The Science of Exoplanets and their Systems

Helmut Lammer[1], Michel Blanc[2], Willy Benz[3], Malcolm Fridlund[4], Vincent Coudé du Foresto[5,6], Manuel Güdel[7], Heike Rauer[8], Stephane Udry[9], Roger-Maurice Bonnet[6], Maurizio Falanga[6], David Charbonneau[10], Ravit Helled[11], Willy Kley[12], Jeffrey Linsky[13], Linda T. Elkins-Tanton[14], Yann Alibert[3], Eric Chassefière[15], Therese Encrenaz[5], Artie P. Hatzes[16], Douglas Lin[17], Rene Liseau[18], Winfried Lorenzen[19], Sean N. Raymond[20]

[1]Austrian Academy of Sciences, Space Research Institute, Graz, Austria
(helmut.lammer@oeaw.ac.at)
[2]IRAP, Observatoire Midi-Pyrénées, UPS-CNRS, Toulouse, France
(michel.blanc@irap.omp.eu)
[3]Physics Institute, University of Bern, Bern, Switzerland
(willy.benz@phim.unibe.ch, yann.alibert@space.unibe.ch)
[4]ESTEC/ESA, Noordwijk, The Netherlands
(malcolm.fridlund@esa.int)
[5]LESIA - Observatoire de Paris, Meudon, France
(vincent.foresto@obspm.fr, encrenaz@obspm.fr)
[6]International Space Science Institute (ISSI), Bern, Switzerland
(rmbonnet@issibern.ch, mfalanga@issibern.ch)
[7]Institute for Astronomy, University of Vienna, Austria
(manuel.guedel@univie.ac.at)
[8]Institut für Planetenforschung, Extrasolare Planeten und Atmosphären, DLR, Berlin
(heike.rauer@dlr.de)
[9]Observatoire de Genève, Switzerland
(stephane.udry@unige.ch)
[10]Dept. of Astronomy, Harvard University, Cambridge, USA
(dcharbonneau@cfa.harvard.edu)
[11]Dept. of Geophysics and Planetary Sciences. Tel-Aviv University, Israel
(rhelled@post.tau.ac.il)
[12]Institute for Astronomy and Astrophysics, University of Tübingen, Germany
(wilhelm.kley@uni-tuebingen.de)
[13]JILA, University of Colorado and NIST, Boulder, Colorado, USA
(jlinsky@jila.colorado.edu)
[14]Dept. of Terrestrial Magnetism, Carnegie Institution for Science, Washington DC, USA
(ltelkins@dtm.ciw.edu)
[15]Univ. Paris-Sud, Laboratoire IDES, CNRS, Orsay, France
(eric.chassefiere@u-psud.fr)
[16]Thüringer Landessternwarte Tautenburg, Germany
(artie@tls-tautenburg.de)
[17]University of California Observatories, Lick Observatory, Santa Cruz, USA
(lin@ucolick.org)
[18]Earth and Space Sciences, Chalmers University of Technology, Gothenburg, Sweden
(rene.liseau@chalmers.se)
[19]University of Rostock, Institute of Physics, Rostock, Germany
(winfried.lorenzen@uni-rostock.de)
[20]Laboratoire d'Astrophysique de Bordeaux, Bordeaux, France
(rayray.sean@gmail.com)

Running Title: Exoplanets and their Systems

Corresponding Author:
helmut.lammer@oeaw.ac.at
Austrian Academy of Sciences, Space Research Institute
Schmiedlstr. 6, A-8042 Graz, Austria

To be submitted to ASTROBIOLOGY

ABSTRACT

A scientific forum on "The Future Science of Exoplanets and their Systems", sponsored by Europlanet[1] and the International Space Science Institute (ISSI)[2] and co-organized by the Center for Space and Habitability (CSH)[3] of the University of Bern was held during December 5 and 6, 2012 in Bern, Switzerland. It gathered 24 well known specialists in exoplanet, Solar System and stellar science to discuss the future of the fast-expanding field of exoplanet research, which has now nearly 1000 objects to analyze and compare and will develop even more quickly over the coming years. The forum discussions included a review of the current observational knowledge, the efforts for exoplanet atmosphere characterization, their formation, water formation, atmosphere evolution, habitability aspects, and our understanding of how exoplanets interact with their stellar and galactic environment through their history. Several important and timely research areas for focusing further research efforts in the field have been identified by the forum participants. These scientific topics are related to the origin and formation of water and its delivery to planetary bodies, the role of the disk in relation to planet formation including constraints from observations as well as star-planet interaction processes and their consequences for atmosphere-magnetosphere environments, evolution and habitability. The relevance of these research areas is outlined in this report and possible themes for future ISSI-workshops are identified, which can be proposed by the international research community over the coming two to three years.

Key Words: exoplanets, disks, planet formation, stellar activity, water origin, water delivery, habitability

[1]Europlanet: http://www.europlanet-ri.eu/

[2]International Space Science Institute (ISSI): http://www.issibern.ch/

[3]Center for Space and Habitability: http://www.csh.unibe.ch/content/index_eng.html

1. INTRODUCTION

The International Space Science Institute (ISSI) in Bern Switzerland is an Institute of Advanced Study where international scientists can meet in a multi- and interdisciplinary setting to reach out for new scientific visions related to a widespread spectrum of disciplines including from the physics of the solar system and planetary sciences up to astrophysics and cosmology, and from Earth sciences to astrobiology. The main function of the ISSI activities is to contribute to the achievement of a deeper understanding of the results from different space missions, ground-based observations and laboratory experiments, and to add value of those results through multidisciplinary research in the framework of international teams, workshops, working groups, and forums.

ISSI forums are informal and free debates among some fifteen to twenty-five high-level participants on open questions of scientific nature or science policy matters. Forums do not necessarily lead to formal recommendations or decisions. They are generally held a few times per year at ISSI for two days. During December 5 and 6, a two day scientific forum, which focused on "The Future Science of Exoplanets and their Systems", sponsored by ISSI through the EU FP7 Research Infrastructure project Europlanet, was organized and brought together 24 globally renowned scientists who contributed to exoplanet, Solar System and stellar science essentially during the past decades to discuss the future of the fast-expanding field of exoplanet research. Now more than 860 exoplanets are known and during the near future observing facilities will become extremely powerful. After the pioneering discovery of the first transiting super-Earth CoRoT-7b by the CoRoT space observatory during 2009 (Léger *et al.*, 2009), more exoplanets of that category have been discovered by ground-based projects and NASA's Kepler satellite (Borucki *et al*., 2011). The first potentially habitable planets have already been discovered around M dwarf stars (e.g. Selsis *et al*., 2007; von Bloh *et al*., 2007) and recently around a K star (Borucki *et al*., 2013). More potentially habitable exoplanets will be discovered during the not so distant future. Because such discoveries will have great impacts on modern planetary science and society as a whole, the particular ISSI forum's main aims were related to debates and discussions on how one can represent observed and modeled planetary properties in the most useful and efficient way. By doing this open questions such as:

- is there a typical architecture of planets and/or planetary systems?
- what is driving planetary formation and evolution?
- what is the relevance of planet formation and a system's impact history to the evolution of Earth-like habitats and planets in general (i.e., its outgassing history, hence relationships between interiors and atmospheres, climate stabilization for habitable planets related to different rock/ice/atmosphere ratios, etc.)?

may be solved during the near future. By dealing within a multi-parameter space, the most relevant observables that can be described with a minimum of complexity to understand planetary evolution have been debated and identified. The discussions addressed the following key objectives:

- the first objective was related to discussions of exoplanet properties, which focused on observables and minimum complexity models in theory (i.e., planet formation, dynamic, interior, atmospheres, etc.), as well as on interdisciplinary aspects;
- the second objective focused on exoplanet environments with the main emphasis on disk evolution and stellar radiation and plasma properties;
- the third objective was related to detailed discussions on the origin and delivery of the earliest atmospheres and planetary water inventories;
- finally, the fourth objective focused on the necessary required for observationally based data, as well as lab data, theoretical models and ground- and space-based proposed and selected projects/missions.

Besides these objectives the related discussions led finally to the identification of important research areas where only interdisciplinary approaches addressed in specialist workshops and related activities will enhance knowledge in the field of exoplanet research. This report on the science of exoplanets and their systems summarizes the main results of this particular ISSI forum.

2. EXOPLANET PROPERTIES

The fast growing field of exoplanet science is currently in an observationally driven phase where the theoretical models that are used to characterize of the discovered new planets are only useful for interpreting these observations. Due to the complex nature of planetary systems, it is highly unlikely that a single theory can explain the discovered systems. Therefore, one must develop several models so that the important and most relevant mechanisms and their outcomes can be understood within the parameter space given by the observations.

2.2 Detection methods

The methods which have been used so far for the discovery of exoplanets can be summarized as:

- the Doppler method;
- the transit method;
- direct imaging;

and

- gravitational microlensing.

Most exoplanets have been discovered by the Doppler method, which monitors the change in Doppler shift, of the spectral absorption lines of the exoplanets host star. From the Doppler shift the minimum mass of the observed target planet can be determined, as well as the body's semi-major axis and orbital eccentricity. Radial velocity measurements on stars related to the search and confirmation of exoplanets are at present mainly performed with the 3.6 m ESO High Accuracy Radial Velocity Planet Searcher (HARPS), the Very Large Telescope (VLT) spectrographs UVES, FLAMES and CORALIE, the 1.93 m SOPHIE spectrograph in the Observatoire de Haute Provence, the Coudé echelle spectrograph from the 2 m telescope in Tautenburg (TLS), Germany, and spectrographs at the McDonald and Keck observatories. The current limiting precision reached by the HARPS project is ~ 0.5 m s^{-1}, while the Earth-Sun signal would be ~ 0.1 m s^{-1}. However, it should be noted that the first Earth-mass exoplanet within a close-in orbit of α Centauri B has been discovered recently (Dumusque *et al.*, 2012). The amplitude of this signal is 0.5 m s^{-1} which is significantly below many other astrophysical signals, including binaries, stellar rotation and long-term magnetic activity.

The second powerful method in exoplanet detection is the transit method which monitors the change in brightness of the planet's host star. With this method the radius of an exoplanet and its semi-major axis can be determined. One should note that not all exoplanets which are discovered by the Doppler method are in an orbit around their stars so that they can also be seen by transit observations (e.g. ~10% transit probability for close-in planets). But exoplanets which are discovered by transits can be re-observed by the Doppler method so that their mass can also be determined if the precision is above the current signal threshold. The discovery of CoRoT-7b, the first small rocky exoplanet with measured radius and mass (Léger *et al*., 2009), and therefore with a known density, has opened up a new research era. While the European COnvection, ROtation and planetary Transits (CoRoT) space observatory has demonstrated that exoplanets can be observed via transits from space, due to the mission design the CoRoT satellite cannot discover Earth-size exoplanets within the habitable zones of their host stars. This important task has been taken over by NASA's Kepler satellite which is in space since March 2009 (e.g., Borucki *et al*., 2011). The current limiting precision for the transit method is given by Kepler with ~ 20 ppm. The Earth-Sun transit signal is ~ 80 ppm. Compared to the Doppler method which cannot measure Earth-mass bodies at 1 AU at present, Earth size exoplanets at a distance of about 1 AU can be discovered by the Kepler space observatory. From the discoveries of exoplanet systems such as Kepler-20, it is known that Earth-sized planets are interspersed among larger Neptune-sized bodies. The Kepler mission has discovered about 2300 exoplanet candidates so far, most of them smaller than Neptune, they could potentially be used for the determination of the occurrence rate of Earth-analogues. It should also be noted that the hunt for exoplanets below the Jovian- and Neptune-class by Kepler is supported by ground-based transit projects such as the MEarth-project in the USA. The MEarth-project is a photometric ground-based survey that monitors about 2000 nearest M-dwarfs for transiting super-Earths with orbits inside of close-in habitable zones. The most interesting discovery of this project so far is a sub-Neptune/super-Earth-class exoplanet with the size of ~ 2.7 Earth-radii with an orbital period of 1.6 days around the small, faint star GJ 1214 (Charbonneau *et al*., 2009).

Direct imaging is the third method for the detection of exoplanets by the determination of the band-integrated luminosity and the projected planet-star separation. From the few directly detected exoplanet systems one can expect that these systems are very young and widely separated. This method does not permit a direct measurement of the mass or size of the imaged planets.

The fourth method which has so far discovered exoplanets is gravitational lensing, which monitors the change in brightness of a distant star because its light is bent and focused by gravity when a star with an orbiting exoplanet passes between the distant star and Earth. From this method the mass of the exoplanet and its semi-major axis can be determined. So far 14 exoplanets have been discovered with the gravitational microlensing method. The disadvantage of this method is that, in general, follow-up observations are not possible. It should be noted that microlensing is the only practical method that can discover the population of gas and ice giants significantly beyond the ice line (see Fig. 6 in Gaudi, 2012). The science programs of ESA's Euclid and NASA's planned WFIRST fundamental physics space missions contain microlensing searches of exoplanets within their science cases.

In the near future ESA's Gaia all-sky survey astrometry space mission will also contribute to the statistics of exoplanets via astrometry (Sozzetti, 2010). For example, the Gaia data, over the next decade, will allow us to significantly refine the understanding of the statistical properties of extrasolar gas giants and will enhance our knowledge on potential exoplanet host star parameters. Also, asteroseismic studies will yield the age of exoplanet host stars.

2.2 Observables and science

From this brief survey of the present day exoplanet detection methods, one understands that the Doppler and transit methods will also dominate the near future compared to direct imaging, gravitational microlensing and space astrometry. Table 1 compares the current limiting precision for the Doppler and transit methods and the corresponding necessary values for an Earth-Sun signal at 1 AU orbit location. Therefore, a short summary of the science that can be obtained by the combination of the transit and Doppler methods is addressed below.

Exoplanet mean density: By knowing the radius and mass of an exoplanet, the mean density can be calculated. The present data base already shows that planet densities span a wide range for any given planet mass. This indicates the existence of hence very different types of planets with similar masses. A big surprise from the available observations of this kind is that there are many close-in hot Jupiters that have inflated radii compared to their expected ones from radius-mass models which work for solar system gas giants. Furthermore, a detailed investigation of the first discovered super-Earths with known size and mass indicate that many of them are most likely surrounded by hydrogen envelopes or dense hydrogen-rich volatiles containing a few percent of their masses (e.g., Lissauer *et al*., 2011; Ikoma and Hori, 2012; Lammer *et al*., 2013). The existance of such envelopes indicates that these planets did not get rid of their nebula-based or outgassed protoatmospheres (Kuchner, 2003; Lammer, 2013; Lammer *et al*., 2013). These discoveries are very important and are closely linked to the formation of the whole system, the host stars early radiation and plasma environment that is connected to the nebula lifetime, the inner structure and related physics of the exoplanets, and finally, in case of super-Earths and Earth-size exoplanets to their habitability. Although the available data suggest that more massive and slightly larger planets compared to Earth with orbital distances > 0.02 AU (around G stars) are more likely mini-Neptunes than a pure rocky planet with a tiny Earth-like atmosphere, but the present error bars in the radius-mass relation are too large and must be reduced. As one can see from the illustration of Fig. 1, a good example is the low-density super-Earth GJ1214b whose radius-mass related structure can be fitted by a dense core model which is surrounded by a dense primordial based H/He envelope or outgassed H_2 as well as by a low density core surrounded by a deep H_2O ocean and a thin hydrogen envelope at the top (Adams *et al*., 2008; Rogers and Seager, 2010; Nettelmann *et al*., 2011; Berta *et al*., 2012).

