Community paper „Extrasolar Planets and their Formation“

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Executive summary

Exoplanetary science was born two decades ago with the discovery of the first exoplanets. The field has since then grown to one of the cornerstones of modern astronomy. The resulting broader view of what planets are has triggered a renaissance in the tightly related field of planet formation, which, thanks to modern computational facilities and detailed observations of protoplanetary disks, has dramatically changed our understanding of how planets form. Both fields are still strongly evolving, with new fundamental discoveries and insights emerging regularly. They are fields with a clear future potential, because the most fundamental questions are still wide open, yet clear opportunities for finding their answers are in sight. In both fields German research groups play a key role internationally. Keeping this position, and strengthening it, requires continued dedication to play a leading role in international space missions and ground based observing facilities and campaigns (both small and large) that are aimed at exoplanets, their characterization and protoplanetary disks. It also requires research networks to connect the many groups across Germany and to strengthen the interplay between exoplanetary and planet formation research.

1. Introduction

In the late 16th century Giordano Bruno entertained thoughts that caused him trouble with the authorities: he believed in the plurality of inhabited worlds. He was brave to openly speculate about a question that many people before and since have been pondering about: *are we alone in the Universe or are there numerous earth-like worlds, inhabited or not, orbiting other stars?* Until 1992 this question was merely philosophical since no evidence existed at all of the existence of planetary objects around other stars. However, several discoveries in the mid-1990s changed this dramatically. In 1992 planets were discovered orbiting a pulsar, and in 1995 the first planet around a main sequence star other than the Sun was discovered. Although the first extrasolar planets ("exoplanets") were rather extreme in their properties (Jupiter-mass planets orbiting very close to their host stars), these discoveries proved that planets exist throughout the universe. Today about 1650 confirmed exoplanets are known, and many more "candidates" are listed. They range from Earth-mass rocky planets to Jupiter-like gas giant planets at a wide range of orbits (see Fig. 1). Entire multiple planetary systems of up to 7 planets have been discovered, arranged like miniature "solar systems". Exoplanet atmospheres show a strong variety: Some planets show strong spectral features while others are featureless due to clouds. Some appear dark, whilst others are conspicuously bright and exhibit distinct weather patterns.

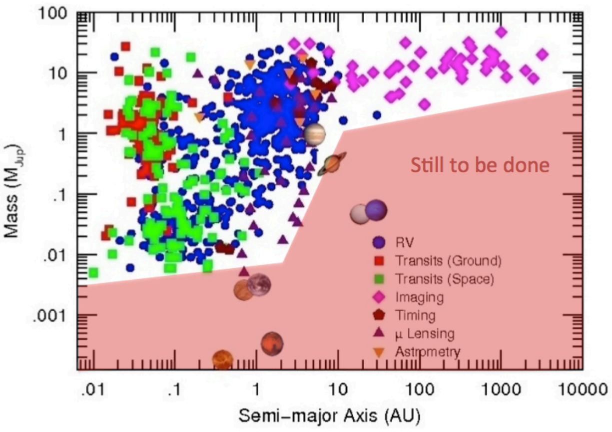

Fig. 1: The known exoplanets in the mass- orbital distance plane discovered by the various detection methods. Also added are the Solar System planets. The red shaded area is the region until now out of reach, but targeted by future observational campaigns.

The second major breakthrough in the mid-1990s was in the field of planet formation, when the Hubble Space Telescope imaged the first *protoplanetary disks*: birthplaces of planets around infant stars. Such a circumstellar disk ("Urnebel") was postulated already in the 17th century by Emanuel Swedenborg, Immanuel Kant and Pierre-Simon Laplace to be the origin of our own Solar System. However, no such disk was ever observed, even though hints of their existence could be taken from excessive infrared emission from young stars. Today, hundreds of protoplanetary disks are known to exist around recently born stars. It is now possible to study these protoplanetary disks in detail (see e.g. Fig. 2). These studies teach us about the environment in which planets are formed, and put important observational constraints on theories of planet formation.

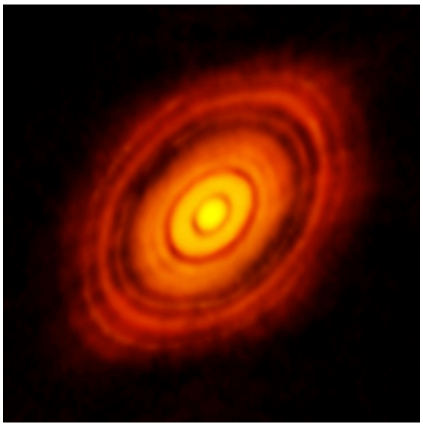

Fig. 2: The protoplanetary disk around the star HL Tau, as observed with the ALMA millimeter wave interferometer (ESO/NAOJ/NRAO, 2014).

