

Evolutionary status of T Tauri stars

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Abstract The problem of determining the masses and ages of T Tauri star (TTS) using their evolutionary status is discussed. We test four pre-main sequence evolutionary models using well determined observational parameters of 12 binary TTSs and two binary red dwarfs. It is shown that the masses derived using the tracks of all models are in good agreement with the masses obtained from the observations of TTSs with masses $M > 0.7 M_{\odot}$ (mean error $\varepsilon \sim 10\%$). Low-mass stars with $M \leq 0.7 M_{\odot}$ have significantly greater mean error: $\varepsilon \sim 50\%$ for the tracks of Bressan et al. and Chen et al., and $\varepsilon \sim 30\%$ for the other tracks. The isochrones of all tested evolutionary models diverge for stars with masses $M \leq 0.7 M_{\odot}$. The difference increases with the mass decrease and can reach 10% of Kelvin-Helmholtz time for stars with mass $M = 0.2 M_{\odot}$. The ages of most of the considered TTSs are smaller than the Kelvin-Helmholtz time. This confirms their evolutionary status of being pre-main sequence stars.

Key words: stars: pre-main sequence stars — stars: binaries — Hertzsprung-Russell diagram

1 INTRODUCTION

We have cataloged information about 57 double-lined spectroscopic binary T Tauri stars (TTSs) with known orbital elements (Dudorov & Eretnova 2016, 2017). There are 14 systems among those with well determined masses and radii. It is possible to determine the masses and radii of other stars using their evolutionary status, i.e. from the positions of stars on the evolutionary tracks and isochrones on the Hertzsprung-Russell diagram.

Dudorov & Eretnova (2016, 2017) used the tracks and isochrones of D’Antona & Mazzitelli (1994) for testing the evolutionary status of particular TTSs. A number of papers were published in the last few years concerning the evolutionary models of pre-main sequence (PMS) stars (Siess et al. 1997, 2000; Baraffe et al. 2002, 2015; Dotter et al. 2008; Bressan et al. 2012; Chen et al. 2014 etc.). There is a problem with choosing the most suitable system of tracks and isochrones for determining the masses and ages of TTSs.

Mathieu et al. (2007) discussed the PMS stellar evolutionary models of Simon et al. (1994), Burrows et al. (1997), D’Antona & Mazzitelli (1994), D’Antona &

Mazzitelli (1997), Baraffe et al. (1998), Palla & Stahler (1999) and Siess et al. (2000). They used 23 PMS stars with well-defined dynamical masses from the observations for testing theoretical models. They have shown that masses of massive stars are determined by evolutionary tracks with an accuracy of 20%. The error in mass determination using the tracks can be 50% or more in the case of low-mass stars.

Stassun et al. (2014) tested 13 PMS evolutionary models on the basis of observational data about 13 eclipsing binary stars with masses $0.04 - 4.0 M_{\odot}$. They concluded that the error does not exceed 10% in the case of stars with masses $M \geq 1 M_{\odot}$. In the opposite case, the error reaches $\sim 50\% - 100\%$. These authors noted the model of Dotter et al. (2008) is more appropriate for determining stellar masses and ages due to smaller errors.

Lacour et al. (2016), Baraffe et al. (2015), Gillen et al. (2014), Stempels et al. (2008) and others also estimated masses and ages of individual young eclipsing binary stars by evolutionary models. All authors note the problem associated with the correspondence between theory and observational data for low-mass stars. Therefore, comparing new evolutionary models of PMS

stars with observational data remains an important problem.

In this paper, we compare new and modified evolutionary tracks and isochrones of low-mass PMS stars from Bressan et al. (2012), Chen et al. (2014) (hereafter Padova) and Baraffe et al. (2015) (hereafter BCAH15) with tracks and isochrones from D’Antona & Mazzitelli (1994) (hereafter DM94) and Dotter et al. (2008) (hereafter referred to as Dartmouth2008). We use the observational data on 12 TTS binaries and two binary red dwarfs with well determined masses. T Tauri type stars with masses $0.5 M_{\odot} < M < 2.5 M_{\odot}$ belong to spectral classes from F to M (Herbig 1962). Red dwarfs are stars with spectral class M and masses $0.15 M_{\odot} < M < 0.5 M_{\odot}$.

The sample of binary TTSs and their main parameters are discussed in the second section. Determination of the masses of TTSs by evolutionary status and their comparison with reliable observational data are presented in Section 3. In Section 4, the ages of the sample of stars are determined by isochrones. The main results are summarized in Section 5.