Exoplanet atmospheres: Planetary transits give not only the size of an exoplanet but also permit the study of its atmosphere, which is so far not possible for non-transiting planets. As illustrated in Fig. 2, the radiation from the exoplanet host star is transmitted through its atmosphere during the transit, while the thermal radiation and the reflected light from the planet disappear and reappear during the secondary eclipse. By measuring the planet-to-star flux ratio as a function of wavelength, one obtains spectra of the planetary atmospheres (Charbonneau *et al*., 2008; Grillmair *et al*., 2008).

Vidal-Madjar et al. (2003) observed the transiting exoplanet HD 209458b with the HST STIS-instrument and discovered an intensity drop in the stellar Lyman-α line which was surprisingly large, considering that the atmosphere of a planet occulted only 1.5% of the star. Subsequent observations at low spectral resolution with the HST STIS/ACS have also confirmed that the transit depth in Lyman-α is significantly greater than the transit depth due to the planetary disk alone (Ben-Jaffel, 2007; Ben-Jaffel and Sona Hosseini, 2010). Recently, another observation of an extended upper atmosphere due to Lyman-α absorption during the transits of a second short periodic Jupiter-type gas giant, HD189733 b was reported (Lecavelier des Etangs *et al*., 2010; 2012). From these observations, one can conclude that hydrogen atmospheres of hot Jupiters expand up to their Roche lobes and that close-in gas giants are surrounded by cometary-type hydrogen clouds as predicted by Schneider *et al*. (1998). Applied hydrodynamic models by Yelle (2004), García Muñoz (2007), Penz *et al.* (2008) and Koskinen *et al.* (2013a; 2013b) support this hypothesis as well as independent HST/STIS and Cosmic Origins Spectrograph (COS) observations where carbon, oxygen and Si were observed beyond the Roche lobe of HD 209458b (Vidal-Madjar *et al*., 2004; Linsky *et al*., 2010) and various metals around the Roche lobe of WASP-12b (Fossati et al., 2010).

The detection and investigation of extended upper atmospheres around exoplanets of all types provides very promising insights into the interaction of the host star's plasma environment and with the planet itself. Lammer *et al*. (2011) and Lammer (2012) showed that it should be possible to detect extended upper atmospheres and their related hydrogen coronae even around small, Earth-size exoplanets orbiting cool M-type stars with space observatories such as the World Space Observatory-UV (WSO-UV) (Shustov *et al*., 2009) which are currently being developed.

From transit spectroscopy by follow-up observations with the Spitzer Space Telescope, even molecules (i.e., H_2O, CH_4, etc.) in hot Jupiter atmospheres have been inferred (e.g., Tinetti *et al*., 2007; Swain et al., 2009; Beaulieu *et al*., 2010). By measuring the combined star-planet flux for determining a longitudinally resolved emission map as a function of wavelength, the day-night circulation of an exoplanet atmosphere can be figured out (Knutson *et al*., 2007; 2012). Transmission spectra modeling on the above discussed transiting super-Earth GJ1214b can also be used for clarifying the uncertainties in the planet's structure. Model simulations of the GJ1214b WFC4 transmission spectrum by Miller-Ricci and Fortney (2010) ruled out the dense core primordial hydrogen envelope scenario of Fig. 3a at 8.3 σ, while their result agrees well with H_2O fractions > 20 % as illustrated in Fig. 3b. This example shows that one can characterize the structure of this exoplanet to a certain point if the radius, the mass and the transmission spectrum are known. Although the observations contain uncertainties, the results point clearly point in a direction that this particular planet may be a water world that is surrounded by a H_2O atmosphere and a hydrogen corona. Unfortunately, due to the brightness properties of the host stars of the known exoplanets, only a tiny fraction, which includes GJ 1214b, of transmission spectra can be observed. Perhaps the James Webb Space Telescope (JWST) and the ground-based ESO Extreme Large Telescope (ELT), Giant Magellan Telescope (GMT), Thirty Meter Telescope (TMT) projects can observe atmospheric species for cooler super-Earths in a similar way as the HST, Spitzer and ground-based projects did so far for some hot Jupiters and Neptunes.

Spin-orbit misalignment determination: By investigating a transiting planet with a known mass the planet's spin-orbit alignment can be determined by the Lossiter-McLaughlin effect (Gaudi *et al*., 2007; Albrecht *et al*., 2012). From such studies it is known that many hot Jupiter systems are misaligned, which has widened the picture of planetary migration models.

Planet-radius distribution: From the survey of the discovered transiting exoplanets and Kepler's discovery of ~ 2300 planet candidates, a statistic related to the planet-radius distribution can be determined. From these discoveries one finds the power law $dN/d\log R_{pl} = kR_{pl}^{\alpha}$ (Howard *et al*., 2012; Batalha *et al*., 2012) with coefficients k = 3.8 ± 0.3 and α = -2.01 ± 0.09, which indicates that exoplanets with small radii are much more numerous compared to Jovian-like gas giants. From the available Kepler survey, one derives an occurrence rate of planets between 0.4 - $4R_{\oplus}$ within orbital periods < 50 days of 0.91 planets per cool star. The occurrence rate of Earth-size planets in the habitable zone of cool stars is ~ 0.1 planets per cool star. From this statistic one finds that with ~ 95 % confidence, there is a transiting Earth-size planet in the habitable zone of a cool star within 23 pc (Dressing and Charbonneau, 2013).

2.3 *Improvements for the future and open questions to be solved*

Although there are more than 850 exoplanets known and about 290 have known size and mass, due to the faintness of their host stars, the atmosphere of these planets can only be studied for a smaller fraction (e.g., Seager and Deming, 2010). With increasing number of detected transiting planets, our knowledge of the physical parameters for characterizing planets increased significantly, showing that planets are much more diverse than we expected from the Solar System. This increasing understanding of planet populations has been triggered by transiting planets for which we can directly measure their bulk parameters (radius, mass, mean density), by using the Rossiter-McLaughlin effect to determine their orbit alignment, measure effective temperatures, albedos and finally even detect atmospheric molecular absorptions. Exoplanet atmosphere observations are evolving as a separate research field that is now firmly established, with more than two dozen atmospheres of hot Jupiters observed. Highlights include:

- the detection of molecular spectral features;
- the observation of day-night temperature gradients;

and

- the constraints on vertical atmospheric structure.

The success of ground-based surveys and, in particular, the CoRoT and Kepler space missions also showed that transits are an efficient method to detect large numbers of planets with well-known parameters. It is true that efficient transit detections are biased to short orbital periods due to the low geometrical transit probability. This disadvantage over the radial velocity method is, however, not true when one considers searches for small terrestrial planets at intermediate to large orbital distances for which also radial velocity detections require a huge investment of observing time per planet. When it becomes possible to determine the entire parameter range for each detected exoplanet, including terrestrial planets, we will enter a new era of planetary science. To date, this is possible only for planets orbiting the brightest host stars among the almost thousand detected exoplanets. To date the results of the CoRoT and Kepler space observatories as well as the ground-based surveys mainly contribute to the exoplanet statistic, but their discoveries are not ideal for spectroscopic follow up observations. The overlap between planets that have been discovered by the Doppler method and transiting planets of bright stars is very small. There are many radial velocity planets with known mass around brighter nearby stars, while transiting exoplanets so far are discovered mainly around fainter stars. This fact results in a target problem for future exoplanet atmosphere characterization projects.

All the participants of the ISSI forum agreed that more detections of exoplanets around *bright* and *nearby stars* are necessary in order to characterize large numbers of exoplanet atmospheres more accurately than presently. When investigating habitable planets which may have evolved to be comparable to the Earth, such detection surveys must include intermediate orbital distances, where we expect temperate planets. Two space missions are currently studied for the detection of exoplanets around nearby bright stars, in the USA, the NASA Transiting Exoplanet Survey Satellite (TESS) mission and in Europe, ESA's PLATO mission.

The TESS space observatory has been selected recently by NASA as an all sky survey of bright, nearby stars mission which should be launched during 2017. Its prime target range is transiting Earths and super-Earth planets. TESS will survey bright host stars at 4.5 mag to 12 mag. It will survey F, G, K stars and also scan the bright M stars within 50 pc. In total, about 500 000 stars will be observed within 2 years mission lifetime. Altogether, it is expected that TESS will discover more than 1000 new exoplanets and several hundred of them will be Neptune-sized or smaller. TESS will operate in a step-and-stare mode to cover the whole sky. The observational coverage of each field (hence of the orbital planet periods scanned for) will depend on its position in the sky. Most of the detections will be made

- for short period planets, but for M dwarf stars planet detections up to their habitable zones will also be possible. Such bright planetary systems will also be prime targets for e.g. spectroscopic follow-up characterization of their atmospheres by planed future projects such as the so far not selected NASA Fast INfrared Exoplanet Spectroscopy Survey Explorer (FINESSE) and/or ESA's Exoplanet Characterisation Observatory (ECHO).

The next generation planet finder mission PLATO has been proposed to ESA for the M3 mission launch opportunity in 2022/24. It is planned as a large-scale detection survey providing statistically relevant numbers of well-characterized exoplanets with highly accurate bulk parameters and ages, in particular, in the Earth to super-Earths domain around bright host stars. PLATO would be the first mission making systematic use of both the transit planet search technique and asteroseismology of the planet hosts. This will not only provide highly accurate parameters for planets and their host stars, but would also allow determining the age of planetary systems on a large scale. The PLATO prime target range is 4 mag to 11 mag. This bright target range allows surveying solar-like F, G, K stars as well as the brightest and nearest M dwarfs for terrestrial planets. PLATO is able to detect thousands of planets of Neptune-size and smaller planets and hundreds of these planets will be in the super-Earth regime, including planets in the habitable zone of bright solar-like stars. The telescope combines a step-and-stare observing strategy with two long-term (up to 3 years) field observations. With a total mission lifetime of ~ 6 years, ~ 50 % of the sky will be scanned for new exoplanets. Its detection range therefore targets

- at intermediate orbital distances, up to the habitable zone of solar-like stars, to significantly expand the number of well-characterized cool and potentially habitable exoplanets;

and

- large numbers of terrestrial planets in this intermediate orbital distance range with well-known bulk parameters and ages as the prime goal for a detection survey operating in the next decade.

Due to technological differences and hence observational capabilities between TESS and PLATO, the selection of these missions has an impact on the accuracy of the observations related to the target planet's orbit location. In the case of expected discoveries by TESS the first accurate characterization of exoplanet atmospheres by a future characterization project will focus on exoplanets that have their orbits inside M-star habitable zones. In case PLATO is selected future characterization missions would probe planet atmospheres in orbital distances within habitable zones around Sun-like stars.

Smaller numbers of presently available or discovered exoplanets in the near future around brighter stars will also be studied with ESA's recently selected first small mission, the Charactizing ExOPlanets Satellite (CHEOPS). CHEOPS is a Swiss-led with European countries and ESA supported small space telescope which is designed for the follow up observation of exoplanets discovered within the overlap of transits and Doppler observations. Ground-based high-precision Doppler spectroscopic surveys have been carried out during recent years and hundreds of stars with exoplanets in the super-Earth to Neptune mass range ($1 < M_{\rm pl}/M_{\rm Earth} < 20$) have been identified. These surveys will continue into the foreseeable future. The characteristics of these stars (brightness, low activity levels, etc.) and the knowledge of the planet ephemerids make them ideal targets for ultra-high precision photometric measurements from space with CHEOPS. This mission which will be launched in 2017 and is the only space observatory which will be able to follow-up all these targets for precise radius measurements in the near future.

The new generation of ground-based transit surveys (e.g. NGTS), should be capable of reaching 1 mmag precision on V < 13 mag stars, so that new targets for CHEOPS can be expected. By the end of 2017, NGTS will provide of order 50 targets with radius less than six Earth-radii for which CHEOPS will be able to measure radii to a precision of 10 %. The studied planets can be selected for further investigations with JWST, ELTs, etc. The most interesting targets for CHEOPS will be hot Neptunes and super-Earths. From the discussions above it is clear that the main challenge is to overcome the problem that if smaller sized planets are discovered the related error bars become more and more relevant. With the space observatories briefly mentioned before and the currently developed instruments which will be installed on available or planned ground-based telescopes the error bars in size and mass determinations will be minimized.

Launched and future Solar System missions such as JUNO or JUICE will certainly contribute to our understanding of Jovian-type gas giants but will not deliver the whole answer. Although we had spacecraft near Jupiter it is not known so far if the closest gas giant has a core, mantle and envelope (three layer structure) or only a core and an envelope (two layer structure) (Nettelmann, 2011). However, the uncertainties due to the used equation of state are getting less important due to advances in ab initio modeling techniques and computer power (e.g., French *et al*., 2012; Nettelmann *et al*., 2012). JUNO will set tighter constraints on Jupiter's core mass and internal structure, including the planets water abundance.

Therefore, the expected results from the JUNO mission will help us to understand Jupiter's origin and via the H_2O-aboundance, possibly the physical/chemical conditions in the nebula and the history of volatiles. The obtained data and their properties can be then related to giant planet formation theories. From the exoplanet surveys we know that Uranus- and Neptune-type planets seem to be a very common planetary category in the Galaxy. Future Solar System missions to one of these planets would indeed help to understand what exoplanets of that kind are made of.

There are still many open questions regarding Uranus and Neptune. Their internal structure and compositions are still poorly understood and in addition, despite their similar masses and radii, they differ in other physical parameters such as the inferred atmospheric composition, obliquity, and thermal emission. It is therefore clear, that further investigation of the origin, evolution and internal structure of intermediate-mass planets is desirable. All of these open questions are directly related to the real *boundary* between gas-rich planets and so-called terrestrial planets (see Fig. 4) where life forms may evolve on the planet's ocean/surface like it did ~ 3.5 – 3.8 Gyr ago on Earth. A detailed observation and study of this boundary bears directly on fundamental open questions related to planet formation such as:

- runaway gas accretion in the core accretion scenario or the loss of primordial H-He atmospheres;

and

- constraints on possible planet migration paths followed during formation and evolution for planets where the clear presence of a massive gaseous envelope cannot be discerned.

These are key habitability questions which have a direct link to a possible architecture of habitable planets and the evolution of Earth-like class I habitats (Lammer *et al*., 2009; Lammer, 2013) where life as we know it can evolve. To solve these questions the theoretical efforts combined with the above enhancements mentioned before in observables related to the following points have to be addressed:

- combining planet formation theories with the formation environments;
- understanding the formation of intermediate-mass planets;
- more accurate measurements of planetary parameters for planets with larger orbital locations;
- combine exoplanet statistics, hence ensemble parameters, with predictions from planet formation models;

and

- obtaining the dimensionless Love number parameters that determine the rigidity of a planetary body and the susceptibility of its shape to change in response to a tidal potential would result in a better feeling on the planet's interior (Kramm *et al.*, 2012).

Due to technological reasons there is at present a bias in the characterization of exoplanets within close orbit locations around their host stars. These close-in planets, however, represent certainly not the main populations and additional complex processes such as heating and interaction processes with the host star will influence the evolution of such planets.

