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PROJECT FINAL REPORT

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Name of the scientific representative of the project's co-ordinator[1], Title and Organisation:

Dr. Alessandro Sozzetti - Senior Researcher

INAF – Osservatorio Astrofisico di Torino

Tel: +39-011-8101923

Fax: +39-011-8101930

E-mail: alessandro.sozzetti@inaf.it

Project website address: https://www.etaearth.eu

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

4.1 Final publishable summary report

4.1.1 Executive Summary

The ETAEARTH project is a transnational collaboration between European countries and the US setup to optimize the synergy between space- and ground-based data whose scientific potential for the characterization of extrasolar planets can only be fully exploited when analyzed together.

We have used Guaranteed Time Observations with the HARPS-N spectrograph on the Telescopio Nazionale Galileo (TNG) for 5 years to measure dynamical masses of transiting terrestrial planet candidates with accurate radius measurements identified by the Kepler and K2 missions. The unique combination of Kepler/K2 photometric and HARPS-N spectroscopic data has enabled precise measurements of the bulk densities of these objects, allowing us to learn for the first time about the physics of their interiors. With the ETAEARTH project we have determined with high precision (20% or better) the composition of 70% of currently known planets with masses between 1 and 6 times that of the Earth and with a rocky composition similar to that of the Earth. With ETAEARTH we have provided the first-ever constraints on the density of a planet, in a multiple transiting system, similar to Earth in mass and orbiting within the Habitable Zone of the star known to-date to be closest in mass to the Sun. We have carried out selected experiments in the original Kepler and K2 fields (mass measurements of multiple-planet systems and circumbinary planets) to probe models of planet formation, orbital migration, and long-term dynamical evolution. We have searched for planets similar to Earth orbiting a carefully selected sample of nearby bright solar-type stars. With ETAEARTH we have found the two closest transiting rocky planets, orbiting a solar-type star only 21 light years away, thus providing suitable candidates for spectroscopic characterization of their atmospheres with next-generation space observatories. We have improved significantly our comprehension of planet formation scenarios and orbital evolution models. Using insights from ETAEARTH results we have gauged possible scenarios for the formation of ultra-short-period rocky exoplanets, and identified novel ways for discriminating observationally between scenarios in which such planets formed originally as rocky objects or they are instead the stripped cores of planets that, initially, had much more substantial gaseous envelopes. We have critically advanced our capabilities in structural modeling of the interiors of low-mass, small-radius planets. We have systematically compared the mass-radius relation for terrestrial transiting exoplanets observationally determined thanks primarily to ETAEARTH results with the two-component iron-magnesium silicate internal composition models we developed, and found that that the rocky analogues of the Earth with accurately (better than 20% precision) determined masses below 6 $M_{\oplus}$ appear to be are well-described by the same fixed ratio of iron to magnesium silicate. We have combined Kepler, HARPS-N, and informed extrapolations of Gaia data products (direct distance measurements) for stars in the Kepler field to underpin the occurrence rates of terrestrial planets ($\eta_{\oplus}$) as a function of stellar properties with unprecedented accuracy. With ETAEARTH we have determined that 1 in 5 solar-like stars host an Earth-like planet, i.e. an object with a size similar to Earth orbiting within the Habitable Zone of its solar-type parent star. ETAEARTH has thus finally provided a new, quantitative answer to an age-old question of mankind: 'How common are Earth analogues in our Galaxy?'

Our unique team expertise in observations and modelling of exoplanetary systems has allowed us to fully exploit the potential for breakthrough science intrinsic to this cutting-edge, multi-techniques, interdisciplinary project, making the best use of data of the highest quality gathered from NASA and ESA space missions and ground-based instrumentation.

4.1.2 Project Context and Objectives

The discovery of a Jupiter-mass companion orbiting 51 Pegb by Mayor & Queloz (1995) heralded the birth of a new field of modern astronomy: extrasolar planets. It took almost thirty centuries of human history before science could provide the first observational data to confirm the Existence Theorem. One cannot regard this but as a remarkable achievement.

Two decades after the first discovery announcement, exoplanet science is a fast-developing, highly interdisciplinary field which holds great promise in alleviating the limitations presented by a single (incomplete) example. Indeed, the observational data on extrasolar planets (~3700 discovered to-date) show such striking properties that we now realize the complexity of planet formation and thermal evolution. A unique window of opportunity into the properties of planetary systems is provided by the transiting class of extrasolar planets. Photometric transit observations reveal a planet's radius, and in combination with radial-velocity measurements, permit a determination of the planet's mass. This combination of measurements provides the only available direct constraint on the density and hence bulk composition of exoplanets. A decade after the discovery of the first transiting extrasolar planet, HD 209458b, studies of the physical structure and atmospheres of transiting planets are heralding a new era of 'comparative planetology', in which our Solar System can finally be put in the broader context of the astrophysics of planetary systems.

The hundreds of gas giant transiting exoplanets known today (most being strongly irradiated, short-period objects) have radii and masses measured to better than 10%, thus allowing for challenging comparisons with interior composition models. Indeed we know today that gas giants with masses within a factor of a few of the mass of Jupiter can have a very wide range of radii, particularly those with puzzlingly low densities that challenge standard evolutionary theories.

The observed variety of structural properties of transiting giants is being to be observed also in the quickly growing sample of lower-mass, smaller-radius transiting planets, which are usually categorized as Neptunes, sub-Neptunes, and super-Earths. The latter category, composed up of massive terrestrial planets in the mass range 2-10 $M_\oplus$, is of particular interest. On the one hand, super-Earth planets have surface conditions that are most similar to those on the early Earth; their study could hold clues to understanding the origins of complex chemistry we call life. On the other hand, degeneracies in their interior models on the mass-radius diagram indicate a wide range of possible compositions for similar masses and radii. Precisely determining these two fundamental physical parameters is thus mandatory in order to, for example, a) distinguish between water-rich and dry planets, and b) characterize the transition between super-Earths and sub-Neptunes.

The sample of transiting rocky planets has been quickly augmented in recent years thanks to space-based detections. In particular, the ultra-high photometric precision of NASA's Kepler and K2 missions has allowed so far discovering about 3700 transiting planet candidates. Approximately 30% of these objects have radii smaller than 2 $R_\oplus$, with several tens being comparable to Earth's in size, or even smaller! For many of these candidates, the likelihood of being false positives is very low, thus they are identified as validated planets.

However, to confirm and characterize the rocky planets identified by Kepler and K2, it is critical to determine spectroscopic orbital solutions so that the planetary masses can be established reliably. Our team, the ETAEARTH Consortium, is collaboration between various institutes of different European countries (Switzerland, Italy, and the UK) and the US for the fabrication and operation of HARPS-N. The HARPS-N instrument is a high-precision spectrograph, a twin of the HARPS instrument on the 3.6-m ESO telescope in Chile. It is in operations in the Northern hemisphere at the Telescopio Nazionale Galileo (TNG), located at the Roque de los Muchachos Observatory, to allow for synergy with the Kepler and K2 missions. With its ability to measure velocities with a precision better than 1 m/s (in a 1-hr integration for a V=12 mag star), HARPS-N has provided a unique capability for determining the masses of Kepler planets similar to the Earth.

The ultimate exoplanet science goal is to answer the enigmatic and ancient question, ‘Are we alone?’ via detection of biosignatures in the atmosphere of an Earth twin. Our ambitious science program will allow us to determine masses and radii of rocky planets similar in composition to Earth in the habitable zone of stars not much different from our Sun, thus proving the Existence Theorem and bringing us within one step from the answer to this age-old question

The ETAEARTH Project is an unprecedented international collaborative enterprise to analyse, model and interpret the exquisitely precise space-borne photometric data of NASA’s Kepler and K2 missions in combination with the highest-precision ground-based spectroscopic measurements enabled by the HARPS-N spectrograph, and complemented by the extremely accurate direct distance estimates of ESA’s Gaia global astrometry mission. The HARPS-N spectrograph was commissioned at the TNG during spring 2012. The ETAEARTH Consortium had guaranteed access to HARPS-N@TNG through a conspicuous GTO program of 80 observing nights/yr for five years. We utilized our guaranteed time observations with HARPS-N@TNG to carry out a research program with a broad, bold, challenging, manifold scientific objective: We wanted to fully exploit the scientific value of space mission (Kepler and K2) data of exquisite quality that had the potential to unveil the existence of true Earth analogs (similar to Earth in composition, just a bit more massive and bigger in size). Our ultimate objective can be seen as structured in 7 major, interconnected goals:

Goal 1 - Planetary Systems Physics Studies: The first goal, and primary aim, of the ETAEARTH Consortium can be further subdivided into five scientific objectives for the full exploitation of the synergy between Kepler/K2 photometry and HARPS-N spectroscopy. We utilized a significant fraction of our GTO time to:
a) Infer the composition of a planet similar to Earth (in mass and radius) in the habitable zone of a G5V star or later;
b) Characterize the structural properties of Earth-like planets of 2-5 $M_\oplus$ (‘super-Earths’) in various orbits with enough precision to distinguish between water-rich and dry planets;
c) Characterize the transition between super-Earths and sub-Neptunes near 10 $M_\oplus$, with a precision of 10% in mass, or better;
d) Study the dependence of Super-Earth planets interior properties as a function of stellar mass, combining Kepler photometry and HARPS-N spectroscopy of transiting candidates around late-type stars;
e) Provide a leap forward in the theoretical understanding of structural properties of planets in a mass range (2-10 $M_\oplus$) not seen in our Solar System.

