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An inTerdisciplinary pAthway to the identification of Solar SystEm anaLogs (TASSEL)

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Abstract. How common are true Solar System analogs? This is a key question at the forefront of research in exoplanetary science. Detection techniques have unveiled the astonishing diversity of properties of exoplanets, but their sensitivity to Solar System-like architectures (i.e. inner rocky planets in the stellar temperate zone, outer giant companions, asteroid belts, cometary reservoirs) is still limited. In the TASSEL project we assembled for the first time an Italy-wide scientific collaboration among major experts in observations and modeling of exoplanets and Solar System, and information technology for astrophysics. In this interdisciplinary project we combined, modelled, and interpreted data of the highest quality gathered from NASA and ESA space missions and from the ground, to measure the properties of planetary systems with hierarchy in mass and orbital separation resembling our own, thus provided a decisive step forward towards the identification and frequency determination of true Solar System analogs

Key words. planets and satellites: formation — planets and satellites: dynamical evolution and stability

1. Introduction

The comparison with the astonishing diversity of the orbital and physical properties of known planetary systems to-date indicates that the one we live in is unlike any others. However, the limited sensitivity of detection techniques to Solar-System-like architectures (i.e. with inner rocky planets in the stellar temperate zone, outer giant companions, asteroid belts, and cometary reservoirs) suggests that the result could be due to observational biases rather than an intrinsically low frequency of true analogs of the Solar System. This is about to change, however, thanks to the increased capabilities of space- and ground-based observational programs now starting and coming online in the next decade.

The goal of the TASSEL project was to provide a decisive step forward towards identifying and estimating the occurrence rate of true Solar System analogues. The project aimed to use very high quality photometry data from the K2, TESS (Transiting Exoplanet Survey Satellite) and CHEOPS (CHaracterising ExOPlanet Satellite) missions in conjunction with very high precision radial velocity (RV) measurements obtained with the high resolution spectrographs HARPS, HARPS-N (High Accuracy Radial velocity Planet Searcher, and its twin in the Northern hemisphere) and ESPRESSO (Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations) to measure radii, masses, densities and orbital configurations of hot and temperate Super Earths and sub-Neptunes transiting stars with a wide range of masses and ages. These were combined with information on astrometric accelerations and non-single star solutions from the third intermediate catalog of the Gaia mission (DR3), radial velocity measurements and high-contrast image observations with the SPHERE/VLT (Spectro-Polarimetric High-contrast Exoplanet REsearch instrument at the Very Large Telescope) instrument to discover the presence of massive planets at intermediate and wide separation in transit systems. The synergy between Hipparcos-Gaia absolute astrometry and direct imaging observations allowed determining the dynamical masses of reference objects detected directly around young primaries. Kinematic measurements based on Gaia DR3 allowed reconstructing the dynamic history of nearby young associations. For the sample of multiple planet systems with well-characterized mass and orbital properties for both the inner (low-mass) and outer (massive) companions, within the project we produced detailed studies to evaluate their long-term dynamical stability. We further analyzed the history of their dynamic evolution by comparing it with other planetary systems, to find evidence of possible correlations between multiplicity order, mass hierarchy and orbital properties. The results of the dynamical modeling allowed us to verify the existence of intervals of orbital separations in which different populations of minor bodies (asteroids and comets) could reside. In our Solar System, minor bodies undergo intense dynamic and collisional evolution. We numerically investigated their collisional evolution history to identify possible observables, paying particular attention to the statistics of impacts between minor bodies and planets. The analysis included an evaluation of gas production by possible cometary material, both through thermal and collisional processes. Finally, our results allowed us to make inferences about the effective frequency of planetary system architectures analogous to that of the Solar System, which could be studied in the future, with for example, PLATO (PLAnetary Transits and Oscillations of stars) and NGRST (Nancy Grace Roman Space Telescope). To reach the projects goals, we assembled an Italy-wide team with observational and theoretical knowledge on the Solar System and exoplanetary science, and with expertise on information technology applied to astrophysics.

In this paper we illustrate the TASSEL activities and the main results as they were obtained within the context of the four scientific Work Packages of the project: inner regions of planetary systems (WP2, Sect. 2), outer regions of planetary systems (WP3, Sect. 3), dynamics and database access (WP4, Sect. 4), and minor bodies evolution (WP5, Sect. 5). We draw conclusions and future prospects in Sect. 6.

2. Inner regions of planetary systems

We achieved the project objectives within the activities of WP2 with a multi-tiered approach.

The systematic analysis of the internal regions of planetary systems was carried out

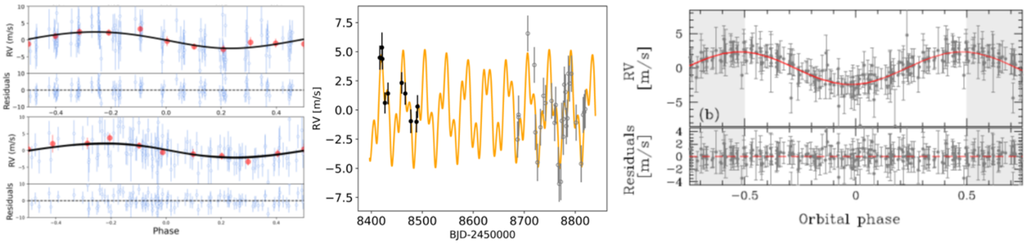

Fig. 1. Left: HARPS-N RV data phase-folded to the period of TOI-1422 b (top) and TOI-1422 c (bottom), along with their residuals over the model. The red circles represent the average value of phased RV data points (adapted from Naponiello et al. 2022). Center: ESPRESSO RV times series for HD 5278 with the bestfit two-planet solution being overplotted (yellow curve (adapted from Sozzetti et al. 2021). Right: Phase-folded bestfit RV curve overplotted to the HARPS-N data (top) and RV residuals (bottom) for TOI-1807 b (adapted from Nardiello et al. 2022).