Therefore, it is important to obtain data from planets on orbital locations which are further out. Theoreticians who model planetary composition and structure should investigate if one can separate first order uncertainties in their models for instance to obtain information if a planet has a three layer or two layer structure. It is important to point out that it makes not much sense to apply a very complex theoretical model if the input parameter space is so uncertain that every result can be hypothetically possible – including unrealistic ones. It is very important to understand how one quantifies the theories within the available constraints and parameter space. For instance, to understand in an interdisciplinary way how planets such as discovered in the densely packed Kepler-11 system originated and evolved contains incredible theoretical efforts. Thus, the forum participants agreed that it is important for theory to know to which extent first order uncertainties in theoretical models can be solved with high-precision radius and mass measurements.

3. DISK EVOLUTION AND ORIGIN OF PLANETS, THEIR ATMOSPHERES AND WATER INVENTORIES

Planet formation is closely connected to star formation and early stellar evolution (see e.g., Bodenheimer, 1997; Mannings *et al.*, 2000; Wuchterl *et al.*, 2000; Boss, 2003). Stars form from collapsing clouds of gas and dust. The collapse leads to the formation of the protostar in the center, which contains most of the mass of the cloud, and a circumstellar disk, which retains most of the angular momentum of the cloud. Because stars have various disk sizes and masses, there is no reason that a given star has given disk properties (Williams and Cieza, 2011). Thus, a huge variation can be expected. In the Solar System, the circumstellar disk is estimated to have had a mass of a few percent of the Sun's mass. The planets form from the material in the circumstellar disk, which is in this stage also referred to as the protoplanetary disk.

3.1 Protoplanetary disk evolution

Most protoplanets are formed within the accretion disk during the nebula lifetime which lasts between ~ 10^6 – 10^7 years (e.g., Montmerle *et al*., 2006). After 10 Myr most nebular gas is evaporated from the system. Because the accretion disk contains about 99 % gas and 1 % dust, planets can accumulate nebula gas (e.g., Ikoma and Genda, 2006) which results in a nebula-captured hydrogen-rich protoatmosphere of the newborn planet. The amount of captured nebula gas depends mainly on

- nebula dissipation time and properties such as grain depletion factors, etc.;
- planetary growth rate and related protoplanet mass and size.

Disks are hydrodynamically stable and magnetohydrodynamic (MHD) turbulence which is linearly unstable plays a major role in disk physics. The nebula dissipation time is also related to the activity of the host star and the presence of massive stars and supernovae in the neighborhood of the particular system. The removal of the disk is related to efficient angular momentum transport processes, the X-ray and EUV radiation field, and the stellar plasma flow during the T-Tauri, post-T-Tauri and activity saturation stage of the host star.so-called "normal" disks and "transition" disks which show a wide gap of missing warm dust near the central star.

Dust in the disks is produced as a by-product of collisions between planetesimals, and planetary embryos related to the planet formation process. Planetary debris disks represent the almost final stage of the circumstellar disk evolution process, i.e., they are the evolutionary products of ongoing or completed planet formation.

The general disk evolution scenarios are illustrated in Fig. 5. In protoplanetary disks, the inner radial boundary between magnetorotational instability (MRI) turbulent (active) and MRI quiescent (dead) zones plays an important role in some planet formation scenarios and in disk evolution models. The extreme X-rays, EUV, FUV, flux and winds of the young active star clear the nebula gas in time. Inside the evolving disk are dust particles, a magnetically inactive dead zone and the growing protoplanets. One should also point out that many assumptions mainly related to the unknown dust properties and related opacities have to be made. These unknowns influence the results of each theoretical simulation. The discovered exoplanets move around in the disk and are not formed at the location where we observe them later. Further, as shown in Fig. 6 planets within a disk create torques and momentum exchange so that the semi-major axis changes also (Kley and Nelson, 2012). Tidal forces can also push the planets out of resonance. The disk acts as a damping process on eccentricity and inclination. If a planet becomes massive it opens up a gap in the disk and if there are several planets they act on the disk and against each other. For example numerical simulations of two massive gas giants in the system HD 73526, which join a large gap in the disk show that the outer planet can be pushed inward by the outer disk, while the inner planet is pushed outward by the inner disk (Sandor *et al*., 2007).

Many planets may also fall to the star. Migration may be too fast but due to corotating torques the fast migration may slow down. Planets are captured into resonant systems which can be seen in observations so one can conclude that migration should occur. The data from exoplanets discovered by the Kepler satellite indicate that many systems are in (near) resonance, which indicates a resonant capture through convergent migration process which is related to dissipation forces due to planet-disk interaction. Thus, the evidence for planetary migration is confirmed due to the existence of:

- resonant systems and flat Kepler systems;

and

- hot Jupiters and Neptunes.

To overcome the related uncertainties in disk physics, such as migration in turbulent disks, in self-gravitating disks, tidally driven migration, type-III migration and stellar irradiation it is very important and timely that theoreticians co-operate more with observers so that a powerful strategy for missing observables related to theoretical disk models could be established. For instance the accretion luminosity could be high so that one should search for a protoplanet inside a disk (Kraus and Ireland, 2012). One main task for the future should therefore be:

- to observe protoplanets in evolving disks.

3.2 Protoatmospheres and early water formation

Another challenge related to the discovery and characterization of exoplanets and their structure, particularly in the rocky planet domain is to study protoatmospheres and initial water inventories, their formation and evolution. As illustrated in Fig. 7 the initial atmospheres and the water content of terrestrial planets are related to a complex interplay between the nebula dissipation time, the growth rate/time of a proto-planet from planetesimals and planetary embryos, the orbit location and water content of the initial building blocks (i.e., planetesimals and planetary embryos), outgassing processes from the interior, the impact history and finally the host star's radiation and plasma environment.

The first atmosphere is created by the capture and accumulation of hydrogen, He and other gases from the surrounding disk around the growing proto-planet (rocky core). Depending on the nebula properties, its life time and the gravity potential of the growing and embedded protoplanet, an extensive amount of gas could be attracted so that optically thick, dense hydrogen envelopes accumulate around rocky cores (e.g., Mizuno, 1980; Hayashi et al., 1979; Wuchterl, 1993; Ikoma et al., 2000; Ikoma and Genda, 2006; Rafikov, 2006; Ikoma and Hori, 2012).

The recent discovery of low-density super-Earths with short orbital periods such as those in the Kepler-11 system indicate that fast growing more massive planets compared to Earth or Venus may have a problem getting rid of their nebula captured gaseous envelopes (Ikoma and Hori, 2012; Lammer, 2013; Lammer *et al*., 2013). Preliminary results indicate that the atmospheres of massive rocky bodies undergo runaway disk gas accretion, while the atmospheres of light rocky bodies undergo significant erosion during disk dispersal. In the atmospheric erosion, the heat content of the rocky body plays an important role (Ikoma and Genda, 2006; Ikoma and Hori, 2012).

As one can see, the formation of dense nebula-based hydrogen envelopes around super-Earths is completely connected to the open questions and future challenges discussed briefly in the previous sections and shows that the structural characterization of low-density super-Earths with future space missions like CHEOPS, TESS, and PLATO, provide important clues for understanding planetary accretion and disk evolution. The second atmosphere formation occurs by catastrophically outgassing of dense hot H_2O, CO_2, CH_4, NH_3 atmospheres during the magma ocean solidification process when the planet's accretion ended. Earth- or super-Earth-type planets with silicate mantles and metallic cores, will obtain a major amount of their initial water and carbon compounds during the second atmosphere formation process.

As illustrated in Fig. 8, modern terrestrial planet formation model simulations indicate that terrestrial planets originate from differentiated planetesimals to large planetary embryos with sizes of several hundred to a few thousand kilometers (Kokubo and Ida, 2000; Raymond *et al*., 2004; Alibert et al., 2007; Raymond *et al*., 2009; Lunine et al., 2011; Walsh *et al*., 2011; Morbidelli *et al*., 2012). After the evaporation of the nebula gas due to the extreme EUV phase of the young Sun/Star the protoplanets continue to grow through the capture and collisions of remaining large planetesimals and planetary embryos. Impact studies related to Mercury and the Moon indicate that giant impacts between planetary embryos do not completely devolatilize a planet.

During huge impacts a fraction of the volatiles remain inside the growing planetary body while some volatiles are pushed outward and may escape to space.

Geochemical studies revealed that a fraction of Earth's water originated from comets while the rest came from chondritic rocky materials (Mumma and Charnley, 2011). Recent studies indicate that most of the water most likely originates from rocky planetesimals (Alexander *et al*., 2012). Meteorites are therefore candidate planet-building block materials which have a wide range of carbon and water contents. Various degassing and formation scenarios during accretion for a wide range of atmospheric masses and composition of exoplanets within 1 to $30M_\oplus$ have been modeled (Elkins-Tanton and Seager, 2008; Elkins-Tanton, 2011).

By using primitive and differentiated meteorite compositions these studies reveal that degassing alone can produce a wide range of planetary atmospheres which range from ≤ 1 % of a planet's mass up to ~ 6 % by mass of hydrogen, ~ 20 % by mass of H_2O, and ~ 5 % by mass of carbon compounds (Elkins-Tanton and Seager, 2008). As shown in Fig. 10 depending on the initial volatile contents and planetary building blocks, magma ocean outgassing models can produce early steam atmospheres with surface pressures up to several 10^4 bar (Elkins-Tanton, 2011). One should also note that hydrogen-rich atmospheres can also be formed by outgassing due to oxidation of metallic Fe with H_2O and that atmospheric escape processes which are powered by the high radiation and plasma environment of the young host star are not included in the results shown in Fig. 9. Catastrophically outgassed steam atmospheres during the magma ocean solidification are expected to be related to the formation of the earliest oceans on Earth (e.g., Elkins-Tanton, 2008; Lammer *et al*., 2012; Hamano *et al*., 2013) or exoplanets within the habitable zone in general (e.g., Elkins-Tanton, 2011).

However, one should note that differentiated large planetary embryos as shown in Fig. 8 will also form magma oceans; so that H_2O and other volatiles may be step wise outgassed and could be lost to a great extent as illustrated in Fig. 10 before the final magma ocean solidifies at the time when the final planet's accretion ends. If wet planetary embryos loose much of their water inventories during their growth to the final planetary body, the volatile content which is outgassed in the final stage would be lower than expected. Such a scenario would agree with the hypothesis of Albarède and Blichert-Toft (2007) that the terrestrial planets in the Solar System accreted dry and obtained most of their water during the late veneer via impacts. On the other hand, the discoveries of H_2O/volatile-rich super-Earths like GJ 1214b support the outgassing hypothesis as briefly discussed before. From the first discovery of lower mass and size exoplanets one can also see that we cannot take the Solar System planets as a base for extrapolations, because it may only represent a particular outcome of a huge possibility of final planet scenarios, which may however, fit within the three overall categories illustrated in Fig. 7.

One should also not forget atmosphere producing processes which are related to secondary outgassed atmospheres of H_2O, CO_2, N_2 and other trace gases, via tectonic activities, volcanos, and impact events such as the late heavy bombardment in the Solar System. Most likely, terrestrial planets may obtain their initial atmospheres by a mixture of all briefly discussed scenarios in one or more ways.

The participants of the ISSI forum were convinced that detailed research activities and studies related to the latest and near-future discoveries of Earth- and super-Earth-like exoplanets, their characterization in structure and atmosphere together with the expertise and knowledge obtained within the Solar System and geochemistry communities is highly timely and necessary to understand how terrestrial planets obtained and lose their initial water inventories and volatiles. These are crucial questions related to habitability aspects in general, and from the discussion within the ISSI forum panelists one can understand that several interacting and connecting processes related to the disk properties, nebula dissipation time, planetary growth rate, host star powered atmospheric escape processes and the general impact history of a particular system play important roles.

4. STELLAR ENVIRONMENTS AND EXOPLANET HOST STARS

The long time evolution of planets and their atmospheres can only be understood if one understands also the evolution of the planet host stars. Planets cannot be seen as isolated objects because the radiation and plasma environment of their host stars constitute a permanent forcing of the upper atmosphere-magnetosphere environments of the exposed bodies. The main effect of these forcing factors is to ionize, chemically modify, heat, expand, evaporate and erode the upper atmosphere throughout the lifetime of a planet (e.g., Lammer, 2013). The host star and its related activity influence the detection ability and make the measuring of exoplanet parameters such as mass and radius more difficult. Physical and fundamental properties for exoplanet host stars are, the star's mass, radius, chemical composition, and rotation period which is connected to magnetic activity and age. These properties can be determined by the
following methods

- calibrations (from binaries, clusters, etc);
- stellar evolution models;
- asteroseismology;
- age: kinematics, asteroseismology, activity, chemical abundances (Li, Be), theoretical models, while the radiative properties can be studied if one obtains a detailed spectral energy distribution from X-rays to IR, and radio. Short-term variations up to years can be studied by establishing time-series with photometry. For longer timescales observations of stellar proxies or stars of the same spectral class with different ages are the best options. Because the host star's activity evolution is different for different stellar spectral types, and furthermore depends on the stellar age and the location of the habitable zone around the host star, one can expect that the atmospheric evolution of exoplanets is strongly coupled with the activity evolution (X-rays, EUV, FUV, winds, CMEs, SEPs, etc.) of the host star.

4.1 The relevance of the stellar Lyman-α emission line observation and reconstruction methods

For the characterization of exoplanet atmospheres as well as the observation/detection of stellar mass loss it is important to measure the Lyman-α emission line of the particular star. Accurate investigations of the chemical composition of exoplanet atmospheres can only be carried out if the near-ultraviolet (NUV: λ = 170 – 320 nm), far-ultraviolet (FUV: λ = 117 – 170 nm), extreme ultraviolet (EUV: λ = 30 – 91.1 nm), XUV (λ = 10 – 30 nm), and X-ray (λ < 10 nm) radiation from the host star, which control important molecular photodissociation and photoionization processes, are known. The Lyman- α emission line dominates the FUV spectra of late-type stars and is a major source for the photodissociation of important atmospheric molecules such H_2O, CH_4, NH_3, CO_2. For the Sun, the Lyman-α emission is ~ 20 % of the total flux between 1 – 170 nm. For example, the solar Lyman-α line is responsible for ~ 50 % of the photodissociation rate of H_2O molecules between 114.8 and 194 nm, and ~ 70 % of the total photodissociation rate of CH_4 between 5.6 - 152 nm. The Lyman-α line emission is even more important for cooler low mass stars, such as M dwarfs, because the photospheric emission at λ > 170 nm decreases rapidly with decreasing effective temperature. A comparison between the quiet spectrum of the Sun and that of GJ 876 which has an exoplanet within its habitable zone, indicates that as seen by an exoplanet in the habitable zone the near UV is weaker by 4 orders of magnitude but the FUV is much stronger compared to the Sun. For GJ 876 the Lyman-α flux is about 2 times as high. M stars seem to be brighter in Lyman-α compared to more massive solar-like stars, and the age of the stars which is related to their activity in general plays also a major role (France *et al.*, 2013; Linsky *et al.*, 2013).

Exoplanet atmospheres absorb the Lyman-α flux from their host stars without attenuation, neutral hydrogen in the interstellar medium (ISM) scatters most of the Lyman-α flux out of the line-of-sight between the star-exoplanet system and Earth. Because of this reason, the Lyman-α emission line cannot be directly measured because neutral hydrogen in the interstellar medium (ISM) attenuates the majority of the flux before it reaches the Earth (Linsky *et al.*, 2013). Therefore, it is important to

- reconstruct the stellar Lyman-α profiles and flux by correcting the ISM absorption.