Goal 2 – Architectures of Planetary Systems Studies: the second aim of our project is to improve our understanding of several key open issues in connection to planetary systems formation and dynamical evolution processes. We aimed at improving planet population synthesis, orbital migration, and tidal evolution models using open time with HARPSN@TNG to address two subsets of ‘targets of opportunity’:
a) To determine the degree of spin-orbit misalignment angles for ‘ice giants’ (Neptunes) through measurements of the Rossiter-McLaughlin effect during primary transit observations. These experiments allowed us to test theories of orbital migration, planet-planet scattering and tidal capture against the observed distributions of misalignment angles as a function of stellar effective temperature, planet mass, orbital separation and eccentricity;
b) To provide mass measurements for i) multiple-planet systems containing super-Earths and Neptunes where the transit timing variation technique using Kepler data alone does not allow any mass determination, and for ii) circumbinary planets. These experiments allowed us to better inform population synthesis models by including the influence of the earliest stages of star formation right

through to the longer-term evolution of multiple planetary systems and the tidal evolution of short-period planetary systems.

Goal 3 - Discovery and Characterization of Earth Analogs around Nearby Stars: The third aim of our project is to use the remaining fraction of our GTO time and competitively awarded open time with HARPS-N to observe a sample of the brightest, least active, and least noisy northern stars. This sample was initially composed of stars more like our Sun , and then extended to included low-mass, relatively bright M dwarfs. The goal was to discover planets as close as possible in characteristics to Earth (even in multiple-planet systems). The choice to include M-dwarfs in the sample was driven by the fact that low-mass planets are more easily detected around lower-mass primaries. Furthermore, the habitable zone of these cool stars is closer in, and this relaxes the requirements on an observing strategy aimed at probing the corresponding range of orbital separations. The added value of such discoveries is that a number of exciting follow-up possibilities (photometric, spectroscopic, and polarimetric) become possible for such nearby objects, both from the ground and in space. Such discoveries would directly impact the plans of future infrared ESA and NASA space missions dedicated to the photometric and spectroscopic characterization of exoplanets atmospheres (e.g. JWST, ARIEL).

Goal 4 - Planetary Systems Properties in the Kepler Field: The fourth aim of our project is to combine the exquisite Kepler photometry, the ultra-high-precision ground-based HARPS-N spectroscopy, and the extremely accurate space-based Gaia parallaxes (expected to become available through the first and second major intermediate catalogue releases during the last 1.5 years of our project) in a grand, global statistical analysis of planetary systems in the Kepler field. Gaia direct distance estimates would allow improving the knowledge of the absolute luminosities of all stars in the Kepler field. This is turn will permit more refined determinations of the fundamental stellar parameters (e.g., mass and radius) and as a consequence of the planetary parameters themselves. The properties of fully characterized systems and candidate systems, and the estimates of their frequencies, including that of planets with masses and/or radii close to that of the Earth, will then be cross-correlated with the (very accurately determined) characteristics of their parent stars, in a global statistical analysis that will utilize as comparison sample a large subset of Kepler stars without detections. We will then be capable of answering questions such as: Is the sample of stars with planets identified by Kepler typical of the stellar mix in the Kepler field itself? And most importantly, inferences of planetary frequencies, including $\eta_{\oplus}$, as a function of, e.g., stellar metallicity and mass will then be put on very solid statistical grounds.

Goal 5 - Stellar Parameters Determination: The fifth aim of our project is to provide a first fundamental element of support towards the fulfilment of Goals 1 through 4. We planned to combine the spectroscopic information from the HARPS-N spectra (effective temperature, surface gravity, metallicity) with the photometric information on the stellar density from the Kepler data to determine, using cross-correlation techniques with large grids of stellar evolutionary tracks, the fundamental physical parameters of the host stars evolutionary age, mass, radius). Accurate and precise (to better than 5%, particularly when Gaia parallaxes would become available) stellar masses and radii will be utilized to derive improved values of the planetary mass and radii (and hence densities) of the transiting planets, thus advancing our understanding of their structural properties, by comparison with interiors models.

Goal 6 - Stellar Activity Studies: The sixth aim of our project is to provide a second fundamental element of support towards the fulfilment of Goals 1 through 4. We planned to analyze individual stellar spectra to measure activity levels in each observation and assess stellar variability levels of each host star by verifying the consistency between photometric (Kepler data) and spectroscopic

(HARPS-N data) variability. Stellar activity is in fact the first source of astrophysical noise for planet detection with the Doppler method, and by carefully gauging its impact on the quality of the radial velocities derived from the HARPS-N spectra we would learn how to calibrate this effect out by modifying our observing strategies or we would optimize the down-selection of the most favorable targets.

Goal 7 - Data Access, Analysis, and Interpretation Tools: The seventh aim of our project is to build the software tools necessary to achieve all of the above goals. We defined and implemented an adaptive observing strategy for radial velocity measurements with HARPS-N, taking into account scheduling constraints which are environmental in nature (e.g., weather, target observability) and due to the targets themselves (stellar activity, planets orbital properties and expected RV signals). We created and maintained the science archive, with database containing all relevant, multi-technique data products. Finally, we designed and implemented integrated web-based tools for multi-technique data products access, combined visualization, analysis and interpretation.

4.1.3 Main Results

The main results of the ETAEARTH project are categorized in terms of the achievements towards the fulfilment of each of the scientific objectives described above and in terms of a range of important cooperation/collaboration activities.

Goal 1 - Planetary Systems Physics Studies

The identification of the first Earth-sized planet with and Earth-like density (Kepler-78b), the successful determination of the masses of intermediate-period (HD 3167d, Kepler-20g) non-transiting planets in multiple transiting systems, the early investigations of the composition of new rocky terrestrial planets (e.g., Kepler-20b, Kepler-21b) all the way in the regime of ultra-short period (USP) companions (K2-141b), and the identification of a peculiar non-rocky object among the ultra-short period transiting sample (WASP-47e) are very significant results for the ETAEARTH project, and they testify of the project's ability to set new standards beyond the state-of-the-art of the field. The most spectacular achievement of the project comes from the determination of the first constraints on the bulk composition of the three small-radius transiting companions in the K2-3 system, and in particular for K2-3d, that straddles the habitable zone of what is to-date the brightest host closest in mass to that of our Sun. Overall, the HARPS-N GTO observations alone executed within ETAEARTH have contributed to populate 55% of the Mass-Radius diagram of USP terrestrial planets, and overall 70% of the mass radius diagram of small-radius, low-mass planets (in single and multiple systems) with precisely determined masses (< 30% relative error). The full set of results obtained toward the achievement of this Project Goal is detailed as follows:

1) The discovery of Kepler-78b, the first Earth-sized planet with an Earth-like density (Pepe et al. 2013, Nature). Recent analyses of data from the NASA Kepler spacecraft have established that planets with radii within 25 per cent of Earth's ($R_\oplus$) are commonplace throughout the Galaxy, orbiting at least 16.5 per cent of Sun-like stars. Because these studies were sensitive to the sizes of the planets but not their masses, the question remained whether these Earth-sized planets are indeed similar to the Earth in bulk composition. The smallest planets for which masses have been accurately determined are Kepler-10b (1.42$R_\oplus$) and Kepler-36b (1.49$R_\oplus$), which are both significantly larger than the Earth. The planet Kepler-78b was discovered recently and found to have a radius of only 1.16$R_\oplus$. Our HARPS-N GTO programme observations allowed us to determine the mass of this planet to be 1.86 Earth masses. The resulting mean density of the planet is 5.57 g cm^{-3}, which is similar to that of the Earth and implies a composition of iron and rock.
2) Improved constraints on Kepler-10b's composition and first mass determination for Kepler-10c (Dumusque et al. 2014, ApJ). With 148 high-quality HARPS-N radial-velocity measurements we improved the precision of the mass determination for Kepler-10b to 15%. With a mass of 3.33 $M_\oplus$ and an updated radius of 1.47$R_\oplus$, Kepler-10b has a density of 5.8 g/cc, very close to the value predicted by models with the same internal structure and composition as the Earth. We determined a mass for the 45-day period planet Kepler-10c with an even better precision of 11%. With a mass of 17.2 $M_\oplus$ and radius of 2.35 $R_\oplus$, Kepler-10c has a density 7.1 g/cc. Kepler-10c appears to be the first strong evidence of a class of Neptune-mass solid planets with longer orbital periods;
3) Characterization of the Kepler-101 planetary system (Bonomo et al. 2014, A&A). With mass of 51.1 $M_\oplus$, radius of 5.77 $R_\oplus$, and density 1.45 g/cc, Kepler-101b is the first fully characterized super-Neptune, and its density suggests that heavy elements make up a significant fraction of its interior; more than 60% of its total mass. Kepler-101c has a radius of 1.25 $R_\oplus$, which implies the absence of any H/He envelope, but its mass could not be determined because of the relative faintness of the parent star for highly precise radial-velocity measurements (K_p = 13.8) and the limited number of radial velocities. The 1σ upper limit of $M_p < 3.8\ M_\oplus$, excludes a pure iron composition with a

probability of 68.3%. The architecture of the planetary system Kepler-101 − containing a close-in giant planet and an outer Earth-sized planet with a period ratio slightly larger than the 3:2 resonance − is certainly of interest for scenarios of planet formation and evolution. This system does not follow the previously reported trend that the larger planet has the longer period in the majority of Kepler systems of planet pairs with at least one Neptune-sized or larger planet;