on the basis of the selection of small-sized transiting planet candidates ($< 4\ R_{\oplus}$) starting from photometric data from the K2 and TESS missions. Subsequent spectroscopic follow-up was planned and performed with the ESPRESSO (Guaranteed Time Observations program, GTO) and HARPS-N (GTO and Global Architecture of Planetary Systems, GAPS, long-term program) spectrographs. Some of the selected candidates turned out to be multiple systems and became priority targets for detecting transit time variations (TTVs) with the combination of TESS and CHEOPS data. A system of two hot Neptunians identified by TESS around the young star TOI-942 has been successfully validated using a combination of tools for the photometric and spectroscopic characterization of the properties of the central star and the two transiting planets (Carleo et al. 2021). The combination of K2 and TESS photometry and radial velocity data with ESPRESSO (GTO) and HARPS-N (GTO) enabled the high-precision measurement of the density of three super-Earths and one sub-Neptune around HD 39091/π Mensae (Damasso et al. 2020), K2-111 (Mortier et al. 2020), TOI-1634 (Cloutier et al. 2021) and TOI-130 (Sozzetti et al. 2021), respectively. By combining TESS, SOPHIE (Spectrographe pour l'Observation des Phénomènes des Intérieurs stellaires et des Exoplanètes) and HARPS-N data, a short-period super-Neptune was identified around TOI-1710 (König et al. 2022), and a low-density Neptune around TOI-1422 (Naponiello et al. 2022). Examples of RV orbital fits obtained for some of the companions discussed above are shown in Figure 1. The discovery of an ultra-short-period ultra-dense, super-massive Neptune-sized companion around TOI-1853 (Figure 2) calls into question formation processes involving multiple collisions between protoplanets (Naponiello et al. 2023). The combination of TESS and HARPS-N/ESPRESSO data also allowed the characterization of the compact system of 4 small planets around TOI-561, containing in particular an ultra-short period super Earth with a very low density (Lacedelli et al. 2021), the characterization of the multiple system around HD 23472, containing three super-Earths and two potential super-Mercuries (Barros et al. 2022), the identification of a short-period rocky planet with only half the mass of Venus around the low-mass star L98-59 and the density measurement for two other Earth-type planets in the same system (Demangeon et al. 2021). HARPS-N and ESPRESSO data revealed a second (non-transiting) Neptunian-type planet around K2-111 and TOI-130, respectively, and a fourth non-transiting super-Earth companion in the L98-59 system.

The combined analysis of TESS photometry and very high precision radial velocities with HARPS-N/HARPS/ESPRESSO has finally allowed the characterization of a young system of two short-period sub-