So far a reconstruction of the intrinsic Lyman-α line has been only carried out for a limited number of nearby bright enough stars, but is not feasible for distant or faint host stars. Recently Linsky *et al.* (2013) identified 5 methods for the reconstruction of the intrinsic Lyman-α flux from main-sequence stars between spectral types F5 to M5. From this study it is shown that the quality of the data determines which reconstruction method yields the most accurate result.

The most accurate method for the reconstruction of stellar Lyman-α emission was developed by Wood *et al.* (2005) and requires high-resolution spectra of the Lyman-α line and knowledge of the interstellar velocity structure based on high-resolution spectra of the Deuterium Lyman-α and metal lines. The errors from such reconstructed profiles are at ~ 20 %. At present only the STIS instrument on HST can provide such data for nearby stars. Another method developed by France *et al*. (2012) requires also high-resolution spectra of the hydrogen Lyman-α emission line, but does not require spectra of the deuterium Lyman-α line or any other interstellar absorption line. One should note that this particular reconstruction method fails when the interstellar velocity structure has many components, which is unknown in the absence of high-resolution interstellar absorption lines. A third method described in Linsky *et al.* (2013) requires flux measurements of the stellar C IV, C II, O I, Mg II, or Ca II lines and the best fit correlations of these lines with fluxes of the reconstructed Lyman-α lines in existing data sets. The accuracy of Lyman-α flux estimates for F5–K5 dwarf stars by this method is about ~ 18–25 %. To obtain these accuracy values one has to correct high-resolution spectra of the Mg II lines for interstellar absorption. This particular method is based on the hypothesis that the ratios of the Lyman-α line flux to C IV, C II, O I, Mg II, and Ca II line fluxes, for stars of similar spectral type depend only gradually on line flux. The method does not work well for M0 – MV dwarf stars. For these stars the dispersions are larger because of the stellar variability between the observing times of Lyman-α and the other lines (Linsky *et al*., 2013). The largest uncertainty here is the stellar metal abundance, therefore

- more observations of M-type stars-, are necessary to better understand the uncertainties associated with low metal abundances.

In case there are no UV or Ca II line flux observations available but X-ray measurements within an energy range similar to ROSAT observations, a method can provide estimates of the intrinsic Lyman-α flux from least-squares fits to the intrinsic Lyman-α /X-ray flux ratio vs. the X-ray flux. The average dispersions about the fit lines for F5 – G9 and K0 – K5 stars are of the order of ~ 20 – 30 %. However, this method should not be applied to M stars which show a much larger dispersion because of the large time variability of X-rays and the comparison of X-ray and Lyman-α data obtained at different times. When no Lyman-α, UV emission lines and X-ray data are available from observations, one can reconstruct the Lyman-α flux for F5 to M5 stars based only on the stellar effective temperature and stellar activity measurements and stellar parameters within an accuracy of 30 – 40 % (Linsky *et al.*, 2013).

4.2 Radiation and plasma impact on planetary atmospheres and habitability

Activity in late type stars (i.e., spectral types G, K, M) has been intensively studied during the past decades with satellites such as ASCA, ROSAT, Chandra, XMM-Newton, EUVE, FUSE and IUE. In particular, the radiation environment of solar-like G-stars has been studied for several so-called solar proxies with ages from ~ 100 Myr – ~ 8.5 Gyr with high accuracy within the “Sun in Time” project (Dorren and Guinan, 1994; Dorren *et al*., 1995; Güdel *et al*., 1997; Ribas *et al*., 2005; Claire *et al*., 2012). From these data one can conclude that the integrated flux between 0.1 – 120 nm was ~ 100 times more intense than that of today’s Sun during the first 100 Myr after its arrival at the zero age main sequence (ZAMS) (Ribas *et al*., 2005; Claire *et al*., 2012) before it decreased according to a power law to a factor of 6, ~ 3.5 Gyr ago. This activity-age relation indicates that lower mass M-type stars spend more time in this highly active but saturated phase before their activity begins to decrease. It is found that low mass M dwarfs have saturated emission periods up to 0.5 – 1 Gyr and possibly longer for late type M stars (Scalo *et al*., 2007).

Fig. 11 shows the X-ray to bolometric luminosity for all stars with masses < 0.9MSun which are given in the ROSAT catalogue with distances which have been measured by Hipparcos (Scalo *et al*., 2007). Because the X-ray luminosities are given in relation to the total stellar luminosity they correspond also to the X-ray flux which exposes a planetary upper atmosphere within the habitable zone of the particular star. The X-ray/bolometric luminosity value for the present Sun is given by the tiny black dot on the bottom of the right y-axis. From these observations one can conclude that for an average dMe star, the steady coronal X-ray flux above the atmosphere of a habitable planet could be about a thousand times larger than at the present-day Earth, while during the largest flares this flux could be a million times larger.

The response of the upper atmosphere of an Earth-like exoplanet to such high short wavelength radiation levels would be tremendous. As it was shown by Tian *et al.* (2008a; 2008b) and Lichtenegger *et al.* (2010), similar to hydrogen-rich upper atmospheres an Earth-like N_2-dominated thermosphere would also experience a rapid transition to a hydrodynamic expansion regime if it is exposed to XUV flux values ≥ 7 times that of today's Sun.

Because nitrogen is no strong IR-cooler the upper atmosphere will move above expected magnetopause stand-off distances so that the neutral constituents beyond the magnetopause can be ionized and picked up by the stellar wind. The stellar plasma can lead to efficient non-thermal atmospheric loss processes especially at close-in exoplanets (i.e., terrestrial planets within low mass M star habitable zones), which are exposed to dense plasma flows close to their host stars. During the past decade several indirect methods for the study of stellar winds of solar-type stars have been developed. The method which was so far most successful was the search for astrosphere absorption in the region where the stellar wind plasma collides with the local interstellar medium and energetic neutral hydrogen atoms are produced via charge exchange. From the rise in absorption on the blue side of the stellar Lyman-α line one can estimate the mass loss rate (Wood *et al*., 2002; 2005). Mass loss rates of about a dozen solar-like stars and cooler stars have been derived by this method from observations with the HST/STIS spectrograph. Depending on the age of the observed star, the mass loss rates are in the order of < 0.2 – 100 times the present solar rate. From these mass loss rates one can estimate the stellar wind density and velocity at orbital distance of a planet (Grießmeier *et al*., 2004). The corresponding estimates for the stellar wind of a 500 Myr old solar like star yield a factor 30 – 200 denser wind at 1 AU which is about twice as fast as the present one (Lichtenegger *et al*., 2010). Unfortunately, at present there are no accurate stellar mass loss observations for main-sequence stars which are younger than 0.7 Gyr. However, there is evidence of a possibly preferred appearance of CMEs in polar regions of rapidly-rotating young stars/Sun (Strassmeier, 2009), which may lead to the propagation of shocks and magnetic ropes off the ecliptic plane during this early period (Zaqarashvili *et al*., 2011). These are crucial questions which need to be answered in order to understand the influence of winds and plasma outflows of very young stars after their arrival at the ZAMS. Upper limits to mass loss rates of young solar-like stars may also directly be detected directly during the near future with ALMA, by measuring the millimeter-wave bremsstrahlung flux emitted by the ionized stellar wind. This method becomes possible for the first time at millimeter wavelengths, thanks to ALMA's unprecedented sensitivity.

A stellar/solar wind which is 30 times denser and 2 times faster than the present proton outflow of our Sun is able to erode a 1 bar N_2 atmosphere which is exposed to a 20 times higher XUV flux compared to that of the present Sun from an Earth-size and mass planet at 1 AU during ~ 10 Myr (Lichtenegger *et al*., 2010). Because the XUV flux within M-star habitable zones remains at high levels for much longer times than for G stars (see Fig. 11)

- it is unlikely that Earth-like habitats with nitrogen dominated atmospheres can evolve under such extreme environments (Lammer *et al*., 2009; Lichtenegger *et al*., 2010; Lammer *et al*., 2012),

while,

- mini-Neptunes, extreme water worlds with hydrogen-envelopes and super-Earths with massive CO_2-rich atmospheres will be more resistant against the high XUV radiation.

Lower-mass planets which are exposed to such high radiation values may lose their atmospheres and end most likely as Mercury or Martian-type bodies. Thus, from the stellar radiation point of view, Earth-like planets with stable nitrogen-rich atmospheres may be much more numerous within habitable zones of G-stars compared to lower mass dwarf stars. Furthermore, the detection of stellar winds and related mass loss from young stars would also enhance our understanding of the evolution of stellar mass and its related luminosity. A better understanding of the mass and luminosity evolution of young stars is directly linked to the so-called Faint Young Sun Paradox (FYSP) which touches on the fundamental question on paleoclimate and the origin of life on Earth, and is therefore in the focus of present-day astrobiology research.

Another important point related to stellar forcing of upper atmospheres is the production of abiotic oxygen, which could have important consequences for future spectroscopic bio-marker search in exoplanet atmospheres. For example a super-Earth near the inner boundary of the system's habitable zone will outgas a dense steam atmosphere which results in surface pressures of 10^4 bars (Elkins-Tanton, 2008; 2011). For such dense steam atmospheres, preliminary atmospheric escape studies indicate that a huge fraction of a few Earth ocean equivalent amount of oxygen resulting from the dissociation of H_2O molecules by the host star's XUV radiation can remain in the upper atmosphere (Lammer *et al*., 2012).

Because it is very unlikely that several Earth ocean equivalent amounts of oxygen can be lost by non-thermal atmospheric escape processes or oxidized at the planet's surface, one may expect that there are exoplanets where this remaining oxygen forms an ozone layer of abiotic origin in the atmosphere. Such results agree with previous suggestions of Kasting (1995) and Chassefière (1996) that there may be planets, depending on their size, mass, orbital distance, as well as their host star's XUV flux evolution, which could accumulate huge amounts of abiotic oxygen. In the worst case related to bio-marker search in exoplanet atmospheres, one may observe a planet which has H_2O and a dense abiotic O_3 layer in its atmosphere. Thus, the probability that such planets and atmospheres may exist, raises the possibility of future false-positive detections of atmospheric bio-markers.

From the intense discussions related to the various issues briefly summarized before the ISSI Forum participants pointed out that the characterization of exoplanet atmospheres can only be done accurately if the host star's chemical and physical parameters and evolutionary stage are also known to a great extent. Moreover, for understanding the evolution of exoplanets and their structure the host star parameters over their age should also be known. As illustrated in Fig. 12, to understand really how planetary atmospheres and their water inventories can survive the extreme X-ray and EUV activity of their host stars after they arrived at the ZAMS, one has to study thermal- and non-thermal upper atmosphere processes by developing self-consistent multi-species ionospheric-thermospheric-exosphere models, for studying hydrostatic and non-hydrostatic dynamically expanding thermosphere-exosphere regions, including the investigation of the photochemical production of exothermal “hot” atoms, their collisional interaction and transport within highly XUV exposed thermospheres and the formation of energetic neutral atoms or ENAs).

5. FUTURE OUTLOOK

From the intensive discussions during this ISSI forum it became clear that exoplanet discoveries and science have a strong link to Solar System research, but one cannot use the planets in the Solar System as a blueprint for exoplanets, because each system and their evolving planets has an own and different history which results in various end products. On the other hand, the different planets in the Solar System are the only ones which can be studied in situ, they should be used as a kind of “test-cases” in exoplanet studies. In Solar System sciences many important data and expertise as well as sophisticated numerical models have been collected and developed during the past decades, therefore, the research activities have to be merged with the emerging field of exoplanet planetology in a comparative way.

For instance, coordinated studies on the behavior of the upper atmospheres, ionospheres, magnetosphere environments and thermal and non-thermal atmospheric loss processes on Venus, Earth, and Mars during extreme solar events (i.e., enhanced solar EUV and X ray radiation, neutron fluxes, CMEs, intense energetic solar proton/electron fluxes (e.g., SEPs), auroral phenomena, magnetic storms) can be used as proxies for enhancing our knowledge of particular exoplanet atmospheres orbiting within extreme stellar environments such as M-star habitable zones. The same studies would also serve as a proxy for the influence of the active young Sun with implications for the evolution of planetary atmospheres of younger Solar System planets.

Other areas which have important implications between the fast evolving field of exoplanet science and Solar System research are related to the early systems, planet and protoatmosphere formation as well as the origin and delivery of water to planetary bodies. The discovery of small transiting exoplanets within the size and mass domains from Earth- to Neptune-type bodies at various orbital distances will allow us to define a realistic radius-mass boundary for Earth-like planets from where they can lose their protoatmospheres so that they can evolve to Earth-type habitats and not to mini-Neptunes or hydrogen/volatile-rich water worlds. Because the origin and loss of the protoatmospheres depend on the activity of the stellar spectral type, the related disk physics and nebula evaporation time and planetary growth rate, one can expect a host star-type related variation radius-mass boundary for Earth-like planets. The origin, delivery and loss of water during the formation of planets from planetesimals via planetary embryos to protoplanets were also identified as a hot and very important science case. This field is highly interdisciplinary and connects studies related to planet formation, meteorite, asteroid and comet research, geochemical studies related to magma oceans, outgassing, impact research, stellar/solar physics and aeronomy in relation to water escape from small and Mars-size bodies.

Finally, all previously recommended research activities are connected for understanding habitability and the evolution of planets within habitable zones to potential habitats of various kinds. How many of these huge numbers of different planetary end products could evolve to habitable planets where life originated will certainly be one of the big research endeavors during the next decades. Because the mass of Earth-size and super-Earths within close-in M-star habitable zones can be determined more easily compared to an Earth in a Sun-like system at 1 AU, and M stars are the most numerous spectral type, the habitability of dwarf star planets is currently highly debated. Recent estimates based on the Kepler survey indicate that there are numerous dwarf stars with terrestrial planets within their habitable zones in our Galaxy (e.g., Dressing and Charbonneau, 2013).

However, due to the host stars emitted long lasting short wavelength radiation (X-rays, EUV), the near location of the habitable zone (dense stellar winds, CMEs) and several geophysical differences (tidal-locking, climate, etc.) compared to Earth-like planets in orbits within habitable zones of solar-like stars, one may expect possible exotic habitats, but planets more similar than Earth will be certainly be rare in such extreme stellar environments (Scalo *et al*., 2007; Lammer *et al*., 2009; Lammer *et al*., 2012). Besides M-star planet ground based research projects such as MEarth, the TESS space observatory and future characterization missions (ECHO, FINESS), including the JWST would be tools for the discovery and characterization of M-star terrestrial planets/exotic-habitats. For understanding wheater Earth-like habitats that are geophysically active during Gyr periods with liquid water plus continents on their surface are common or rare, one must discover terrestrial exoplanets from Earth- to super-Earth-size within G-star habitable zones around 1 AU. For such targets the precision for the Doppler method must be pushed down from the present 5 m s^{-1} to ~ 1 m s^{-1} so that the masses of the discovered planets could be measured, while the transit search for Earth-size planets/habitats in orbits of bright nearby solar-like stars by a mission like PLATO and follow up characterization projects could be carried out. From the discussions during the ISSI forum, the following recommendations and outcome can be summarized as:

- that more exoplanets detections around *bright* and *nearby stars* are essential if one would like to characterize exoplanet atmospheres more accurately then presently in great extent.