The focus in exoplanetary research was until not long ago primarily on detecting new objects, thereby increasing the statistics of their masses, their orbital distances and their orbital eccentricities. Over the last few years a new focus is being put on exoplanet *characterization*: what are these worlds made of, and why? Are they potentially habitable to the kind of life forms we are familiar with? So far only few exoplanets could be characterized, even for their most fundamental parameter: mean density. Identification of an Earth-twin is still out of reach, but not for long anymore with ESA's selected PLATO mission coming up in the mid-2020s. Those planets for which a glimpse on their nature could be obtained have revelead a range of diversity far beyond of what was previously predicted. For the most massive exoplanets it is currently possible to obtain spectra of their atmospheres (see e.g. Fig. 3), and identify weather patterns and global atmospheric circulations. In the next decade exoatmosphere spectroscopy is expected to flourish enormously.

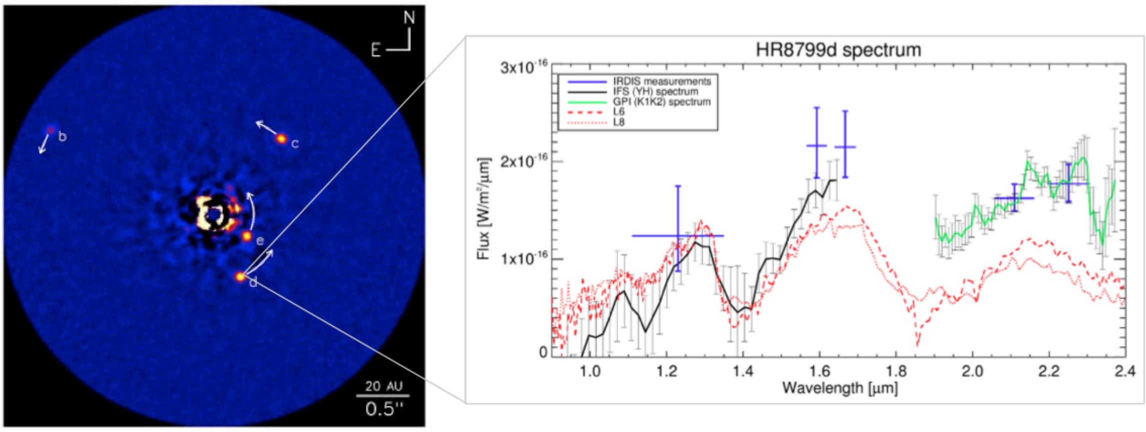

Fig. 3: The planetary system of the star HR 8799. Left: the directly imaged planets with their orbital motion given by arrows (From *Marois et al., 2010, adapted by Zuckerman*). Right: Spectrum of planet "d" obtained with the VLT SPHERE instrument (blue: IRDIS photometry and black: IFS spectroscopy) with a comparison spectrum of a Brown Dwarf of L6, L8 type overplotted (From *Zurlo et al., 2016*).

The observational studies of protoplanetary disks have also improved greatly over the last two decades. Infrared spectroscopy with the Spitzer Space Telescope and the Herschel Space Telescope has revealed the material properties of 100s of such disks. And with the Atacama Large Millimeter Array (ALMA) as well as large ground-based optical telescopes such as the Very Large Telescope (VLT), we can now study detailed spatially resolved images of these disks. What is seen is surprising: some disks consist of numerous concentric rings (see Fig. 2), some contain extremely one-sided dust concentrations, and some display m=2 spirals. The meaning of these structures is still hotly debated. Meanwhile our theoretical understanding of the structure, chemistry and (magneto-/radiation-)hydrodynamics of protoplanetary disks has made giant steps forward, in large part due to the fact that theorists are now, thanks to large scale computing facilities, able to make sophisticated 2-D/3-D computer models of such disks. Similar improvements in computational power and the development of highly sophisticated special-purpose computational algorithms have led to enormous progress and paradigm-shifts in the field of planet formation. New concepts such as the "gravoturbulent planetesimal formation" (Fig. 6), "pebble accretion" and "dust traps" are replacing older models. Laboratory-based input physics make the models more realistic. And "planet synthesis models" are maturing and make predictions that can be directly compared to exoplanet statistics.

The two fields of study (exoplanets and their atmospheres on the one hand and planet formation and protoplanetary disks on the other hand) are strongly linked. Theories of planet formation must not only explain how the solar system planets formed, but they also have to explain the enormous diversity of extrasolar planets (Fig. 1). Our own Solar System may be an extremely special outlier in which the conditions are *just right* for intelligent life to exist. To understand the principles of planet formation we therefore *must* also look at other planetary systems that do not suffer from this bias. The number of exoplanetary systems now known is starting to become large enough to do meaningful statistics. Observational techniques are not yet able to pick up Solar System analogs, but we are getting close (see Fig. 1).

The observational and theoretical study of exoplanets and their formation is, however, a major technical challenge. In the following two subsections we will describe these challenges in more detail so that it becomes clear where the field is going in the next decade.

