013), and a second planet in the closest M-dwarf system (triple M-dwarf system) known to host transiting planets (Winters et al. 2022). Also, several lower-order systems at high significance include two planets orbiting a young Sun-like star (Dai et al. 2020; Mann et al. 2020), a planet around a star in a young star cluster (Mann et al. 2016), planetary transits for a naked-eye star ($V = 5.8$) (Kane et al. 2020), short-period planets (Malavolta et al. 2018), and two smaller, inner planets in a known hot Jupiter system (Figure 4.2 and Becker et al. 2015).

4.2. Eclipsing Binaries

Although the primary focus by the VSG initially was directed toward exoplanet detections, signals from EBs can resemble that of planets, making a vast collection of EBs a natural byproduct (Schmitt et al. 2016). This has resulted in large catalogs for Kepler (Kirk et al. 2016), K2 (Armstrong et al. 2015; LaCourse et al. 2015) and TESS (Prša et al. 2022). Also, LaCourse & Jacobs (2018) presented a catalog of single eclipses found in K2 C0-C14.

The VSG also hunts for cataclysmic variable stars (Gies et al. 2013; Yu et al. 2019), active, spotted eclipsing giant stars (Oláh et al. 2018, 2020) and EBs with pulsating components (Lee et al. 2018, 2019, 2020). Also, a post-Algol system experiencing occultations from an active accretion disk was found (Zhou et al. 2018).

4.3. Multistellar Systems

In recent years, the VSG has developed a growing interest in hierarchical systems which has resulted in discoveries of triply eclipsing triple systems (Borkovits et al. 2019, 2020, (Figure 4.3 and Borkovits et al. 2022), Rappaport et al. 2022), several