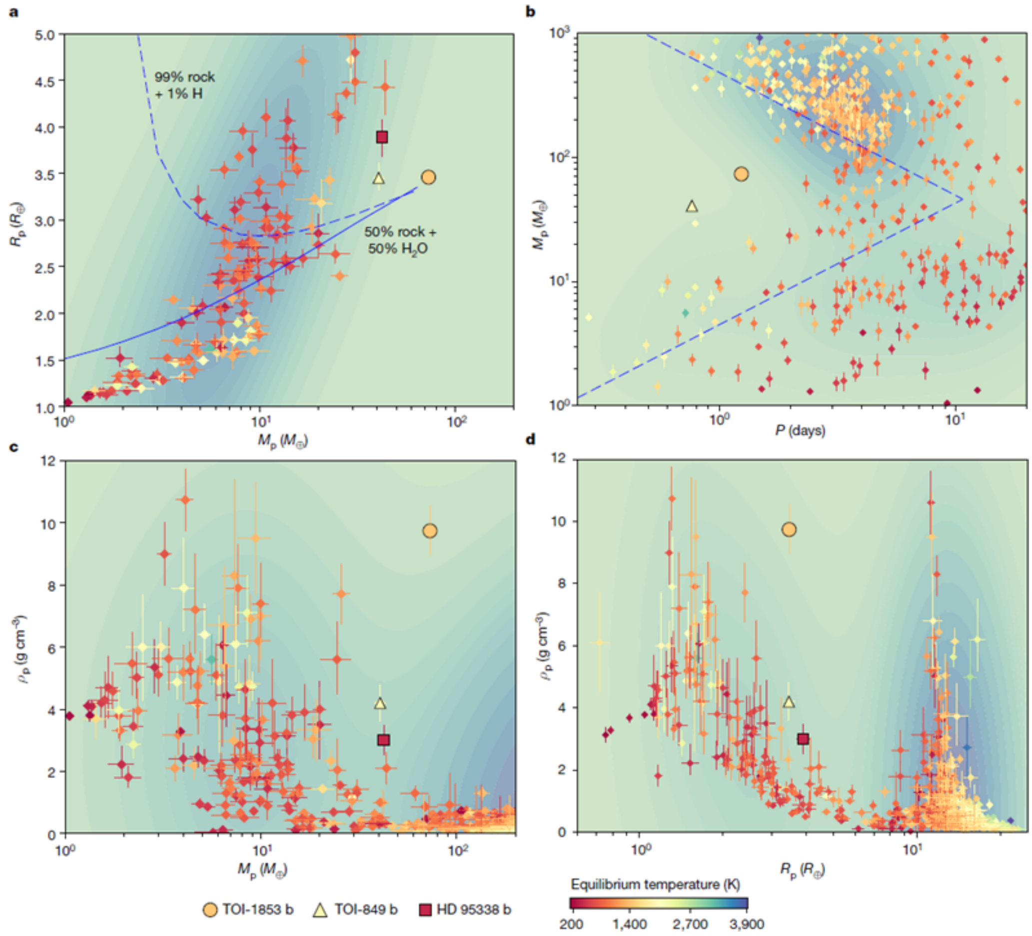

Fig. 2. Diagrams of known transiting exoplanets (diamonds), placing TOI-1853 b in context. Color-coding is associated with an object's equilibrium temperature. Along with TOI-1853 b (circle), TOI-849 b (triangle) and HD 95338 b (squares) are also shown. Top left: Radius– mass diagram with blue lines representing different internal compositions (dashed line, 99% Earth-like rocky interior + 1% H layer (at temperature and pressure of 1,000 K and 1 mbar, respectively); solid line, 50% Earth-like + 50% water). Top right: Period–mass diagram, in which the dashed blue line encloses the Neptunian desert. Bottom left: Mass–density diagram. Bottom right: Radius–density diagram. (adapted from Naponiello et al. 2023).

Neptunes around HD 63433 with an estimated age of 400 Myr (Damasso et al. 2023a), the characterization of a Neptunian companion on a short-period, high eccentricity orbit around TOI-179 with an estimated age of 400 Myr (Desidera et al. 2023), the precise measurement of the density of a young super-Earth of ultra-short period around TOI-1807 with an estimated age of 300 Myr (Nardiello et al. 2022), and the density measurement of the two outermost companions in the multiple planetary system around V 1298 Tau, with an estimated age of 20 Myr (Suárez Mascareño et al. 2021). The high density of the two objects, which implies an accelerated contraction of their radii contrary to theoretical predictions, stimulated further analyzes with CHEOPS, for an improvement in the determination of the orbital and physical parameters of the outermost companion (Damasso et al. 2023b).

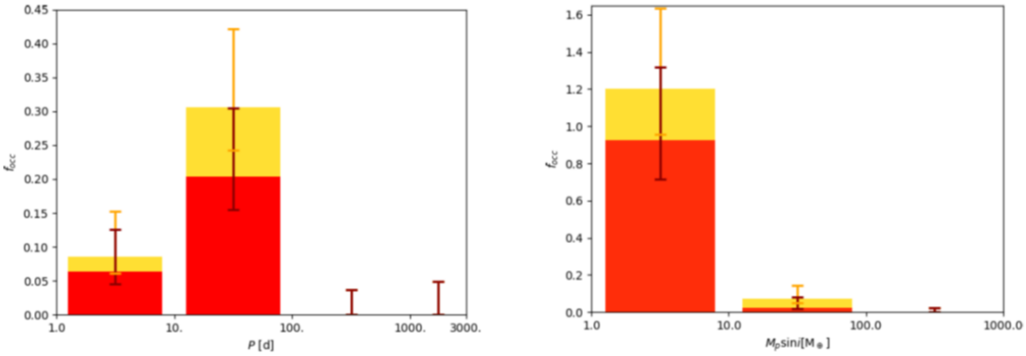

Fig. 3. Planetary occurrence rates around early M dwarf primaries from the HADES survey as a function of orbital period and minimum mass. The red and yellow distributions correspond to the occurrence rates derived from confirmed-only, and confirmed+candidates planets, respectively (adapted from (Pinamonti et al. 2022)).

As part of the GAPS collaboration, short-period Neptunian-type companions were identified thanks to high-rate HARPS-N observations at the TNG (Telescopio Nazionale Galileo) around stars known to have massive long-period outer companions (cool Jupiters with periastron > 1 au), BD-114672 (Barbato et al. 2020), HD 164922 (Benatti et al. 2020), GJ 328 (Pinamonti et al. 2023) and HD 13931 (Pinamonti et al. in prep.). The discovery of these systems has allowed us to fundamentally increase the number of multiple systems with a hierarchy of separation and mass similar to that of our Solar System, i.e. containing super-Earths with small separations and giant planets with separations beyond the snow-line of ice.

Three fundamental statistical analyses were produced during the project: 1) based on the analysis of long-term RV time series collected with HARPS-N within the GAPS project, in Pinamonti et al. (2022) the occurrence rate f(SN) of low-mass planets (super-Earths and Neptunes) at short separation from M0-M3 spectral type primaries was determined (Figure 3), finding that f(SN) = 85±30% for super-Earths ($1 < M_p < 10\ M_\oplus$) within 100 d of orbital period, but f(SN) = 10% for Neptunian-type companions ($10 < M_p < 30\ M_\oplus$); 2) always using long-term HARPS-N observations, in Pinamonti et al. (2023) we determined the frequency f(SN|CJ) of short-period super-Earths and Neptunes around M dwarfs in the presence of a cold Jupiter-type companion on external orbit, finding that f(SN|CJ) = 25% for Neptunian type companions. This implies that f (SN|CJ) > f(SN) with a probability of 95%. The fact that short-period Neptunes appear more common around M dwarfs with an outer Jupiter is an extremely important result as a test of models of planet formation around cool stars; 3) based on long-term RV monitoring with HARPS-N of small-scale transiting systems discovered by Kepler and K2, in (Bonomo et al. 2023) we discovered 5 cold long-period Jupiters in three systems, and determined the occurrence rate f(CJ|SN) of outer Jupiters ($1 - 10$ au) in the presence of super-Earths and inner sub-Neptunes around stars of solar type, finding that f(CJ|SN) = 10%. This estimate implies that the impact of the presence of outer Jupiters on the formation of small planets in the inner regions could be different around primaries of different mass. A new RV monitoring program is being executed with HARPS-N/TNG and the FIES (FIbre-fed Echelle Spectrograph) on the NOT (Northern Optical Telescope) telescope (PI: M. Pinamonti), to search for low-mass companions in systems with long-period Jupiters around spectral type stars K, intermediate between those of the solar type and the M dwarfs, in order to establish with further statistical confidence the existence of a dependence of the frequencies of architectures of planetary systems similar to that of the Solar System with the mass of the central star.