4) HARPS-N mass determination for Kepler-93b and a study of the composition of terrestrial planets (Dressing et al. 2015, ApJ). Kepler-93b is a 1.48 $R_\oplus$ planet with a 4.7 day period around a bright (V=10.2), asteroseismically-characterized solar-type host. Based on 86 HARPS-N radial velocity observations and 32 archival Keck/HIRES observations, we derived a precise mass estimate of 4.02 $M_\oplus$. The corresponding high density of 6.88 g/cc is consistent with a rocky composition of primarily iron and magnesium silicate. We compared Kepler-93b to other dense planets with well-constrained parameters and found that between 1-6 $M_\oplus$, all dense planets including the Earth and Venus are well-described by the same fixed ratio of iron to magnesium silicate. There are as of yet no examples of such planets with masses > 6 $M_\oplus$: All known planets in this higher mass regime have lower densities requiring significant fractions of volatiles or H/He gas. We also constrained the mass and period of the outer companion in the Kepler-93 system from the long-term radial velocity trend and archival adaptive optics images. As the sample of dense planets with well-constrained masses and radii continues to grow, we will be able to test whether the fixed compositional model found extends to the full population of 1-6 $M_\oplus$ planets.

5) The first planet discovery from the K2 mission: A super-Earth transiting the bright K dwarf HIP 116454 (Vanderburg et al. 2015, ApJ). The star was observed by the Kepler spacecraft during its Two-Wheeled Concept Engineering Test in February 2014. During the 9 days of observations, K2 observed a single transit event. Using a new K2 photometric analysis technique (Johnson & Vanderburg 2014, PASP) we were able to correct for small telescope drifts and recover the observed transit at high confidence, corresponding to a planetary radius of 2.53 $R_\oplus$. Radial velocity observations with the HARPS-N spectrograph revealed an 11.82 $M_\oplus$ planet in a slightly eccentric 9.1 day orbit, consistent with the transit depth, duration, and ephemeris. Follow-up photometric measurements from the MOST satellite confirmed the transit observed in the K2 photometry and provided a refined ephemeris, making HIP 116454b amenable for future follow-up observations of this latest addition to the growing population of transiting super-Earths around nearby, bright stars.

6) The Kepler-454 System: A small, not-rocky inner planet, a Jovian world, and a distant companion (Gettel et al. 2015, ApJ). Kepler-454 (KOI-273) is a relatively bright (V = 11.69 mag), Sun-like star that hosts a transiting planet candidate in a 10.6 d orbit. From spectroscopy, we estimate the stellar temperature to be T_{eff} = 5687 K, its metallicity to be [m/H] = 0.32, and the projected rotational velocity to be Vsini <2.4 km/s. We combine these values with a study of the asteroseismic frequencies from short cadence Kepler data to estimate the stellar mass to be 1.028 M_{SUN}, the radius to be 1.066 R_{SUN} and the age to be 5.25 Gyr. We estimate the radius of the 10.6 d planet as 2.37 $R_\oplus$. Using 63 radial velocity observations obtained with HARPS-N and 36 observations made with the HIRES spectrograph at Keck Observatory, we measure the mass of this planet to be 6.8 $M_\oplus$. We also detect two additional non-transiting companions, a planet with a minimum mass of 4.46 M_J in a nearly circular 524 d orbit and a massive companion with a period >10 years and mass >12.1 M_J. The twelve exoplanets with radii <2.7 $R_\oplus$ and precise mass measurements appear to fall into two populations, with those <1.6 $R_\oplus$ following an Earth-like composition curve and larger planets requiring a significant fraction of volatiles. With a density of 2.76 g/cm^3, Kepler-454b lies near the mass transition between these two populations and requires the presence of volatiles and/or H/He gas.

7) A 1.9 Earth Radius Rocky Planet and the Discovery of a Non-transiting Planet in the Kepler-20 System (Buchhave et al. 2016, AJ). Kepler-20 is a solar-type star (V = 12.5) hosting a compact system of five transiting planets, all packed within the orbital distance of Mercury in our own solar system. A transition from rocky to gaseous planets with a planetary transition radius of 1.6 $R_\oplus$ has

recently been proposed by several articles in the literature. Kepler-20b ($R = 1.9 R_\oplus$) has a size beyond this transition radius; however, previous mass measurements were not sufficiently precise to allow definite conclusions to be drawn regarding its composition. We present new mass measurements of three of the planets in the Kepler-20 system that are facilitated by 104 radial velocity measurements from the HARPS-N spectrograph and 30 archival Keck/HIRES observations, as well as an updated photometric analysis of the Kepler data and an asteroseismic analysis of the host star ($M_* = 0.948$+/- 0.051 M_{SUN}; and $R_* = 0.964$+/- 0.018 R_{SUN}). Kepler-20b is a 1.868(-0.034+0.066) $R_\oplus$ planet in a 3.7 day period with a mass of 9.70(-1.44+1.41) $M_\oplus$, resulting in a mean density of 8.2(-1.3+1.5) g/cm^3, indicating a rocky composition with an iron-to-silicate ratio consistent with that of the Earth. This makes Kepler-20b the most massive planet with a rocky composition found to date. Furthermore, we report the discovery of an additional non-transiting planet with a minimum mass of 19.96(-3.61+3.08) $M_\oplus$ and an orbital period of ˜34 days in the gap between Kepler-20f (P ˜ 11 days) and Kepler-20d (P ˜ 78 days);

8) The Orbit and Mass of the Third Planet in the Kepler-56 System (Otor et al. 2016, AJ). While the vast majority of multiple-planet systems have orbital angular momentum axes that align with the spin axis of their host star, Kepler-56 is an exception: its two transiting planets are coplanar yet misaligned by at least 40° with respect to the rotation axis of their host star. Additional follow-up observations of Kepler-56 suggest the presence of a massive, non-transiting companion that may help explain this misalignment. We model the transit data along with Keck/HIRES and HARPS-N radial velocity data to update the masses of the two transiting planets and infer the physical properties of the third, non-transiting planet. We employ a Markov Chain Monte Carlo sampler to calculate the best-fitting orbital parameters and their uncertainties for each planet. We find the outer planet has a period of 1002 ± 5 days and minimum mass of 5.61 ± 0.38 M_{Jup}. We also place a 95% upper limit of 0.80 m/s/yr on long-term trends caused by additional, more distant companions;

9) Kepler-21b: A Rocky Planet around a V = 8.25 Magnitude Star (Lopez-Morales et al. 2016, AJ). HD 179070, aka Kepler-21, is a V = 8.25 F6IV star and the brightest exoplanet host discovered by Kepler. An early detailed analysis by Howell et al. of the first 13 months (Q0-Q5) of Kepler light curves revealed transits of a planetary companion, Kepler-21b, with a radius of about 1.60 ± 0.04 $R_\oplus$ and an orbital period of about 2.7857 days. However, they could not determine the mass of the planet from the initial radial velocity (RV) observations with Keck-HIRES, and were only able to impose a 2-sigma upper limit of 10 $M_\oplus$. Here, we present results from the analysis of 82 new RV observations of this system obtained with HARPS-N, together with the existing 14 HIRES data points. We detect the Doppler signal of Kepler-21b with a RV semi-amplitude K = 2.00 ± 0.65 m/s, which corresponds to a planetary mass of 5.1 ± 1.7 $M_\oplus$. We also measure an improved radius for the planet of 1.639 (+0.019/-0.015) $R_\oplus$, in agreement with the radius reported by Howell et al. We conclude that Kepler-21b, with a density of 6.4 ± 2.1 g/cm^3, belongs to the population of small, $\lesssim 6 M_\oplus$ planets with iron and magnesium silicate interiors, which have lost the majority of their envelope volatiles via stellar winds or gravitational escape. The RV analysis presented in this paper serves as an example of the type of analysis that will be necessary to confirm the masses of TESS small planet candidates.