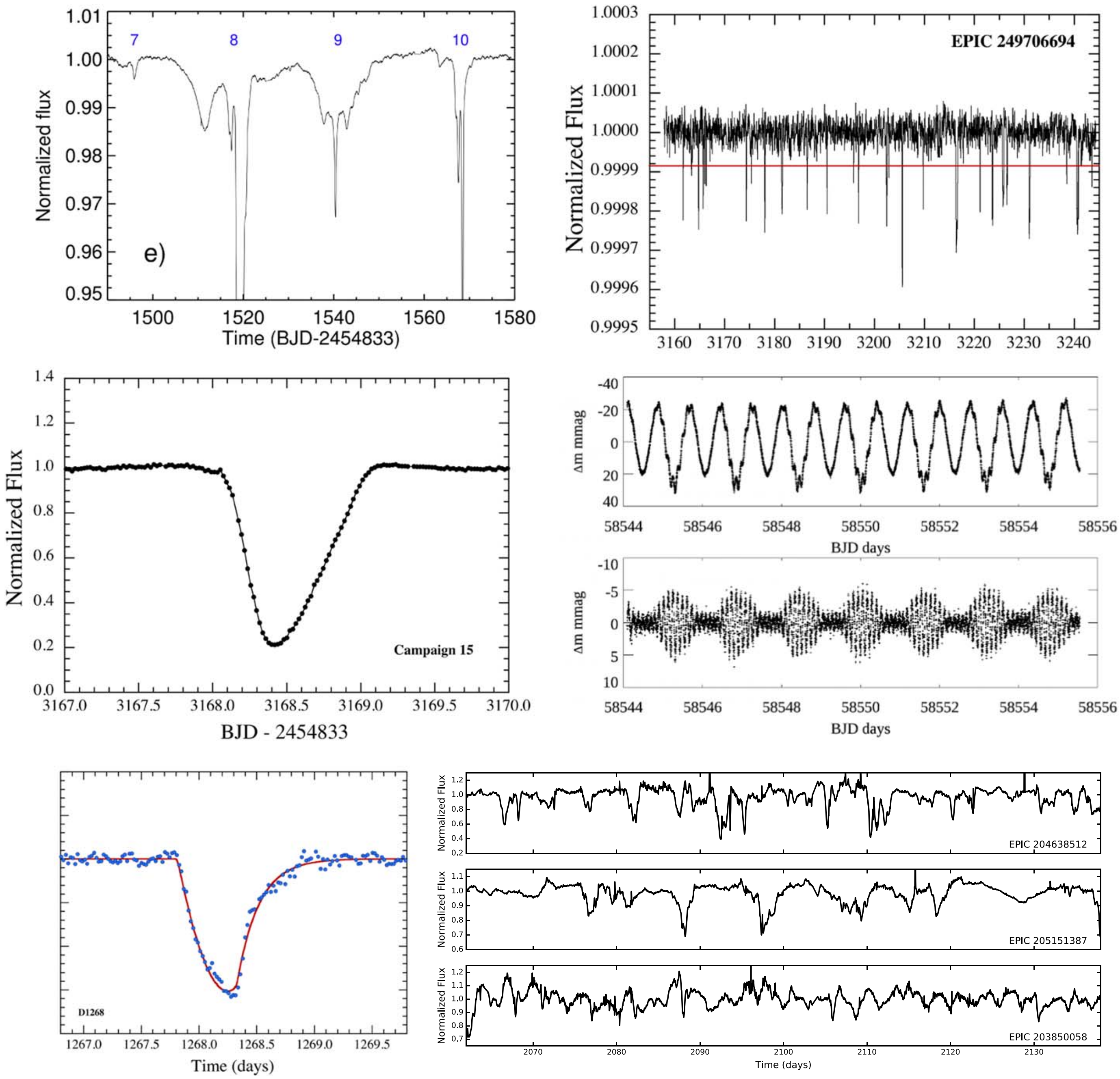

Figure 5. Further snapshots of some VSG highlight results. Starting from the first row of panels, and working downward, these are: (5.1) a zoom-in on mysterious dips from Boyajian's star (Boyajian et al. 2016); (5.2) all 28 dips of the Random Transiter after removal of stellar spot modulations (Rappaport et al. 2019a); (5.3) the asymmetric ≈80% flux occultation (EPIC 204376071, Rappaport et al. 2019b); (5.4) stellar pulsator in a binary whose pulsation axis has been tilted to align with the tidal axis of the binary (HD 74423, Handler et al. 2020); (5.5) a likely exocomet transit (KIC 3542116, Rappaport et al. 2018); (5.6) light curve profiles of three "dipper" stars (EPICs 204638512, 205151387 and 203850058, Ansdell et al. 2016a).

quadruple systems where both binaries are eclipsing (Figure 4.4 and Borkovits et al. 2018) including a strongly interacting quadruple (Rappaport et al. 2017), the nearest known quadruple (Borkovits et al. 2021), and the most eccentric, low-mass, short-period, eclipsing binary known (Han et al. 2021), which is also part of a quadruple system. Using TESS, the VSG presented the largest catalog of newly discovered doubly eclipsing quadruple candidates (Kostov et al. 2022), and also contributed

Table 2
Publication Categories for 72 Publications Authored by the VSG Including Primary and Secondary Topics of the Papers

Topic	Pri.	Sec.	Highlight
Exoplanets	30	33	Vanderburg et al. (2016)
Eclipsing binaries	12	29	LaCourse et al. (2015)
Multistellar systems	12	15	Powell et al. (2021a)
Variable stars	6	8	Handler et al. (2020)
Black swans	7	9	Boyajian et al. (2016)
Dipper stars	5	6	Capistrant et al. (in-review)
Total	72		Section 4

to the PH-TESS discovery of a massive, compact hierarchical system (Eisner et al. 2022). Adding to this collection, are a quintuple system (Rappaport et al. 2016) and the first sextuply eclipsing sextuple star system (Powell et al. 2021a).

4.4. Variable Stars

While searching for exoplanets and EBs, the VSG-members record a variety of others objects, e.g., variable stars (Armstrong et al. 2015), stars with rigidly rotating magnetospheres (Jayaraman et al. 2022) and stellar flares (Günther et al. 2020; Ilin et al. 2021). In this regard, a catalog of false positive flare signals and newly discovered SSO-candidates is being compiled for a K2-campaign (M. Kristiansen et al. 2022, in preparation). During a TESS-survey, the VSG discovered a brand new and important class of pulsators in binary systems called "Tidally Tilted Pulsators" (TTPs). In these systems, the pulsation axis has been tilted into the plane of the binary along the tidal axis. This allows the observer, for the first time, to view a pulsator at aspect angles all the way from 0° to 360° (Figure 5.4 and Handler et al. 2020; Kurtz et al. 2020).