3. Outer regions of planetary systems

The activities carried out within WP3 tackled successfully a number of lines of investigation.

The detection and characterization of long-term companions using the Hipparcos/Gaia proper-motion difference technique coupled to direct imaging observations and RVs has been applied extensively using SPHERE, revisiting SPHERE-GTO data and with new open-time data. The results of these observations demonstrated the potential of this approach, achieving an order of magnitude increase in the detection efficiency of substellar companions with direct imaging (Bonavita et al. 2022). Particularly important in this context is the discovery of the planet AF Lep b in the beta Pic group (Mesa et al. 2023, + INAF-Press release, ASI-TV video, ESO picture of the week, see Figure 4). Coupling this revelation with those known from the literature in this association and with further objects with significant astrometric signature, a very high frequency of substellar objects in the ice snow-line region was obtained (> 58% for a confidence level of 95% , nominal frequency close to 100% for isolated stars with mass > 1 $M_{\odot}$ in a low-density environment such as the beta Pic moving group. See Gratton et al. 2023). Furthermore, the combination of imaging techniques with astrometry and possibly RV offers the possibility of determining the dynamic masses of substellar companions, allowing a better physical characterization of the detected objects. This technique has also been used in other systems with primaries of different ages and evolutionary status (GJ 3446, Beta Cyg). Furthermore, a combined RV + direct imaging analysis with SPHERE allowed us to produce important constraints on the characteristics of the cold super Earth candidate announced orbiting 1.5 AU from Proxima Cen (Gratton et al. 2020). Finally, the combined RV analysis + Hipparcos-Gaia DR3 absolute astrometry (Figure 5) allowed the measurement of the dynamical mass of the super-Jovian companion (3.6 $M_{\rm Jup}$) orbiting 3.5 au from GJ 463, an M dwarf with 0.49 $M_{\odot}$ (Sozzetti 2023). This object is particularly relevant, given that its existence is not explained naturally within the standard model of planet formation around low-mass stars. The investigation into the presence of possible internal low mass companions is under development.

The characterization of the external regions of the transiting candidates selected by WP2 for their validation was carried out in a systematic way considering the Hipparcos/Gaia DR2/DR3 absolute astrometry and speckle imaging, available for all objects. The effectiveness of the combinatorial technique was initially tested as part of the characterization of the well-known multiple star system Albireo (Drimmel et al. 2021). Furthermore, a sample of 10 young stars (< 800 Myr) with transiting planets was observed with SPHERE at the VLT, reaching sensitivity up to the presence of giant planets in the outer zones of the system. This program produced the detection of a low-mass companion at the boundary between brown dwarfs and very low mass stars (TOI-179 B, see Figure 4), which also causes significant astrometric and RV trends of the central star and could be directly responsible for the eccentricity of the transiting planet (Desidera et al. 2023). Furthermore, the physical association of companion candidates was confirmed (from the discovery articles) around K2-100 and K2-136, stars with transiting planets that are members of open clusters (Hyades and Presepe, respectively).

The combination of TESS photometry, ESPRESSO (GTO) data and Hipparcos/Gaia absolute astrometry has enabled the first high-precision determination of strong misalignment between the orbits of the transiting super-Earth and the long-period super-Jovian companion (Figure 5) in the π Mensae system (Damasso et al. 2020). Through the analysis of the Hipparcos/Gaia proper motion differences and detailed simulations based on the RUWE (Renormalized Unit Weight Error) statistics of Gaia DR3 (indicator of the quality of the single star fit) it was also possible to place stringent limits on the presence of long-term companions around TOI- 130 (Sozzetti et al. 2021), TOI-1634 (Cloutier et al. 2021), TOI-

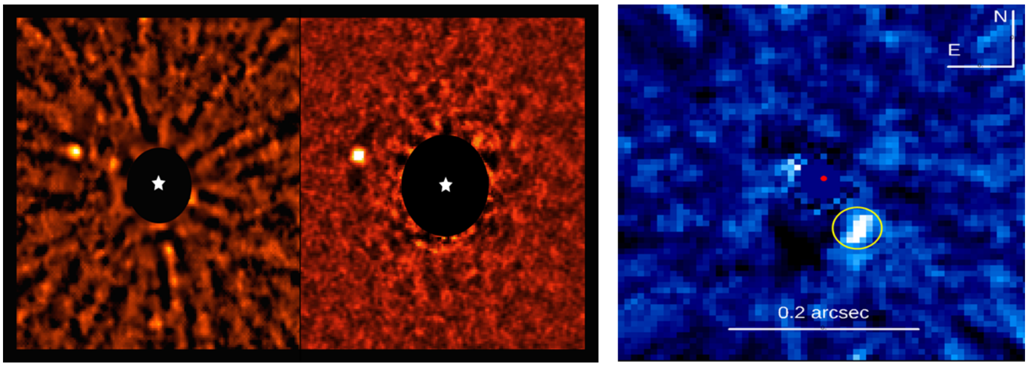

Fig. 4. Left: S/N maps around AF Lep (star image subtracted) both for SPHERE/IFS (left) and SPHERE/IRDIS (right). The low-mass companion is clearly visible in all the images northeast of the star (adapted from Mesa et al. 2023). Right: Detection of the low-mass companion TOI-179 B in the non-coronagraphic SPHERE images. The red dot gives the position of the star and the yellow circle shows the companion (adapted from Desidera et al. 2023).

