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Understanding the evolution of planetary systems with GAPS2

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Abstract. The INAF Global Architecture of Planetary Systems (GAPS) project, gathers a large part of the Italian community working on exoplanets by using the high resolution spectrographs mounted at the TNG. In particular, the Young Objects sub-program aims to investigate the origin of the observed diversity of the planetary systems by observing them at young ages (up to a few hundreds of Myr), when planets are closer to their formation time and possibly to their birth-sites, and the formation and evolution processes are still at play. The main difficulty in this kind of study is the high level of stellar activity of the host stars, able to mask planet-induced signals in radial velocity time series. The main results of the survey include the confirmation and the retraction of known planet candidates, the contribution in the evaluation of the frequency rate of planets around young stars, and the characterization of young transiting planets with the measurement of their mass. GAPS observations are also supported by simulations of the atmospheric photo-evaporation and the dynamical scenarios of the systems. All these studies contribute to unveil the still poorly known scenario of the formation and evolution of young close-in planets.

Key words. Planetary systems – Planets and satellites: detection – Stars: activity – Techniques: radial velocities

1. Introduction

In the last decades, more than 5000[1] exoplanets in single or multi-planet systems were discovered, showing huge differences in their physical, orbital and architectural properties. The origin of the planetary system diversity should be studied by considering the initial conditions of their formation (e.g. properties of the protoplanetary disc, stellar multiplicity, crowded environment) and the mechanisms acting on different timescales (early planetary migration through the disc, Baruteau et al. 2014; secular high-eccentricity migration followed by tidal circularization, Chatterjee et al. 2008; atmospheric photo-evaporation, Owen & Lai 2018). Observations of planetary systems around young stars (from few to a few hundreds of Myr) is the only way to investigate their original configurations and physical properties. At this stage, the planets are

[1] http://exoplanet.eu/

potentially closer to their formation time and possibly to their birth-sites. However, some exceptions show that the planetary migration processes are still not completely understood (see e.g. Sect. 3.4). Young planetary systems are the most suitable for a global investigation of both their inner and outer regions: the former through the radial velocities and transits techniques, the latter by using direct imaging, which exploits the infrared emission of the planet due to the residual heat from the formation process (e.g. Desidera et al. 2022).

In the particular case of close-in young exoplanets, the blind detection through a radial velocity (RV) survey is very challenging due to the intense stellar activity of their host stars, which can easily mask planet-induced signals (Huélamo et al. 2008; Carleo et al. 2018). On the other hand, transit space missions are providing more robust candidates to be followed-up with dedicated RV surveys (e.g. Benatti et al. 2021). In fact, if the stellar photometric modulation is not extremely variable with different time-scales, the typical transit duration (a few hours) is shorter than the rotational modulation (a few days), so uninterrupted photometric time-series are in principle less affected by the stellar activity with respect to the spectroscopic ones.

The Young Objects (YO) sub-program of the "GAPS" (Global Architecture of Planetary Systems) project (see Covino et al. 2013; Carleo et al. 2020), is currently performing such investigation by using the high resolution spectrographs mounted at the Telescopio Nazionale Galileo (TNG). To date, the main results of our survey, described in Section 3, include the confirmation and the retraction of known planet candidates and the characterization of young transiting companions, giving the first clues on the properties of the young close-in planets population.

2. The GAPS2-Young Objects survey

One of the main objectives of the YO sub-program is the monitoring of young (< 20 Myr) and intermediate age (< 700 Myr) stars to search for hot/warm Jupiters and Neptune-like planets in formation or during the early stage of their evolution within the timescales of migration. This allows us to confirm or retract the apparent high frequency of hot Jupiters around very young stars (Donati et al. 2016; Yu et al. 2017). To perform such investigation, we selected a list of interesting targets, organized in three different samples:

- known planet candidates from RV surveys;
- targets with no previous indications of planet companions (i.e. blind search);
- young transiting candidates provided by the NASA TESS (Ricker et al. 2014) and K2 (Howell et al. 2014) space missions.

The orbital periods of our sample range between ~ 0.55 and ~ 45 days, with typical value around 12 days. The radii range between ~ 1.3 and ~ 12 $R_\oplus$ with typical value of ~ 3.2 $R_\oplus$. An overview of the orbital and physical parameters of the planets investigated by our Team is presented in Sect. 4.

