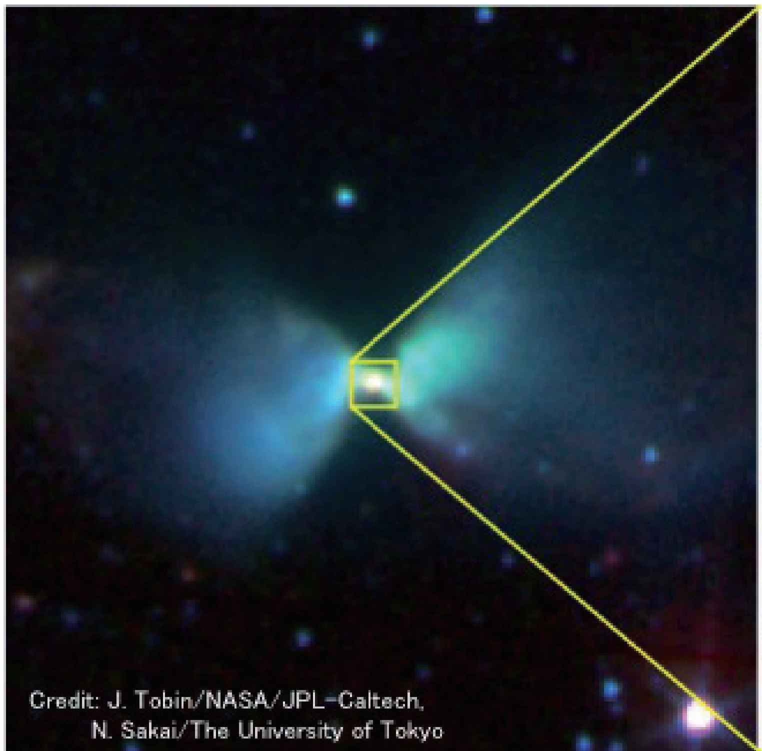
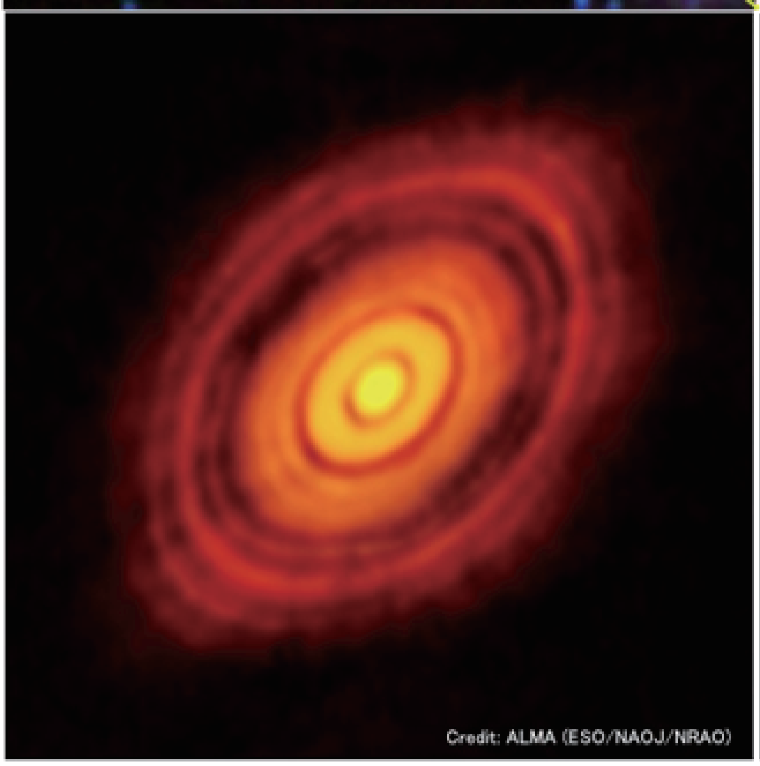
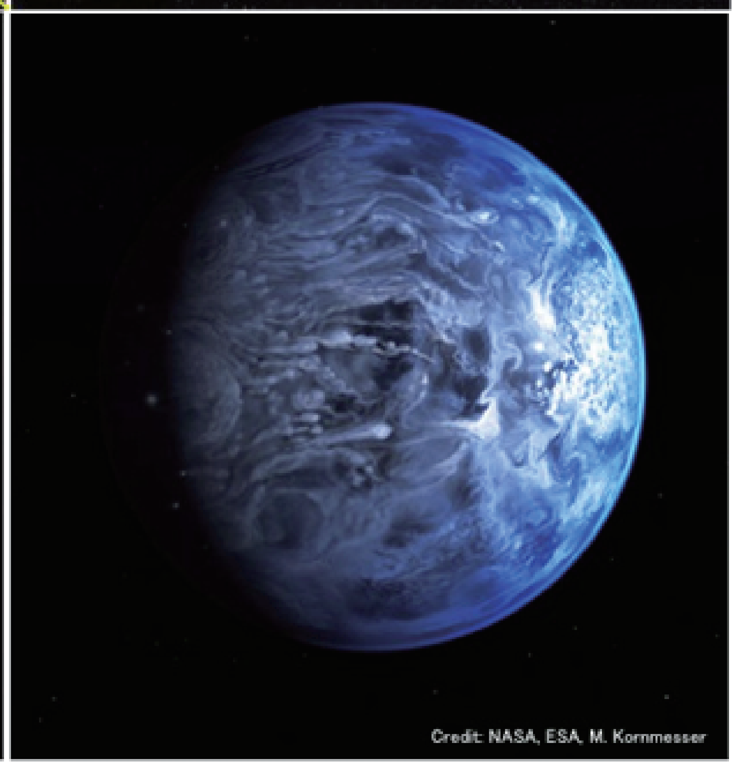
3rd DTA Symposium
The Origins of Planetary Systems: from the Current View to New Horizons





