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A Search for Exoplanets in Open Clusters and Young Associations based on TESS Objects of Interest

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Abstract

We report the results of our search for planet candidates in open clusters and young stellar associations based on the Transiting Exoplanet Survey Satellite (TESS) Objects of Interest Catalog. We find one confirmed planet, one promising candidate, one brown dwarf and three unverified planet candidates in a sample of 1229 open clusters from the second Gaia data release. We discuss individual planet-star systems based on their basic parameters, membership probability and the observation notes from the ExoFOP-TESS website. We also find ten planet candidates ($P > 95\%$) in young stellar associations by using the BANYAN Σ Multivariate Bayesian Algorithm. Among the ten candidates, five are known planetary systems. We estimate the rotation periods of the host stars using the TESS light curves and estimate their ages based on gyrochronology. Two candidates with periodic variations are likely to be young planets, but their exact memberships to young stellar associations remain unknown.

Key words: (stars:) planetary systems – (Galaxy:) open clusters and associations: general – planets and satellites: detection – catalogs

1. Introduction

Young planets (<100 Myr) are especially useful in understanding the early stages of planet formation and evolution when major physical changes happen (Pollack et al. 1996; Lopez & Fortney 2013; Owen & Wu 2013). A planet has the potential to migrate, either by planet–disk interactions (Kley & Nelson 2012; Nelson et al. 2017) or planet–planet interactions (Chatterjee et al. 2008), and as a result may induce atmospheric interactions (Lammer et al. 2003; Fortney et al. 2011). The formation of planets and the characteristics of planetary systems (e.g., mass, compositions) are correlated with the chemical abundances of their host stars (Brugamyer et al. 2011; Ramírez et al. 2011; Saffe et al. 2017). These physical processes could be explored by studying planetary systems with different ages.

Ages are key parameters in understanding the timing of different physical processes, and are strongly correlated with the internal structure and evolutionary processes of these young planets. Coeval populations (e.g., globular clusters, open clusters, young stellar associations) have better determined stellar parameters (e.g., age, chemical composition) and clearer stellar evolution history than individual field stars (Sun 2021). For example, the age of an open cluster could be derived from photometry by fitting an isochrone to the color–magnitude diagram of member stars (Sun et al. 2020). These coeval populations are thus ideal for performing systematic planet searches and statistical comparisons of planetary systems at different ages.

The Transiting Exoplanet Survey Satellite (TESS, Ricker et al. 2015) identifies exoplanet candidates around nearby bright stars thanks to its full sky coverage, providing a valuable source for young exoplanet candidates. The TESS Objects of Interest Catalog (Guerrero et al. 2021) includes 5038 planetary candidates from the TESS survey, among which only ~170 are confirmed planets,[3] leaving a large number of candidates waiting to be confirmed. Several searches of planets in open clusters have been successful in the nearby Hyades (~750 Myr, Quinn et al. 2014) and Praesepe (~790 Myr, Quinn et al. 2012; Obermeier et al. 2016). The TESS Hunt for Young and Maturing Exoplanets (THYME) survey has been focused on finding transiting planets in nearby young stellar associations (Newton et al. 2019, 2021; Mann et al. 2020, 2021; Rizzuto et al. 2020; Tofflemire et al. 2021). However, the number of planetary systems in these coeval populations is still low. We expect to find more planetary systems in open clusters and young stellar associations based on a systematic TESS search.

The TESS project has reported individual discoveries of planets in open clusters (e.g., Bouma et al. 2020). Based on the TESS mission, a few statistical assessments of the frequency of planets and age-planet radius distribution relations in open

[3] From the TESS publication website: https://tess.mit.edu/publications, retrieved 2022 January 2.

clusters have been reported (Nardiello et al. 2020, 2021). Different from these statistical studies of planet properties, in this paper we search over 5000 planet candidates from the TESS Objects of Interest Catalog in 1229 open clusters (Cantat-Gaudin et al. 2018) from the second Gaia data release (Gaia Collaboration et al. 2018, hereafter Gaia DR2). We perform an analysis to see if any candidates happen to be an open cluster member, discuss individual candidates of interest and promising ones for follow-up studies.

The open cluster members are tightly bound together by gravity, with typical ages between several tens of Myr to a few Gyr. The TESS survey mainly searches for exoplanets around nearby bright stars, so the number of TESS planets detected in open clusters may be limited as a majority of open clusters are faint and old ($\geqslant$100 Myr). Young stellar associations are loosely grouped young stars with coeval populations, so they have the same advantages as open clusters as discussed above. We even expect to find more planets in young associations as they are mostly nearby and bright compared to open clusters. In this paper, we evaluate the membership probability of TESS Object of Interest (TOI) candidates in a list of 27 young associations with ages between 1 and 800 Myr by using the BANYAN Σ Multivariate Bayesian Algorithm (hereafter called BANYAN Σ, Gagné et al. 2018). We measure rotation periods of the host stars using TESS light curves and estimate their ages based on gyrochronology. We then discuss individual candidates and promising ones for follow-up studies.

This paper is arranged as follows: Section 2 describes our data analysis procedure, and search results in open clusters and in young associations; Section 3 discusses each individual candidate of interest and promising ones for follow-up studies; Section 4 summarizes the paper.