This paper is based on a talk presented at the “Stars and Interstellar Medium” section of the All-Russian Astronomical Conference VAK-2017 that was held on 2017 September 17-22 (see Samus & Li (2018) for a review of the section).

2 SAMPLE OF T TAURI STARS

The main parameters of binary TTSs and red dwarfs with well-defined absolute and relative elements are presented in Table 1. Eleven systems are observed as eclipsing double line spectroscopic binary stars (EB+SB2), while three stars are visual spectroscopic binaries (VB+SB2). Nine eclipsing binary stars are the same as in Stassun et al. (2014). We have added the two eclipsing spectroscopic binary stars AK Sco and BM Ori, and three visual spectroscopic binaries to them.

Table 1 contains the stars and their periods (first column), masses M_{12} , radii R_{12} , luminosities L_{12} and effective temperatures T_{12} of the components (second, third, fourth and fifth columns, respectively). The upper lines in each column show the parameters of the primary components, while lower lines list parameters of the secondary components. The sixth column contains the name of the parent star formation region and the distance r to it. The last column provides the references. The param-

eters of stars are listed with errors if they are given in the referred papers. We use the nomenclature defined in the General Catalogue of Variable Stars (Samus’ et al. 2017). If a different identifier for a star is used in the referred papers, it is shown in parentheses. If the star is not in the General Catalogue of Variable Stars, its identifier from the referred article is indicated.

3 MASSES OF T TAURI STARS

Let us discuss the DM94, Dartmouth2008 and Padova evolutionary models for stars with masses $0.15 M_{\odot} < M < 2.5 M_{\odot}$ and the BCAH15 model for stars with $0.15 M_{\odot} < M < 1.4 M_{\odot}$. The models are constructed for stars with chemical composition $X = 0.7$, $Y = 0.28$ and $Z = 0.02$, using OPAL opacity and mixing length theory (MLT) convection.

Figure 1 and Table 2 show that all evolutionary tracks of stars with masses $M > 0.7 M_{\odot}$, except for Padova tracks, are similar to each other. The temperature steps for the Dartmouth2008 and Padova models are $\Delta T = 80 - 100$ K, and for the BCAH15 and DM94 tracks $\Delta T = 150 - 180$ K. It follows from Table 2 that the temperature difference between tracks of various models does not exceed the grid step of the tracks associated with the given system for stars with $M > 0.7 M_{\odot}$. Temperature difference for the Padova tracks is greater. In addition, the profiles of Padova tracks for small masses are very different from the other ones and have segments with a negative slope in the profile, which probably indicates instability in stellar models.

Figure 2 shows the system of Dartmouth2008 evolutionary tracks and isochrones. The squares in the figure represent the positions of binary TTSs from Table 1 with known masses. We estimate the masses of the stars with the help of interpolation between the evolutionary tracks with errors of the order of 10%. They are presented in Table 3 (third, fifth, seventh and ninth columns). The top line in each column provides the mass of the primary component, and the bottom line lists the mass of the secondary component. The fourth, sixth, eighth and tenth columns contain errors of mass estimation by tracks with respect to the observed values of mass

$$\varepsilon = \frac{M_{\text{obs}} - M_{\text{HR}}}{M_{\text{obs}}}, \quad (1)$$

where M_{obs} is mass determined from observations and M_{HR} is mass estimated using tracks.