10) The Kepler-19 System: A Thick-Envelope Super-Earth with Two Neptune-Mass Companions Characterized Using Radial Velocities and Transit Timing Variations (Malavolta et al. 2017, AJ). We report a detailed characterization of the Kepler-19 system. This star was previously known to host a transiting planet with a period of 9.29 days, a radius of 2.2 $R_\oplus$, and an upper limit on the mass of 20$M_\oplus$. The presence of a second, non-transiting planet was inferred from the transit time variations (TTVs) of Kepler-19b over eight quarters of Kepler photometry, although neither the mass nor period could be determined. By combining new TTVs measurements from all the Kepler quarters and 91 high-precision radial velocities obtained with the HARPS-N spectrograph, using dynamical simulations we obtained a mass of 8.4±1.6 $M_\oplus$ for Kepler-19b. From the same data, assuming system coplanarity, we determined an orbital period of 28.7 days and a mass of 13.1±2.7 $M_\oplus$ for Kepler-19c and discovered a Neptune-like planet with a mass of 20.3±3.4 $M_\oplus$ on a 63-day orbit. By

comparing dynamical simulations with non-interacting Keplerian orbits, we concluded that neglecting interactions between planets may lead to systematic errors that can hamper the precision in the orbital parameters when the data set spans several years. With a density of 4.32±0.87 g cm−3 (0.78±0.16 $\rho_{\oplus}$) Kepler-19b belongs to the group of planets with a rocky core and a significant fraction of volatiles, in opposition to low-density planets characterized only by transit time variations and an increasing number of rocky planets with Earth-like density. Kepler-19 joins the small number of systems that reconcile transit timing variation and radial velocity measurements.

11) Three's company: an additional non-transiting planet in the HD 3167 System, and masses for all three planets (Christiansen et al. 2017, AJ). HD 3167 is a bright (V=8.9 mag), nearby K0 star observed by the NASA K2 mission (EPIC 220383386), hosting two small, short-period transiting planets. Here we present the results of a multi-site, multi-instrument radial-velocity campaign to characterize the HD 3167 system. The masses of the transiting planets are 5.02±0.38 $M_{\oplus}$ for HD 3167b, a hot super-Earth with a likely rocky composition (ρ_b = 5.60±2.10 g/cm^3), and 9.80±1.25 $M_{\oplus}$ for HD 3167c, a warm sub-Neptune with a likely substantial volatile complement (ρ_c =1.97±0.5 g/cm^3).We explore the possibility of atmospheric composition analysis and determine that planet c is amenable to transmission spectroscopy measurements, and planet b is a potential thermal emission target. We detect a third, non-transiting planet, HD 3167d, with a period of 8.509±0.045 d (between planets b and c) and a minimum mass of 6.90±0.71 $M_{\oplus}$. We are able to constrain the mutual inclination of planet d with planets b and c: we rule out mutual inclinations below 1°.3 because we do not observe transits of planet d. From 1°.3 to 40°, there are viewing geometries invoking special nodal configurations, which result in planet d not transiting some fraction of the time. From 40° to 60°, Kozai–Lidov oscillations increase the system's instability, but it can remain stable for up to 100 Myr. Above 60°, the system is unstable. HD 3167 promises to be a fruitful system for further study and a preview of the many exciting systems expected from the upcoming NASA TESS mission.

12) Precise Masses in the WASP-47 System (Vanderburg et al. 2017, AJ). We present precise radial velocity observations of WASP-47, a star known to host a hot Jupiter, a distant Jovian companion, and, uniquely, two additional transiting planets in short-period orbits: a super-Earth in a ≈19 hr orbit, and a Neptune in a ≈9 day orbit. We analyze our observations from the HARPS-N spectrograph along with previously published data to measure the most precise planet masses yet for this system. When combined with new stellar parameters and reanalyzed transit photometry, our mass measurements place strong constraints on the compositions of the two small planets. We find that, unlike most other ultra-short-period planets, the inner planet, WASP-47e, has a mass (6.83 ± 0.66 $M_{\oplus}$) and a radius (1.810 ± 0.027 $R_{\oplus}$) that are inconsistent with an Earth-like composition. Instead, WASP-47e likely has a volatile-rich envelope surrounding an Earth-like core and mantle. We also perform a dynamical analysis to constrain the orbital inclination of WASP-47c, the outer Jovian planet. This planet is likely orbiting close to the plane of the inner three planets, suggesting a quiet dynamical history for the system. Our dynamical constraints also imply that WASP-47c is much more likely to transit than a geometric calculation would suggest. We calculate a transit probability for WASP-47c of about 10%, more than an order of magnitude larger than the geometric transit probability of 0.6%.

13) An Ultra-Short Period Rocky Super-Earth with a Secondary Eclipse and a Neptune-Like Companion around K2-141 (Malavolta et al. 2018, AJ). Ultra-short period (USP) planets are a class of low mass planets with periods shorter than one day. Their origin is still unknown, with photo-evaporation of mini-Neptunes and in-situ formation being the most credited hypotheses. Formation scenarios differ radically in the predicted composition of USP planets, it is therefore extremely important to increase the still limited sample of USP planets with precise and accurate mass and density measurements. We report here the characterization of an USP planet with a period of 0.28 days around K2-141 (EPIC 246393474), and the validation of an outer planet with a period of 7.7 days in a grazing transit configuration. We derived the radii of the planets from the K2 light curve and used high-precision radial velocities gathered with the HARPS-N spectrograph for mass

measurements. For K2-141b we thus inferred a radius of 1.51 ± 0.05 $R_{\oplus}$ and a mass of 5.08 ± 0.41 $M_{\oplus}$, consistent with a rocky composition and lack of a thick atmosphere. K2-141c is likely a Neptune-like planet, although due to the grazing transits and the non-detection in the RV dataset, we were not able to put a strong constraint on its density. We also report the detection of secondary eclipses and phase curve variations for K2-141b. The phase variation can be modelled either by a planet with a geometric albedo of 0.30±0.06 in the Kepler bandpass, or by thermal emission from the surface of the planet at around 3000K. Only follow-up observations at longer wavelengths will allow us to distinguish between these two scenarios.

14) An Accurate Mass Determination for Kepler-1655b, a Moderately-Irradiated World with a Significant Volatile Envelope (Haywood et al. 2018, AJ). We present the confirmation of a moderately-irradiated (F = 155±7 $F_{\oplus}$, P = 11.8728787±0.0000085 days), small Neptune with a substantial gas envelope orbiting the relatively quiet, Sun-like G0V star KOI-280. Based on our analysis of the Kepler light curve, we determined KOI-280 b's radius to be 2.213±0.082 $R_{\oplus}$. We acquired 95 high-resolution spectra with TNG/HARPS-N, enabling us to characterize the host star and determine an accurate mass for KOI-280 b of 5.0±3.1 $M_{\oplus}$ via Gaussian-process regression. Our mass determination excludes an Earth-like composition with 98% confidence. Our analysis provides accurate mass and radius determinations for a planet that straddles the boundary between rocky and gaseous exoplanets known to date. It receives moderate irradiation levels and thus also lies close to the observed edge of the exoplanet population at high irradiation levels.

15) Eyes on K2-3: A court of three likely sub-Neptunes characterized with HARPS-N and HARPS (Damasso et al. 2018, A&A). M-dwarf stars are very promising targets to search for and characterize potentially habitable planets. K2-3 is a nearby (45 pc), early-type M dwarf hosting three small-size transiting planets discovered by K2, with the outermost companion orbiting in close proximity to the inner edge of the stellar (optimistic) habitable zone. This system is particularly interesting for characterization studies, aimed at determining precise masses and bulk densities of the three planets. Using a total of 329 radial velocities collected over 2.5 years with the high-precision and high-stability HARPS-N and HARPS spectrographs, we aim at determining new estimates for mass and bulk density of the K2-3 planets through a proper treatment of the stellar activity contribution, which is dominant in the data. We use our results to investigate the physical structure of the planets. We analyze radial velocity time series extracted with two independent pipelines by using Gaussian process regression. We adopt a quasi-periodic kernel to model the stellar magnetic activity jointly with the planetary signals. We use Monte Carlo simulations to investigate in detail the significance of our results concerning the mass of planets K2-3c and K2-3d, and to explore the potential of intensive data sampling to improve their significance. We find that the stellar activity component is the dominant signal present in the radial velocity time-series, with amplitude of around 3 m/s. We derive a precise and accurate mass M_b = 6.6±1.1 $M_{\oplus}$ for planet K2-3b, and M_c = 3.1±1.3 $M_{\oplus}$ for K2-3c. Through simulations, we find that our estimate of Mc is accurate, even though the significance is less than 3σ. It turns out that K2-3b and K2-3c likely have the same bulk density (ρb=3.0±1.3 and ρ_c=3.1±1.5 g/cm^3). The Doppler signal due to K2-3d is undetected, and this is probably related to the amplitude of the stellar activity and to the proximity of the stellar rotation period to the orbital period of K2-3d. Our results are independent from the algorithm used to extract the radial velocities. We tentatively estimate K2-3d mass as M_d=2.7±1.0 $M_{\oplus}$ by using simulations. Based on this result, K2-3 d may have a bulk density similar to that of the other two planets (ρ_d=3.1±1.5 g/cm^3). K2-3 planets may have a similar composition: they could have small H/He envelopes (<1%) on top of rocky cores, or be water-worlds (with water content around 50% of their total mass). While this appears as a robust conclusion for K2-3b, more accurate and precise observations are necessary for a better characterization of planets c and d. Finally, our study also suggests that an intensive data sampling carried out during the last semester with HARPS-N and HARPS would not have allowed the detection of the K2-3d signal.