1.1 Discovering and characterizing Exoplanets

Finding exoplanets, even around the nearest stars, is an enormous technical challenge. Directly "seeing" them (the *direct detection method*) has only become possible in the last few years, and so far only a few (mostly young and massive) exoplanets have been discovered this way (e.g. Fig. 3). Most exoplanets discovered until now are discovered by *indirect* techniques. The two most prominent techniques are the *radial velocity method* and the *transit method*. In the *radial velocity method* ("RV-method") the gravitational recoil of the (unseen) planet onto the (observed) star can be measured through a tiny periodic Doppler shift in the star's spectrum. If the host star's mass is known, the RV method yields the orbital distance and (a lower limit of) the mass of the planet. In the *transit method* exoplanets are discovered if they periodically pass in front of their host star. As this blocks a few promille of the star's light, a tiny dip in the star's brightness can be observed. The period of recurrence gives the orbital distance to the host star, and the depth of the transit gives the size of the planet. As other effects can mimic such a transit signal, a follow-up RV confirmation is desirable and yields, as a bonus, the planet's mass and interior density. This allows one to make inferences of the composition of the planet (Fig. 4), which gives clues to the planet's formation history and subsequent evolution. A further indirect method of exoplanet discovery is the *gravitational lensing method*, in which an exoplanet is discovered by its amplifying effect on the light of an observed background star. And finally it is expected that ESA's Gaia mission will detect exoplanets with the *astrometric method* by measuring variations of the host star's position on the sky caused by an exoplanet.

All these methods are high-precision measurements at the limit of what can be done. In Fig. 1 it is seen that the lower-right corner (low mass planets at relatively large distance to their host star) is so far not yet explored, because it requires improved techniques and longer observational baselines (years to tens of years) to access. As one can see from the location of the Solar System planets in that plot: if we wish to search for solar system analogs, we are just about entering the era where this becomes possible.

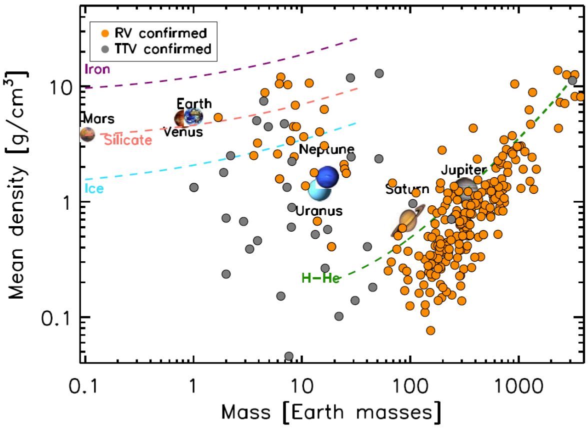

Fig. 4: The density versus mass for transiting exoplanets. Dashed lines indicate models for different bulk compositions. (Update from *Rauer et al., 2014*).

Although obtaining knowledge of an exoplanet's orbit, mass, size and mean density gives a first indication of what kind of planet it is (Fig. 4), one is compelled to ask further questions such as: does it have a rocky surface, does it have an atmosphere, does it have water, molecular oxygen, carbon dioxide, does it have oceans and landmasses, what is the climate/weather like, and in general: what are these planets made of and are they potential hosts of life? To answer these questions we must take *spectra of exoplanets*. This is one of the biggest technological challenges of exoplanetary science, yet one of the most important ones. The most straightforward method of exoplanet spectroscopy is spectrally dispersed direct detection (Fig. 3), but this technique remains limited by the number of available sources. High contrast imaging with large telescopes (VLT and E-ELT) is the driver of this method. Meanwhile the prime method of exoplanetary atmospheric characterization is *transit spectroscopy*: If exoplanetary transits (both primary and secondary) are measured with extreme precision at different wavelengths, a rough spectrum of the planet's atmosphere can be derived. This technique has been succesfully used both from space (with Hubble, Spitzer, CoRoT and Kepler) and from the ground. Although these first exoplanetary spectral studies could only target Jupiter-sized planets and still suffered from very low spectral resolution, they made the first steps in the new field of comparative exoplanetology. With new space missions (CHEOPS, JWST, PLATO, TESS) approaching their launch date, it is expected that exoplanet spectroscopy will soon yield much higher-resolution spectra, and probe much lower-mass (i.e. more "earthlike") exoplanets. This will also stimulate more theoretical and numerical modeling of exoplanet atmospheres, including the comparison to atmospheric phenomena known from the Earth and other Solar System planets.