2. Data Analysis

The TESS Objects of Interest Catalog includes basic parameters of over 5000 exoplanet candidates (e.g., orbital periods, transit depths/size) and main stellar parameters of their host stars (e.g., effective temperature, log g). The TESS Objects of Interest Catalog is available online,[4] and also by querying through the Mikulski Archive for Space Telescopes (MAST) list.[5]

2.1. Open Cluster

By using parallax and proper motion information from Gaia DR2, Cantat-Gaudin et al. (2018, CG18) identified and derived membership probabilities for over 0.4 million stars in 1229 open clusters. We match TOI candidates with the list of possible open cluster members using the coordinates, parallax and proper motion information. The TESS Follow-up Observing Program (TFOP) working group (TFOPWG[6]) aims to confirm and characterize planet candidates identified by TESS. One of the subgroups of TFOP—Seeing-limited Photometry (SG1)—performs ground-based photometric followup observations to better determine the transit ephemeris and identifies false positives. The TFOP-SG1 disposition is publicly available from the Exoplanet Follow-up Observing Program for TESS (ExoFOP-TESS) website.[7]

After combining the TOI and TFOF-SG1 dispositions, we exclude all the false positives from our search results. The false positives include TOI 1535.01 (nearby eclipsing binary), TOI 861.01 (nearby eclipsing binary), TOI 517.01 (eccentric eclipsing binary), TOI 2959.01 (nearby eclipsing binary), TOI 1918.01 (eclipsing binary), TOI 4397.01 (nearby eclipsing binary), TOI 1188.01 (nearby eclipsing binary), TOI 1321.01 (nearby eclipsing binary), TOI 1497.01 (nearby eclipsing binary), TOI 2451.01 (nearby planet candidate), TOI 496.01 (eclipsing binary) and TOI 580.01 (possible nearby eclipsing binary). We summarize our final list of planet candidates in open clusters in Table 1 (the false positives are not included here). The table shows selected parameters from the TOI catalog. The associated errors and descriptions of each parameters could be found in Guerrero et al. (2021). Note that all the candidates are singles and have ".01" in their TOI Id. Column 14 is the candidate's membership probability to the specific open cluster in Column 15 retrieved directly from CG18.

We find one confirmed planet, one brown dwarf and four planet candidates in open clusters. The confirmed planet is TOI 837.01, discovered by Bouma et al. (2020) as a transiting planet in the open cluster IC 2602. TOI 681.01, the transiting companion of TOI 681, is a confirmed brown dwarf (Grieves et al. 2021). We remind the reader that the TESS Objects of Interest Catalog mainly includes bright, nearby planets, whereas many open clusters are older, relatively far and faint. The current TESS Objects of Interest Catalog also includes the ones from the Quick-Look Pipeline (QLP) faint star search, which extends the magnitude limit to $T \sim 14.0$ mag (TESS magnitude, Kunimoto et al. 2021). Our search results are likely constrained by the magnitude limit. Future searches of fainter stars in a broader region may lead to more discoveries of planetary systems in open clusters.

2.2. Young Association

Gagné et al. (2018) developed the BANYAN Σ algorithm with the multivariate Gaussian functions in six-dimensional space to calculate the membership probability of a star belonging to young associations. The algorithm includes bona

4 Data retrieved on 2022 January 2 from https://tev.mit.edu/data/collection/193/.
5 https://astroquery.readthedocs.io/en/latest/mast/mast.html
6 https://tess.mit.edu/followup/
7 https://exofop.ipac.caltech.edu/tess/

Table 1
Planet Candidates in Open Clusters

TIC Id[a]	TOI Id[a]	R.A.[a] (degree)	Decl.[a] (degree)	TESS[a,b] Disposition	TMag[a] (mag)	Orbital[a] Period (days)	Transit[a] Duration (hr)	Transit[a] Depth (ppm)	$T_{\rm eff}$[a] (K)	log g[a]	Star[a] Radius ($R_\odot$)	Planet[a] Radius (R_E)	$P^3_{\rm mem}$	OC[c]	TFOP-SG1[d] Disposition
142938659	4668.01	52.6471645	−35.2036955	PC	13.837	1.0049552	0.92	8600	3210.0	4.80594	0.42	5.19	1.0	Alessi 13	PC
59859387	1881.01	110.3697368	−45.5677871	PC	10.276	1.120	2.387	1739	6564.4	4.26	1.47	9.90	0.7	Alessi 3	VPC+
460205581	837.01	157.037444	−64.505257	CP	9.916	8.325	1.647	4360	6513	4.53694	1.01	7.60	0.9	IC 2602	VP
443115574	2538.01	95.226324	−7.298935	PC	10.523	2.910	3.606	1480	7340.8	4.09	3.50	12.26	0.8	NGC 2215	PC
410450228	681.01	117.89497	−60.412452	PC	10.656	15.780	3.386	6808	7447	3.79	1.69	18.27	0.4	NGC 2516	VPC+
180987952	581.01	130.2615216	−41.4428264	PC	9.529	1.389	1.476	630	10585	4.35	1.84	4.84	0.3	Trumpler 10	PPC

Notes.
[a] TESS Input Catalog (TIC) Id and key parameters, data retrieved from the TOI Catalog (https://tev.mit.edu/data/), associated errors and descriptions of each parameters can be found in Guerrero et al. (2021).
[b] "PC" stands for "possible candidate" and "CP" means "confirmed planets" (Master disposition keywords from the TOI catalog).
[c] The membership probability of the planet-hosting star to an existing open cluster.
[d] Master Dispositions from TFOP-SG1. "VPC+" stands for "Verified Achromatic Planet Candidate," "VP" signifies "validated planet," "PC" means "Planet Candidate" and "PPC" corresponds to "Promising Planet Candidate" (disposition keywords can be found on the ExoFop website).

fide members of 27 young associations within 150 pc of the Sun, with typical ages between 1 and 800 Myr.

We use the algorithm to identify planet candidates with previously unknown membership in young associations for all TOIs. We incorporate the TOI and the publicly available TFOP-SG1 disposition to eliminate false detections (mainly eclipsing binaries). The false detections include TOI 447.01 (eclipsing binary), TOI 450.01 (ambiguous planetary candidate), TOI 456.01 (likely nearby eclipsing binary), TOI 4636.01 (eclipsing binary), TOI 235.01 (likely eclipsing binary from the TFOPWG notes), TOI 831.01 (ambiguous planetary candidate), TOI 1047.01 (nearby planet candidate), TOI 278.01 (likely stellar variation), TOI 2496.01 (likely eclipsing binary), TOI 935.01 (eclipsing binary), TOI 734.01 (likely eclipsing binary), TOI 1433.01 (ambiguous planetary candidate), TOI 919.01 (eclipsing binary), TOI 1500.01 (nearby eclipsing binary) and TOI 224.01 (ambiguous planetary candidate).