16) The theoretical framework of two-component iron-magnesium silicate internal composition models we have developed was systematically applied to the cases of the Kepler-78, Kepler-10, Kepler-93, HIP 116454, Kepler-20, Kepler-21, Kepler-454, Kepler-19, HD 3167, WASP-47, K2-141, and K2-3 systems. We compared the results to those for other dense planets with well-constrained parameters and found that between $1-6M_\oplus$, all dense planets including the Earth and Venus are well-described by the same fixed ratio of iron to magnesium silicate. This conclusion holds exclusively for planets smaller than $2.7R_\oplus$ with masses measured to better than 20%. Some low-mass worlds with very low densities are known, notably the Kepler-11 system, KOI-314c, and presumably the three sub-Neptunes in the K2-3 system. While it is then possible that not all planets less massive than $6M_\oplus$ obey a single mass-radius relation, our results rather suggest that the rocky analogues of the Earth might do so.
17) Several small dense exoplanets are now known, inviting comparisons to Earth and Venus. Such comparisons require translating their masses and sizes to composition models of evolved multi-layer interior planets. Such theoretical models rely on our understanding of the Earth's interior, as well as independently derived equations of state, but so far have not involved direct extrapolations from Earth's seismic model: the Preliminary Reference Earth Model (PREM). To facilitate more detailed compositional comparisons between small exoplanets and the Earth, we derived a semi-empirical mass–radius relation for two-layer rocky planets based on PREM, $R/R_\oplus$ = (1.07 - 0.21*CMF) * $(M/M_\oplus)1/3.7$, where CMF stands for core mass fraction. It is applicable to planets with masses 1 ∼ 8 $M_\oplus$ and a CMF of 0.0 ∼ 0.4. Applying this formula to Earth and Venus and several known small exoplanets with radii and masses measured to better than ∼30% precision gives a CMF fit of 0.26±0.07 (Zeng, Sasselov & Jacobsen 2016, ApJ). The final outcome of the work carried out for the development of interior models for the Project is captured in a convenient web-based tool "Manipulate Planet" for interactive exploration of large grids of 3-component models of rocky planets. Finally, a recent exploration of analytical scaling relations among rocky exoplanets is presented in Zeng & Jacobsen (2017), applicable for objects with core mass fraction in the range 0.2–0.35 and mass between 0.1–30 $M_\oplus$.

Goal 2 – Architectures of Planetary Systems Studies

We investigated (Rice 2015, MNRAS) the scenario in which Kepler-78b could have been perturbed into its current orbit through interactions with an outer stellar companion on an inclined orbit (Kozai-Lidov cycles). Given the size of the Kepler sample and the likely binarity, our results suggest that Kepler-78b may indeed have been perturbed into its current orbit by an outer stellar companion The likelihood of this happening, however, is low enough that other processes - such as planet-planet scattering - could also be responsible. We also investigated the efficiency with which disk fragmentation processes can form planetary-mass bodies, and found such object can be produced only rarely (Rice, Lopez, et al. 2015, MNRAS).
Using models of planet evolution, we showed (Lopez 2017, MNRAS) that the new population of ultra-short-period (USP) transiting planets uncovered by Kepler and K2, with orbital periods less than a day, is the likely outcome of formation processes from water-poor material within the snow-line. This sample includes the recent discovery of K2-141b, while the oddball WAWP-47e (less dense than most of the USP planets) might be a consequence of a different formation/evolution path due to the WASP-47 system complexity.
Using models of atmospheric photo-evaporation, we showed (Lopez & Rice 2018, MNRAS submitted) that the value of the transition radius (approximately 1.5 $R_\oplus$) from a population of predominantly rocky super-Earths to non-rocky, low-density sub-Neptunes with substantial volatile envelopes should decrease with orbital period, if most bare rocky planets are the evaporated cores of sub-Neptunes. Using N-body simulations of planet formation we also showed that the value of the

transition radius should instead increase with orbital period if most rocky planets formed after their disks dissipate, and thus without initial gaseous envelopes.
We advanced our population synthesis models to incorporate formation scenarios via direct gravitational collapse (Forgan et al. 2018, MNRAS). These tend to be massive, young planets and their origin is still not clear. In Vigan et al. (2017, A&A) we compared synthetic exoplanet populations with the known population of directly imaged planets. The overall conclusion was that this population is unlikely to have formed via core accretion, but could have formed via direct gravitational collapse in massive protostellar discs. To extend this investigation we also looked at the properties of objects that form via direct gravitational collapse (Hall et al. 2017, MNRAS) and the role of turbulence in the promotion of such a process (Rice & Nayakshin 2018, MNRAS in press). This is currently the most advanced set of population synthesis model for planets that form via direct gravitational collapse and we will continue to compare the results of such models with the constantly increasing population of wide-orbit exoplanets.
Finally, in collaboration with other colleagues members of our team computed a set of new thermal and structural evolution models and use these models in comparison with properties of 47 transiting planets (mass, radius, age) under low stellar insolation (and thus not affected by the hot Jupiter radius inflation mechanism) to determine their heavy element masses. A clear correlation emerges between the planetary heavy element mass Mz and the total planet mass, approximately of the form M_z = M1/2. This finding is consistent with the core accretion model of planet formation. We also studied how stellar metallicity [Fe/H] affects planetary metal-enrichment and found a weaker correlation than has been previously reported from studies with smaller sample sizes. We confirmed a strong relationship between the planetary metal-enrichment relative to the parent star Z_{planet}/Z_{star} and the planetary mass, but saw no relation in Z_{planet}/Z_{star} with planet orbital properties or stellar mass. The large heavy element masses of many planets (> 50 $M_\oplus$) suggest significant amounts of heavy elements in H/He envelopes, rather than cores, such that metal-enriched giant planet atmospheres should be the rule. We also discussed a model of core-accretion planet formation in a one-dimensional disk and showed that it agrees well with the derived relation between mass and Zplanet/Zstar (Thorngren et al. 2017, ApJ).

Goal 3 - Discovery and Characterization of Earth Analogs around Nearby Stars

For the search and characterization of Earth analogs around the nearest solar-like stars, the two most relevant results obtained towards the goal are the following:

1) HD 219134b: A transiting rocky planet in a multi-planet system at 6.5 pc from the Sun (Motalebi et al. 2015, A&A). The detection of a system of four low-mass planets around the bright (V = 5.5) and close-by (6.5 pc) star HD 219134 is the first result of the Rocky Planet Search programme with HARPS-N. The inner planet orbits the star in 3.0935 days, on a quasi-circular orbit with a semi-major axis of 0.0382 AU. Spitzer observations allowed us to detect the transit of the planet in front of the star, making HD 219134b the nearest known transiting planet to date. From the amplitude of the radial velocity variation (2.25 m/s) and observed depth of the transit (359 ppm), the planet mass and radius are estimated to be 4:36 $M_\oplus$ and 1.606 $R_\oplus$, leading to a mean density of 5.76 g/cm^3, suggesting a rocky composition. One additional planet with a minimum mass of 2.78 $M_\oplus$ moves on a close-in, quasi-circular orbit with a period of 6.767 days. The third planet in the system has a period of 46.66 days and a minimum-mass of 8.94 $M_\oplus$, at 0.233 AU from the star. Its eccentricity is 0.46. The period of this planet is close to the rotational period of the star estimated from variations of activity indicators (42.3 days). The planetary origin of the signal is, however, the preferred solution as no indication of variation at the corresponding frequency is observed for activity-sensitive parameters. Finally, a fourth additional longer-period planet of mass of 71 $M_\oplus$ orbits the star in 1842 days, on an eccentric orbit (e = 0.34) at a distance of 2.56AU.

2) The discovery of two transiting planets in the HD219134 system (Gillon et al. 2017, Nature Astronomy). The Spitzer Space Telescope detected a transit of the innermost of these planets, HD 219134 b, whose mass and radius (4.5 $M_\oplus$ and 1.6 $R_\oplus$ respectively) are consistent with a rocky composition. Here, we report new high-precision time-series photometry of the star acquired with Spitzer revealing that the second innermost planet of the system, HD 219134c, is also transiting. A global analysis of the Spitzer transit light curves and the most up-to-date HARPS-N velocity data set yields mass and radius estimations of 4.74 ± 0.19 $M_\oplus$ and 1.602 ± 0.055 $R_\oplus$ for HD 219134 b, and of 4.36 ± 0.22 $M_\oplus$ and 1.511 ± 0.047 $R_\oplus$ for HD 219134 c. These values suggest rocky compositions for both planets. Thanks to the proximity and the small size of their host star (0.778 ± 0.005 $R_\odot$), these two transiting exoplanets — the nearest to the Earth yet found — are well suited for a detailed characterization (for example, precision of a few per cent on mass and radius, and constraints on the atmospheric properties) that could give important constraints on the nature and formation mechanism of the ubiquitous short-period planets of a few Earth masses.