4010 (Kunimoto et al. 2023) and the M dwarfs GJ 740 (Toledo-Padrón et al. 2021), GJ 720 A (González-Álvarez et al. 2021), GJ 9689 (Maldonado et al. 2021), GJ 514 (Damasso et al. 2022), GJ 1002 (Suárez Mascareño et al. 2023), and GJ 1151 (Blanco-Pozo et al. 2023) around which short-period super Earths and sub-Neptunes have been identified. The sample of stars with known long/intermediate period planets observed with HARPS-N at the TNG (see WP 2) was also studied to evaluate the presence of further companions in more external orbit (8 – 20 au, periods 25 – 80 yr), revealing three new substellar companions in a sample of 16 objects. The synergy with astrometry and direct imaging has allowed us to derive the orbital parameters and masses of these new companions (Ruggieri et al.; in prep.).

The release of Gaia DR3 occurred on June 13, 2022, which left insufficient time for systematic exploitation within the timeline of the TASSEL project in terms of orbital and acceleration solutions. A high-cadence RV monitoring program with HARPS-N of a small number of super-Jupiter candidates in orbits with $a > 1$ au around bright stars began in the last six months of the project's lifespan. The project delivered the spectroscopic confirmation of the astrometric signal of a Jovian-mass companion around the nearby low-mass star HIP 66074 (Sozzetti et al. 2023), which turned out to be on a very high-eccentricity orbit (Figure 6).

Preliminary statistical investigations of the connection between the presence of planets and debris disks were conducted as part of a PhD thesis and scholarship (C. Lazzoni). As part of the study of the HD 114082 system, the debris disk was spatially resolved thanks to observations acquired with SPHERE, while the analysis of the TESS photometric data allowed the discovery of a giant planet thanks to the identification of a single transit (Engler et al. 2023). The first detection of the disk in diffuse light around the young star EX Lupi was obtained (Rigliaco et al. 2020).

As regards the characterization of stellar associations, the history of the Upper Scorpius association was reconstructed by identifying numerous sub-components of different ages and a spatially widespread and older component (Squicciarini et al. 2021). The Lupus I star formation region was studied, selecting new member candidates from Gaia and confirming 12 of them thanks to spectroscopic observations obtained with X-SHOOTER at the VLT (Majidi et al. 2023). Thanks to Gaia astrometry and dedicated spectroscopic observations, a new group of young stars (age around 10 Myr) has been identified in the Cepheus region (Desidera et al. in prep.). Finally, as part of the stellar characterization of hosts of young

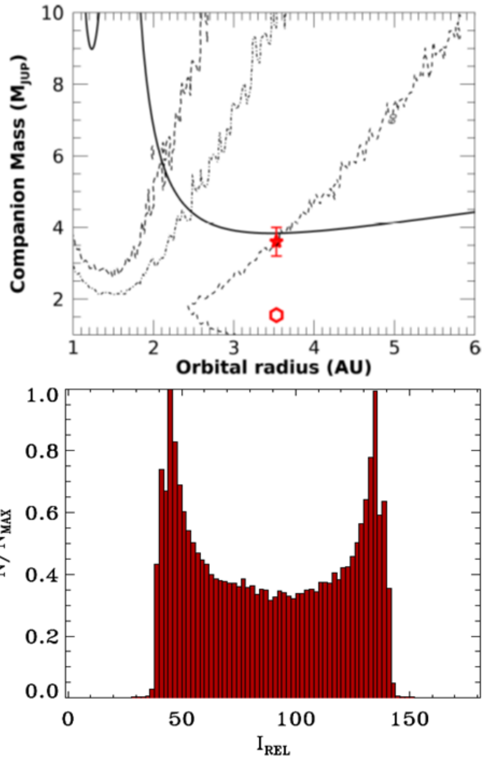

Fig. 5. Top: Hipparcos-Gaia PMA and Gaia DR3 sensitivity to companions of a given mass (in $M_{\rm Jup}$) as a function of the orbital semi-major axis (in au) orbiting GJ 463. Dashed, dashed-dotted, and long-dashed lines correspond to iso-probability curves for 60%, 95%, and 99% probability of a companion of given properties to produce RUWE > 1.407. The solid line identifies the combinations of mass and separation explaining the observed PMA at the mean epoch of Gaia DR3. The red hexagon and star indicate the $M_b \sin i$ value from Endl et al. (2022) and the true M_b value, respectively (adapted from Sozzetti 2023). Bottom: Distribution of possible mutual inclinations between π Mensae b and c based on a combined analysis of ESPRESSO RVs, TESS photometry, and Hipparcos-Gaia absolute astrometry (adapted from Damasso et al. 2020).

transiting planets, a new association with an age of 300 Myr has been identified thanks to Gaia data and TESS photometry which includes TOI-1807 and TOI-2076 and 21 other members (Nardiello et al. 2022) and the Group X association (which includes the planet host TOI-2048) was characterized, obtaining a gyrochronological sequence at an intermediate age between the Hyades and the Pleiades, to be used as a reference in this age interval (Messina et al. 2022).

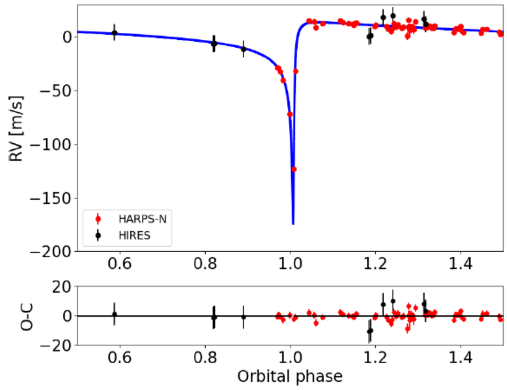

Fig. 6. Phase-folded HIRES and HARPS-N RVs of HIP 66074 superposed to the bestfit Keplerian orbit (blue curve), calculated using the median values of the posteriors. Phase zero (or phase one) corresponds to the time of inferior conjunction. The residuals of the best-fit model are shown in the bottom panel (adapted from Sozzetti et al. 2023).