We show the search result in Table 2, which only includes planet candidate (PC) and known planet (KP). The table shows basic parameters of the planet candidates and their membership probability to young stellar associations.

3. Discussions

In this section, we discuss planet candidates listed in Tables 1 and 2, some of which may be interesting for follow-up studies. We recommend the readers to check ExoFop-TESS for public comments, available data products and contact the TFOP group for latest updates on candidate status.

3.1. Open Clusters

To give readers an overall impression of the planet candidates listed in Table 1, we detrend, remove outliers and normalize the flux of the TESS light curves with the `lightkurve` package in Python, and then further remove stellar variability to create phase-folded light curves by using the `Juliet` package in Python. The TESS light curves and phase-folded transits are displayed in Figure 1 for candidates in Table 1. The flux used to plot the figure is pre-search Data Conditioning SAP flux (PDCSAP, systematic trends removed and light dilution corrected). TOI 4668 does not have PDCSAP available, so we use the QLP detrended light curves instead (KSPSAP flux). Based on the transit light curves, public comments and publicly available data products, in the rest of this section we discuss individual candidates listed in Table 1.

TOI 4668 is an early M dwarf found by the QLP faint star search. Its transit signal is V-shaped and needs further validation.

TOI 1881 is a hot F star reported as a Community TESS Objects of Interest (CTOI). The latest TFOP-SG1 note says the object is an achromatic verified planet candidate (VPC+). Precise radial velocity measurement may be tough due to its fast rotation. Further observations of the Rossiter–McLaughlin effect (Triaud 2018) could measure the spin–orbit angle and help validate the planet.

TOI 837.01 is a confirmed young transiting planet in the open cluster IC 2602 (Bouma et al. 2020).

TOI 2538 is a member of NGC 2215, whose spectrum looks very broad ($V_{\mathrm{ROT}} = 180$ km s^{-1}) with a prominent H_{α} line. TFOP-SG1 note says the object is located in a crowded field and the TESS team reports a centroid shift. The target is hard to validate or confirm.

TOI 681.01 is a confirmed brown dwarf (Grieves et al. 2021).

TOI 581 (A0 or B star) is less likely to be a member of Trumpler 10. Speckle images (HRCam) and spectra (CORALIE, CHIRON) are publicly available for this object.

3.2. Young Association

Gagné et al. (2018) recommend treating candidates with BANYAN Σ probability greater than 95% as probable young stellar association members, so we limit our discussions to the ten candidates with $P > 95\%$ in the following text. TOI 4668 is a member of the open cluster Alessi 13 from Table 1, and in the meantime it is included in Table 2 as a member of the X^1 For (XFOR) moving group. Alessi 13 and the XFOR moving group are synonymous according to SIMBAD (Wenger et al. 2000). Similar to Figure 1, in Figure 2 we show phase-folded transit light curves for YA candidates with $P > 95\%$ except for TOI 4668 to avoid redundance. In Figure 2, TOI 200, TOI 2221 and TOI 1098 display variations during the transit phase, which are due to the light curves themselves and our data reduction processes. After detrending and normalizing with the `lightkurve` package, light curves of the three candidates still show large stellar variations. To further reduce the variations and in the meantime avoid erasing the transit signal, we mask the transit and fit to the rest of unmasked data points, so later when we add back the masked transits they still show variations.

Five of the candidates host known planets: TOI 200.01 (DS Tuc Ab) in the 45 Myr old Tucana-Horologium (THA) young stellar association was discovered by the THYME group (Newton et al. 2019); TOI 2221.01 (AU Mic b) is a transiting 22 Myr old planet orbiting star AU Microscopii in the β Pictoris moving group (β PMG, Plavchan et al. 2020); TOI 1227.01 was recently validated by the THYME group to be a member of the Lower Centaurus Crux (LCC) OB association, rather than a member of ϵ Chamaeleontis (EPSC) from BANYAN Σ; TOI 1098.01 is a sub-Neptune-sized planet orbiting the young star HD 110082 in the 250 Myr old association MELANGE-1 (Tofflemire et al. 2021); TOI 1779.01 (LP 261-75 b) is a known planet orbiting a low mass brown dwarf (Reid & Walkowicz 2006), but its membership to AB Doradus (ABDMG) has not been verified yet. It is promising that the remaining five candidates are young planets belonging to young associations. Table 3 lists the proper