Table 1 Parameters of T Tauri Stars

Star, period (1)	M_{12} (M_{\odot}) (2)	R_{12} (R_{\odot}) (3)	L_{12} (L_{\odot}) (4)	T_{12} (K) (5)	r (pc) (6)	Reference (7)
EB+SB2: both components are TTSs						
RS Cha 1.67 ^d	1.89±0.01 1.87±0.01	2.15±0.06 2.36±0.06	14.8±2.8 13.5±2.6	7640±80 7230±70	97 η Cha cluster	Alecian et al. (2005) Clausen & Nordstrom (1980)
ASAS J052821+0338.5 3.8729 ^d	1.375±0.010 1.333±0.008	1.83±0.01 1.73±0.01	2.05±0.16 1.38±0.11	5100±100 4700±100	280±30 Orion OB1a	Stempels et al. (2008)
AK Sco 13.609453 ^d	1.35±0.07 1.35±0.07	1.59±0.35 1.59±0.35	4.09±1.23 4.09±1.23	6500±100 6500±100	145±30 Upper Sco-Cen	Alencar et al. (2003)
V1642 Ori (RX J0529.4+0041) 3.03772 ^d	1.27±0.01 0.93±0.01	1.44±0.05 1.35±0.05	1.37±0.25 0.52±0.15	5200±150 4220±150	325 Orion OB1a	Covino et al. (2004)
V 1174 Ori 2.634727 ^d	1.009±0.015 0.731±0.008	1.339±0.015 1.065±0.011	0.64±0.07 0.17±0.02	4470±120 3600±100	419±21 Orion NC	Stassun et al. (2004)
CoRoT 223992193 3.8745745 ^d	0.670±0.01 0.495±0.05	1.30±0.04 1.11±0.04	0.30±0.05 0.17±0.03	3750±200 3500±200	800±100 NGC 2264	Gillen et al. (2014)
Par 1802* 4.673903 ^d	0.391±0.032 0.385±0.032	1.73±0.02 1.62±0.02	0.49±0.04 0.305±0.025	3675±150 3365±150	440±45 Orion NC	Chew et al. (2012)
JW 380* 5.29918 ^d	0.262±0.025 0.151±0.013	1.19±0.11 0.89±0.10	0.213±0.017 0.069±0.006	3590±120 3120±110	470 ONC	Irwin et al. (2007)
EB+SB2: only the second component is a TTS						
BM Ori 6.471 ^d	5.9 2.18	940 5.9	2.1 31.4	22000 9020	420 Orion Trapez.	Popper & Plavec (1976) Antokhina et al. (1989)
TY CrA 2.88878 ^d	3.16±0.02 1.64±0.01	1.80±0.10 2.08±0.14	67±12 2.4±0.8	12000±500 4900±400	129±11 -	Casey et al. (1998)
EK Cep 4.4277954 ^d	2.02±0.02 1.12±0.01	1.58±0.02 1.32±0.02	14.8±1.5 1.55±0.25	9000±200 5700±200	190 -	Popper (1987) Claret (2006)
VB+SB2: both components are TTSs						
V773 Tau A 51.1033 ^d	1.54±0.14 1.332±0.097	2.22±0.20 1.74±0.19	2.56±0.35 1.37±0.15	4900±150 4740±200	136.2±3.7 Taurus-Auriga	Boden et al. (2007)
V397 Aur (NTT 045251+3016) 2525 ^d	1.45±0.19 0.81±0.09	1.53 1.46	0.755±0.09 0.306±0.05	4345±160 3550±100	145±8 Taurus-Auriga	Steffen et al. (2001)
HD 98800 B 314.3 ^d	0.699±0.064 0.582±0.051	1.09±0.14 0.85±0.11	0.330±0.075 0.167±0.031	4200±150 4000±150	46.7±2 TW Hya	Boden et al. (2005)

Notes: * Components of Par 1802 and JW 380 are red dwarfs.

Mean values of errors in mass determination using tracks ε_m , mean values of absolute errors $|\varepsilon|_m$ and standard deviations σ from mean values are given in Table 4.

Table 3 shows that masses M_{HR} and M_{obs} are in good agreement for most TTSs with $M > 0.7 M_{\odot}$. The error $\varepsilon \leq 15\%$ is used for all evolutionary models. The errors $\varepsilon \sim 30\% - 50\%$ are only for components of NTT 045251+3016 and for the secondary component of

V1174 Ori. NTT 045251+3016 is a visual spectroscopic binary star. The stars with $M \leq 0.7 M_{\odot}$ have a significantly larger difference between M_{HR} and M_{obs} (they are italicized in Table 3). The error $\varepsilon \leq 30\%$ for the TTSs, while ε can be $\sim 100\%$ for red dwarfs. Such errors for individual stars cannot be explained by errors in the effective temperatures and luminosities (see Table 1).

Table 2 Maximum Track Offsets Relative to the Dartmouth2008 Tracks ($\Delta T = T - T_{\text{Dartmouth}}$)

Model	Track masses							
	$1 M_{\odot}$	$0.9 M_{\odot}$	$0.8 M_{\odot}$	$0.7 M_{\odot}$	$0.6 M_{\odot}$	$0.5 M_{\odot}$	$0.4 M_{\odot}$	$0.2 M_{\odot}$
BCAH15, $\Delta T(\text{K})$	+40	+70	+60	+55	+40	+50	+45	+10
DM94, $\Delta T(\text{K})$	+40	+70	+60	+100	+110	+150	+165	+160
Padova, $\Delta T(\text{K})$	+120	+210	+220	-220	-250	-250	-285	-400