Abstract Booklet
June 1 - June 4, 2015, NAOJ, Tokyo

国立天文台
NAOJ
National Astronomical Observatory of Japan

Scientific Rationale:

Ever since the first discovery of an extrasolar planet orbiting around a Sun-like star in 1995, more than 1900 exoplanets (+ about 4000 candidates) have been observed so far. A number of ongoing and future surveys do and will keep increasing the population of observed exoplanets. In addition, the advent of ALMA with significantly upgraded capabilities has recently enabled the unprecedented high resolution observations at (sub)mm wavelengths. For instance, the long-baseline science verification campaign reveals multiple gaps in a circumstellar disk around HL Tau, a young (< Myrs) YSO, which may be a signature of planet formation. These revolutionary observations are currently triggering the rapid progress on the understanding of the formation and evolution of planets, which may occasionally require paradigm shifts. It is fascinating that planet formation can serve as a fundamental platform to unite these observations and related sciences.

Aims and Scopes:

In a golden era of planetary sciences, it would be of essential importance to

(1) examine both theoretically and observationally the current understanding of how planetary systems are born out of their natal circumstellar disks and of how the systems evolve with time,

(2) summarize unresolved issues and open questions, and

(3) attempt to develop new ideas/visions to derive a better understanding of planet formation.

This workshop will be designed to cover the above points.

Specifically, this workshop will stimulate the following activities;

- review the current status of both theory and observations
- discuss the latest results of both theoretical and observational work
- summarize key questions that will/should be addressed in the near future
- trigger new collaborative work among theorists and observers
- enhance interactions between theorists and observers
- encourage involvement of young people including postdocs and students
- provide young students with plenty of chance to interact both with active researchers in the world and with key scientists in Japan

Schedule:

Sunday, May 31, Day 0: Welcome party at 6pm-

Monday, June 1, Day 1:

9:00 - 10:00 Registration

10:00-12:15 (135mins) Current view of planet formation + HL Tau

10:00 - 10:10 **Hasegawa, Yasuhiro** (NAOJ)
(SOC chair) Opening remark

10:10 - 10:55 **Adibekyan, Vardan** (Institute of Astrophysics and Space Sciences – CAUP)
(review) Heavy meteal rules: star-planet connection

10:55 - 11:40 **Kokubo, Eiichiro** (NAOJ)
(review) (theory of planet formation)

11:40 - 12:15 **Akiyama, Eiji** (NAOJ)
(keynote) (ALMA + HL Tau)

12:15 - 13:30 Lunch

13:30 - 15:30 (120mins) Disk formation in the context of star formation I

13:30 - 14:15 **Sakai, Nami** (RIKEN)
(review) (YSO (disk) observations)

14:15 - 15:00 **Li, Zhi-Yun** (University of Virginia)
(review) (disk formation, initial stage)

15:00 - 15:20 **Tsukamoto, Yusuke** (RIKEN)
(contributed) Two types of circumstellar disk evolution induced by the Hall term

15:20 - 15:30 Poster short talks
Matsumoto, Yuji (NAOJ)
Okada, Kazsushi (the University of Tokyo)
Ono, Tomohiro (Kyoto University)

15:20 - 16:00 Break

16:00 - 17:40 (100mins) Disk formation in the context of star formation II

16:00 - 16:45 **Machida, Masahiro** (Kyushu University)
(review) Disk Formation and Jet Driving in Collapsing Cloud Cores

16:45 - 17:05 **Kunitomo, Masanobu** (Nagoya University)
(contributed) Pre-main sequence evolution of low-mass stars: Effects of planet formation on stellar composition