Because no other mission/project besides the proposed PLATO and the TESS missions will fill the technological-related present gap of exoplanet discoveries around bright nearby stars from close-in habitable zones (TESS) up to Solar System-like habitable zones at 1 AU (PLATO), the forum participants agreed that these space observatories are necessary to ensure that planned future exoplanet atmosphere characterization missions can fulfill their proposed science cases. From the observational side, the forum participants agreed it is very important that:

- The accuracy of the exoplanet mass determination with the Doppler method should be pushed down from the present day precision of 0.5 m s^{-1} to a precision of 0.1 m s^{-1}, so that the masses of Earth-like planets at orbital distances up to the habitable zone around a Sun-like star at 1 AU can be measured.
- For the characterization of exoplanet atmospheres and their systems, a large number of exoplanets from Earth to Jovian-size should be discovered around *bright* and *nearby* stars.
- For obtaining more accurate mean densities and resulting bulk composition of exoplanets the present time error bars related to planet size (and mass, see first point) have to be minimized by ultra-high precision photometry, etc. This is very relevant because the bulk composition which could in theory be determined from precise mass-radius relations is directly connected to the planet's interior and is necessary for the characterization of new planet categories such as super-Earths (exo-Mercury's), water worlds and mini-Neptunes (see Figs. 1 and 4). Because,

we do not know what kind of material is in the interior of Jupiter in the Solar System, one may never get the detailed information on the inner structure of an exoplanet. However, together with precise radius-mass measurements and transmission spectroscopy during transits dense gaseous layers or primordial gas captured from the nebular during the planets early formation could be identified. As discussed above for GJ1214b, these combined methods may reveal even information related roughly to the core properties (i.e., dense rocky core, low density core, icy core, and deep water layer).

- The age of planetary systems should be better constraint, e.g. by asteroseismology, to study potential evolutionary aspects.

Furthermore, the forum participants advise that ISSI may support workshops during the next two years, where the above-mentioned research areas will strongly benefit. The identified timely workshop topics which should be proposed to ISSI during 2013/2014 by the international research community are related to

- the origin, formation and the delivery of water from planetary embryos to protoplanets,
- the disk in relation to the formation of planets and their protoatmospheres by constraining the formation from observations,

and

- Star-planet atmosphere interaction vs. stellar distance and evolutionary consequences (spectral type – M star habitable zone planets -, chemistry, magnetosphere, etc.).

6. REFERENCES

Adams, E. R., Seager, S., Elkins-Tanton, L. (2008) Ocean planet or thick atmosphere: on the mass-radius relationship for solid exoplanets with massive atmospheres. *ApJ*, **673**, 1160 - 1164.

Albarède, F., Blichert-Toft, J. (2007) The split fate of the early Earth, Mars, Venus, and Moon. *C. R. Geoscience*, **339**, 917 - 927.

Albrecht, S., Winn, J. N., Johnson, J. A., Howard, A. W., Marcy, G. W., Butler, R. P., Arriagada, P., Crane, J. D., Shectman, S. A., Thompson, I. B., Hirano, T., Bakos, G., Hartman, J. D. (2012) Obliquities of Hot Jupiter Host Stars: Evidence for tidal interactions and primordial misalignments. *ApJ*, **757**, art. id. 18.

Alexander, C. M. O'D., Bowden, R., Fogel, M. L., Howard, K. T., Herd, C. D. K., Nittler, N. R. (2012) The Provenances of Asteroids, and Their Contributions to the Volatile Inventories of the Terrestrial Planets. *Science*, **337**, 721 – 723.

Alibert, Y., Broeg, C., Benz, W., Wuchterl, G., Grasset, O., Sotin, C., Eiroa, C., Henning, T., Herbst, T., Kaltenegger, L., Léger, A., Liseau, R., Lammer, H., Beichman, C., Danchi, W., Fridlund, M., Lunine, J., Paresce, F., Penny, A., Quirrenbach, A., Röttgering, H., Selsis, F., Schneider, J., Stam, D., Tinetti, G., White, G.J. (2007) Origin and formation of planetary systems. *Astrobiology*, **10**, 19 – 32.

Batalha, N. M., Rowe, J. F.; Bryson, S. T., Barclay, T. B., Christopher, J., and the Kepler Team (2012) Planetary candidates observed by Kepler, III: Analysis of the first 16 months of data. ApJS submitted, eprint arXiv:. 2012arXiv1202.5852B.

Beaulieu, J. P., Kipping, D. M., Batista, V., Tinetti, G., Ribas, I., Carey, S., Noriega-Crespo, J. A., Griffith, C. A., Campanella, G., Dong, S., Tennyson, J., Barber, R. J., Deroo, P., Fossey, S. J., Liang, D., Swain, M. R., Yung, Y., Allard, N. (2010) Water in HD 209458b's atmosphere from 3.6 - 8 microns IRAC photometric observations in primary transit. *MNRAS*, **409** (3), 963 - 974.

Ben-Jaffel, L. (2007) Exoplanet HD 209458b: Inated hydrogen atmosphere but no sign of evaporation. *ApJ*, **671**, L61-L64.

Ben-Jaffel, L., Sona Hosseini, S. (2010) On the existence of energetic atoms in the upper atmosphere of exoplanet HD 209458b. *ApJ*, **709**, 1284-1296.

Berta, Z. K., Charbonneau, D., Désert, J.-M., Miller-Ricci, K. E., McCullough, P. R., Burke, C. J., Fortney, J. J.; Irwin, J., Nutzman, P., Homeier, D. (2012) The flat transmission spectrum of the super-Earth GJ1214b from wide field camera 3 on the Hubble Space Telescope. ApJ, 747, art. id. 35, pp. 17.

Bodenheimer, P. (1997) The role of dust in star and planet formation: Theory. In: From stardust to planetesimals (eds. Y. J. Pendleton, A. G. G. M. Tielens), ASP Conference Series **122**, pp. 37.

Borucki, W. J., Koch, D. G., Basri, G., Batalha, N., Brown, T. M., and the Kepler team (2011) Characteristic of Kepler planetary candidates based on the first data set. *ApJ*, **728**, art. id. 117, 20 pp.

Borucki, W. J., Eric, A., Francois, F., Kaltenegger, K., and the Kepler team (2013) Kepler-62: A five-planet system with planets of 1.4 and 1.6 Earth radii in the habitable zone. *Science*, **340**, 587 – 590.

Boss, A. P. (2003) Rapid formation of outer giant planets by disk instability. *ApJ*, **599**, 577 - 581.

Charbonneau, D., Knutson, H. A., Barman, Travis, Allen, L. E., Mayor, M., Megeath, S. T., Queloz, D., Udry, S. (2008) The broadband infrared emission spectrum of the exoplanet HD 189733b. *ApJ*, **686**, 1341 – 1348.

Charbonneau, D., Berta, Z. K., Irwin, J., Burke, C. J., Nutzman, P., Buchhave, L. A., Lovis, C., Bonfils, X., Latham, D.W., Udry, S., Murray-Clay, R. A., Holman, M. J., Falco, E. E.,Winn, J. N., Queloz, D., Pepe, F., Mayor, M., Delfose, X., Forveille, T. (2009) A super-Earth transiting a nearby low-mass star. *Nature*, **462**, 891–894.

French, M., Becker, A.; Lorenzen, W., Nettelmann, N., Bethkenhagen, M., Wicht, J., Redmer, R. (2012) Ab initio simulations for the material properties along jupiter's adiabat. *ApJS*, **202**, art. id. 5, 11 pp.

Chassefière, E. (1996) Hydrodynamic escape of oxygen from primitive atmospheres: applications to the cases of Venus and Mars. *Icarus*, **124**, 537 – 552.

Claire, M. W., Sheets, J., Cohen, M., Ribas, I., Meadows, V. S., Catling, D. C. (2012) The evolution of solar flux from 0.1 nm to 160 μm: quantitative estimates for planetary studies. *ApJ*, **757,** 95 (12 pp).

Dorren, J. D., Guinan, E. F. (1994) *The Sun in time: Detecting and modeling magnetic inhomogenities on Solar-type stars*, in *The Sun as a Variable Star: Solar and Stellar Irradiance Variations* (eds. Pap, J. M., C. Fröhlich, H. S. Hudson, and S. K. Solanki), Proceedings of IAU Colloquium 143, held in Boulder, Colorado, USA, June 20 – 25, 1993, Cambridge University Press, Cambridge, UK, New York, USA, 206–216 pp.

Dorren, J. D., Guedel, M., Guinan E. F. (1995) X-Ray emission from the Sun in its youth and old age. *ApJ*, **448**, 431–436.

Dressing, C. D., Charbonneau, D., (2013) The occurrence rate of small planets around small stars. *ApJ,* in press, eprint arXiv: 2013arXiv1302.1647D.

Dumusque, X., Pepe, F., Lovis, C., Ségransan, D., Sahlmann, J., Benz, W., Bouchy, F., Mayor, M., Queloz, D., Santos, N., Udry, S. (2012) An Earth-mass planet orbiting α Centauri B. *Nature*, **491**, 207-211.

Elkins-Tanton, L. T. (2008) Linked magma ocean solidification and atmospheric growth for Earth and Mars. *Earth and Planet. Sci. Lett*., **271**, 181–191.

Elkins-Tanton, L., Seager, S. (2008) Ranges of atmospheric mass and composition of super-Earth exoplanets. *ApJ*, **685**, 1237–1246.

Elkins-Tanton, L. T. (2011) Formation of water ocean on rocky planets. *Astrophys. Space Sci*., **332**, 359–364.

Fossati, L., Haswell, C.A., Froning, C.S., Hebb, L., Holmes, S., Kolb, U., Helling, C., Carter, A., Wheatley, P., Cameron, A.C., Loeillet, B., Pollacco, D., Street, R., Stempels, H.C., Simpson, E., Udry, S., Joshi, Y.C., West, R.G., Skillen, I., Wilson, D. (2010) Metals in the exosphere of the highly irradiated planet WASP-12b. *ApJ*, **714**, L222 - L227.

France, K., Linsky, J. L., Tian, F., Froning, C. S., Roberge, A. (2012) Time-resolved ultraviolet spectroscopy of the M-dwarf GJ 876 exoplanetary system. *ApJ*, **750**, article id. L32, 5 pp.

France, K., Froning, C. S., Linsky, J. L., Roberge, A., Stocke, J. T., Tian, F., Bushinsky, R., Désert, J.-M., Mauas, P., Vieytes, M., Walkowicz, L. M. (2013) The Ultraviolet Radiation Environment around M dwarf Exoplanet Host Stars. *ApJ*, **763**, art. id. 149, 14 pp.

García Muñoz, A. (2007) Physical and chemical aeronomy of HD 209458b. *Planet. Space Sci*., **55**, 1426-1455.

Gaudi, B. S., Winn, J. N. (2007) Prospects for the characterization and confirmation of transiting exoplanets via the Rossiter-McLaughlin effect. *ApJ*, **655**, 550 – 563.

Gaudi, B. S. (2012) Microlensing surveys for exoplanets. *Annu. Rev. Astron. Astrophys*., **50**, 411 – 453.

Grießmeier, J.-M., Stadelmann, A., Penz, T., Lammer, H., Selsis, F., Ribas, I., Guinan, E. F., Motschmann, U., Biernat, H. K., Weiss, W. W. (2004) The effect of tidal locking on the magnetosphericand atmospheric evolution of "Hot Jupiters". *A&A*, **425**, 753–762.

Grillmair, C. J., Burrows, A., Charbonneau, D., Armus, L., Stauffer, J., Meadows, V., van Cleve, J., von Braun, K., Levine, D. (2008) Strong water absorption in the dayside emission spectrum of the planet HD189733b. *Nature*, **456**, 767 – 769.

Güdel, M., Guinan, E. F., Mewe, R., Kaastra, J. S., Skinner, S. L. (1997) A determination of the coronal emission measure distribution in the young solar analog EK Draconis from ASCA/EUVE spectra. *ApJ*, **479**, 416–426.

Hamano, K., Abe, Y., Genda, H. (2013) Emergence oft wo types of terrestrial planet on solidification of magma ocean. *Nature*, 497, 607 – 611.

Hayashi, C., Nakazawa, K., Mizuno, H. (1979) Earth's melting due to the blanketing effect of the primordial dense atmosphere. *Earth Planet. Sci. Lett.*, **43**, 22–28.

Howard, A. W., Marcy, G. W., Bryson, S. T., Jenkins, J. M., Rowe, J. F., and the Kepler Team (2012) Planet occurrence within 0.25 AU of solar-type stars from Kepler. *ApJS*, **201**, art. id. 15, 20 pp.

Ikoma, M.,Nakazawa,K., Emori, H. (2000) Formation of giant planets: dependences on core accretion rate and grain opacity. *ApJ*, **537**, 1013–1025.

Ikoma, M., Genda, H. (2006) Constraints on the mass of a habitable planet with water of nebular origin. *ApJ*, **648**, 696-706.

Ikoma, M., Hori, Y. (2012) In-situ accretion of hydrogen-rich atmospheres on short-period super-Earths: implications for the Kepler-11 planets. *ApJ*, **753**, 1, art. id. 66.

Kasting, J. F. (1995) O_2 concentrations in dense primitive atmospheres: commentary. *Planet. Space Sci.*, **43**, 11–13.

Kley, W., Nelson, R. P. (2012) Planet-disk interaction and orbital evolution. *Ann. Rev. Astron. Astrophys*., **50**, 211-249.

Knutson, H. A., Charbonneau, D., Allen, L. E., Fortney, J. J., Agol, E., Cowan, N. B., Showman, A. P., Cooper, C. S., Megeath, S. T. (2007) A map of the day-night contrast of the extrasolar planet HD 189733b. *Nature*, **447**, 183 – 186.

Knutson, H. A., Charbonneau, D., Cowan, N. B., Fortney, J. J., Showman, A. P., Agol, E., Henry, G. W., Everett, M. E., Allen, L. E. (2009) Multiwavelength constraints on the day-night circulation pattern of HD 189733b. *ApJ*, **690**, 822 – 836.

Koskinen, T. T., Harris, M .J., Yelle, R. V., Lavvas, P. (2013a) The escape of heavy atoms from the ionosphere of HD209458b. I. A photochemical-dynamical model of the thermosphere. *Icarus*, in press, eprint: 2012arXiv1210.1536K

Koskinen, T. T., Yelle, R. V., Harris, M .J., Lavvas, P. (2013b) The escape of heavy atoms from the ionosphere of HD209458b. II. Interpretation of the observations. *Icarus*, in press, http://dx.doi.org/10.1016/j.icarus.2012.09.026.

Kokubo, E., Ida, S.: Formation of protoplanets from planetesimals in the solar nebula. *Icarus*, **143**, 15–27 (2000)

Kramm, U., Nettelmann, N., Fortney, J. J., Neuhäuser, R., Redmer, R. (2012) Constraining the interior of extrasolar giant planets with the tidal Love number k2 using the example of HAT-P-13b. *A&A*, **538**, art. id. 146, 8 pp.

Kraus, A: L., Ireland, M. J. (2012) LkCa 15: A young exoplanet caught at formation? *ApJ*, **745**, art. id. 5 12 pp.

Kuchner, M. J. (2003) Volatile-rich Earth-mass planets in the habitable zone. *ApJ*, **596**, L105 - L108.

Léger, A.,Rouan, D., Schneider, J., Barge, P., Fridlund, F., and the CoRoT Team (2009) Transiting exoplanets from the CoRoT space mission VIII. CoRoT-7b: The first super-Earth with measured radius. *A&A*, **506**, 287–302.