Goal 4 - Planetary Systems Properties in the Kepler Field

We carried out a systematic reanalysis of the stellar and planetary parameters for confirmed/validated and candidate transiting planets in the Kepler field and provided a new derivation of $\eta_\oplus$, the fraction of solar-type stars with Earth-like planets, using an extrapolation of the expected accuracy in pre-DR2 Gaia parallaxes for the sample. A delay in the release of Gaia DR2 prevented us from using actual distance estimates from Gaia, but we achieved the main Goal nonetheless. We found that Gaia is not expected to provide dramatic improvements in the determination of the estimated uncertainty on the two relevant stellar quantities, typically reduced by 25%. The availability of Gaia parallaxes will make however the estimates both precise AND accurate. Confirmed/validated planet will benefit for a typical improvement in the precision in radius determination of a factor of 1.7, and this is rather significant. Finally, we provided a revised evaluation of the frequency of Earth-like planets orbiting Sun-like stars based on the combination of Kepler transit data and Gaia's extrapolated measurements of stellar parallaxes, following the work outlined in Petigura et al. (2013). We focused our attention on validated planets with R=1.0-1.75 $R_\oplus$ orbiting inside the host star's habitable zone. Based on a more accurate and restrictive definition of the habitable zone (Kopparapu et al. 2013), we obtained a new value of $\eta_\oplus$ = 20.8±7.1%. This broadly confirms the Petigura et al. (2013) results, further corroborating the inference that solar-type stars appear to be orbited by Earth-*like* companions in non-negligible numbers.

Goal 5 - Stellar Parameters Determination

We systematically utilized the large number of high-SNR spectra gathered by HARPS-N to accurately determine the stellar parameters of Kepler-78, Kepler-10, Kepler-93, HIP 116454, Kepler-20, Kepler-56, Kepler-21, Kepler-454, Kepler-19, HD 3167, WASP-47, K2-141, and K2-3 using the stellar parameter classification (SPC) Pipeline developed by members of our team and an independent assessment based on the classic curve-of-growth approach (using the MOOG software and Kurucz model stellar atmospheres). The stellar parameters from SPC and MOOG have been input to the Yonsei–Yale stellar evolutionary models to estimate the mass and radius of the host stars. These new determinations allowed us to refine the estimates of the planetary parameters (mass and radius).

Goal 6 - Stellar Activity Studies

A multi-faceted approach to the treatment of the impact of stellar activity was instrumental for appropriate modelling of the RV variations in all the characterization studies carried out by our team.

We tackled the problem by combining pre-whitening by the rotation period and harmonics, studies of the correlation with activity indicators and photometric variations, and treating stellar activity as an additional noise term in the parametric description adopted to model the RVs. This combined approach was particularly useful to unambiguously determine the intermediate-period signal of Kepler-10c and of the non-transiting planet Kepler-20g as Keplerian in nature, precisely gauge its amplitude, and thus accurately measure the planet's mass.

We developed a Gaussian process–based framework for the study of the impact of active stellar regions (and their modelling) in RV datasets, when searching for and modelling planetary signals. Gaussian processes provide a mathematically-tractable and flexible framework for performing Bayesian inference about functions. They are particularly suitable for the joint modelling of deterministic processes (such as signals induced by planets) with stochastic processes of unknown functional forms such as activity signals. Despite not knowing the functional form of these stochastic processes, we usually know some of their properties. We are modelling RV time series jointly with one or more ancillary spectroscopic activity indicators and using prior knowledge on stellar rotation from (primarily Kepler/K2) time series photometry. This allows the activity component of the RV time series to be constrained and disentangled from planetary components. The framework has been tested with spectacular success within the context of the radial velocity fitting challenge (Dumusque et al. 2017, A&A), that aimed at comparing the efficiency of different methods to recover extremely low-mass planets despite stellar RV signals using extensive synthetic RV datasets, at to which several ETAEARTH team members participated directly. The first relevant application on real data of this framework has concerned the successful detailed modelling of the Kepler-21 system. The most spectacular application of Gaussian process regression was carried out in connection to the data analysis of the K2-3 multiply transiting system, and the interpretation of the system properties also greatly benefited from this approach.

We used the Sun as a benchmark case study for investigating the impact of stellar activity in Doppler data. We first compared HARPS spectra of integrated sunlight reflected off 4/Vesta with synthetic data extracted from SDO data (Haywood et al 2016, MNRAS), and subsequently used the HARPS-N solar telescope (Dumusque et al. 2015, ApJ). This work has confirmed that in solar-type stars, suppression of granular blue-shift by magnetic fields in facular and network regions is the major contributor to the activity-driven RV signal in Sun-like stars.

Improved processing and modelling of the solar telescope datasets (now entered routine operation and will observing the Sun every clear day for several hours) continued until the end of the reporting period. We have continued using these radial velocities combined with data from solar satellites to improve our understanding of stellar noise and develop optimal correction methods. In the near future, these new methods should enable the detection of Venus over the next two to three years, thus demonstrating the possibility of detecting Earth-twins around other solar-like stars using the radial velocity technique.

Finally we used autocorrelation analysis to determine mean activity levels and stellar spot lifetimes as a function of spectral type in a large sample of Kepler stars with previously-measured rotation periods (Giles et al. 2017, MNRAS). Our results helped improve the understanding of relevant aspects of the connection between spectral type, activity, and rotation/age, highlighting for example a correlation between the decay time of starspots and their inferred size, and a strong dependence of decay times with stellar temperature, with cooler stars having spots that last much longer, in particular for stars with longer rotational periods.

Goal 7 - Data Access, Analysis, and Interpretation Tools

We have provided at the TNG a physical repository (science archive) for storing a copy of the HARPS-N data products. This activity has included the harmonization with the raw database from HARPS-N observations, the definition of the data structure for the database and its activation, the

control of the data flow from observations and the data reduction pipelines, and the provision for updates of the data content with additional observations and with output from the scientific analysis. Data access was offered with different levels of privacy to the project participants and the public, in accordance with the respective data access rights.
In order to optimize and fully exploit the observing time allocated to the HARPS-N GTO program, we developed an adaptive observing strategy algorithm that, depending on the characteristics (expected RV signal, orbital period, etc.) of the Kepler/K2 candidates in our list, allowed us to experiment different scheduling options of the observations to fit our needs (e.g., using half nights, taking into account different schemes for the cadence of the observations, etc.). A first successful application of our optimized, adaptive observing strategy is constituted by the very efficient use of observing time for confirmation of the radial-velocity signal induced by Kepler-78b on its primary, which we could pin down in spite of the presence of intrinsic stellar RV jitter in excess of the planetary signal thanks to a clever combination of intensive monitoring during a given night with observations taken only twice per night around quadrature (at maximum and minimum expected radial-velocity) to minimize observing time and to maximize the information on the amplitude. Most of the other systems whose physical properties have been determined with high accuracy by ETAEARTH strongly benefited from the optimization of observing resources allocated using our adaptive scheduling tool.
We developed two integrated web-based tools designed to a) provide all members of the ETAEARTH Consortium with access to all the information needed for effective planning and execution of observations to follow up planet candidates identified by the Kepler and K2 missions, and b) allow our team to combine the multi-techniques datasets of Kepler/K2 and HARPS-N in an effectively combined analysis of all available stellar and planetary parameters for integrated interpretation.
The observations planning and follow-up web-based tool (KHDAT) provides access to all the relevant data products (system parameters) from the Kepler/K2 missions and it also provided direct access and/or links to other sources of useful information concerning the planet candidates (e.g., lightcurves). It is the repository for the radial velocities and other results from the HARPS-N observations, and it provides visibility and phase plots for Kepler/K2 candidates.
The second tool (COMBFIT) is a web-based software module for visualizing and analyzing/fitting the HARPS-N radial velocity data in combination with the Kepler/K2 photometry. A combined fit to radial-velocity (RV) and photometric (transit) data to determine the system (orbital and physical) parameters and their associated uncertainties is performed in a Bayesian framework by using a differential evolution Markov chain Monte Carlo (DE-MCMC) method, which is the MCMC version of the differential evolution genetic algorithm and thus allows an optimal exploration of the parameter space.

Cooperation/Collaboration Activities:

1) Members of the ETAEARTH Consortium carried out tasks within the context of Goal 2 (Determination of spin-orbit misalignment angles for ice-giant and gas-giant planets via measurements of the Rossiter-McLaughlin effect) and Goal 3 (RV search and characterization of low-mass planets around nearby M dwarfs) in cooperation with the large collaborative project Global Architecture of Planetary Systems (GAPS, A. Sozzetti PI), that was awarded a total of 344 observing nights over 10 consecutive semesters on HARPS-N, starting in February 2013. In addition, cooperation activities within the context of Goal 5 (Stellar parameters) were carried out with the GAPS Consortium in the framework of the GAPS observing programme segment focused on a Doppler search for planets around a sample of low-metallicity dwarfs. We underline the fact that all the above mentioned activities were carried out by members of the ETAEARTH Consortium as part of their respective Project tasks and at the same time in the context of the GAPS project activities.