Table 2
Probable Planet Candidates in Young Associations

TIC Id	TOI Id	R.A.[a] degree	Decl.[a] degree	TOI Disposition	TMag[a] mag	Orbital[a] Period day	Transit[a] Duration hour	Transit[a] Depth ppm	$T_{\rm eff}$[a] K	log g[a]	Star[a] Radius $R_\odot$	Planet[a] Radius R_E	P (YA)[b]	LIST_PROB_YA[c]	SG1[d] Disposition Disposition	Notes
410214986	200.01	354.914556	−69.195787	KP	7.771	8.14	3.32	3576	5414	4.4	0.95	6.95	0.999	Tucana-Horologium (THA)	VP	DS Tuc Ab (THYME planet, Newton et al. 2019)
142938659	4668.01	52.6471645	−35.2036955	PC	13.837	1.00	0.92	8600	3210	4.81	0.42	5.19	0.998	X[a] For (XFOR)	PC	Unlikely a YA member
359357695	1880.01	182.7268485	−75.1318983	PC	13.061	1.73	1.73	9681	3631	4.69	0.56	6.57	0.998	ϵ Chamaeleontis (EPSC)	VPC	Age discrepancy with EPSC, likely wrong YA disposition
441420236	2221.01	311.2897	−31.3409	KP	6.755		3.57	2872	3588	4.60	0.70	4.03	0.994	β Pictoris (β PMG)	P	AU Mic b(Plavchan et al. 2020)
34077285.01	880.01			PC		6.39	2.61	3510				5.04			VPC	Unlikely a YA member
34077285.02	880.02	94.1644691	−13.987437	PC	9.256	2.57	2.48	740	4935	4.52	0.82	2.78	0.99	Argus (ARG)	VPC	potential multi-planet system
34077285.03	880.03			PC		14.33	1.60	990			0.82	2.87				
383390264	1098.01	192.592205	−88.121055	PC	8.739	10.18	2.85	715	6153	4.35	1.20	3.26	0.990	Octans (OCT)[e]	P	HD 110082 (THYME planet, Tofflemire et al. 2021)
360156606	1227.01	186.76803	−72.45179	PC	13.757	27.36	4.14	27234	3050	4.44	1.00	16.52	0.986	ϵ Chamaeleontis (EPSC)[f]	VPC	TOI 1227 b (THYME planet, Mann et al. 2021)
67646988	1779.01	147.7690653	35.96929602	KP	12.437	1.88	1.24	102854	3138	4.92	0.31	9.93	0.968	AB Doradus (ABDMG)	KP	LP 261-75 b (Reid & Walkowicz 2006)
142937186	2427.01	52.2909729	−31.3630447	PC	9.014	1.31	0.63	560	4072	4.58	0.68	2.00	0.954	Argus (ARG, 73); Carina-Near (CARN, 27)	VPC	Unlikely a YA member
150151262.01	712.01					9.53	1.83	959				2.52				Age discrepancy with ABDMG, likely wrong YA disposition
150151262.02	712.02	92.936152	−65.825972	PC	9.845	51.70	4.76	1882	4504	4.59	0.72	3.14	0.953	AB Doradus (ABDMG)	VPC+	potential multi-planet system
150151262.03	712.03					53.75	5.59	1558				3.26				
150151262.04	712.04					679	5.56	1557				2.789				
89256802	457.01	58.7249	−26.4237	PC	13.801	1.18	0.99	14881	3054	5.09	0.51	7.72	0.946	Argus (ARG)	VPC—	
20318757.01	1027.01	167.1337084	−29.6531909	PC	10.21	3.28	1.38	1220	4272	4.6	0.68	2.70	0.945	Argus (ARG)	VPC+	potential multi-planet system
20318757.02	1027.02					11.03	3.16	1770				3.12				
157115010	4319.01	100.9720399	−43.89332391	PC	10.82		7.73	6743	4438	4.44	0.73	6.55	0.940	Argus (ARG)	STPC	
464646604	4399.01	287.7410437	−60.272202	PC	7.758	7.71	2.43	728	5985	4.4	1.09	3.00	0.890	AB Doradus (ABDMG)	PC	
290348383	1099.01	328.713617	−77.338017	PC	7.394	6.44	1.83	827	4867	4.44	0.80	2.46	0.862	Carina-Near (CARN)	VPC	
260647166.01	1233.01			CP		14.18	3.85	846		4.44		2.63				HD 108236 d (Daylan et al. 2021)
260647166.02	1233.02	186.574587	−51.362819	CP	8.618	19.59	4.17	1161	5724	4.44	0.86	3.22	0.846	AB Doradus (ABDMG)	VP	HD 108236 e
260647166.03	1233.03			CP		6.20	3.00	698				2.46				HD 108236c
260647166.04	1233.04			CP		3.80	2.31	322				1.67				HD 108236 b

Table 2
(Continued)

TIC Id	TOI Id	R.A.[a] degree	Decl.[a] degree	TOI Disposition	TMag[a] mag	Orbital[a] Period day	Transit[a] Duration hour	Transit[a] Depth ppm	$T_{\rm eff}$[a] K	log g[a]	Star[a] Radius $R_\odot$	Planet[a] Radius R_E	P (YA)[b]	LIST_PROB_YA[c]	SG1[d] Disposition Disposition	Notes
406672232	1263.01	309.353389	22.65461489	PC	8.533	1.02	1.06	258	5098	4.55	0.82	1.43	0.762	AB Doradus (ABDMG)	PC	
360630575	1097.01	189.7766743	−74.5739909	PC	8.722	9.19	2.48	420	5876	4.48	0.98	2.17	0.702	Lower Centaurus Crux (LCC)	CPC	
429302040	1905.01	188.386857	−10.146147	KP	10.474	5.72	2.65	25549	4233	4.64	0.73	12.84	0.681	Argus (ARG)	KP	WASP-107 b (Anderson et al. 2017)
77253676	697.01	69.704057	−36.681466	PC	9.304	8.61	3.68	555	5447	4.40	0.97	2.62	0.659	Argus (ARG)	CPC	
391903064.01	3353.01	106.529799	−75.819712	PC	8.751	4.67	3.04	647	6365	4.55	1.02	2.33	0.638	Lower Centaurus Crux (LCC, 69); AB Doradus (ABDMG, 31)	PC	
391903064.02	3353.02					8.82	3.11	490				2.33				
148883384	2522.01	107.1185305	−12.1478068	PC	9.124	2.10	4.37	350	5531	4.45	0.97	1.67	0.631	Columba (COL)	PC	
451645081	783.01	172.15656	−54.784245	PC	9.859	16.22	2.10	1262	4499	4.5	0.67	2.394	0.538	Argus (ARG)	CPC?	

Notes.
[a] Selected parameters from the TESS Objects of Interest Catalog. Due to space constraints, errors associated with these parameters are not shown in the table, but can be found in the online catalog. Detailed descriptions of each parameter can be found in Guerrero et al. (2021).
[b] Probability that the planet-hosting star belongs to a young association, calculated from BANYAN Σ algorithm.
[c] A list of young associations that the planet-hosting star probably belongs to. When two associations are given, individual probability (in percentage) is included in parentheses.
[d] TFOP-SG1 Disposition, abbreviations have the same meaning as in Table 1. In addition to those already appearing in Table 1, "VPC" stands for "Verified Planet Candidate;" "P" means "confirmed planet" and "KP" signifies "Known planet" (disposition keywords can be found on the ExoFop website).
[e] HD 110082 is a member of the newly discovered 250 Myr Association MELANGE-1, rather than the Octans association from the BANYAN Σ algorithm.
[f] TOI 1227 is a member of the Lower Centaurus Crux (LCC) OB association (Mann et al. 2021), rather than ϵ Chamaeleontis (EPSC) from the BANYAN Σ algorithm.