Lammer, H., Bredehöft, J. H., Coustenis, A., Khodachenko, M. L., Kaltenegger, L., Grasset, O., Prieur, D., Raulin, F., Ehrenfreund, P., Yamauchi, M., Wahlund, J.-E., Grießmeier, J.-M., Stangl, G., Cockell, C. S., Kulikov, Yu. N., Grenfell, L., Rauer, H. (2009) What makes a planet habitable? *Astron. Astrophys. Rev*., **17**, 181–249.

Lammer, H., Eybl, V., Kislyakova, K. G., Weingrill, J., Holmström, M., Khodchenko, M. L., Kulikov, Yu. N., Reiners, A., Leitzinger, M., Odert, P., Xian Grüß, M., Dorner, B., Güdel, M., Hanslmeier, A. (2011) UV transit observations of EUV-heated expanded thermospheres of Earth-like exoplanets around M-stars: Testing atmosphere evolution scenarios. *Astrophys. Space Sci*., **335**, 39–50.

Lammer, H., Kislyakova, K. G., Odert, P., Leitzinger, M., Schwarz, R., Pilat-Lohinger, E., Kulikov, Yu. N., Khodachenko, M. L., Güdel, M., Hanslmeier, A. (2012) Pathways to Earth-like atmospheres: extreme ultraviolet (EUV)-powered escape of hydrogen-rich protoatmospheres. *Orig. Life Evol. Biosph*., **41**, 503–522.

Lammer, H. (2013) *Origin and evolution of planetary atmospheres: Implications for habitability*. Springer Briefs in Astronomy, Springer Publishing House, Heidelberg / New York, pp. 98.

Lammer, H., Erkaev, N. V., Odert, P., Kislyakova, K. G., Leitzinger, M., Khodachenko, M. L. (2013) Probing the blow-off criteria of hydrogen-rich “super-Earths”. *MNRAS*, **430**, 1247 - 1256.

Lecavelier des Etangs, A., Ehrenreich, D., Vidal-Madjar, A., Ballester, G. E., Désert, J.-M., Ferlet, R., Hébrard, G., Sing, D. K., Tchakoumegni, K.-O., Udry, S. (2010) Evaporation of the planet HD 189733b observed in H I Lyman-α. *A&A*, **514**, A72.

Lecavelier des Etangs, A., Bourrier, V., Wheatley, P. J., Dupuy, H., Ehrenreich, D., Vidal-Madjar, A., Hébrard, G., Ballester, G. E., Désert, J.-M., Ferlet, R., Sing, D. K. (2012) Temporal variations in the evaporating atmosphere of the exoplanet HD 189733b. *A&A*, **543**, art. id. L4, 4 pp.

Lichtenegger, H. I. M., Lammer, H., Grießmeier, J.-M., Kulikov, Yu. N., von Paris, P., Hausleitner, W., Krauss, S., Rauer, H. (2010) Aeronomical evidence for higher CO_2 levels during Earth's Hadean epoch. *Icarus*, **210**, 1–7.

Linsky, J. L., France, K., Ayres, T. (2013) Computing intrinsic Lyman-alpha fluxes of F5 V to M5 V stars. *ApJ*, **766**, article id. 69, 10 pp., 2013.

Lissauer, J. J., and the Kepler team (2011) A closely packed system of low-mass, low-density planets transiting Kepler-11. *Nature*, **470**, 53–58.

Lunine, J. I., O'Brien, D. P., Raymond, S. N., Morbidelli, A., Qinn, T., Graps, A. L. (2011) Dynamical models of terrestrial planet formation. *Adv. Sci. Lett.*, **4**, 325 – 338.

Mannings, V., Boss, A. P., Russell, S. S. (2000) *Protostars and Planets IV*. University of Arizona Press, Tucson.

Miller-Ricci, E., Fortney, J. J. (2010) The Nature of the atmosphere of the transiting super-Earth GJ 1214b. *ApJ*, **716**, L74 - L79.

Rogers, L. A.; Seager, S. (2010) Three possible origins for the gas layer on GJ 1214b. *ApJ*, **716**, 1208 – 1216.

Mizuno, H. (1980) Formation of the giant planets. *Prog. Theor. Phys.*, **64**, 544–557.

Montmerle, T., Augereau, J.-C., Chaussidon, M., Gounelle, M., Marty, B., Morbidelli, A., (2006) 3. Solar system formation and early evolution: the first 100 million years. *Earth, Moon, Planets*, **98**, 39 – 95.

Morbidelli, A., Lunine, J. I., O'Brien, D. P., Raymond, S. N., Walsh, K. J. (2012) Building terrestrial planets. *Ann. Rev. Earth Planet. Sci.*, **40**, 251-275.

Mumma, M. J., Charnley, S. B. (2011) The chemical composition of comets - emerging taxonomies and natal heritage. *Ann. Rev. Astron. Astrophys.*, **49**, 471 – 524.

Nettelmann, N. (2011) Predictions on the core mass of Jupiter and of giant planets in general. *Astrophys. Space Sci.*, **336**, 47-51.

Nettelmann, N., Fortney, J. J., Kramm, U., Redmer, R., (2011) Thermal evolution and structure models of the transiting super-Earth GJ 1214b. *ApJ*, **733**, 1, art. id. 2., 11 pp.

Nettelmann, N., Becker, A., Holst, B., Redmer, R. (2012) Jupiter Models with Improved Ab Initio Hydrogen Equation of State (H-REOS.2). *ApJ*, **750**, art. Id. 52, 10 pp.

Penz, T., Erkaev, N. V., Kulikov, Yu. N., Langmayr, D., Lammer, H., Micela, G., Cecchi-Pestellini, C., Biernat, H. K., Selsis, F., Barge, P., Deleuil, M., Léger, A. (2008) Mass loss from "Hot Jupiters": Implications for CoRoT discoveries, Part II: Long time thermal atmospheric evaporation modeling. *Planet. Space Sci.*, **56**, 1260-1272.

Rafikov, R.R. (2006) Atmospheres of protoplanetary cores: critical mass for nucleated instability. *ApJ*, **648**, 666–682.

Raymond, S. N., Quinn, T., Lunine, J. I. (2004) Making other Earths: dynamical simulations of terrestrial planet formation and water delivery. *Icarus*, **168**, 1–17.

Raymond, S. N., O'Brien, D. P., Alessandro, M., Kaib, Nathan, A. (2009) Building the terrestrial planets: Constrained accretion in the inner Solar System. *Icarus*, **203**, 644-662.

Ribas, I., Guinan, E. F., Güdel, M., Audard, M. (2005) Evolution of the solar activity over time and effects on planetary atmospheres. I. High-energy irradiances (1–1700 Å), *ApJ*, **622**, 680 – 694.

Sándor, Zs., Kley, W., Klagyivik, P. (2007) Stability and formation of the resonant system HD 73526. *A&A*, **472**, 981 – 992.

Seager, S., Deming, D. (2010) Exoplanet atmospheres. *Ann. Rev. Astron. Astrophys*., **48**, 631 – 672.

Selsis, F., Kasting, J. F., Levrard, B., Paillet, J., Ribas, I., Delfosse, X. (2007) Habitable planets around the star Gliese 581? *A&A*, **476**, 1373 – 1387.

Scalo, J., Kaltenegger, L., Segura, A. G., Fridlund, M., Ribas, I., Kulikov, Yu. N., Grenfell, J. L., Rauer, H., Odert, P., Leitzinger, M., Selsis, F., Khodachenko, M. L., Eiroa, C., Kasting, J., Lammer, H. (2007) M stars as targets for terrestrial exoplanet searches and biosignature detection. *Astrobiology*, **7**, 85–166.

Shustov, B., Sachov, M.,, Gomez de Castro, A. I., Ana, I., Pagano, I. (2009) WSO-UV ultraviolet mission for the next decade. *Astrophys. Space Sci*., **320**, 187–190.

Sozzetti, A. (2010) The Gaia Astrometric Survey. EAS Publication Series, *IAU Highlights Astron*., **15**.

Strassmeier, K. G. (2009) Starspots. *Astron. Astrophys. Rev*., **17**, 251–308.

Swain, M. R., Tinetti, G., Vasisht, G., Deroo, P., Griffith, C., Bouwman, J. Chen, Pin; Yung, Y., Burrows, A., Brown, L. R., Matthews, J., Rowe, J. F., Kuschnig, R., Angerhausen, D. (2009) Water, methane, and carbon dioxide present in the dayside spectrum of the exoplanet HD 209458b. *ApJL*, **704**, 2, 1616 – 1621.

Tian, F., Kasting, J. F., Liu, H., Roble, R. G. (2008a) Hydrodynamic planetary thermosphere model: 1. The response of the Earth's thermosphere to extreme solar EUV conditions and the significance of adiabatic cooling. *J. Geophys. Res.*, **113**, doi:10.1029/2007JE002946.

Tian, F., Solomon, S. C., Qian, L., Lei, J., Roble, R. G. (2008b) Hydrodynamic planetary thermosphere model: 2. Coupling of an electron transport/energy deposition model. *J. Geophys. Res.*, **113** (E7), E07005.

Tinetti G., Vidal-Madjar, A., Liang, M. C., Beaulieu, J. P., Yung, Y. L., Carey, S., Barber, R. J., Tennyson, J., Ribas, I., Allard, N., Ballester, G. E., Sing, D. K., Selsis, F. (2007) Water vapour in the atmosphere of a transiting extrasolar planet. *Nature*, **448**, 163 – 171.

Vidal-Madjar, A., Lecavelier des Etangs, A., Désert, J.M., Ballester, G.E., Ferlet, R., Hébrard, G., Mayor, M., (2003) An extended upper atmosphere around the extrasolar planet HD209458b. *Nature*, **422**, 143-146.

Von Bloh, W., Bounama, C., Cuntz, M., Frank, S. (2007) The habitability of super-Earths in Gliese 581. *A&A*, **476**, 1365 – 1371.

Walsh, K. J., Morbidelli, A., Raymond, S. N., O'Brien, D. P., Mandell, A. M. (2011) A low mass for Mars from Jupiter's early gas-driven migration. *Nature*, **475**, 206-209.

Williams, J. P., Cieza, L. A. (2011) Protoplanetary disks and their evolution. *Ann. Rev. Astron. Astrophys.*, **49**, 67 – 117.

Wood, B. E., Müller, H.-R., Zank, G., Linsky, J. L. (2002) Measured mass loss rates of solar-like stars as a function of age and activity. *ApJ*, **574**, 412–425.

Wood, B. E., Müller, H.-R., Zank, G. P., Linsky, J. l., Redfield, S. (2005) New mass-loss measurements from astrospheric Ly-α absorption. *ApJ*, **628**, L143–L146.

Wuchterl, G. (1993) The critical mass for protoplanets revisited - Massive envelopes through convection. *Icarus*, **106**, 323 - 334.

Wuchterl, G., Guillot, T., Lissauer, J. J. (2000) *Giant planet formation*. In: *Protostars and planets IV* (eds. V. Mannings, A. P. Boss, S. S. Russell), University of Arizona Press, Tucson, 1081 - 1109.

Yelle, R. V. (2004) Aeronomy of extra-solar giant planets at small orbital distances. *Icarus*, **170**, 167-179.

Zaqarashvili, T. V., Oliver, R., Ballester, J. L., Carbonell, M., Khodachenko, M. L., Lammer, H., Leitzinger, M., Odert, P. (2011) Rossby waves and polar spots in rapidly rotating stars: implications for stellar wind evolution. *A&A*, **532**, A139.

TABLES

Table 1: Current possible precision limits and necessary signals for the detection of an Earth-analogue planet at an orbit at 1 AU around a Sun-like star.

Method	Limited precision	Earth-Sun signal at 1 AU
Doppler method (mass)	0.5 m s^{-1}	0.1 m s^{-1}
Transit method (radius)	20 ppm	80 ppm

FIGURE CAPTIONS

Fig. 1: Illustration of two possible scenarios of the structure of the low density super-Earth GJ 1214 which can be derived from the radius-mass relation within the present uncertainties. Left scenario (a) would correspond to a mini-Neptune with a dense core which is surrounded by a primordial or outgassed dense hydrogen envelope. Right scenario (b) corresponds to a low density core which is surrounded by a huge amount of H2O and a thin hydrogen envelope (courtesy D. Charbonneau).

Fig. 2: Illustration of exoplanet atmosphere effects during the transit and secondary eclipse of an exoplanet. During the transit the radiation form the star is transmitted through the planet's atmosphere, while during the secondary eclipse the thermal radiation and reflected light from the planet disappear and reappear.

Fig. 3: Illustration of the recently selected TESS (top left) and planned PLATO (top right) future transit search missions for planets in orbits around nearby bright host stars. Below illustration of the Swiss-led Characterizing ExOPlanets Satellite (CHEOPS) recently selected by ESA within their small mission program. CHEOPS main science aims will be the determination of the radius-mass relation of exoplanets, the identification of significant gaseous envelopes around the planet's core and the probing of known hot Jupiter atmospheres in order to study the physical mechanisms and efficiency for the energy transport from the dayside to the night side of the planet (NASA/ESA).

Fig. 4: Illustration of Earth and a super-Earth which mimics a mini-Neptune because it may not have lost its nebula-based captured hydrogen envelope or outgassed hydrogen dominated volatile-rich protoatmosphere.

Fig. 5: Illustration of disk evolution and planet formation. a) Strong X-rays, EUV and FUV as well as winds interact with the gas/dust disk in its earliest stage. b) planetesimals and planetary embryos form due to collisions, the disk settles and evaporation continues. Depending on the gravity potential of the embedded planetary embryos and protoplanets

nebula gas is attracted. c) Photoevaporation continues and planetary embryos and protoplanets which orbit near their host stars become decoupled from the evaporating nebula gas first. d) After a few Myr but latest at about 10 Myr the debris disk remains and planets may continue to form (after Williams and Cieza, 2011).

Fig. 6: Planet-disk interaction results in: a) Spiral arm formation that create Lindblad torques on the planet, resulting in inward moving planets; and b) in Horseshoe regions that create corotation torques which can result in outward moving planets (from Kley and Nelson, 2012).

Fig. 7: Illustration of the evolution from protoplanets to various end products, which can be Venus- or Mars-like dry or frozen CO_2-rich one-plate planets, geophysically active, water-rich Earth-like planets with continents and nitrogen atmospheres (CO_2 in carbonates), or in case the early planet accumulated too much nebula-gas or originated with too much volatiles so that it cannot get rid of them by host star-powered atmospheric escape processes a mini-Neptune or water world with a surrounding hydrogen corona similar as in Figs. 2 and 5 remain.

Fig. 8: Illustration of protoplanet growth and formation due to collisions between differentiated planetesimals and planetary embryos. The red areas correspond to magma, the other layers to mantle and core materials (courtesy L. Elkins-Tanton).

Fig. 9: Initial water and carbon contents in wt % and resulting water ocean depths after condensation of an outgassed steam atmosphere. The range of water used in the figure includes meteorites that are likely building blocks for terrestrial planets (Jarosewich, 1990). The dashed lines show the resulting water ocean depth in kilometers produced by a collapsed degassed steam atmosphere of a planet related to the initial bulk mantle water content (courtesy L. Elkins-Tanton).