4. Dynamics and database access

Within the scope of WP4 activities, the training a) of a data model update of the tool ExoplAn3T (Exoplanet Analysis and 3D Visualization Tool), produced by SSDC and available at `https://tools.ssdc.asi.it/exoplanet/`, and b) of the new algorithm for calculating the normalized angular momentum deficit (NAMD) was carried out through direct access to data of multiple planetary systems from an integrated version of existing catalogs (NASA Exoplanet Archive, Extrasolar Planet Encyclopedia, ExoMercat). The final version of ExoplAn3T allows the manipulation and visualization of various categories of parameters, planetary and stellar, photometric and spectroscopic, thanks to the implementation of a new data model. With the inclusion of the results relating to the characterization of systems with mass hierarchy and orbital separation similar to the Solar System obtained from WP2 and WP3, with ExoplAn3T we have

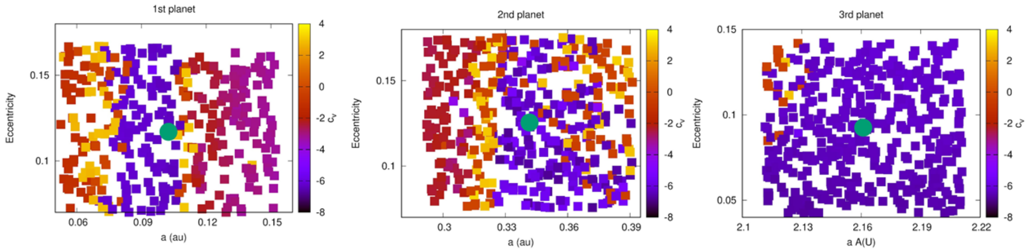

Fig. 7. Stability maps for the three planets of the HD 164922 system. They are obtained by fixing the orbital elements of the other two planets and varying the semi-major axis and eccentricity of the third. Darker colors indicate less diffusion in the phase space and therefore greater stability.

produced an updated catalog of systems with "Solar System-type" architectures.

Sophisticated codes and numerical simulations have been used to investigate the long-term dynamic evolutionary history of a selected number of particularly representative planetary systems. The applied methodology required the use of two different methods for determining the level of chaos of a planetary system, i.e. frequency analysis and MEGNO (Mean Exponential Growth of Nearby Orbits) stability indicator. Areas of dynamical stability (including the stellar habitability zone) were investigated in the three planetary systems around BD-114672, HD 164922 and π Mensae, known to have a long-period Jovian companion and which revealed the presence of super- Short-period Earths and Neptunes using HARPS-N data. For HD 164922, the stability of the system was studied first for small variations in the orbital elements of the 3 planets. All three planets are in a stable zone even if that relating to the two innermost planets is quite narrow. This implies that moderate variations in the orbits of the two inner planets would cause the system to be chaotic over relatively short times (Figure 7). With the same method, the possibility that a fourth planet, not yet discovered, could be found between the orbits of those already discovered was evaluated. A small stable region was found between 0.18 and 0.21 au (30-36 days of orbital period) within which a planet with a mass equal to that of the Earth could move without destabilizing the system and a larger one between 0.6 and 1.0 au (300-500 days orbital period). In the case of BD-114672, regions of dynamical stability were studied around the orbit of the new planet identified by HARPS-N of Neptunian mass. The system features a massive planet of about half the mass of Jupiter orbiting outward with a period of 1667 days. The investigation was carried out using the MEGNO stability indicator. The stability map for the orbit of the outermost planet, of which the semi-major axis and eccentricity have been varied, shows how the outer planet cannot have too high an eccentricity ($>$ 0.15), otherwise the entire system will destabilize. The possible presence of a terrestrial-type planet in the habitable zone of the system was also explored, demonstrating that a terrestrial planet has a wide range of possible orbital elements that guarantee its long-term stability. For semi-major axis values close to 0.6 au, the orbit can also be very eccentric with $e \sim 0.3$. In the case of π Mensae, the interest in dynamical analysis is dictated by the high mutual inclination between the inner planet and the outer brown dwarf which suggests the possibility of a Kozai-type eccentricity evolution. The numerical integration of the orbits of the two bodies of the system shows how the inner planet can reach high eccentricities and its orbit can even become retrograde (Figure 8). This result was obtained by assuming an initial eccentricity equal to zero, but different evolutions can be obtained with different initial values. The system therefore requires deeper dynamic exploration. Similarly, preliminary investigations of the possible dynamic interactions between the transiting Neptunian and the external massive companion (whose orbit is not completely constrained) in the TOI-179 system have allowed us to discard the sce-

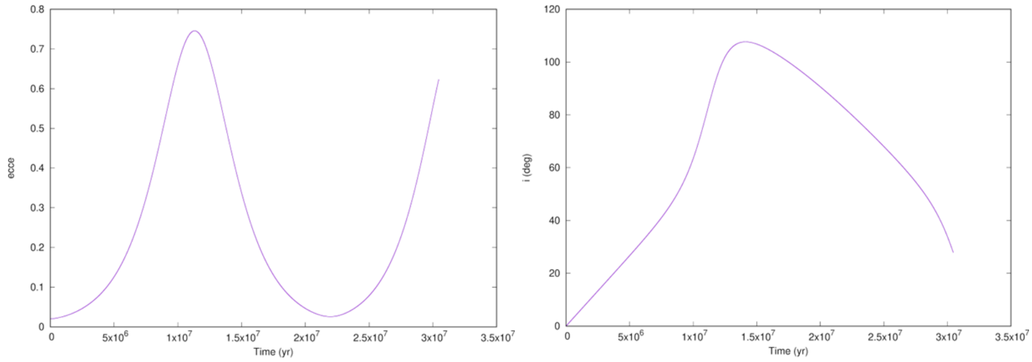

Fig. 8. Left: π Mensae c eccentricity vs. time. Right: π Mensae c inclination vs. time.

nario of excitation of the eccentricity of the internal planet via the Kozai mechanism, indicating a more likely origin in phases of dynamical instability with other companions in the system.