1.2 Models of planet formation and observations of protoplanetary disks

The planet formation process starts with the coagulation of micron-sized dust in the protoplanetary disk, forming dust clumps of centimeters to meters in size. The dynamic coupling between these dust clumps and the disk's gas tends to lead to non-linear instabilities out of which planetesimals form (see e.g. Fig. 6). Full-size planets are subsequently formed by gravitational agglomeration of planetesimals and accretion of additional dust clumps. The gravitational pull of the planet modifies the disk's structure by inducing spiral waves and opening a gap, which feeds back on the planet's orbit, leading to the planet's orbital migration, which dramatically affects the final architecture of the planetary system. Meanwhile the disk itself evolves through viscous accretion, turbulence, magnetic torques, photoevaporation and changes in the opacity due to dust coagulation and chemical evolution. When the gas of the disk is gone (after a few Megayear) the formation process is not yet over: during this final gas-free *debris disk* phase, complex gravitational dynamics and collisions between planets bring the system into its final form.

All these ingredients are coupled, and they cover spatial scales from micrometers to billions of kilometers, making the problem immensely complex. Traditionally theoretical studies have focused on individual aspects, to keep the problem tractable. But the trend goes to studying how various aspects influence each other. For instance: how does dust coagulation affect the disk's chemistry? Or how does the abundance of free electrons affect the magnetorotational instability and hence the accretion flow in the disk? Complemetary to this is the class of the *planet synthesis models.* Here the aim is to model the *full* planet formation and disk evolution process using highly idealized "effective submodels" to keep the computation feasible, where these effective submodels are "fits" to the much more detailed and realistic models. This way the model becomes computationally fast enough that actual predictions for exoplanet statistics can be made and tested.

Observations of protoplanetary disks and debris disks are the crucial counterpart to planet formation theory. These observations tell us what the initial conditions are, in which environment planets are formed, what the raw material of planets is like, etc. And since the process of planet formation is predicted to have observable effects on the structure of protoplanetary- and debris disks (e.g. gaps, rings, vortices, spirals, as well as spectral signatures of dust growth, chemistry and other effects), such observations are critical tests of planet formation theory. In particular the recent revolution in spatially-resolved protoplanetary disk observations driven by the ALMA array (e.g. Fig. 2) and by new developments in large optical telescopes (high-contrast spectro/polari/angular-differential imaging, as well as interferometry) makes for exciting times: For the first time we can now see the spatial structure of these disks in detail, allowing us to truly test theories of planet formation. And the first hints of "planet formation caught in the act" (nascent exoplanets still embedded in the protoplanetary disk from which they form) have already been observed.

2. Key Questions for the Upcoming Decade

While the last two decades were the era of the discovery of exoplanetary diversity, the coming decade will be the era of exploring and characterizing this diversity and trying to understand how it comes about. Continued leaps in instrumental capabilities will not only refine our knowledge, but also open new corners of discovery space. There is a clear trend emerging of attempting to link theories of planet formation to understand more than just mass - orbit diagrams: to understand exoplanetary composition in terms of the planet's formation, migration history and long-term evolution. Exoplanet photometry and spectroscopy combined with detailed modelling will be the main driver for this. Also with the high-resolution studies of protoplanetary disks, possibly with nascent planets embedded in them, the theory of planet formation is being more strongly linked to the nature of protoplanetary disks. Finally, the community is looking forward to detecting Earth analogs around nearby stars which can be investigated for their habitability.

To be more concrete, some of the key questions for the coming decade are:

1. What are the properties of exoplanets (orbit, mass, radius, multiplicity) as a function of host star spectral type, metallicity and multiplicity?
2. What is the atmospheric and interior composition of exoplanets, and how do they relate to the planet's formation, migration history and long term evolution?
3. What are the structure and dynamics of exoplanetary atmospheres like (weather phenomena, clouds)? How do these relate to the planet's orbit and host star type, metallicity and multiplicity?
4. What are the properties of exoplanets in the "habitable zone" (the distance from the host star where temperatures are right for water to exist in liquid form), and are they conducive of life as we know it?
5. What do the complex structures found in protoplanetary disks with high-resolution telescopes (VLT, ALMA and in the future: E-ELT) tell us about the processes of planet formation? What is the nature of the "transition disks" in this regard? Can we determine the exact locations of the various "snow lines" of H_2O, CO_2, CO, CH_4, NH_3, and what their role is in planet formation?
6. What can debris disks tell us about exoplanetary systems? Can we find evidence for ongoing rocky planet formation in debris disks and water delivery by comets?
7. One of the goals is finding more and better observations of "planet formation caught in the act". Can we find evidence of circumplanetary disks (the birthplaces of moons)?
8. How are planetesimals and planetary embryos formed from cosmic dust? What is the critical role played by turbulence, streaming instabilities, icy dust growth, pebble accretion, dust traps, and possible still to be discovered phenomena?
9. How, whereto and how fast do planets migrate?
10. Can we construct a "standard model of planet formation" that, at least in principle, explains both the exoplanetary data as well as the structure of protoplanetary disks?
11. Which properties make a planet habitable?
12. Can signatures of life (biosignatures) be detected on extrasolar planets?