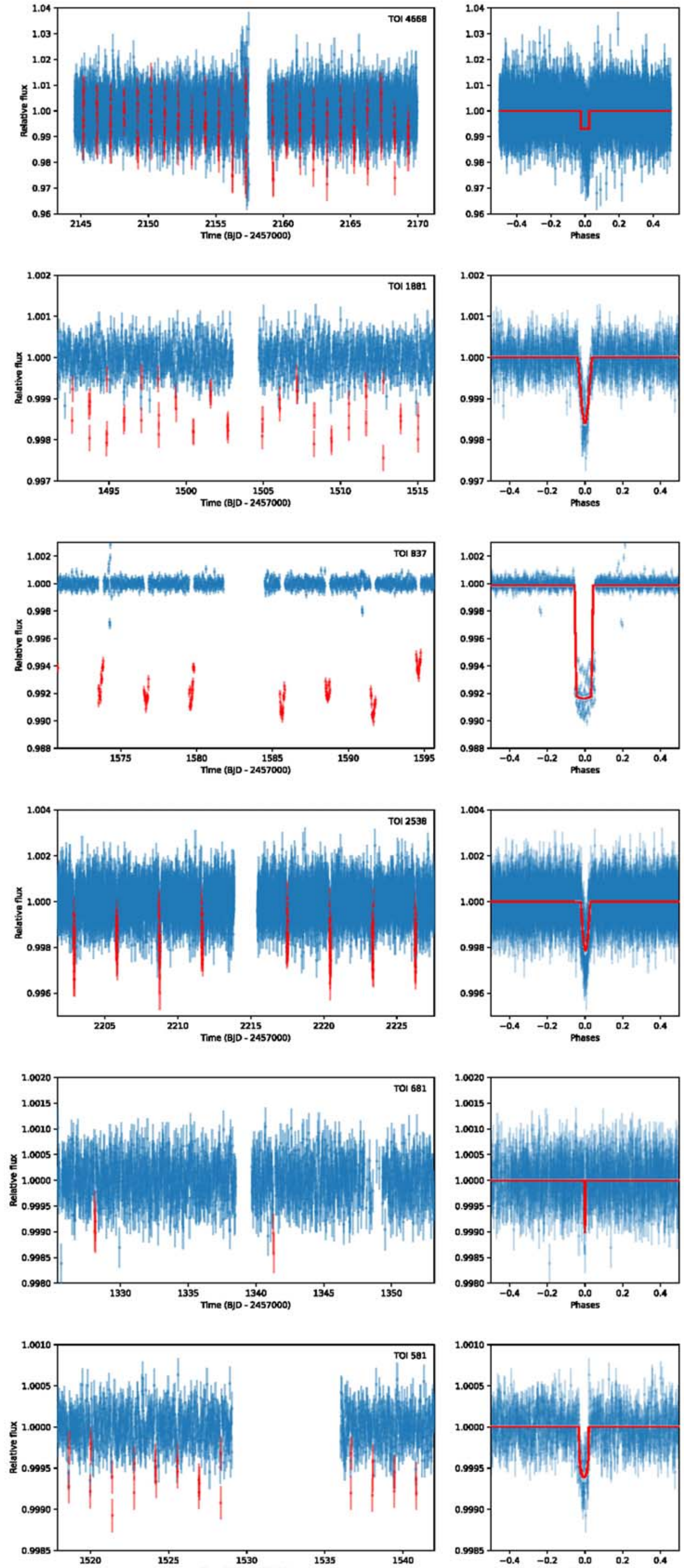

Figure 1. TESS detrended light curves (left panel) and phase-folded transit light curves (right panel) for planet candidates in OC. From top to bottom are TOI 4668, TOI 1881, TOI 837 TOI 2538, TOI 681 and TOI 581. Potential transits are marked using red dots in the left panel, and the fitting results are plotted using red lines in the right panel.