The discovery and characterization of the multiple system around V1298 Tau has produced a particular effort to investigate the dynamic stability present, in order to shed light on the peculiar configuration of the system and on the high density of the two outermost companions (b and e). In Turrini et al. (2023) we performed detailed N-body simulations to explore the link between the densities of V1298 Tau b and e and their migration and planetesimal accretion within the initial circumstellar disk. We combined N-body simulations and stability metrics to characterize the dynamic state of V1298 Tau and link it to the system's formation history. The high densities of V1298 Tau b and e suggest that they formed quite distant from their host star, probably beyond the CO2 snowline. The higher nominal density of V1298 Tau e suggests that it formed further away than V1298 Tau b. The current architecture of V1298 Tau does not feature a resonant chain and is unstable (Figure 9). Scattering phenomena with an outer planet are the most likely cause of the instability.

5. Minor bodies evolution

The primary focus of the activities of WP5 concerned a systematic investigation of the statistics of collisions within standard prototypes of debris disks, intervening mainly on the parameters of the possible disturbing planet. A series of simulations were then carried out, comparing the results with what was predicted by analytical theories, and more precisely the relationship that provides the average impact velocity as the position in the disk varies developed by Mustill & Wyatt (2009). These simulations were carried out with a Monte Carlo code capable of dealing with the dynamic behavior of the disk particles described according to the model developed in the first phase of the project. The numerical code, extensively tested in the case of collisions between asteroids in our Solar System, is able to calculate not only the average collision velocity, but also its distribution as well as the temporal frequencies of collision (Figure 10).

The results confirm the qualitative trend of the analytical theory, however highlighting quantitative differences in different aspects. The first concerns the explicit limits of the analytical theory, i.e. the hypothesis that the disk is unlimited in semi-major axis and that the inclinations, which determine the thickness of the disk, are zero. The first hypothesis does not take into account edge effects where particles placed at the inner (external) edge of the disk interact only with particles with a larger (smaller) semi-major axis, while our numerical model correctly deals with these cases. Remaining within the limitless thin disk hypothesis, and adapting the parameters of our model to this case, our numerical simulations indicate that the analytical theory systemati-

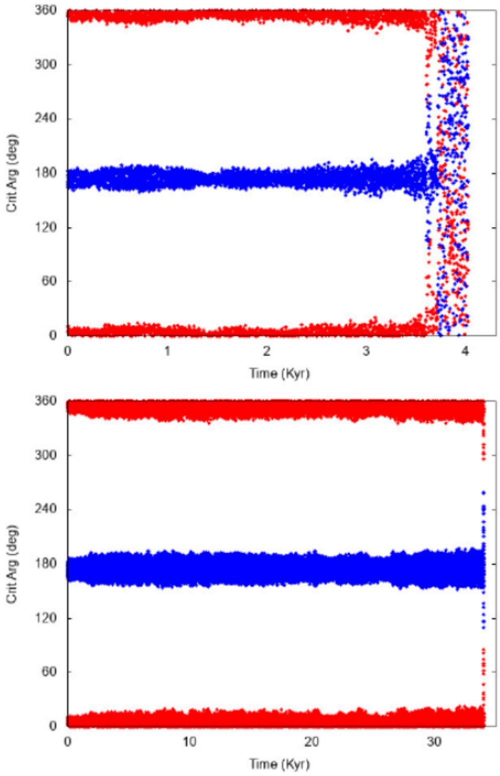

Fig. 9. Evolution of the critical argument of the outer planet pair (b and e) in the V1298 Tau system initially locked in a 3:2 resonance. In the upper panel, the additional planet has a mass $m = 200\ M_\oplus$, $a = 8$ au, $e = 0.95$, and $i = 10°$. In the bottom panel, a more massive planet on a less eccentric orbit was adopted ($m = 2\ M_{\rm Jup}$, $a = 4$ au, $e = 0.85$, and inclination $i = 2°$). In both cases, after a period of chaotic evolution, the onset of repeated close encounters breaks the resonance lock and leads to fast instability (adapted from Turrini et al. 2023).

cally overestimates by 10% to 20%, depending on the case, the average speed of collision.

However, if it is assumed that the inclinations of the particles are not zero, as the inclinations increase the average collision speed progressively increases, as is natural to expect, to the point of overcompensating for the difference highlighted above with respect to the analytical theory. It was also highlighted that the inclinations of the particles have a further effect in modifying the dependence of the average impact speeds on the position in the disk. The analytical theory of the thin disk predicts that in the case in which the disturbing planet is internal (external) to the disk, the average collision velocity decreases (increases) with the distance from the central star. The simulations have shown that in the second case (external planet), allowing the particles to have increasingly higher inclinations, this dependence first cancels out and soon reverses, i.e. the average impact velocity tends to decrease with the distance from the star. An effect also occurs in the case of the internal perturbing planet, where as the inclinations increase the rate of decrease in the average collision speed with the distance from the star tends to decrease, compared to that predicted by analytical theory (Figure 10.