3. Key Results from the German Community of the Previous Decade

The German astronomical community has traditionally had a strong involvement in the topics of exoplanets and planet formation. Several research networks on these topics have been funded by the DFG over the last decade, among which were FOR 759 "Planet Formation: The Critical First Growth Phase", GrK 1351 "Extrasolar Planets and their Host Stars", SPP

1385 "The First 10 Million Years of the Solar System", and currently includes SPP 1833 „Building a Habitable Earth“, FOR 2285 "Debris Disks in Planetary Systems" and SPP 1992 "Exploring the Diversity of Extrasolar Planets". Here we give a few research highlights from German groups, which is by no means a complete list.

An early direct detection of a planetary candidate was made in 2005 by a team from Jena, who imaged a low-mass companion of GQ Lup with a mass of 25±20 $M_{Jupiter}$. Since objects with mass > 13 $M_{Jupiter}$ are considered Brown Dwarfs instead of planets, it is not sure if this companion is indeed formally a planet, but it remains one of only a small number of directly imaged planetary candidates. A collaboration between Jena and Hamburg has recently discovered two planets around the T Tauri star CVSO 30: one close-in planet detected with the transit method, one wide-orbit planet detected with direct imaging. If confirmed, this would be the first such system to be found.

The first exoplanet search from space was done with the CoRoT space telescope from the French space agency CNES, in partnership with, among others, the Deutsches Zentrum für Luft und Raumfahrt (DLR). The Institut für Planetenforschung of DLR has been a major partner in the discovery of 32 exoplanets through the transit method. One of the exoplanets discovered, CoRoT-7b, is the first confirmed rocky exoplanet. The combined radial velocity and transit detection (Fig. 5; data from the international CoRoT team, the final analysis by the Tautenburg team) yielded a density about twice that of Earth. The Kepler space telescope from NASA has so far been most prolific in producing transit-detected exoplanetary candidates, and a series of multi-planetary systems of 3 or more exoplanets. Recently a team led by a German collaboration (Berlin and Tautenburg) discovered that the system KIC 11442793 has 7 exoplanets, and is thereby the current record holder in terms of the number of exoplanets, and has an architecture reminiscent of a miniature Solar System.

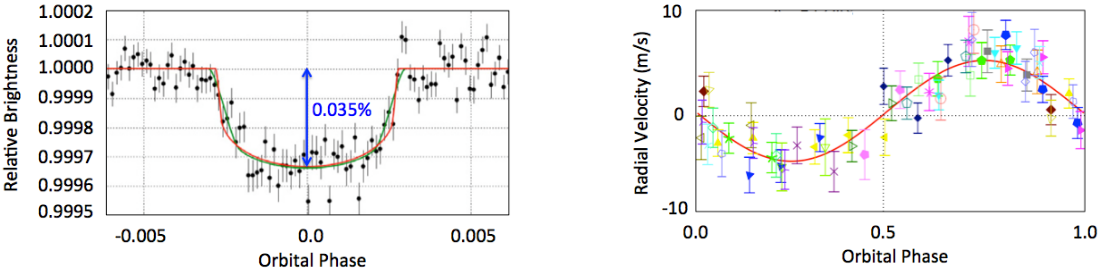

Fig. 5: The discovery of the first confirmed rocky exoplanet: CoRoT-7b. Left: the transit measured with CoRoT providing planet radius (Adapted from *Leger et al., 2009*). Right: the radial velocity confirmation, providing orbital parameters and the planet mass (Adapted from *Hatzes et al. 2011*). Combined transit and radial velocity measurements like these yield the planet's average density, which is a key measurement for determining the planet's likely composition.

A German team from Tautenburg confirmed, using the RV technique, the first transiting exoplanet around an A star: WASP-33. Given the star's rotational velocity of 90 km/s this was an enormous challenge. Since around such stars protoplanetary disks live less long, such close-in planets give important insight into the speed of planetary migration. Heidelberg scientists (henceforth Heidelberg/M means the MPIA and Heidelberg/U means the University) managed to detect gas giant planets around around giant stars using the RV method (HAT-South project) and a K2 collaboration for finding Super-Earths around M stars is set up (Heidelberg/M).

With the RV method a team from Göttingen discovered several small planets that are among those most like Earth, among them a system with several super-Earths and a planet around the nearest halo red-dwarf. Göttingen leads the field to push RV spectroscopy to infrared wavelengths and operates laboratory facilities and telescopes to push RV calibration beyond the 1 m/s limit. With a gas-cell developed in Göttingen a few m/s precision was achieved in a VLT survey at infrared wavelengths.

Germany also plays an important role in direct detection and characterization of exoplanets at large orbits around stars. Researchers from Heidelberg/M, Jena and Hamburg have found several such planets, and Heidelberg/M recently announced the discovery of a planet embryo inside its birth disk in the system HL Tau. Heidelberg/M co-developed (and is co-PI of) the SPHERE instrument for ESO's Very Large Telescope, which is currently producing spectacular high-contrast/high-resolution images of protoplanetary disks. SPHERE has also obtained its first results on exoplanets by determining the spectra of the directly imaged planets around the star HR 8799 (Fig. 3).