Coordination, collaboration, and cooperation efforts with the GAPS Consortium, including the joint analysis of RV data gathered on ETAEARTH/GTO and GAPS observing time, occurred at no additional costs for the Project.
The focus of the first urgent publication (Affer et al. 2016, A&A) was on the discovery of a system of short-period Super Earths around a low-mass M1 dwarf (GJ3998). The innermost companion, with a minimum mass of only 2.2 $M_\oplus$, was the objective of follow-up observations with the Spitzer space telescope to search for its transit, which was unfortunately not found. Other relevant results include a) the discovery of a 2.82 ± 0.51 $M_\oplus$ Super-Earth on the inner edge of the habitable zone of the nearby M dwarf GJ 625 (Suarez Mascareno et al. 2017, A&A), b) the detection of a 7.1 $M_\oplus$ Super Earth companion to the early M dwarf GJ 3942 (Perger et al. 2017b, A&A), c) the determination of the planetary masses and densities for the multiple sub-Neptunes system K2-3 (Damasso et al. 2018, A&A), d) the discovery of a two-planet system around the early-M dwarf GJ15A, the multi-planet system closest to Earth (3.57 pc), and hosting the longest period RV sub-jovian mass planet discovered so far (Pinamonti et al. 2018, A&A), and e) the detection of two massive long-period giant planets around metal-poor stars in the GAPS sample (Sozzetti et al., A&A in prep.). Additional intriguing low-mass candidates around stars in the M-dwarf and low-metallicity samples will be the objective of future, additional investigations. Finally, a detailed study of the orbital obliquity of eight close-in massive planets hosted by the dwarf G- and K-type stars WASP-43, HAT-P-20, Qatar-2, HAT-P-3, HAT-P-12, HAT-P-22, WASP-39 and WASP-60 was published in Esposito et al. (2017, A&A), and Mancini et al. (2018, A&A).

2) The ETAEARTH Consortium established the general framework for a cooperative effort with the Geneva University and the Swiss National Science Foundation through which integration of the web-based software tools KHDAT and COMBFIT for combined data access, visualization and analysis of Kepler and HARPS-N data developed for the project was eventually realized within a larger platform, called Data Analysis Center for Exoplanets (DACE), for the storage, access, selection, visualization and combined analysis of level-1 data products obtained from various techniques and instrumentation, both from the ground and in space.

3) Members of the ETAEARTH Consortium were engaged throughout the duration of the project in cooperative projects with colleagues at the University of Porto, the Laboratoire d'Astrophysique the Marseille, the Paris Observatory and other institutes in the UK and the US, within the general frameworks of Goals 1,2,3,5, and 6. Such efforts were aimed at the sharing/transfer of knowledge acquired and tools developed to successfully exploit HARPS-N data gathered for a) the characterization of transiting planets uncovered by Kepler and K2 space missions and by the ground-based WASP project, b) the measurement of the spin-orbit alignment in systems not in the Kepler field of regard, c) the precise determination of spectroscopic parameters, chemical abundances, and activity information in stellar samples (particularly low-mass stars) with and without detected planets, d) the detection and characterization of planetary systems in dense stellar environments, and e) the study of the impact of stellar metallicity in the characterization of the physical properties of small-size planets in the Kepler field and on the determination of the occurrence rates and on the understanding of the orbital architectures of planetary systems as function of varied metal content of the primaries. Collaborative research between ETAEARTH scientists and other researchers produced an additional several tens of scientific journal articles, as a testimony of the profound impact and ramifications of the project.

4.1.4 Impact and Dissemination

4.1.4.1 Impact

The ETAEARTH project has had impacts on five main areas: a) the exploitation of data from space missions, b) the understanding of several key questions of the scientific community, c) the coordination and synergy efforts on European and national levels and the enhancement of the relations with established international space powers, d) opportunities for career development, and e) the awareness of the greater public towards astronomy's leap forward in providing the answer to an age-old question of mankind. The truly fascinating science topics we have addressed in our project will easily prove very appealing to policy-makers, interest groups, media and the public at large. These impacts are detailed in the following paragraphs.

A) Impact on Space Missions

Our project has set a new, high standard to the systematic analysis and exploitation of space mission data in the field of planetary systems formation and structural evolution. First, we have vastly enhanced the exploitation of Kepler and K2 data. The primary products of these missions are light curves, i.e. plots of brightness of a star as a function of time. Sophisticated software corrects for systematic errors produced by the space craft and other sources. Further algorithms are deployed to detect variations, or transits, that could be caused by a planet passing in front of its host star. The shape and size of the transit gives information about the fractional size of the planet compared to its host star. The Kepler team have deployed additional software that can statistically estimate whether the event is likely to be caused by a planetary companion as other astrophysical sources can mimic these events. However, spectroscopic data is needed to determine whether the transiting object is indeed planetary in mass. Kepler data on its own can give a statistical view of some aspects of planetary science, such as the size distribution of transiting candidates. However even in this case a good understanding of spacecraft systematics is important and these biases are likely to be inbuilt into the data. Clearly, to realize the potential of Kepler data significant ground based spectroscopic data is required. The technology employed by the high throughput HARPS-N spectrograph has changed this situation. While the 3.5m TNG is significantly smaller than, e.g., the 10-m class Keck Telescopes, HARPS-N has enabled the best targets to be monitored at much greater accuracy. The HARPS-N spectrograph is a unique machine for Doppler planet detection, offering unprecedented stability, and guaranteeing sub-m/s accuracy for V=12 stars in 1 hr integration. The experience with building and operating the hugely successful HARPS spectrograph for the 3.6m ESO telescope at La Silla in Chile brought in to the ETAEARTH Consortium by several of its members has been the warranty that our team would deliver. HARPS-N in the Doppler domain is a true match to Kepler in the photometric domain. There is no other instrument in the Northern hemisphere capable of reaching the performance in Doppler measurements precision that HARPS-N@TNG has guaranteed. The unique synergy between Kepler and HARPS-N has enabled new and exciting science to be undertaken by the ETAEARTH project with the Kepler and K2 data, including, e.g., the first-ever identification of Earth-sized planets with and Earth-like density (Kepler-78b) the first-ever constraints on the density of a transiting temperate, super Earth planet (K2-3d) potentially hospitable to a complex biology in orbit around a star not much different from our Sun, and the determination with high precision (20% or better) of the density for 70% of currently known planets with masses between 1 and 6 times that of the Earth and with a rocky composition similar to that of the Earth. Without the ground-based spectroscopic observations of HARPS-N, the Kepler/K2 photometric data with the highest potential impact in the field would have remained unexploited: The transiting Earth-size planet candidates, particularly those at habitable zone distances from their parent stars, would have remained 'candidates'. No information on their mass and thus actual composition would have been retrievable. Our project has thus added a special value to the Kepler/K2 space mission data.

Combined with the Earth-based observations of HARPS-N our programme has significantly contributed to the effective scientific exploitation of collected data by the Kepler/K2 spacecrafts. Second, our project will have a deep impact on space- and ground-based programs focused on exoplanet characterization. In particular, our comparative planetology studies in the Kepler and K2 campaign fields have allowed identifying bright transiting systems which will be ideally suited to inject extraordinary momentum in upcoming and future space- and ground-based programs having the spectroscopic characterization of exoplanet atmospheres as a centerpiece of their scientific agenda. The systems with transiting terrestrial planets whose properties have been accurately determined by the ETAEARTH project, such as HD 219134, Kepler-21, WASP-47, HD3167, K2-141, and K2-3 are now prime targets for community-wide observatories (JWST), next-generation instrumentation on the ELTs (e.g., HIRES@E-ELT), and dedicated missions (ESA's ARIEL) targeting transiting exoplanets' atmospheres.

B) Impact on the Science of Extrasolar Planets

The ETAEARTH project has produced a number of breakthrough measurements aiming at progress in the astrophysics of planetary systems. Generally speaking, the transiting super Earth and sub-Neptune planets (in single and multiple systems) the Kepler/K2 and HARPS-N data combination has allowed to characterize has helped directly to revolutionise our knowledge in several areas.

First, the combination of Kepler/K2 and HARPS-N data has offered the first possibilities to undertake comparative planetology with statistically significant numbers of low mass planets. The ETAEARTH project results as a whole have provided a leap forward in the theoretical understanding of structural properties of planets in a mass range (2-10 $M_\oplus$) not seen in our Solar System. Central to the exploration of the terrestrial-type exoplanets discovered by Kepler and K2 is our ability to separate the different types of planets – at the least, dry rocky planets from water-rich (>10% by mass) planets. On the one hand, such clear separation is crucial to planet formation and architecture models; on the other hand, any progress in interpreting atmospheric characterization of super-Earths hinges on understanding their interiors. The observations of mass and radius confront the theoretical structure models, but they also need them for consistent interpretation. There are two outstanding problems in preparing structure models for super-Earths observations on the Mass-Radius diagram. First, the Mass-Radius diagram has intrinsic degeneracy – non-uniqueness in the solutions for all but the highest density planets. The degeneracy is caused by the fact that the dozens of solid material phases inside planets fall into 3 families, when it comes to equations of state and equilibration of melts. Thus 3 types of materials constrained by only 2 observables produce unique structure models in case the amount of one of the materials can be fixed, e.g. as in the case of high-density planets which can be shown to contain no water (like Kepler-10b). The second outstanding problem is the fact that planets in the mass range of super-Earths experience interior pressures up to 2 orders-of-magnitude above most experimental data for the materials involved. Current models rely on extrapolations into that regime, many of which are very questionable. Overall, the HARPS-N GTO observations alone executed within the ETAEARTH project have contributed to populate 55% of the mass-radius diagram of ultra-short-period (USP, with orbital periods less than 1 day) terrestrial planets, and about 70% of the mass radius diagram of small-radius, low-mass planets (in single and multiple systems) with precisely determined masses (< 30% relative error). This golden sample of planets with well-constrained parameters allowed us to infer that between $1-6M_\oplus$, all dense planets including the Earth and Venus are well-described by the same fixed ratio of iron to magnesium silicate. This conclusion holds exclusively for planets smaller than $2.7R_\oplus$ with masses measured to better than 20%. Some low-mass worlds with very low densities are known, notably the Kepler-11 system, KOI-314c, and presumably the three sub-Neptunes (or water-worlds) in the K2-3 system. While it is then possible that not all planets less massive than $6M_\oplus$ obey a single mass-radius relation, our results rather suggest that the rocky analogues of the Earth might do so.