Fig. 10: Illustration of a late growth scenario which could be expected for Venus and Earth. Mars-size planetary embryos will lose outgassed volatiles and their initial water

inventories during collisions and growth to larger protoplanets. Finally, not much H_2O would remain in the final planet, and oceans have to be produced by later impacts of water-rich material.

Fig. 11: Scatterplot of the ratio of soft X-ray to bolometric luminosity as a function of stellar mass, for every star with mass < $0.9M_{\mathrm{Sun}}$ in the ROSAT catalogue within Hipparcos distances, compared to the present Sun. The vertical gray lines show the amplitude variations of very large X-ray flares of well-studied M-stars. The X-ray luminosities are given relative to the star's total luminosity so that they represent also the fraction of flux above the atmosphere of any planet, in particular habitable zone (after Scalo *et al*., 2007).

Fig. 12: Illustration chart about the general approach and connections between stellar/solar environment observations and modeling efforts within Solar System and exoplanetary research, which should lead to the development of state-of-the-art exoplanet atmosphere-thermosphere-exosphere models and to a better understanding of aeronomically related atmospheric evolution and habitability aspects for terrestrial exoplanets in general.

Fig. 1

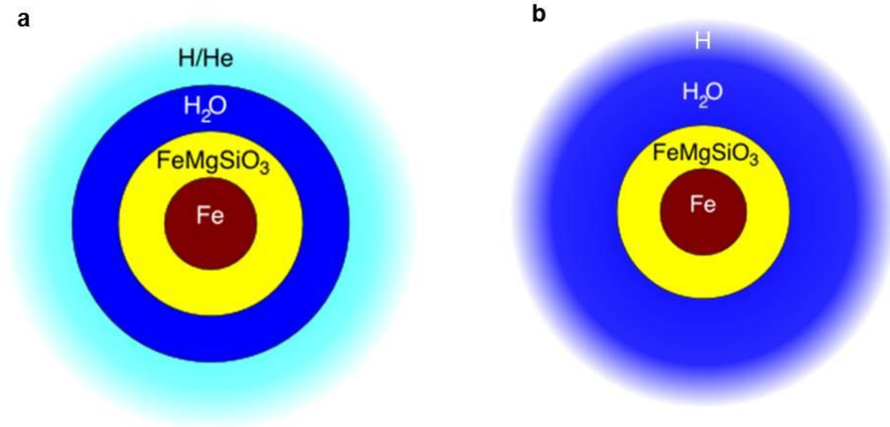


Fig. 2

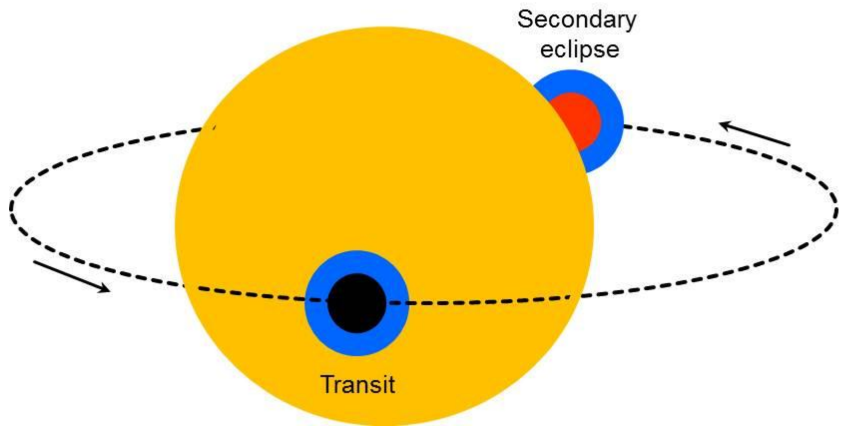


Fig. 3

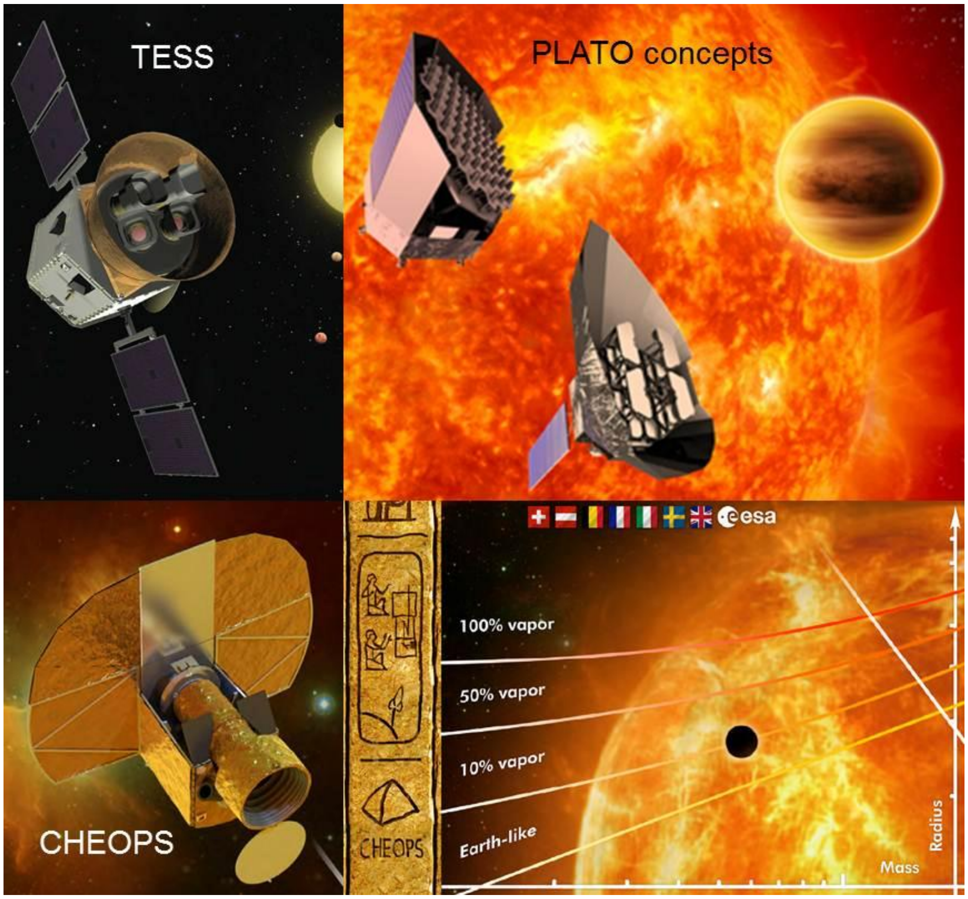

TESS
PLATO concepts
CHEOPS
esa
100% vapor
50% vapor
10% vapor
Earth-like
CHEOPS
Mass
Radius

Fig. 4

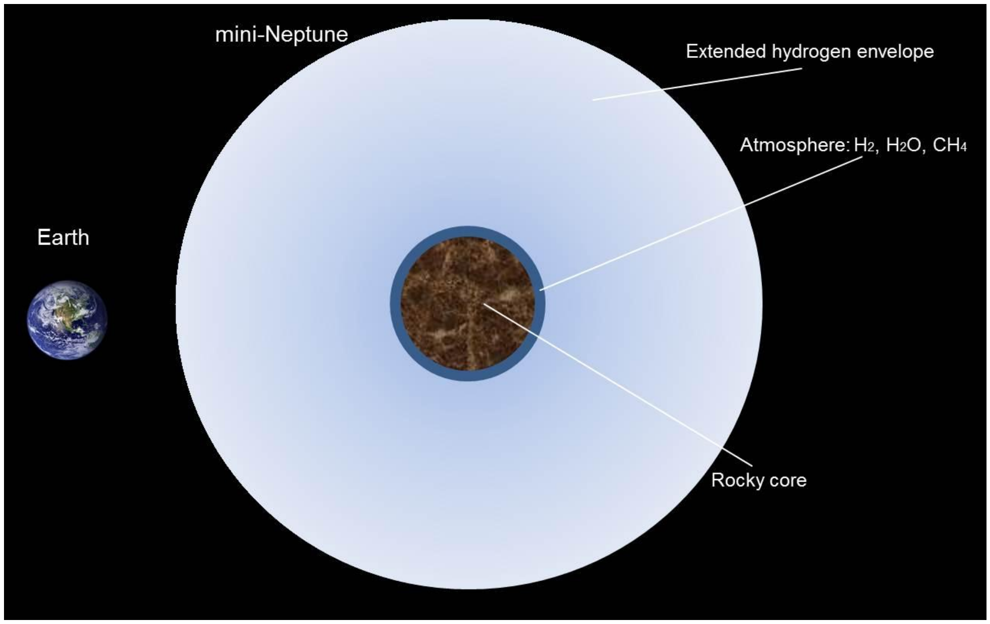

mini-Neptune
Extended hydrogen envelope
Atmosphere: H2, H2O, CH4
Earth
Rocky core

Fig. 5

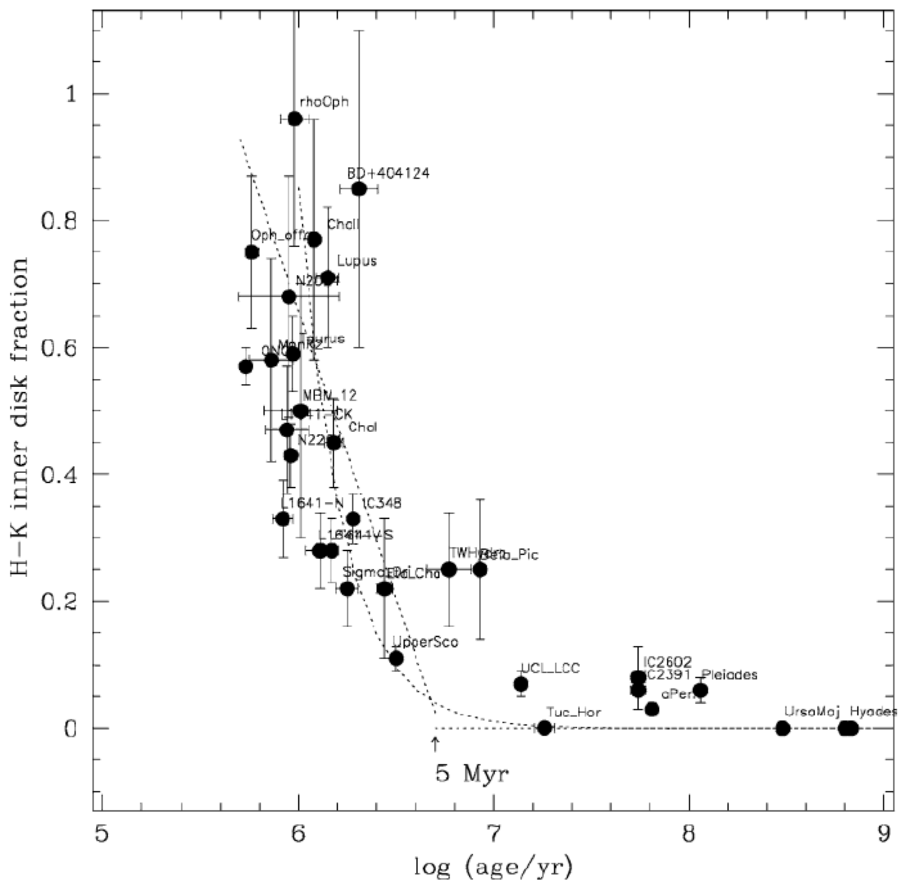

H-K inner disk fraction
log (age/yr)
5 Myr
rhoOph
BD+404124
Oph_off
ChaII
Lupus
N2024
MonR2
Taurus
MBM_12
ChaI
IC348
L1641-N
UpperSco
UCL_LCC
Tuc_Hor
IC2602
IC2391
Pleiades
aPer
UrsaMaj
Hyades
Beta_Pic

Fig. 6

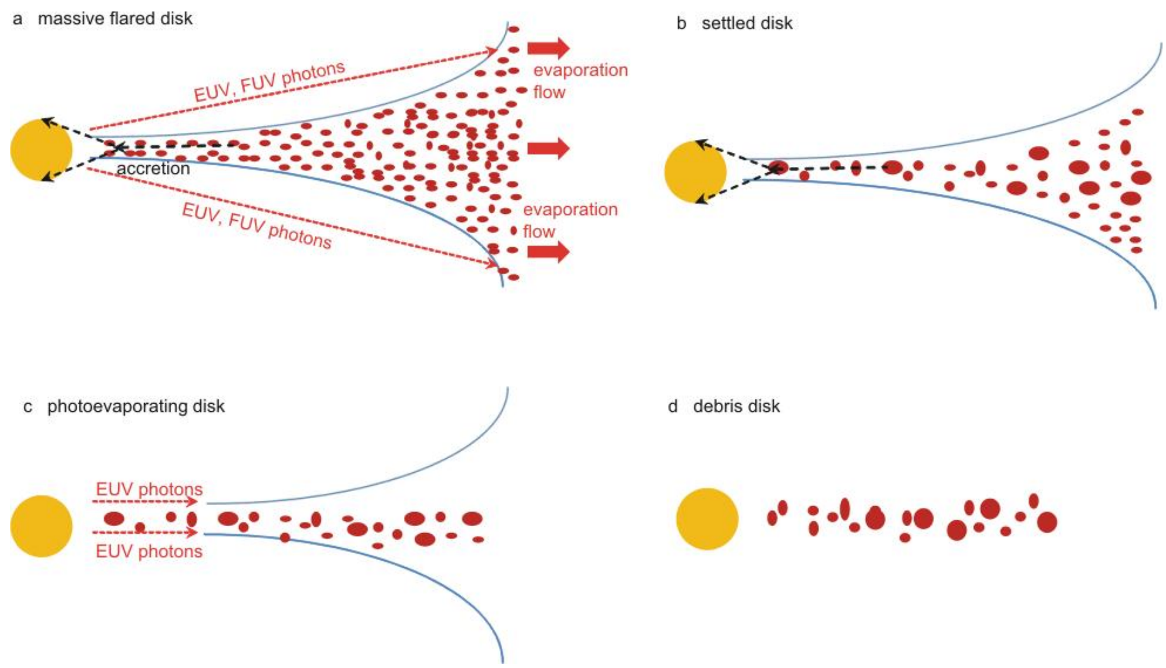

a massive flared disk
EUV, FUV photons
evaporation flow
accretion
EUV, FUV photons
evaporation flow
b settled disk
c photoevaporating disk
EUV photons
EUV photons
d debris disk