In addition to discoveries, German groups in Berlin, Hamburg, Göttingen and Heidelberg/M+U play an important role in the development of planetary atmosphere models, both for rocky planets as well as for gas giant planets. These models are key to putting the main observables into perspective, and to connecting the insights into the planet atmospheres with the planet formation and evolution. Such modeling efforts are bridging the gap between the astronomical and planetary science communities.

Also in the field of planet formation the German community plays a strong international role. Planet formation starts with the coagulation (the sticking together) of the micron-sized cosmic dust particles in the protoplanetary disk, to form ever larger dust aggregates. However, growing in this way from micron-sized dust all the way to kilometer-sized planetesimals has long been known to be hard, because intermediate sized dust aggregates are not very sticky. Groups in Braunschweig and Heidelberg have, in a collaboration between laboratory and modeling teams, mapped for the first time the exact conditions under which these "growth barriers" occur and when not. The problem how to grow from millimeter pebbles to kilometer-sized planetesimals has, however, not been made easier, though growth of icy dust grains may hold a vital clue, as several Japanese groups argue. The study of icy aggregates is therefore a clear pathway for the future.

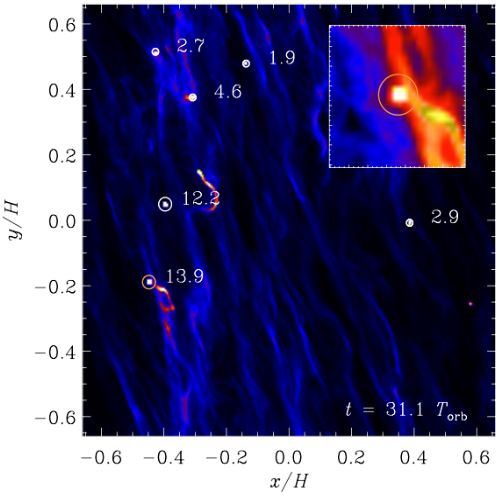

Fig. 6: The formation of planetesimals via the streaming instability followed by gravitational collapse. This simulation was done on a massively parallel computer cluster using 4096 cores. (From *Johansen et al., 2011*).

Currently the most widely believed model of the formation of planetesimals (the ~1-100 kilometer size building blocks of planets) is the *streaming instability* followed by gravitational collapse of dense clouds of "pebbles" (see Fig. 6). This model was introduced in 2007 by scientists from Heidelberg/M, and has led to a true paradigm shift in the field. Models of this kind are, however, very computationally expensive, which means that progress in this area relies on funding of large scale computational facilities. The same is true for another breakthrough in the field: The improved understanding of the role of the corotation torque, its saturation, and the disk thermal structure in the speed and direction of planetary migration, where the Tübingen group plays a leading role.

And finally, in the area of observations of protoplanetary disks and debris disks and their interpretation, German teams have been quite succesful as well. Starting with the early measurements of disk masses with millimeter wave telescopes (IRAM, SEST, APEX), in the first decade of the 21st century German teams were very succesful with detailed spectroscopic studies of the dust and gas in the infrared with the Spitzer and Herschel space telescopes as well as the VLT (CRIRES, MIDI). The VLT/MIDI instrument (built in Heidelberg/M) allowed spatially resolved spectra using interferometry, allowing spectroscopic analysis of the "earth-forming zone" in protoplanetary disks. The successor instrument MATISSE (Nice, Heidelberg/M, Bonn, Leiden, Kiel, Wien) is nearing completion. With the VLT/SPHERE instrument a series of spectacular scattered light images of non-axisymmetric features in protoplanetary disks was recently taken with German involvement, showing that protoplanetary disks are much more complex than believed in the past. Likewise with the ALMA millimeter array rings and strong non-axisymmetric features are seen in these disks. This led recently to the first identified observed dust trapping vortex in the source Oph IRS 48 (Leiden, Garching and Heidelberg/U). German theorists (Heidelberg/M) have long ago predicted such dust trapping vortices to exist and play a key role in planet formation.

4. Particular Role/Strengths of Research Groups in Germany

In the international arena of exoplanet and planet formation research Germany is particularly strong in instrument/telescope development and their subsequent application (both for exoplanet detection/characterization as well as for protoplanetary disk studies); in numerical modeling of protoplanetary disks, planet formation, exoplanet atmospheres and exoplanet interiors; and in laboratory astrophysics. In this section we give a condensed overview.