After more than four years of GAPS2-YO observations and the extraordinary TESS contribution in the field, we found no evidence of high frequency of hot Jupiters around young stars (Damasso et al. 2020). We also confirmed that RV-based discoveries are heavily hampered by the high level of the stellar activity of the young hosts (tens of times larger than the planet signal). For this reason, our observing strategy evolved with the time, giving higher priority to young transiting planet candidates observed with high cadence RV sampling. This is mandatory to provide constraints to our modelling tools (e.g. Gaussian processes, GP) for the activity mitigation. On the other hand, the observation of the same planet with both transit and RV allows its full characterisation, since the two methods provide the measure of the radius and the mass, respectively.

Our observations are mainly obtained with the high-resolution HARPS-N spectrograph in the visible range (Cosentino et al. 2012). At the beginning of our program we also exploited the GIARPS configuration (Claudi et al. 2017) to obtain simultaneous data from HARPS-N and GIANO-B (Oliva et al. 2006), the high-resolution spectrograph in the near-IR (see Sect. 3.1). However, the characteristics of the transiting candidates in our sample limited the RV monitoring with GIANO-B: being the spectrograph not stabilised like e.g. HARPS-N, it can not provide enough precise RVs. Finally, we also perform quasi-simultaneous photometric follow-up (STELLA robotic observatory, Strassmeier et al. 2004; INAF-REM telescope, Molinari et al. 2004 and the Schmidt Telescope in Asiago, Italy) to monitor the stellar activity.

Our work is complemented by additional efforts to evaluate the age of the targets in our sample (e.g. Carleo et al. 2021; Messina et al. 2022), their stellar parameters and abundances (Baratella et al. 2020), the characterization of the host activity (Di Maio et al. 2020; Maldonado et al. 2022) and the evaluation of the high-energy irradiation effects of the star on the planet atmosphere (Maggio et al. 2022). Finally, we pay attention to the optimization of the RV extraction and simulations to test the robustness of our results (Damasso et al. 2020).

3. Results

In this Section, we report the main results of the GAPS2-YO survey obtained to date.

3.1. Confirmation of HD 285507 b and rejection of AD Leo b

In Carleo et al. (2020) we exploited the GIARPS configuration to confirm the presence of a hot Jupiter orbiting every 6.09 days around the Hyades star HD 285507 (Fig. 1) On the contrary, the RV signal of the claimed super Earth around the young M dwarf AD Leo is not recovered in our data. We ascribe the putative planetary periodicity to the stellar activity signal of the host.

3.2. Is V830 Tau b really there?

In Damasso et al. (2020) we presented three different RV extraction methods and GP modelling supported by simulations to recover the claimed hot Jupiter around the 2-Myr old star V830 Tau (Donati et al. 2016). No signal was detected in our HARPS-N data dominated by the rotation, putting some doubts on the presence of this companion and the high frequency of giant planets around very young stars.

3.3. Two hot Neptunes around TOI-942

The first young multi-planet system detected by TESS was validated by Carleo et al. (2021) (alongside Zhou et al. 2021) around the 50-Myr old K star TOI-942 (TYC 5909-319-1). According to the analysis of TESS data (Fig. 2), the two transiting hot Neptunes show periods of 4.3 and 10 days. Mass upper limits of 16 and 37 $M_{\oplus}$, respectively, resulted from the GAPS data. We also performed simulations on the atmospheric mass loss of the planets according to their mass upper limit: a quick evaporation is expected, in particular for planet b. Further observations are ongoing to measure or better constrain the masses of the planets.

3.4. The benchmark system of V1298 Tau

V1298 Tau is a 20 Myr old K star with four transiting planets detected by K2. We share the efforts with a team of Spanish collaborators and perform a joint RV and light curve model and obtained the mass determination for the two outer planets (Suárez Mascareño, Damasso et al. 2021). With a mass of 0.6 and 1.2 M_{Jup} and radius of 0.87 and 0.73 R_{Jup}, respectively, these planets show an unexpected high density. This result leads to a negligible photo-evaporation of their atmospheres (Maggio et al. 2022), confirming that relatively massive planets can reach their final position in the mass-radius diagram very early in their evolutionary history. Further observations are ongoing to measure the masses of the two inner planets and to clarify the actual period of planet e. Finally, in Turrini et al. (submitted) the formation history and the dynamical evolution of this intriguing system is investigated.