Second, we now have an advanced understanding, from a theoretical perspective, of the planet formation process and are able to synthesize planet populations with models that include a significant amount of detail, such as orbital migration, a variety of multi-planet interactions, and photo-evaporation effects. The sample or systems with well-determined properties now available thanks to Kepler, K2, and HARPS-N has finally given us a greater ability to make comparisons with the results from theoretical models. For examples, the ETAEARTH-based characterization of Kepler-78b, a roughly Earth-mass/radius planet with a very short period, we demonstrated that a possible scenario for the formation of systems such as Kepler-78b would call into question scattering processes onto its current orbit from an initially wider orbit. Using models of planet evolution, we showed that the new population of USP transiting planets uncovered by Kepler and K2 is the likely outcome of formation processes from water-poor material within the snow-line. This sample includes the recent discovery of K2-141b, while the oddball WASP-47e (less dense than most of the USP planets) might be a consequence of a different formation/evolution path due to the WASP-47 system complexity. Using models of atmospheric photo-evaporation, we showed that the value of the transition radius (approximately 1.5 $R_{\oplus}$) from a population of predominantly rocky super-Earths to non-rocky, low-density sub-Neptunes with substantial volatile envelopes should decrease with orbital period, if most bare rocky planets are the evaporated cores of sub-Neptunes. Using N-body simulations of planet formation we also showed that the value of the transition radius should instead increase with orbital period if most rocky planets formed after their disks dissipate, and thus without initial gaseous envelopes.

C) Impact on the Relations between the EU and other Space-Faring Nations

The ETAEARTH Consortium was set up as a platform from which to undertake an enterprise that has added great value to space missions and Earth-based observations, combining multi-technique datasets of the highest quality for effective scientific exploitation of collected data, to expand their use, and to contribute to the dissemination of space mission data on a global scale. Our project has also achieved a three-fold goal with a strong impact in the relations between EU and other space-faring nations. First, the unique capabilities of the Europe-based HARPS-N spectrograph have enabled NASA researchers in the Kepler and K2 mission teams to take full advantage of the potential value of the highest-visibility Kepler/K2 datasets, i.e. the photometric measurements of stars with candidate transiting planets with radii close to Earth's. In turn, the scientific program of the ETAEARTH Consortium has facilitated the access to, and appropriate use of, the Kepler/K2 data for those European scientists who were not part of the US teams having obtained the space mission data. As a direct consequence, our ambitious project has acted as a beacon to enhance the EU relations with another established international space power (the US), while adding value to existing activities on European and national levels in the arena of extrasolar planetary systems. In summary, our transnational collaboration has promoted concerted efforts that will raise the awareness of coordination and synergy efforts among stakeholders in a field of astronomy that has seen EU and US scientific communities effectively interact only rarely in the past, and more often than not fragment into small research units of below critical mass.

D) Impact on opportunities for career development

The presence of many expert staff team members and the vibrant environments in both the observational and theoretical sides of exoplanet astrophysics at each of the ETAEARTH participating institutes has helped young researchers hired on the project to acquire training in specialist skills of the highest quality. They have had direct access to the best-quality data in the field and they have been exposed to cutting-edge tools for combined analysis of planetary systems parameters in the presence of stellar activity. To further promote and motivate the hired young researchers, they have been invited as collaborators of the ETAEARTH Consortium. These collaborators have been acknowledged for their work by being associated to relevant scientific publications related to the project, thus further boosting their early researchers' careers. At the end of their appointments as early stage researchers for ETAEARTH, 50% of them have already secured staff positions, and an additional 30% has been awarded highly competitive fellowships for independent research at Universities and research institutes in Europe and the US.

E) Impact on the non-scientific community

The outputs from this project have touched on some of the oldest (and newest) questions posed by human beings: is the Earth a solitary outpost where life could exist? If not, how common are Earth-like planets? The combination of Kepler/K2 and HARPS-N data has, for the first time, allowed significant numbers of terrestrial planets and their properties to be disseminated to the greater community. The core scientific topic of our project, the identification and characterization of an Earth analogue, sits at the peak of appeal in the scale of intellectual curiosity of humanity. Spectacular successes of the ETAEARTH project such as the identification of the first Earth-sized planet with an Earth-like density (Kepler-78b) and the first-ever constraints on the density of a planet (K2-3d), in a multiple transiting system, similar to Earth in size and orbiting within the Habitable Zone of the star known to-date to be closest in mass to the Sun. have guaranteed that the degree of the impact of the dissemination of our results to the wide public would be very significant: we have improved the public awareness of the fact that we are finally entering the era of Comparative Exoplanetology, we have made the general audience realize the deep intellectual and sociological consequences of our discoveries, and we have directly contributed to inspire the next generation of scientists. Our team includes excellent communicators, and our experience has been put to the service of relevant outreach activities which have been channelled through the expert hands of collaborators at each of our institutes who are engaged in the wide variety of public outreach and educational aspects of the dissemination of Astronomy among the greater public.

4.1.4.1 Dissemination

There are two main dissemination paths the ETAEARTH project has vigorously pursued, i.e. professional readership and outreach activities.

First, as a fundamental activity of the project, our team has output refereed journal articles covering the many facets of our scientific achievements in terms of observations (planet confirmation and discovery announcements), and theoretical modelling (impact on planet formation, dynamical evolution, and structural models). We have consistently published our high-visibility, high-impact results in peer-reviewed astronomy journals such as Astronomy & Astrophysics (A&A), Monthly Notices of the Royal Astronomical Society (MNRAS), the Astrophysical Journal (ApJ), and the Astronomical Journal (AJ). These high-level astronomy journals have impact factors ranging between ~4.5 and ~7.5. The highest profile results were suitable for publications in Nature and Nature Astronomy (impact factors ~40). The dissemination levels among peers have not only guaranteed that our results become drivers of the field (being highly cited), but they have also provided a) relevant training resources for both students at undergraduate and graduate levels and for young scientists entering the field, and b) reference teaching materials for the preparation of university courses. To further assess the the degree of knowledge transfer for the project we used three success metrics: 1) Networking (meeting participation and interaction): ETAEARTH members have presented Project results at a total of 39 scientific meetings / conferences held in 4 continents throughout the duration of the Project. The global level of meeting participation and its temporal distribution testify of the strong impact the Project results have had among the scientific community of reference; 2) Collaborative research (works carried out with non-ETAEARTH researchers): Collaboration and cooperation efforts between ETAEARTH members and researchers in the field of exoplanets have sparked a total of 85 papers directly linked to the project research themes and goals. Such a high degree of collaborative research developed thanks to the knowledge gathered as ETAEARTH unfolded was not at all anticipated at the beginning of the project. It should be considered among the most spectacular successes of the project; 3) Citation records (stimulation of new research based on ETAEARTH results): The project's 17 primary papers have received a large degree of attention by the scientific community, with as many as 112 citations (Pepe et al. 2013, Nature), and an average number of citations close to 50.

Second, the results of the ETAEARTH project have naturally floated into the suite of public talks that each member regularly gives in their home countries and during open days, public observing evenings and science exhibitions. We have accompanied our highest-visibility results with press releases (a combined number exceeding 30), we have engaged in radio and TV interviews (even exploiting newer communication channels such as blogs). The enterprise of dissemination of our professional scientific results among the greater public has been carried out taking advantage and with the help of media-professionals at each of our institutes, who engage daily in a variety of activities that warrant a highly reliable, uninterrupted communication flow of 'big' science results from astronomers to the media.

In summary, the ETAEARTH project has helped placing the European community in the future of planetary science, and its spectacular results will provide inspiration for younger scientists in cross-disciplinary fields. The ETAEARTH project and its legacy will allow transferring the scientist's curiosity towards some of the most fundamental questions of modern astronomy (is Earth unique? How varied is the class of potentially habitable terrestrial planets?) across the European society.

4.1.5 Project Website and Contact Details

1) The public project website address is: https://www.etaearth.eu

2) The list of Project Partners is the following:

- Istituto Nazionale di Astrofisica, Italy
- Università degli Studi di Padova, Italy
- Université de Genève, Switzerland
- The University Court of the University of St. Andrews, United Kingdom
- The Queen's University of Belfast, United Kingdom
- The University of Edinburgh, United Kingdom
- Smithsonian Institution, USA
- The Warwick University, United Kingdom

3) Lead Partner (Coordinator): Istituto Nazionale di Astrofisica, Italy

4) Contact details of Coordinator:
Dr. ALESSANDRO SOZZETTI – Senior Researcher
Tel: +39 0118101923
Email: alessandro.sozzetti@inaf.it