4.5. Black Swans

KIC 8462852, also known as Boyajian's star (Figure 5.1 and Boyajian et al. 2016, 2018) was the first black swan discovery with VSG-contribution. The media quickly dubbed it an alien megastructure by way of inspiration from Wright et al. (2015). Despite the apparent rarity of the system (a properly comparable analog has yet to be discovered in Kepler, K2 or TESS data), subsequent ground-based observations have established that dusty material is the most likely explanation for the irregular sharp variations in flux (see e.g., Hitchcock et al. 2019). Also found with Kepler photometry, Rappaport et al. (2018) reported the first transit signals likely caused by extra solar comets (Figure 5.5). This represented a major step forward in terms of detecting very small objects orbiting stars via a trail of dust emissions. With K2, an interesting M-dwarf with a deep, asymmetric drop in flux ≈80% was discovered (Figure 5.3 and Rappaport et al. 2019b), and a Sun-like star experiencing 28 transit-like dips of similar depths but showing no periodicity (Figure 5.2 and Rappaport et al. 2019a). More recently, TESS has revealed a mysterious dust-emitting object that orbits its host star every 20 days (Powell et al. 2021b), complex and rapidly rotating M-dwarfs (Günther et al. 2022), and an unanticipated find of TTPs (Section 4.4, Figure 5.4).

4.6. Dipper Stars

Early in the repurposed K2-mission, when Kepler was pointed toward the ecliptic plane, the first K2-dippers surfaced (Figure 5.6 and Ansdell et al. 2016a, 2016b). These stars are young with dusty orbiting material showing irregular flux variations in their light curve profiles. These stars are of particular interest in the regime of planet formation scenarios (Gaidos et al. 2019). Although dipper stars' flux variations frequently are deep, shallow dipper-events have also been recorded (Ansdell et al. 2019). Using TESS photometry, Capistrant et al. (in-review) presents the largest catalog of dippers to date and thereby double the known dipper population. Most of the dippers in this catalog were found by the VSG.

5. Discussion and Conclusion

In this work, we have presented the VSG and its Pro-Am collaborative nature, including its history, survey-methods and discoveries. Over the past decade, the VSG has collectively surveyed nearly 10 million light curves manually and authored 69 peer-reviewed papers primarily focusing on exoplanets, eclipsing multistellar objects and "black swans." However, the quantity of data produced by TESS is too immense to keep up a completely updated, thorough and manual search. Although the manual search-method by far has been the dominant approach used by the VSG, a combination of automated and manual searches is becoming more frequent. This said, no group members intend to phase out the manual search since it not only complements the prevailing approaches but simultaneously is able to reveal some of the hidden gems of our local universe.

Concerning manual searches, there are several limitations worth mentioning. These include eye fatigue, light curve scrolling misses due to classification speed, light curve size, i.e., number of data points, light curve presentation degradation caused by computer monitor resolution, and simply the loss of focus which most frequently occurs after numerous hours of surveying. By way of example, no additional stars similar to Boyajian's star are expected to hide in the Kepler-data set, but additional shallow exocomets may have been missed, because they are isolated and hard to distinguish in a full light curve. Likewise, manual surveys do not perform particularly well for small exoplanets buried in the noise floor. Also, the human eye is not very good at seeing very short period (comparable to the sampling time) periodic events with low signal to noise, which can be easy to find with various periodogram searches (e.g., Fourier transforms, BLS transforms).

On the other hand, automated programs are not particularly good at recognizing new object patterns, and might thereby discard new and interesting types of phenomena. Several of our findings have illustrated this effect. Overall, we have found that manual surveys nicely complement automated searches and are able to complete occurrence rate studies. In addition, years of experience with manual surveying makes light curve artefacts stand out more and thereby reduces wasted time and effort in tracking down spurious signals that relatively new surveyors might not recognize.

Finally, we invite other researchers to contact us with the purpose of collaboration in mind. We are very open to looking for particular classes of objects that we might not otherwise have paid attention to, but which others find quite interesting. Also, we welcome other experienced surveyors to join the hunt with us in the VSG.

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ORCID iDs

Martti H. K. Kristiansen https://orcid.org/0000-0002-2607-138X
Saul A. Rappaport https://orcid.org/0000-0003-3182-5569
Andrew M. Vanderburg https://orcid.org/0000-0001-7246-5438
Thomas L. Jacobs https://orcid.org/0000-0003-3988-3245
Hans Martin Schwengeler https://orcid.org/0000-0002-1637-2189
Robert Gagliano https://orcid.org/0000-0002-5665-1879
Ivan A. Terentev https://orcid.org/0000-0002-0654-4442
Daryll M. LaCourse https://orcid.org/0000-0002-8527-2114
Allan R. Schmitt https://orcid.org/0000-0002-5034-0949
Brian P. Powell https://orcid.org/0000-0003-0501-2636
Veselin B. Kostov https://orcid.org/0000-0001-9786-1031

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