Germany plays a strong role in the design and building of instrumentation for exoplanet searches and characterization. The DLR team (Berlin) is the PI on the follow-up project of CoRoT: The PLATO mission selected by ESA in 2014 and to be launched in 2024. This is one of the big international exoplanet space missions of the coming 15 years. PLATO will detect thousands of planets with measured radii and masses, and hence mean densities. Among those will be planets in the habitable zone of solar-like stars, which will be a major step towards characterizing planets similar to our Earth. In addition, PLATO will derive accurate ages of the planet's host stars and therefore allow us to study the long-term evolution of planets. DLR is also partner in CHEOPS, a smaller but similar mission lead by a team in Bern, and in NGTS, a ground based transit survey operated from Chile. A German collaboration between Heidelberg/U+M, Göttingen, Hamburg, Munich and Tautenburg with Spanish collaborators has recently commissioned the CARMENES spectrograph on the Calar Alto 3.5 meter telescope. The goal is to search for planetary companions around M dwarf stars using the RV method. One of the motivations is to see if exoplanets can be found in the habitable zone, which is easier accessible around M stars than around sun-like stars. CARMENES is one of a series of RV-capable spectrographs with exoplanet applications built in Germany, which also include CRIRES+ (Göttingen, Heidelberg/M, Tautenburg), E-ELT/HIRES (Göttingen, Hamburg, Heidelberg/M, Potsdam, including spectropolarimetry capabilities to search for circular polarization as a biosignature), and FOCES (Munich), as well as STELLA, GREGOR-at-Night and LBT-PEPSI (Potsdam). This is complemented with research on understanding the stellar signal for RV search, i.e., stellar activity (Hamburg, Göttingen, Potsdam). German-cobuilt instruments for direct detection of exoplanets include VLT/NACO and VLT/SPHERE, with E-ELT/METIS currently being developed (Heidelberg/M). JWST, where Heidelberg/M and Köln contributed to the MIRI instrument, will be *the* planet atmosphere analysis telescope of the coming years.

In terms of the study of protoplanetary disks and debris disks Germany is equally well positioned. Instruments such as VLT/SPHERE (operational) and VLT/Matisse and JWST/MIRI are developed in/with Germany and are powerful tools for finding signatures of planet formation in these disks. ESO's ALMA array is currently, together with the VLT/SPHERE instrument, responsible for a revolution in spatially resolved disk observations and will likely remain among the main drivers of protoplanetary disk research for the coming decade. Numerical and theoretical modeling of protoplanetary disks and planet formation is also strongly represented in Germany, in particular in Tübingen, Kiel, Heidelberg/M+U, Göttingen, Jena, Potsdam and München. On topics such as planet migration, disk instabilities, gas giant planet formation, protoplanetary disk dispersal, dust coagulation, debris disks and radiative transfer these groups are driving forces of their fields internationally. They have developed many powerful new numerical techniques and codes (hydrodynamics with particles, radiation hydrodynamics, dust coagulation, planet synthesis models, etc) specially aimed at solving the complex problems involved in planet formation.. Moreover, Germany has two laboratories that specialize in the experimentation with colliding dust aggregates and the determination of their properties (Braunschweig and Duisburg). These data are critical input to planet formation theories.

German research groups play a leading role in radiative transfer techniques and codes (Kiel, Berlin, Hamburg, Heidelberg/U+M, Munich, Potsdam) as well as astrochemical and atmospheric-chemical codes (Garching, Köln, Heidelberg/M, Berlin). Based on this in-house expertise various German research groups have become internationally leading teams in protoplanetary disk modeling (Heidelberg/U+M, Kiel, Garching, Munich, Jena) and the development and application of exoplanet atmospheric models (Berlin, Hamburg, Heidelberg/M+U). Codes and models such as these are essential to interpret observations of protoplanetary disks and exoplanetary atmospheres. However, they can only produce reliable results if reliable opacities and reaction rates exist. Germany has several laboratories where these properties are measured (Jena, Köln, Kassel, Garching, Heidelberg/M).

Finally, to make the link to the ultimate question: In Heidelberg and Munich interdisciplinary initivates for the investigation of the Origin of Life were founded.