3.5. The youngest USP rocky planet

In Nardiello et al. (2022) we present the mass determination of the ultra-short period (USP) planet TOI-1807 b, first detected by TESS. This rocky planet ($R = 1.37\ R_{\oplus}$, $M = 2.72\ M_{\oplus}$) orbits the K star BD+39 2643 every 0.55 days. Fig. 3 shows both the transit and the RV signal after the removal of the strong ac-

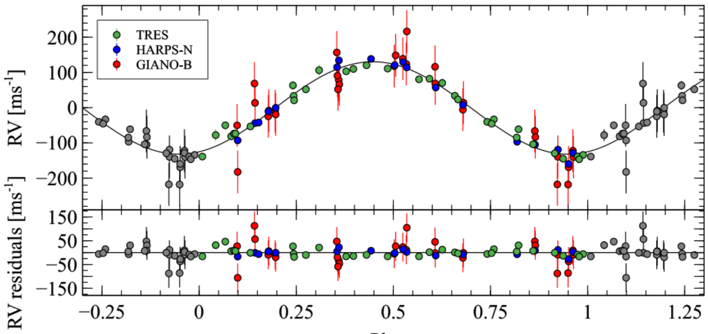

Fig. 1. Orbital fit (black line) of HD 285507 obtained combining the data from HARPS-N (blue diamonds), GIANO-B (red dots), and the available data from the TRES spectrograph (green dots). Credit: Carleo et al. (2020), reproduced with permission ©ESO.

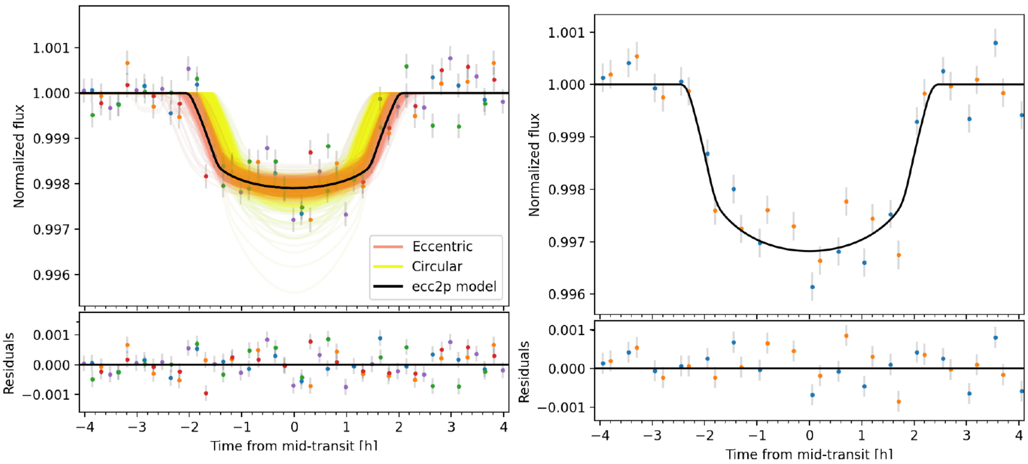

Fig. 2. Transit signals of TOI-942 b and c. Right panel: TESS light curve around the transit of TOI-942 b fitted with different models: the orange, yellow and black fits indicate the eccentric, the circular, and the two-planet eccentric transit model, respectively. Left panel: TESS light curve around the transits of TOI-942 c, with the two-planet eccentric model overplotted. Below each panel, the residual light curve is shown. Credit: Carleo et al. (2021), reproduced with permission ©ESO.

tivity signal of the star. TOI-1807 has been found to be a member of the recently discovered Group X (Tang et al. 2019 and references therein), a stellar moving group subsequently dated through Gyrochronology by Messina et al. (2022). With an age of 300 Myr, TOI-1807 b is the youngest USP planet known so far.

4. Discussion and conclusions

RV surveys like GAPS2-YO, supported by the essential contribution of TESS and K2, allow to put preliminary constraints on the young close-in planets population scenario and to put them in the broader context. The emerging picture can be summarised as follows:

– The apparent high frequency of very young hot Jupiters ($\lesssim$ 50 Myr) has been questioned after the recent results (see also