Table 3 Masses of T Tauri Stars Estimated Using Tracks

Star	$M_{12\text{obs}}$ (M_{\odot})	DM94		Dartmouth2008		Padova		BCAH15	
		$M_{12}(M_{\odot})$	ε	$M_{12}(M_{\odot})$	ε	$M_{12}(M_{\odot})$	ε	$M_{12}(M_{\odot})$	ε
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
EB+SB2: both components are TTSs									
RS Cha	1.89	2.0	0.069	1.79	0.053	1.79	0.053	–	–
	1.87	2.0	7.0	1.78	4.8	1.77	5.4	–	–
ASAS	1.375	1.57	-0.142	1.58	-0.149	1.58	-0.149	1.50	-0.091
J052821+0338.5	1.329	1.33	0.001	1.31	0.014	1.27	0.044	1.38	0.038
AK Sco	1.35	1.46	-0.082	1.35	0.0	1.36	-0.007	1.38	-0.022
	1.35	1.46	-0.082	1.35	0.0	1.36	-0.007	1.38	-0.022
V1642 Ori	1.27	1.30	-0.024	1.31	-0.032	1.31	-0.032	1.29	-0.016
(RX J0529.4+0041)	0.93	0.92	0.011	0.95	-0.022	0.79	0.15	0.92	0.011
V 1174 Ori	1.009	1.09	-0.08	1.10	-0.09	1.04	-0.031	1.10	-0.09
	0.737	0.43	0.412	0.50	0.316	0.69	0.056	0.44	0.398
CoRoT	0.670	0.53	0.201	0.550	0.179	0.70	-0.045	0.51	0.239
223992193	0.495	0.37	0.253	0.39	0.212	0.60	-0.212	0.37	0.253
Par 1802	0.391	0.45	-0.151	0.43	-0.10	0.52	-0.33	0.42	-0.074
	0.385	0.28	0.273	0.28	0.273	0.35	0.091	0.27	0.299
JW 380	0.262	0.40	-0.527	0.44	-0.679	0.64	-1.443	0.40	-0.527
	0.151	0.13	-0.139	0.17	-0.126	0.36	-1.384	0.17	-0.126
EB+SB2: only the second component is a TTS									
BM Ori	5.9	–	–	–	–	–	–	–	–
	2.18	2.4	-0.101	2.20	-0.01	2.18	0.0	–	–
TY CrA	3.16	–	–	–	–	–	–	–	–
	1.64	1.63	0.006	1.55	0.055	1.53	0.067	–	–
EK Cep	2.02	2.0	0.014	1.91	0.055	1.90	0.059	–	–
	1.12	1.18	-0.054	1.18	-0.054	1.18	-0.054	1.14	-0.018
VB+SB2: both components are TTSs									
V773 Tau A	1.54	1.64	-0.065	1.55	-0.007	1.53	0.007	–	–
	1.332	1.35	-0.014	1.35	-0.014	1.30	0.024	1.40	-0.051
V397 Aur	1.45	1.00	0.310	1.01	0.303	0.88	0.393	1.02	0.297
	(NTT 045251+3016)	0.81	0.37	0.543	0.39	0.519	0.53	0.346	0.37
HD 98800 B	0.699	0.90	-0.288	0.92	-0.316	0.81	-0.159	0.86	-0.230
	0.582	0.73	-0.259	0.76	-0.310	0.73	-0.259	0.75	-0.293

Table 4 Mean Errors of Determination for the Masses Using Tracks and Standard Deviations

Model	$M \leq 0.7 M_{\odot}$			$M > 0.7 M_{\odot}$		
	ε_m	$ \varepsilon _m$	σ	ε_m	$ \varepsilon _m$	σ
DM94	-0.08	0.261	0.292	0.028	0.115	0.190
Dartmouth2008	-0.108	0.274	0.325	0.055	0.096	0.163
Padova	-0.477	0.499	0.593	0.054	0.085	0.131
BCAH15	-0.065	0.262	0.303	0.081	0.133	0.210