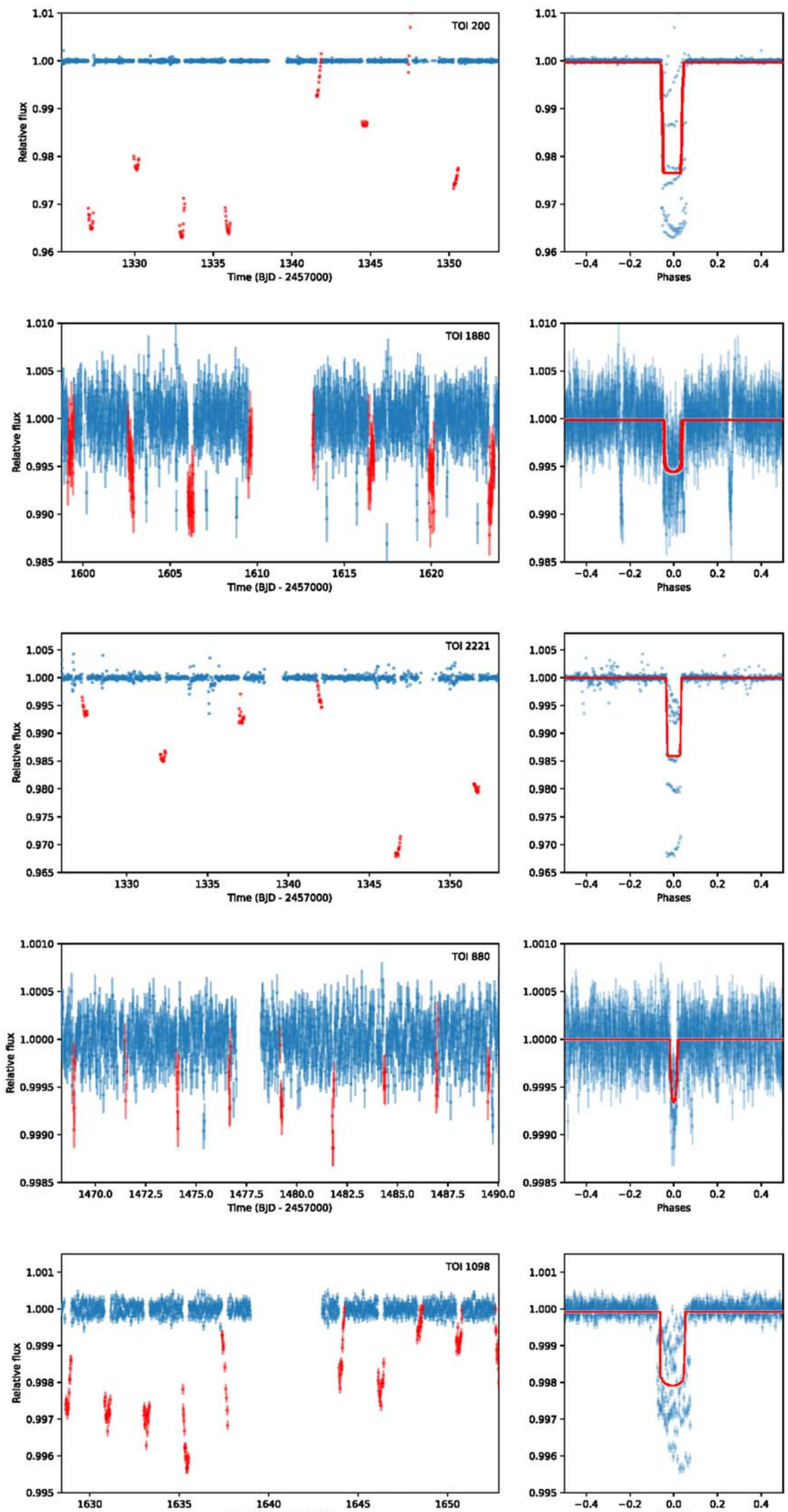

Figure 2. TESS detrended light curves (left) and phase-folded transit light curves (right) for planet candidates in YA. From top to bottom are TOI 200, TOI 1880, TOI 2221, TOI 880, TOI 1098, TOI 1227, TOI 1779, TOI 2427 and TOI 712. The same symbols are used as in Figure 1.

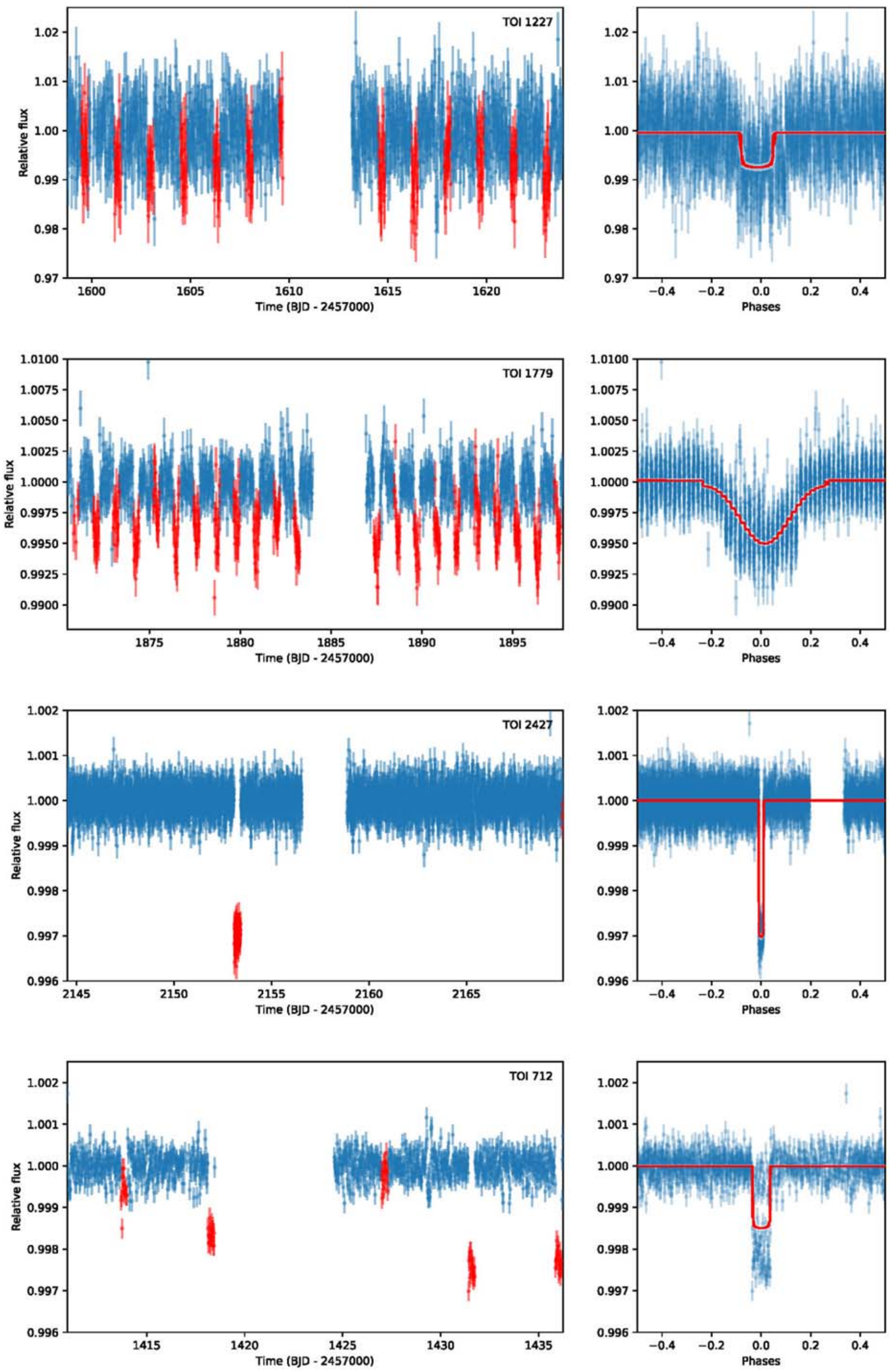

Figure 2. (Continued.)

motion in R.A. ($\mu_{R.A.}$), decl. ($\mu_{decl.}$) and parallax for the five candidates.