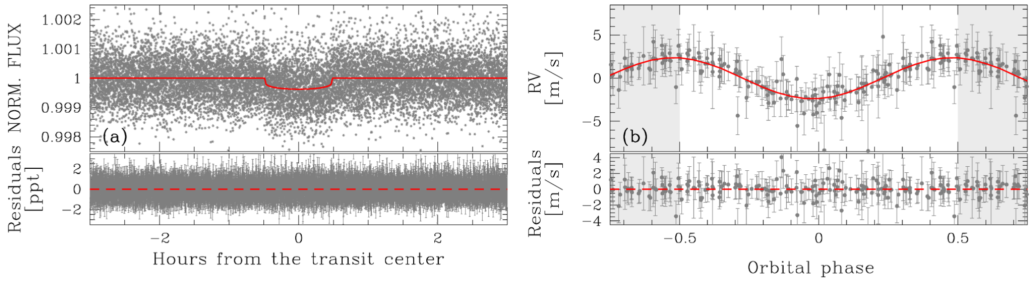

Fig. 3. Photometric and RV modeling of the TOI-1807 b signal. *Left panel*: folded transits data in the TESS light curve and the corresponding model (red line). *Right panel*: HARPS-N RV curve phased with the period of TOI-1807 b and corresponding model (red line). Below each panel, the residuals of the data are shown. Credit: Nardiello et al. (2022), reproduced with permission of the author.

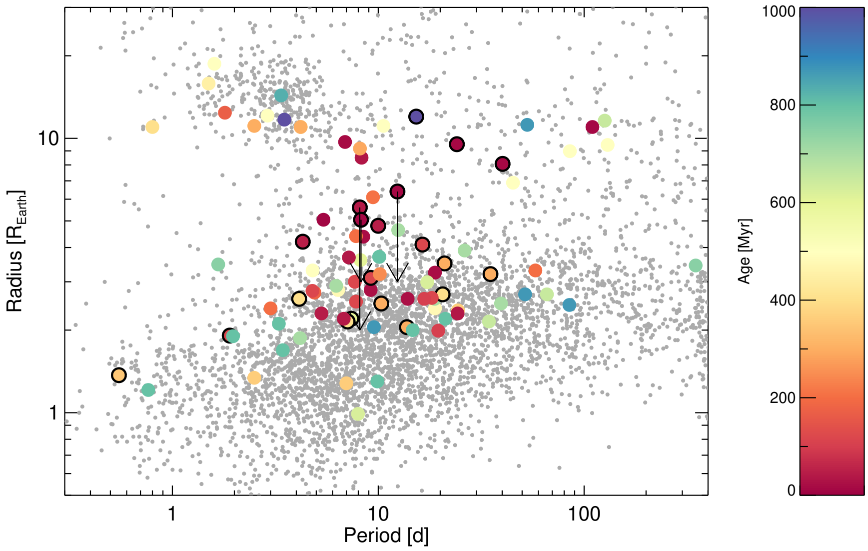

Fig. 4. Period - Radius diagram of the currently known planet polulation (grey dots). Young planets are overplotted with coloured circles according to the age of system, **while those planets investigated by GAPS are highlighted in black. The black arrows indicate the expected final location of a few targets according to our simulations concerning the atmospheric mass loss due to the photo-evaporation.**

Donati et al. 2020) and the TESS data, even if a few of these objects were robustly found (Rizzuto et al. 2020; Bouma et al. 2020). This would confirm the conclusions of Bonomo et al. (2017) who showed that the preferential formation channel of the hot Jupiters is through the planet-planet scattering (from a few hundreds of Myr up to 1 Gyr), even if some exceptions can occur. However, a proper study on the young giants occurrence rate, including the probability that a large photometric variability could mask or affect transit signatures, is still lacking.

– On the contrary, TESS observations suggest that the typical radius of close-in planets younger than a few hundreds of Myr is lower than the Jupiter one (e.g. Benatti et al. 2019; Mann et al. 2020; Newton et al. 2021; Barragán et al. 2022). However,