Table 5 Ages of T Tauri Stars Expressed in Fraction of the Kelvin-Helmholtz Time

Star name	t_{12}/t_{KH}	t_{12}/t_{KH}	t_{12}/t_{KH}	t_{12}/t_{KH}
	DM94	Dartmouth2008	Padova	BCAH15
EB+SB2: both components are TTSs				
RS Cha	4.44	4.17	3.91	–
	3.95	4.22	3.96	–
ASAS	0.62	0.62	0.56	0.68
J052821+0338.5	0.28	0.29	0.26	0.34
AK Sco	3.81	3.81	3.59	3.81
	3.81	3.81	3.59	3.81
V1642 Ori	0.76	0.68	0.68	0.91
(RX J0529.4+0041)	0.25	0.26	0.20	0.28
V 1174 Ori	0.40	0.40	0.32	0.43
	0.10	0.11	0.20	0.11
CoRoT	0.16	0.16	0.24	0.16
223992193	0.12	0.16	0.30	0.14
Par 1802	0.38	0.31	0.51	0.38
	0.21	0.16	0.31	0.18
JW 380	0.69	0.80	1.37	0.69
	0.40	0.40	1.45	0.46
EB+SB2: only the second component is a TTS				
BM Ori	–	–	–	–
	12.1	10.9	12.1	–
TY CrA	1.51	1.51	1.51	–
	0.34	0.29	0.29	–
EK Cephei	5.40	3.40	3.59	–
	1.94	1.83	1.83	2.14
VB+SB2: both components are TTSs				
V773 Tau A	0.40	0.38	0.38	0.45
	0.38	0.38	0.29	0.37
V397 Aur (NTT 045251+3016)	0.12	0.14	0.10	0.14
	0.07	0.06	0.11	0.07
HD 98800 B	0.56	0.56	0.42	0.56
	0.53	0.58	0.53	0.53

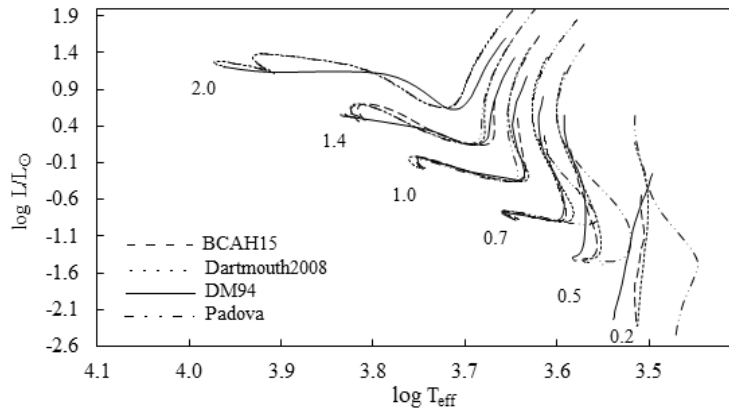


Fig. 1 Evolutionary tracks for PMS stars, labeled by mass (in solar units).

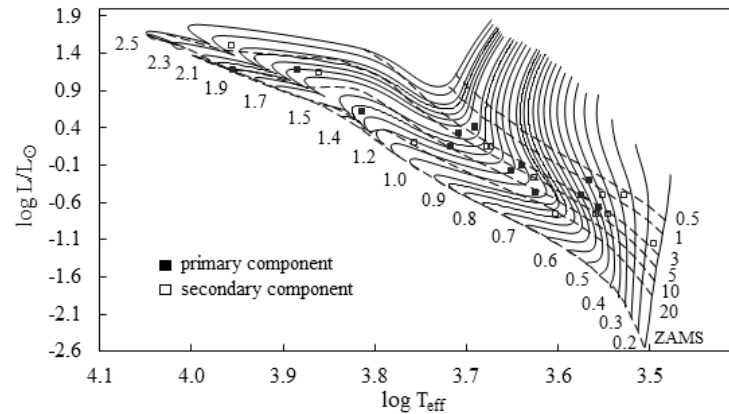


Fig. 2 The Hertzsprung-Russell diagram for TTs. The Dartmouth2008 evolutionary tracks are shown by *solid lines*, labeled by mass (in solar units). The *dashed lines* are the isochrones, labeled by Myr.

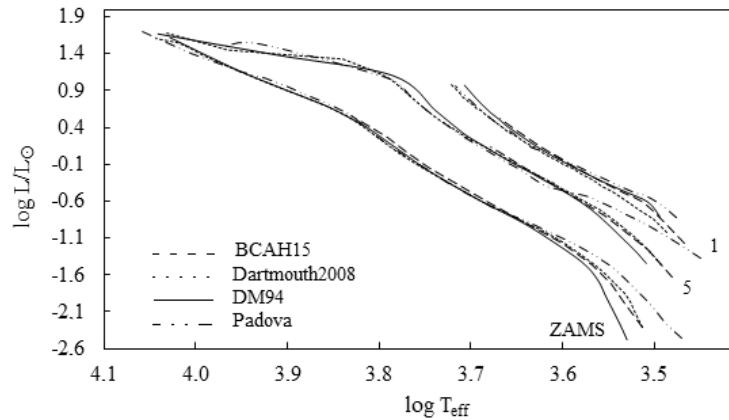


Fig. 3 Isochrones for PMS stars, labeled by age (in Myr).