17:05 - 17:40 Discussion (discussion leader: Nakamura, Fumitaka)

Tuesday, June 2, Day 2:

10:00 - 11:50 (110mins) Protoplanetary disks I

10:00 - 10:45 **Perez, Laura** (NRAO)
(review) (disk observations)

10:45 - 11:30 **Nomura, Hideko** (Tokyo Institute of Technology)
(review) Chemical Processes in Protoplanetary Disks

11:30 - 11:50 **Aikawa, Yuri** (University of Tsukuba)
(contributed) Analytical Formulas of Molecular Ion Abundances and N2H+ Ring in Protoplanetary Disks

11:50 - 12:10 **Fujii, Yuri** (ELSI)
(contributed) Non-equilibrium Ionization Degree and MRI in Protoplanetary Disks

12:10 - 13:30 Lunch

13:30 - 15:15 (105mins) Protoplanetary disks II

13:30 - 14:15 **Lyra, Wladimir** (Caltech/JPL)
(review) (gas dynamics in disks)

14:15 - 14:35 **Inutsuka, Shu-ichiro** (Nagoya University)
(contributed) The Origin and Fate of Rings in HL-Tau: Diversity of Planet Formation Mechanisms

14:35 - 14:55 **Sirono, Sin-iti** (Nagoya University)
(contributed) Collsion simulation of sintered icy aggregates

14:55 - 15:15 **Mori, Shoji** (Tokyo Institute of Technology)
(contributed) Electron Heating and Suppression of Magnetorotational Turbulence in Protoplanetary Disks

15:15 Conference photo

15:15 - 16:00 Break

16:00 - 17:40 (100mins) Protoplanetary disks III

16:00 - 16:45 **Dong, Ruobing** (UC Berkeley)
(review) Observational Signatures of Planets in Protoplanetary Disks

16:45 - 17:05 **Kanagawa, Kazuhiro** (Hokkaido University)
(contributed) Disk-planet interaction and gap formation induced by a giant planet in protoplanetary disks

17:05 - 17:40 Discussion (discussion leader: Fukagawa, Misato)

Wednesday, June 3, Day 3:

10:00 - 11:50 (110mins) Exoplanets: observations

10:00 - 10:35 **Kusakabe, Nobuhiko** (NAOJ)
(keynote) (SEEDS)

10:35 - 11:10 **Hirano, Teruyuki** (Tokyo Institute of Technology)
(keynote) (transit)

11:10 - 11:30 **Omiya, Masashi** (NAOJ)
(contributed) Occurrence rate of giant planets around massive stars

11:30 - 11:50 **Kamiaka, Shoya** (The university of Tokyo)
(contributed) Re-characterization a gravity-darkened and precessing planetary system PTFO 8-8695

11:50 - 13:30 Lunch

13:30 - 15:35 (125mins) Exoplanets: formation & evolution

13:30 - 13:50 **Kominami, Junko** (Tokyo Institute of Technology)
(contributed) High-resolution, global N-body similaton of planetary formation: Outward migration of a protoplanet

13:50 - 14:10 **Wakita, Shigeru** (NAOJ)
(contributed) Constraints on planetesimals implying from Itokawa dust particles

14:10 - 14:55 **Chatterjee, Sourav** (Northwestern University)
(review) (planetary dynamics)

14:55 - 15:15 **Rieder, Steven** (RIKEN)
(contributed) Impact of stellar encounters on planetary systems

15:15 - 15:35 **Kobayashi, Hiroshi** (Nagoya University)
(contributed) Planet Formation and Debris Disks

15:35 - 16:00 Break

16:00 - 17:40 (100mins) GI

16:00-16:45 **Basu, Shantanu** (University of Western Ontario)
(review) (GI)

16:45-17:05 **Takahashi, Sanemichi** (Tohoku University)
(contributed) The revised criterion for the self-gravitational fragmentation of protoplanetary disks

17:05-17:45 Discussion (discussion leader: Ida, Shigeru)

Thursday, June 4, Day 4:

10:00 - 11:55 (115mins) Planetary atmospheres + Future missions

10:00-10:45 **Lopez, Eric** (University of Edinburgh)
(review) (exoplanet atmospheres)

10:45-11:20 **Fukui, Akihiko** (NAOJ)
(keynote) (atmosphere observations)

11:20-11:55 **Narita, Norio** (NAOJ)
(keynote) (K2 + TESS)

11:55 - 13:30 Lunch

13:30 - 15:20 (110mins) Future mission + Astrobiology + concluding remark

13:30-14:05 **Sato, Bun'ei** (Tokyo Institute of Technology); Omiya, Masashi (NAOJ)
(keynote) (IRD)