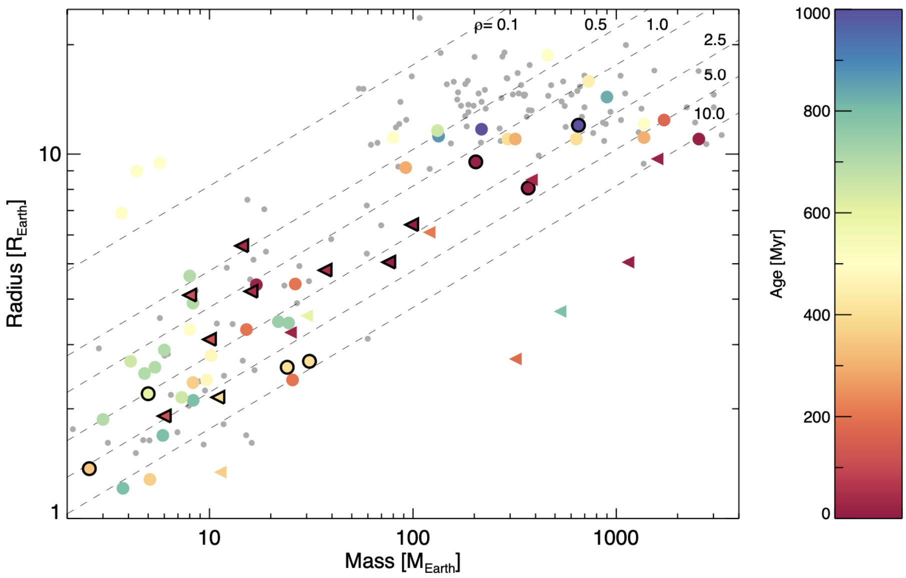

Fig. 5. Mass - Radius diagram of the currently known planet population with robust determination of these two parameters (grey dots). Young planets are overplotted with coloured circles according to the age of system. Triangles pointing toward lower masses indicate that for that particular planet is only available the mass upper limit, i.e. we expect that their position in the diagram to be more on the left. Diagonal dashed lines indicate the loci of equal density (g cm^{-2}). All the planets investigated by GAPS-YO are highlighted in black.

the ongoing Kelvin-Helmholtz contraction and the atmospheric evaporation due to the intense high-energy irradiation from their host star suggest that they can be a highly inflated planets. This confirms the previous findings by K2 (e.g. Kraus et al. 2015), and the theoretical predictions (e.g. Linder et al. 2019). Fig. 4 allows to visualize this scenario. Grey dots represent the mature-age exoplanet distribution in the Period-Radius diagram. The young planets known to date are reported with circles of different colours according to the age of the system, and those investigated by GAPS are highlighted black. Most of them are located in the upper edge of the main distribution and in the triangular-shape region less populated in the diagram. According to our predictions on the atmospheric mass loss rate due to the photo-evaporation, we expect that this unusual distribution is temporary. Possibly, many of those planets with radii between ~ 3 and ~ 7 $R_\oplus$ will "migrate" toward lower radii at the end of their evolution. Some examples of their possible path and their final location is represented by the black arrows depicted for three planets analysed by our team, DS Tuc A b (Benatti et al. 2021) and V1298 Tau c and d (Maggio et al. 2022). It should be note that this is a preliminary distribution, where selection effects can be present. For instance, smaller radii planets are more difficult to discover due to the high level of the stellar activity of their host stars. Moreover, a few planets showing high density represent an exception of the general trend (e.g. V1298 Tau b & e, Suárez Mascareño, Damasso et al. 2021; TOI-179 b, Desidera et al. 2022)

– As a consequence of the above picture, *i)* a dependency of the planet Mass-Radius (M-R) relation with the age is expected. However, the verification of this hypothesis is still conditioned to the difficulties to robustly measure the planetary masses. Fig. 5 compares the M-R relation of the older (grey dots, considering only those planets having measured masses and radii with uncertainty better than 20 and 10%, respectively) and younger (colored as a function of the age and represented with circles when the mass is known at $\sim$ 30% and triangles pointing toward lower masses when only a mass upper limit is available) populations. A clear difference between the distributions is not obvious, in particular if we consider young planets with age $\gtrsim$ 300 Myr. On the other hand, for the most interesting targets, i.e. those younger than 100-200 Myr which represent a significant fraction of the planets identified in the "forbidden" region in Fig. 4, only the mass upper limit is available, being the host stars much more active. We can conjecture that those objects show a lower density with respect to the mature counterparts of equal mass, but this could be verified only with a robust determination of their mass.

– Because of their potential low density and the large scale height, young planets are in principle excellent targets for atmospheric characterisation, e.g. through the transit spectroscopy. However, models from Wang & Dai (2019) and Gao & Zhang (2020) suggest that the presence of high-altitude clouds and hazes could increase the atmospheric opacity, while observations by Palle et al. (2020) and Benatti et al. (2021) show that the stellar activity represents a limit also in the search for atmospheric features, at least for planets younger than $\sim$ 50 Myr. At this stage, the activity features can be highly variable even over the transit time-scale and this represents an obstacle for a proper correction of the data.

The search and characterisation of planets around young stars is a relatively new and fascinating branch of the exoplanets field. Currently, a lot of efforts in terms of evolution modelling, observations, and data analysis techniques are performed by many research teams throughout the world. The GAPS2-Young Objects program is actively contributing to unveil the typical properties of such objects, useful to place robust constraints on the exoplanets formation and evolution history. Beside the results summarised in the present paper, additional works are currently in preparation or submitted. Moreover, the observations of the program are still ongoing, so we plan to present additional studies with further investigations on young exoplanetary systems.

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