We estimate the rotation periods of the host stars using the TESS light curves with the `lightkurve` package and estimate their ages based on gyrochronology. We use the autocorrelation function (ACF) method described in McQuillan et al. (2014) to roughly estimate the rotation periods for the five planet-hosting candidates in Table 2 (TOI 4668, TOI 1880, TOI 880, TOI 2427, TOI 712). We check both the Simple Aperture Photometry (SAP) flux and the PDCSAP flux

Table 3
Period and Age for Planet Candidates in Young Associations

TOI Id	$\mu^1_{\rm R.A.}$ (mas yr^{-1})	$\mu^1_{\rm decl.}$ (mas yr^{-1})	Parallax[a] (mas)	$(B-V)_0$[a] (mag)	Period[b] (day)	Age[b] (Myr)	YA Age[c] (Myr)
TOI 4668	35.8232	−4.51385	9.38875	…[d]	…	…	…
TOI 1880	−39.4012	−7.24975	9.71749	1.689	3.6 ± 0.2	15.8 ± 1.7	$3.7^{+4.6}_{-1.4}$
TOI 880	0.962399	23.2374	16.4543	0.98	non-periodic	…	…
TOI 2427	150.453	41.3865	35.0407	1.393	non-periodic?	…	…
TOI 712	−2.92948	31.0032	17.0297	1.265	5.1 ± 0.2	48.5 ± 3.7	149^{+51}_{-19}

Notes.
[a] The proper motion in R.A. ($\mu_{\rm R.A.}$), proper motion in decl. ($\mu_{\rm decl.}$), parallax and $(B-V)_0$ are from the TESS Input Catalog (TIC) queried through MAST.
[b] Rotation period of the host star. Typical error estimation of the period from ACF is ±0.2 days, and then the error is propagated to age using Equation (1).
[c] The age of young associations (YA) from Gagné et al. (2018), shown for periodic candidates.
[d] $(B-V)_0$ is not available for TOI 4668.

(KSPSAP flux for TOI 4668). The ACFs (KSPSAP flux for TOI 4668, PDCSAP flux for the other five candidates) for each candidate are shown in Figure 3.

TOI 4668 and TOI 880 do not show period rotation signals. TOI 1880 shows short period signals in the light curves and ACFs. The periodic signal of TOI 2427 is less obvious from the ACF. Based on its light curve, TOI 2427 seems to only have one transit. TOI 2427 is probably non-periodic, or may have a very long rotation period. TOI 712 is probably periodic. We show the rotation period for TOI 1880 and TOI 712 in Figure 3 and Table 3.

We then apply the period and Equation (1) (Barnes 2007; Reinhold & Gizon 2015) to estimate the age

$$\log t = \frac{1}{n}[\log P - \log a - b \log X], \quad (1)$$

where P is the period in days and t is age in Myr. We use the gyrochronology relation from Meibom et al. (2009) with $X = (B-V)_0 - c$, $a = 0.7700$, $b = 0.553$, $c = 0.472$ and $n = 0.5200$. The equation only applies to $(B-V)_0 \geqslant 0.50$ mag and period >1.5 days. We calculate ages for the two candidates showing a short period rotation signal, and list the values in Table 3. Ages of the young associations from Gagné et al. (2018) are also displayed in Table 3.

The ages for both of the two periodic candidates are discrepant with the ages of young associations ($>2\sigma$). The BANYAN Σ algorithm calculates probability based on coordinates, proper motion and parallax of the planet-star system, which means the candidates with high probability may coincidentally satisfy the membership criteria to young associations. The proper motion and parallax might just happen to be close to those of the young association, but the coordinates are actually far away, or vice versa. The three candidates are likely young planets with unknown membership to young associations.

If the remaining three non-periodic candidates (TOI 4668, TOI 880, TOI 2427) are true young association members, then with their young ages and spectral types we expect to see a clear short period rotation signal in the TESS light curve, but we do not see them, so perhaps these three candidates are not young stars and the young association dispositions are wrong like the other two. In summary, none of the five unpublished systems with $P > 0.95$ seems to be really associated with the YA reported by BANYAN Σ. For systems with $P < 0.95$, we caution the readers that YA values reported by BANYAN Σ are unreliable.

3.3. Number of TOIs in OC and YA

The planet occurrence rate in OCs/YAs and whether it differs from the occurrence rate in field stars is an important scientific question, which helps understand factors that impact planet formation and evolution in clustering environments (Dai et al. 2021). Whether the occurrence rates are different is still under debate due to the small number of planets confirmed in coeval populations, which can lead to large statistical uncertainties. Using our TOI and OC/YA sample, we would like to give thought to this question. How many planets do we expect to find in OCs and YAs, and does our result comply with the expectations? In the following text of this section we have a rough estimation of the number of planets we expect to find in OCs and YAs.

First, we assume the ratio of the total number of young stars in OCs and YAs($N_{\rm young}$) to the number of all TESS stars ($N_{\rm TESS}$) equals the ratio of the number of young TOIs ($N_{\rm TOI,young}$) to the number of all TOIs ($N_{\rm TOI}$), as expressed in Equation (2)

$$\frac{N_{\rm young}}{N_{\rm TESS}} = \frac{N_{\rm TOI,young}}{N_{\rm TOI}}. \quad (2)$$

The number of stars in the TESS Input Catalog is roughly ∼1.7 billion from the MAST portal (https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html), and after applying a magnitude cut of $T = 14$ mag, we find 29,911,379 records