The values of mean absolute errors and standard deviations are close to each other in all models for TTs with $M > 0.7 M_{\odot}$ (see Table 4). They are $|\varepsilon|_m \sim 10\%$ and $\sigma \sim 15\% - 20\%$. For stars with $M \leq 0.7 M_{\odot}$,

mean absolute errors and standard deviations are $\sim 30\%$ in the DM94, BCAH15 and Dartmouth2008 models, and $|\varepsilon|_m \sim 50\%$ and $\sigma \sim 60\%$ in the Padova model. The masses found on Padova tracks are systematically larger

than the masses obtained from observations for almost all stars with $M \leq 0.7 M_{\odot}$ (mean error $\varepsilon_m = -47.7\%$).

4 AGES OF T TAURI STARS

The position of a star on the isochrones in the Hertzsprung-Russell diagram allows one to determine its age and evolutionary status. Figure 3 illustrates the isochrones of PMS stars. We estimate the ages of the stars in our sample by interpolation between the isochrones.

Table 5 shows the ages of the stars expressed in fractions of the Kelvin-Helmholtz contraction time (Kippenhahn & Weigert 1990)

$$t_{\text{KG}} = 1.6 \cdot 10^7 \cdot \left(\frac{M}{M_{\odot}}\right)^2 \cdot \left(\frac{R_{\odot}}{R}\right) \cdot \left(\frac{L_{\odot}}{L}\right). \quad (2)$$

The upper line in Table 5 gives the age of the primary component, while the lower line is the age of the secondary component. The stars with $M \leq 0.7 M_{\odot}$ are italicized.

Figure 3 and Table 5 demonstrate that the ages of TTSs in our sample, defined using the tracks from various models, are slightly different from each other. The radii of stars with the same age increase with the transition from the DM94 to the Dartmouth2008 and BCAH15 models, and even more when moving to the Padova model. In the region of red dwarfs, isochrones diverge. The difference increases with the mass decrease and can reach 10% of the Kelvin-Helmholtz time for mass $M = 0.2 M_{\odot}$.

The stars RS Cha and AK Sco, and the secondary components of EK Cephei and BM Ori, have the ratio $t/t_{\text{KG}} > 1$. All these stars are at the end of the PMS evolutionary stage. Errors in mass, luminosity, effective temperature and radii determination could lead to an underestimation of the Kelvin-Helmholtz time (2) or to an overestimation of the age found from the tracks.

5 CONCLUSION

We compare modified evolutionary models of Padova (Bressan et al. 2012; Chen et al. 2014) and BCAH15 (Baraffe et al. 2015) with the DM94 (D’Antona & Mazzitelli 1994) and Dartmouth2008 (Dotter et al. 2008) models using well determined observational parameters of 12 TTS binaries and two binary red dwarfs.

Our study shows that the masses and ages of TTSs can be determined using any of the considered evolutionary models of PMS with an accuracy of about 10%. The

temperature difference between tracks of the discussed models exceeds the grid step of the tracks for stars with a mass $M \leq 0.7 M_{\odot}$. Temperature difference for the Padova tracks is very large and the profiles of Padova tracks are very different from the other ones. The stars with $M \leq 0.7 M_{\odot}$ have significantly greater mean values for their absolute error. It is $\varepsilon \sim 30\%$ for the DM94, Dartmouth2008 and BCAH15 tracks and $\varepsilon \sim 50\%$ for the Padova tracks.

The isochrones of all tested evolutionary models diverge from the stars with masses $M \leq 0.7 M_{\odot}$. The ages of most of the stars in our sample are smaller than the Kelvin-Helmholtz time of stars for the corresponding mass. This confirms their evolutionary status of being PMS stars.

In the future, it will be necessary to further improve the theoretical models of low-mass PMS stars, as well as to increase the number of binary stars with well defined parameters from observations. Additional theoretical work is required to improve the convection theory and to take into account the effects of magnetic field and rotation on the internal structure and evolution of low-mass stars.

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