5. Key Infrastructures needed/relevant for Researchers in Germany

Germany is doing well in the fields of exoplanets and planet formation. However, internationally these fields are growing strongly. To maintain a leading role in the field of exoplanetary research it is vital for Germany to keep and expand its involvement in dedicated space missions and ground-based campaigns for exoplanet observations. The PLATO space mission is the prime example, and will play a central role in German exoplanet research. PLATO is the biggest European exoplanet space mission, and Germany's PI-role is a unique chance to consolidate Germany's leading role in this field. In addition, other key involvements in space mission are CHEOPS, JWST, WFIRST, and further into the future a possible HST/JWST follow-up mission (HDST/LUVOIR/?). In particular JWST and WFIRST will be the key space observatories for exoplanetary atmospheric studies in the coming decade. With E-ELT/HIRES such high-resolution exoplanet spectroscopy will also become possible from the ground. With the light collecting power of the E-ELT, the high-precision spectrograph will provide extremely high SNR data of planet-host stars and will allow to study atmospheres of extrasolar planets in a wide wavelength range. Ground-based follow-up and RV surveys at highest precision are crucial for confirming and characterizing exoplanets. For this, access to RV facilities in the timeframe until 2030 for TESS, CHEOPS and PLATO follow-up is essential for German astronomers to reap the fruits of the data from these space missions. To achieve this, support and coordination of the various small-scale (1-2m) RV facilities operated by German institutions is important. Furthermore, an extension of CARMENES, converting it after its main project phase into the German 3.5 m RV follow-up facility, would be a key step to keep Germany competitive in this area. In addition, working toward exoplanetary atmospheric spectroscopy missions is an important aim, since exoplanet characterization is the mid- to long-term future of the field. The JWST telescope will play a key role in the near future, and WFIRST and HDST in the intermediate to long term future.

High-resolution observations of protoplanetary disks and debris disks (in particular ALMA, VLT-SPHERE) are currently revolutionizing the field of planet formation. We are starting to witness dynamical processes in these disks that have direct relevance to the process of planet formation. These successes strongly support continued investment in (and upgrading of) ALMA during the coming decade, as well as in high-contrast, high-resolution imaging with VLT and E-ELT. For now, however, we are still limited to the intermediate to outer disk regions. A key goal is to zoom-in ever closer to the star, where "Jupiters" and "Earths" are formed. Multi-baseline interferometric instruments on the VLT are essential (VLT/GRAVITY, VLT/MATISSE), as are long baseline millimeter-wave telescopes (ALMA, E-VLA). The E-ELT will clearly be the next big step on this trajectory.

Instrument development for ground- and space-based telescopes, is a key strength of Germany and remains essential to Germany's leading role in the fields of exoplanets and planet formation worldwide. But the university institutes need support to maintain their expertise and infrastructure for instrument-development.

However, observations of exoplanets and protoplanetary disks alone are not much worth without a strong theory and numerical modeling effort on questions of exoplanet interiors/atmospheres and planet formation / disks to interpret these observations. While Germany has several highly competitive and internationally recognized teams in these areas, this community still has not reached the critical *size*. The risk exists that observational data produced by German facilities will, from the interpretation perspective, be exploited mostly abroad. Addressing this requires increased personnel and large scale computing facilities.

New research networks in the areas of exoplanets and planet formation, preferentially combining the two, are of major importance for the future. Competitive exoplanetary research in the next decade requires large collaborations. And now that observations start probing the composition and atmospheric properties of these exoplanets with increasing sensitivity, the collaboration between observers, modellers and lab scientists, and between exoplanet- and planet formation-groups becomes even more essential. An increased interdisciplinary approach (including the solar system, geophysical and biological communities) is important to connect exoplanetary research to the question of our own place in the universe. The need for such networks has been recognized now in Germany, with the installation of a new Schwerpunktprogramm (SPP) of the Deutsche Forschungsgemeinschaft: "The Diversity of Extrasolar Planets" (2016) and the Forschergruppe "Debris Disks in Planetary Systems" (2015) as well as the new initiatives for the origin of life. These and further initiatives, in particular strengthening exoplanetary and planet formation research at universities will allow Germany to take the lead in the drive to answer the question what are the origins of exoplanets and their diversity, and how common are habitable worlds.

6. Summary and Conclusion

The fields of exoplanets and planet formation are developing very rapidly and hold great promise for the next decade and beyond. Finding a "second Earth", learning about habitability, understanding how planets (including Earth) formed and why they have the properties they have: these are exciting questions that teach us about who we are, where we come from and whether we are unique or common in the Universe. In a way one can call this the "key question of our origins". This is recognized internationally, and the USA, Canada, Japan and various countries in Europe pour vast amounts of resources in this area. Germany is internationally visible in this field, but this can only be maintained if the required resources are upheld and strengthened. To summarize, our main recommendations are:

- Secure the PLATO mission in the ESA Science program
- Support German participation in other exoplanet space missions as well, with a special emphasis on exoplanet *characterization* (JWST, WFIRST, HDST/LUVOIR)
- Secure CARMENES as Germany's large RV follow-up facility by extending its lifetime
- Support German small telescope facilities in taking part in ground-based RV follow-up
- Support continued ALMA ramp-up for studying planet formation processes in protoplanetary disks at the highest resolution and sensitivity possible
- Support high-contrast, high-resolution optical and infrared imaging, aimed at resolving the planet-forming regions in protoplanetary disks and debris disks (VLT, VLT-I and E-ELT), including the corresponding instrument development
- Complementary to observational teams: Secure funding (personnel and computational facilities) for theoretical research to interpret the observational data
- Strengthen exoplanetary and planet formation research at German universities
- Support interdisciplinary work to understand planets, their formation and evolution as a system, as well as their role in the origin and support of life