Finally, another difference found compared to the analytical theory concerns the dependence of the average impact velocity on the eccentricity of the disturbing planet. In both the case of an inner and outer planet, analytical theory predicts that the average impact velocity is proportional to the eccentricity of the planet. If in the case of internal planets this dependence seems to be substantially confirmed by our simulations, in the case of external planets the average impact velocity is less than proportional to the eccentricity of the disturbing planet. The statistical parameters of the mutual collisions would then be used within a collisional evolution code specifically developed for the study of debris disks. Unfortunately, due to the premature death of a key member of the team, it was not possible to finalize some objectives of the task, in particular the integration of the modules relating to the production of volatile component following mutual collisions (dust and gas) into the codes collisional evolution.

6. Outlook

Exoplanetary astrophysics is today a key priority at the center of the scientific agendas of all the leading international institutions in astronomy as well as space agencies, with a broad, multi-technique portfolio of ground- and space-based programs across a wide range of wavelengths. In the recent past, this topic

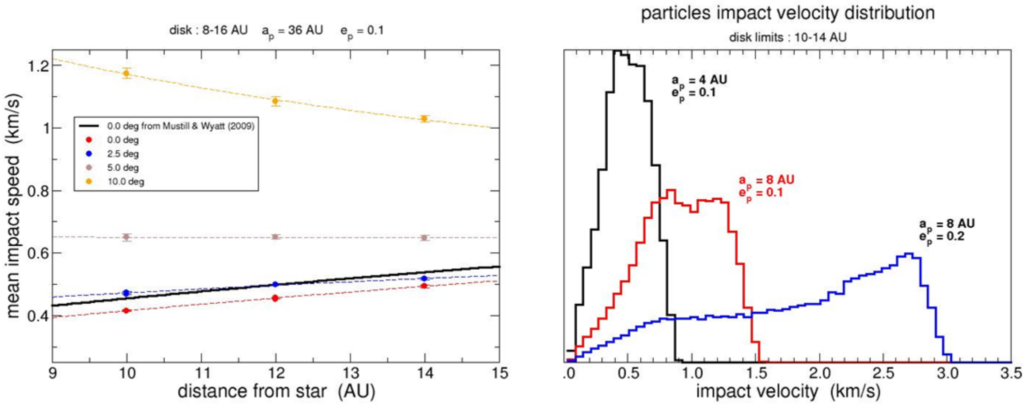

Fig. 10. Left: Mean impact speed as a function of orbital distance for different inclination angles, compared to theoretical predictions from Mustill & Wyatt (2009). Right: the distribution of the impact velocity inside debris disks, for different sets of parameters of the disk and perturbing planet.

has been the objective of important roadmapping exercises, such as that carried out by the Exoplanet Roadmap Advisory Team (EPRAT) for ESA, or those undertaken by the standing Exoplanet Exploration Program Analysis Group (ExoPAG), which is responsible for soliciting and coordinating community input into the development and execution of NASA's exoplanet exploration program. Most recently, the "Planetary Exploration, Horizon 2061" long-term foresight exercise was established, gathering scientists, engineers and technology experts world-wide heavily involved in planetary science, extrasolar planets, and in the space exploration of the Solar System. Its aims are focused on the identification of major scientific questions on planetary systems, on the propositions for space missions and associated key technologies required to address them, an on the ground-based and space-based infrastructures needed in support to these missions. The Horizon 2061 exercise has arisen in the very important context of the current emergence of a unifying paradigm of planetary sciences: the concept of planetary systems as a new class of astrophysical objects which covers and links together the solar system, giant planets systems, protoplanetary disks, and extrasolar planetary systems. By nourishing the (scientific and technological) synergies between Solar System and exoplanet field, the Horizon 2061 initiative provides an important framework to better address key questions on planetary systems, such as their origins, their formation and diversity of architectures, the emergence of potential habitats for life, and its actual detection.

At the national level, the identification and (orbital, structural, atmospheric) characterization of exoplanets are leading activities for both ASI and INAF, with strong involvement and leadership roles of our members of the TASSEL team in strategic programs for the advancement of knowledge in the field conducted with instrumentation of the highest level both in space (Gaia, CHEOPS, PLATO, Ariel) and from the ground (HARPS-N/TNG, GIANO-B/TNG, ESPRESSO/VLT, ANDES/ELT, SPHERE/VLT, SHARK/LBT). Despite the extraordinary potential to propel interdisciplinary work lines and partnerships within the Institute, joint efforts between INAF researchers working in the fields of exoplanets and Solar System are still uncommon. As demonstrated by the Horizon 2061 initiative, it is imperative to start exploiting at the national level the synergy potential between the two fields in order to successfully tackle the most pressing questions outlined above.

Upon completion, the TASSEL project has achieved a three-fold, far ranging impact. First, it has allowed us to define a sample of exoplanetary systems with well-determined architectures resembling that of the Solar System, providing a critical contribution towards a better understanding of the diversity of the architectures of planetary systems, which is one of the key questions identified by the Horizon 2061 initiative. Second, it has allowed for an unprecedented coagulation of observational, theoretical, and technical know-how on Solar System and exoplanetary science throughout our national territory, sowing the seeds for new synergies between different research groups. There are in fact important prospects for continued developments beyond TASSEL, which include: a) combined data analysis with future Gaia DRs for improved system parameters; b) occurrence rates calculations on larger datasets, with more sophisticated approaches; c) very high-resolution dynamical studies; d) systematic studies of minor body reservoirs evolution on consolidated lists of Solar-System-type architectures Finally, it has put our Italy-wide, interdisciplinary collaboration in an advantageous position for the identification and physical characterization of true Solar System analogs with data from future space missions such as PLATO, Jthe James Webb Sapace Telescope (JWST), NGRST, Ariel, and the Habitable Worlds Observatory (HWO), thus establishing Italy as one of the leading countries at the forefront of exoplanetary science.

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