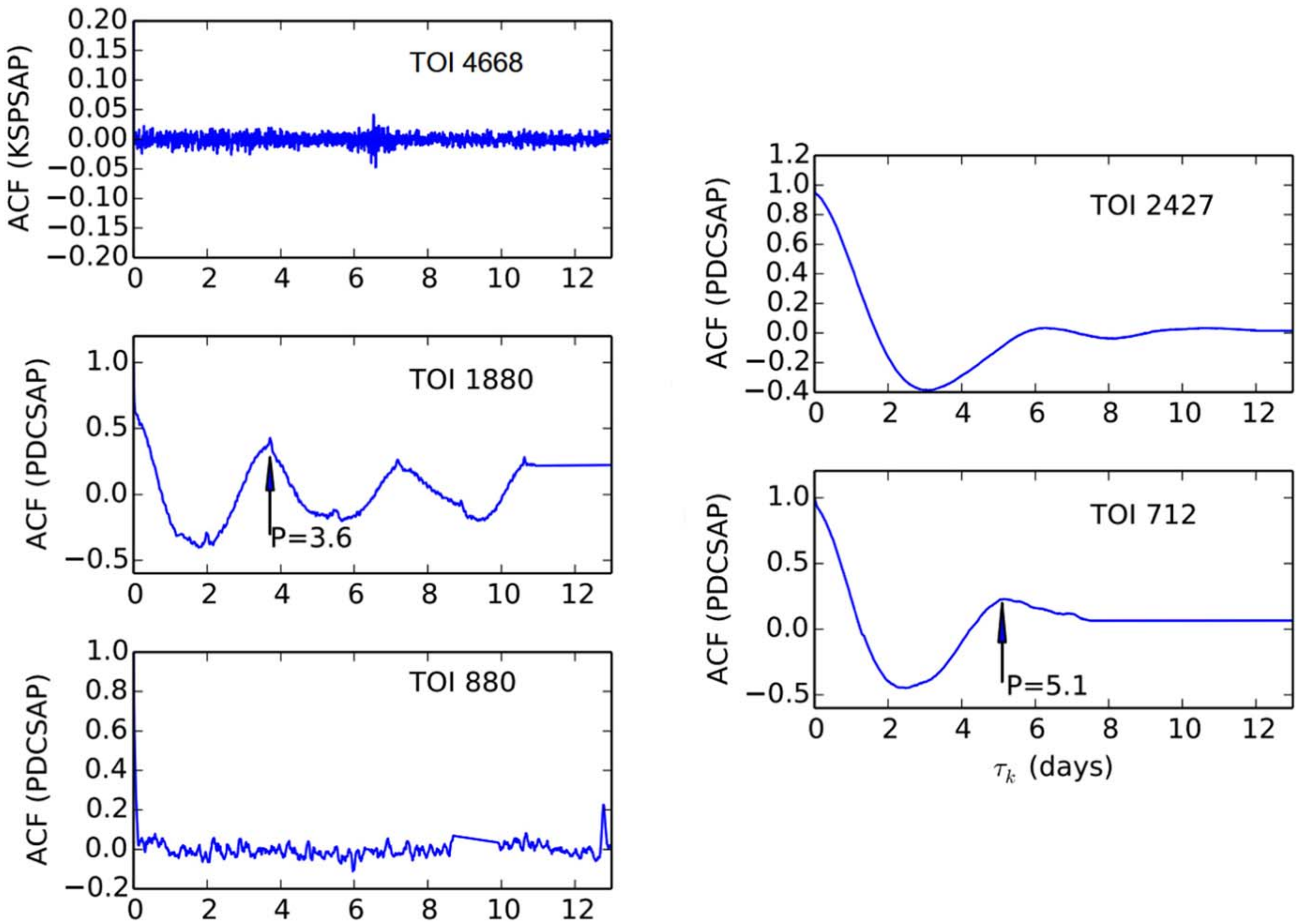

Figure 3. ACF for potential candidates in young associations. The TOI Id's of the candidates are marked on each subplot, and the rotation periods for TOI 1880 and TOI 712 are marked on the corresponding subplots.

(data retrieved on 2022 April 25). To derive $N_{\rm young}$, we start with a concatenated list of young stars from Bouma et al. (2022), which in their Table 3 includes 1,530,726 young stars. After we apply a similar magnitude cut of $G = 14.43$ mag by adopting the relationship from Equation (2) of Stassun et al. (2009, Tmag = Gmag—0.430), we have 388,207 remaining young stars. We then reasonably assume that 50% of the young stars are in an OC or YA environment, to arrive at $N_{\rm young}$ of 194,104.

The number of TOIs is 5038, and after substituting these numbers into Equation (2), we find $N_{\rm TOI,young} \sim 33$. This estimation is generally consistent with, but in the meantime a bit higher than, our total number of planet candidates in OCs and YAs. Note that the 10 planets discussed in Section 3.2 all have BANYAN Σ $P > 95\%$, and given that their BANYAN Σ designations are likely wrong, the other candidates with $P < 95\%$ may belong to another YA undiscovered by BANYAN Σ.

4. Summary

The current TESS Objects of Interest Catalog includes over 5000 young planet candidates nearby. We search for planets in 1229 open clusters based on the TESS Objects of Interest Catalog. We find one confirmed planet (TOI 837.01), one brown dwarf (TOI 681.01), one promising candidate (VPC+, TOI 1881.01) and three more unverified due to lack of data (TOI 4668.01, TOI 2538.01, TOI 581.01). For promising candidates, follow-up studies are possible with large telescopes.

We use the BANYAN Σ algorithm to derive the probability for TOI candidates to be members of nearby young stellar associations. Ten candidates have BANYAN Σ membership probability >95%, among which five are known planet systems. We use the TESS light curves to derive rotation period and apply the gyrochronology method to derive ages for the other five candidates. Two of them show periodic variations likely caused by stellar rotation. Their age discrepancies with the best matched young associations suggest these objects are likely young planets with unknown membership to young associations. The other three non-periodic candidates are likely not young stars and the young association dispositions are wrong. The number of planet candidates in OCs and YAs is consistent with our expectation.

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Facilities: Exoplanet Archive, TESS.

Software: matplotlib (Hunter 2007), BANYAN Σ (Gagné et al. 2018).

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