Fig. 7

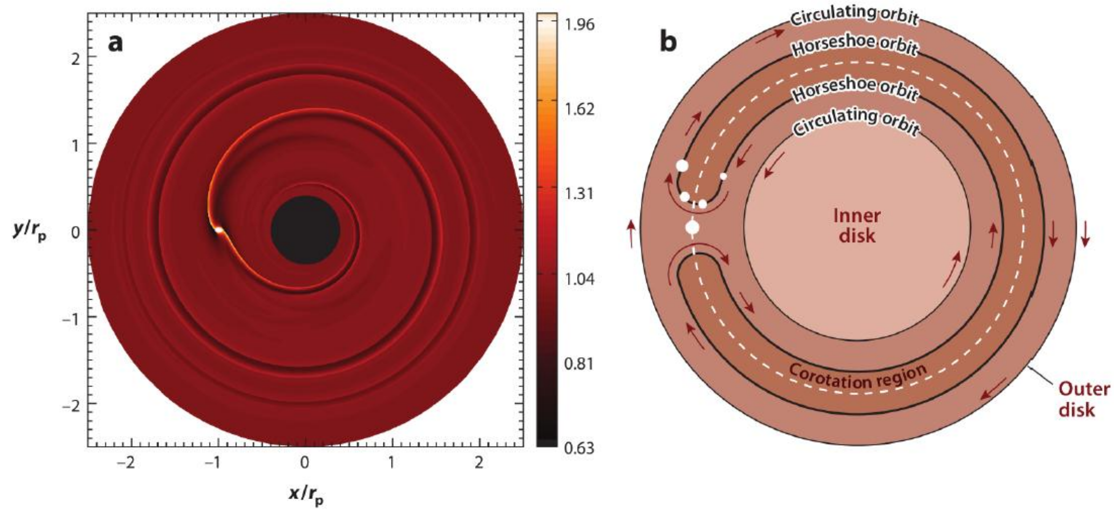

a
1.96
1.62
1.31
1.04
0.81
0.63
y/r_p
x/r_p
b
Circulating orbit
Horseshoe orbit
Horseshoe orbit
Circulating orbit
Inner disk
Corotation region
Outer disk

Fig. 8

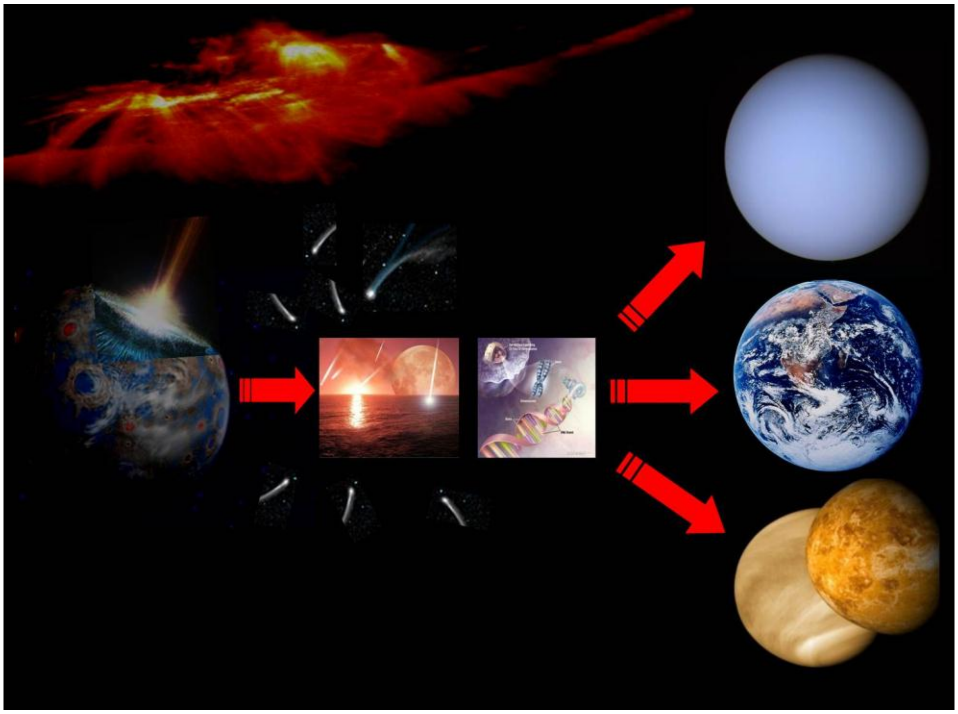


Fig. 9

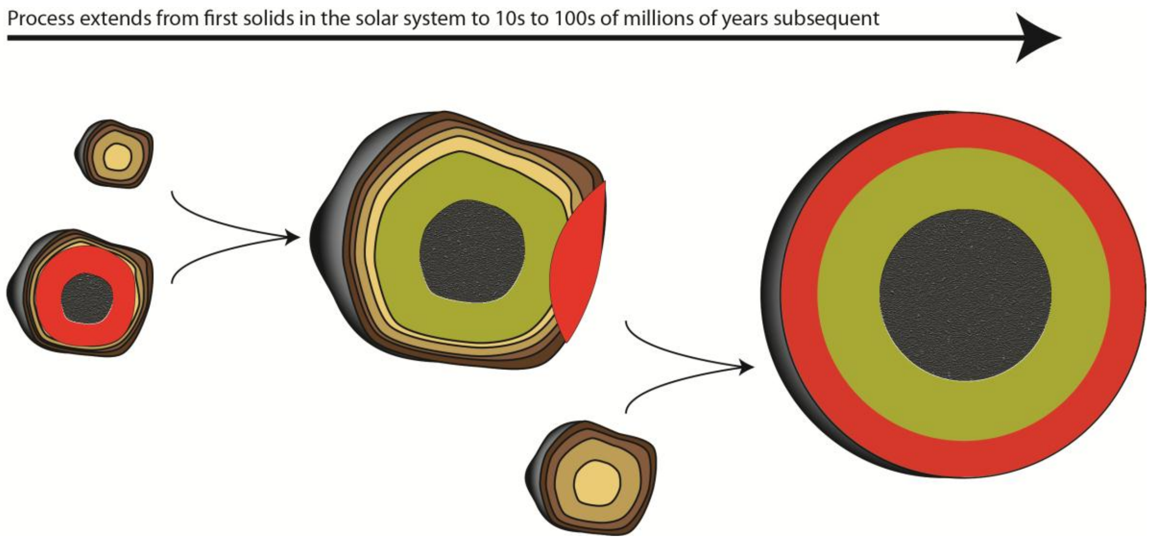

Process extends from first solids in the solar system to 10s to 100s of millions of years subsequent

Fig. 10

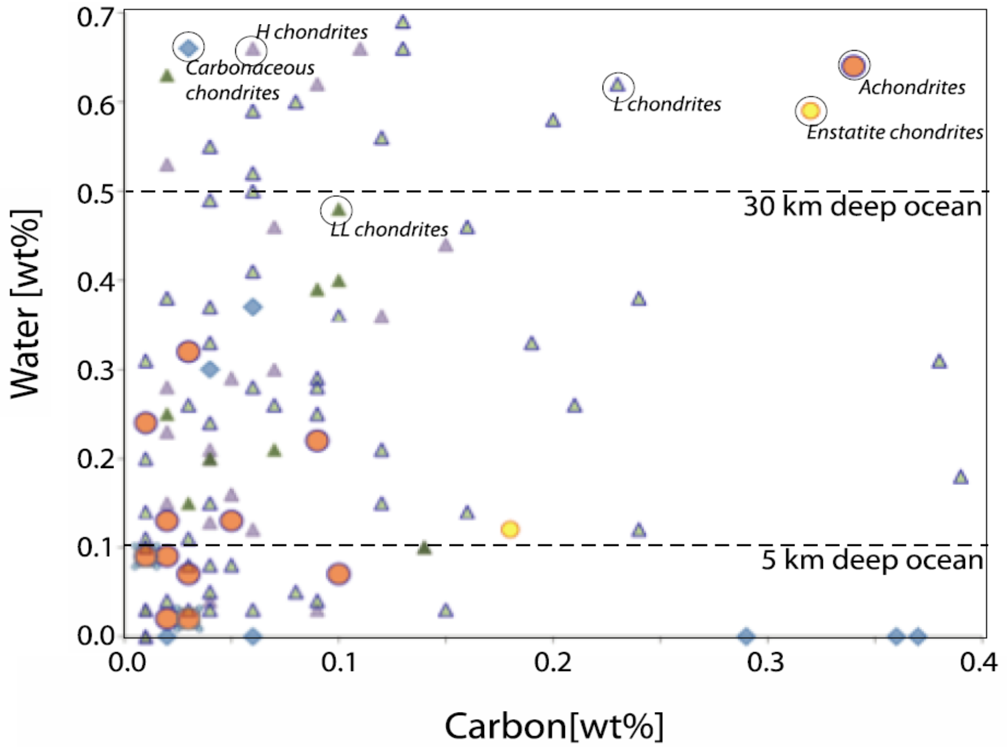

Water [wt%]
Carbon[wt%]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.0
0.1
0.2
0.3
0.4
H chondrites
Carbonaceous
chondrites
L chondrites
Achondrites
Enstatite chondrites
LL chondrites
30 km deep ocean
5 km deep ocean

Fig. 11

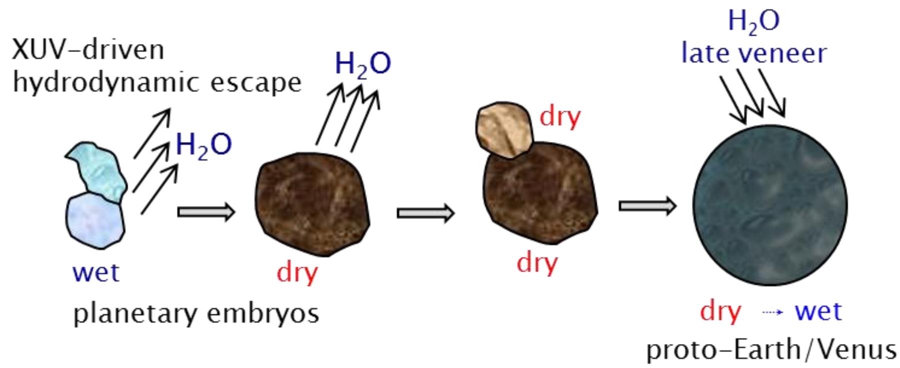
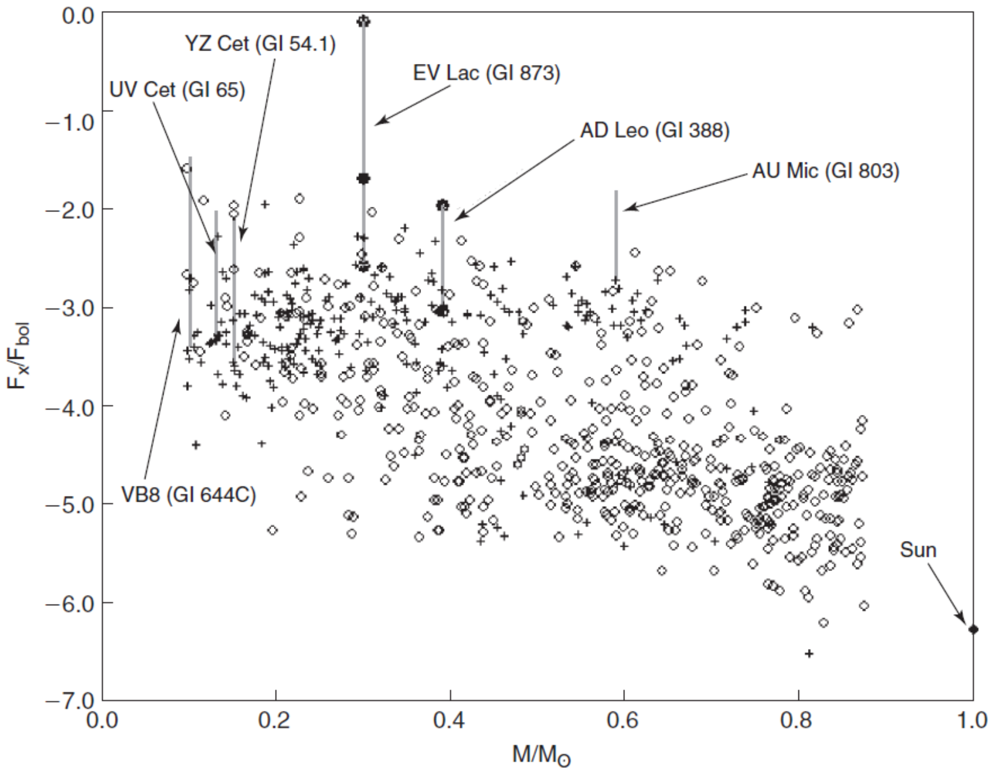
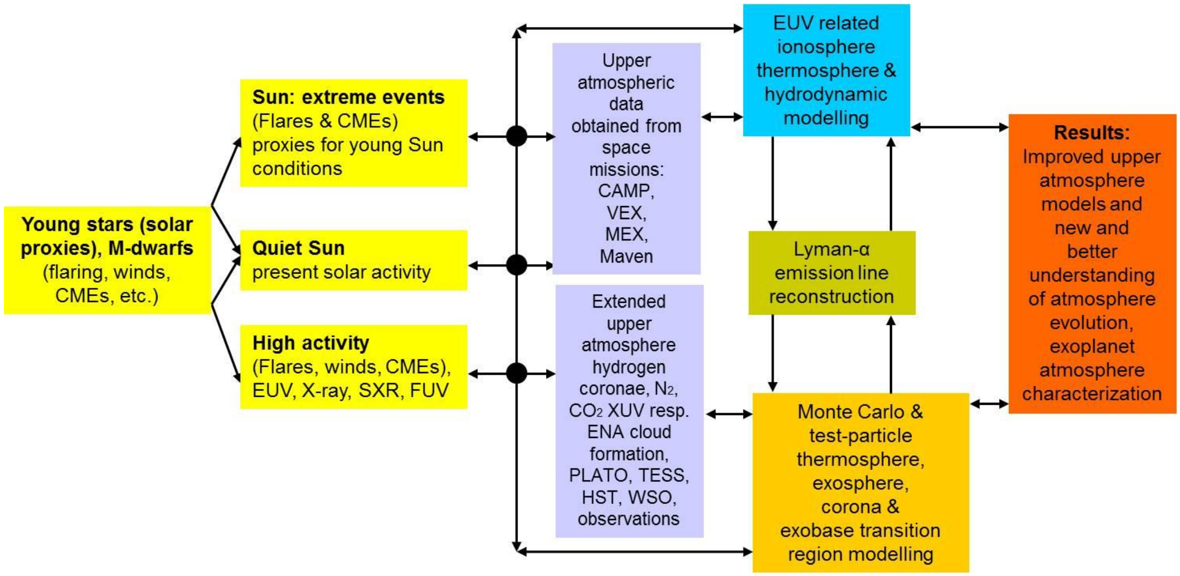

XUV-driven
hydrodynamic escape
H_2O
H_2O
dry
H_2O
late veneer
wet
dry
dry
planetary embryos
dry → wet
proto-Earth/Venus

Fig. 12



YZ Cet (Gl 54.1)
UV Cet (Gl 65)
EV Lac (Gl 873)
AD Leo (Gl 388)
AU Mic (Gl 803)
VB8 (Gl 644C)
Sun
F_x/F_{bol}
$M/M_\odot$
0.0
−1.0
−2.0
−3.0
−4.0
−5.0
−6.0
−7.0
0.2
0.4
0.6
0.8
1.0

Fig. 13


EUV related ionosphere thermosphere & hydrodynamic modelling
Upper atmospheric data obtained from space missions: CAMP, VEX, MEX, Maven
Sun: extreme events (Flares & CMEs) proxies for young Sun conditions
Results: Improved upper atmosphere models and new and better understanding of atmosphere evolution, exoplanet atmosphere characterization
Young stars (solar proxies), M-dwarfs (flaring, winds, CMEs, etc.)
Quiet Sun present solar activity
Lyman-α emission line reconstruction
Extended upper atmosphere hydrogen coronae, N2, CO2 XUV resp. ENA cloud formation, PLATO, TESS, HST, WSO, observations
High activity (Flares, winds, CMEs), EUV, X-ray, SXR, FUV
Monte Carlo & test-particle thermosphere, exosphere, corona & exobase transition region modelling