14:05-14:50 **Tamura, Motohide** (NAOJ)
(review) Exoplanet Researches at the NINS Astrobiology Center (ABC)

14:50-15:20 **Hasegawa, Yasuhiro** (NAOJ)
(SOC chair) concluding remark

16:00 - 17:00 4D2U theater

18:00 - Banquet

Heavy meteal rules: star-planet connection

Vardan Adibekyan (IA-Porto)

Shortly after the discovery of the first extra-solar planet, many studies showed that stars hosting giant planets have significant metallicity excess when compared with the stars without known giant planets. Curiously, this strong metallicity-giant planet correlation is not found for the lowest mass planets. On the other hand studies aimed to clarify whether the planet-hosting stars are different from stars without planets in their content of individual elements (other than iron) yielded contradictory results. I will review the most recent results by discussing the importance of individual light and heavy elements for the formation and evolution of planets. I will also present the latest results about the role of metallicity on the architecture of planets.

A Standard Scenario for Formation of Planetary Systems

Eiichiro Kokubo (NAOJ)

In the standard scenario for formation of planetary systems, a planetary system forms from a protoplanetary disk around a star. A protoplanetary disk is a by-product of star formation and consists of gas and dust. The formation scenario can be divided into three stages: (1) formation of planetesimals from dust, (2) formation of protoplanets from planetesimals, and (3) formation of planets from protoplanets. In stage (1), planetesimals form from dust in the protoplanetary disk through coagulation of dust grains or gravitational instability of a dust layer. Planetesimals are small building blocks of solid planets. Planetesimals grow by mutual collisions to protoplanets or planetary embryos in stage (2). The final stage (3) depends on a type of planets. The final stage of terrestrial planet formation is giant impacts among protoplanets while sweeping residual planetesimals. Large protoplanets (cores) capture a massive gas envelope by self-gravity to become gas giant planets. In the present talk, I review the basic elementary processes of planet formation and discuss the unsolved problems.

ALMA Capabilities and Science Review of HL Tau

Eiji Akiyama (NAOJ)

ALMA has provided an unprecedented level of insight into the structure and evolution of gas and dust in circumstellar disks. Observation with a preliminary ALMA long baseline array, consisting of 23 antennas with baselines between 0.2 and 15 km, has now produced remarkable science outputs. In this talk, I will review some highlights of ALMA updated capabilities and science result with particular emphasis on the structural features of dust component in protoplanetary disk around HL Tau, one of selected as science verification source in ALMA long baseline campaign. Finally, I will show the recent NIR observation of the protoplanetary disk around TW Hya to contrast with the disk structure of HL Tau.

Disk Formation Traced by Chemistry

Nami Sakai (RIKEN)

Understanding formation processes of a rotationally supported disk (Keplerian disk) around a newly formed protostar is an primary target for star formation studies. Although observations of disk structures have extensively been carried out for Class 0 and Class I protostars, it is still controversial when and how the disk structures are formed. Nevertheless, important progresses have been made during these years. With the ALMA Cycle 0 observation, the centrifugal barrier of the infalling-rotating envelope and the associated drastic chemical change there have been found in the low-mass Class 0 protostellar source L1527. CCH, c-C3H2, and CS preferentially exists outward of the centrifugal barrier of 100 AU, while SO only exists in a ring structure around the centrifugal barrier. Since the centrifugal barrier is caused by fundamental physics, i.e. angular momentum conservation, it should also be seen in other protostars. In fact, the SO ring is found in L1489IRS (Yen et al. 2014). The current understanding on formation of the centrifugal barrier and its relation to formation of the Keplerian disk will be discussed in the presentation.

Theory of Protostellar Disk Fromation

Zhi-Yun Li (University of Virginia)

Disk formation, once thought to be a simple consequence of the conservation of angular momentum during the hydrodynamic core collapse, is far more subtle in magnetized gas. In this case, the rotation can be strongly magnetically braked. Indeed, both analytic arguments and numerical simulations have shown that disk formation is suppressed in strict ideal MHD for the observed level of core magnetization. I will discuss the physical reason for this so-called "magnetic braking catastrophe," and review possible resolutions to this problem that have been proposed so far, including non-ideal MHD effects, misalignment between the magnetic field and rotation axis, and especially turbulence.

Two types of circumstellar disk evolution induced by the Hall term

Yusuke Tsukamoto (RIKEN)

We show that the Hall term, which is the least studied non-ideal magnetohydrodynamical effect, significantly affects the formation of circumstellar disks. In our simulations, when the rotation vector and the magnetic field of the host cloud core were anti-parallel, a large ($r \sim 20$ AU) and massive disk was formed almost simultaneously with the protostar formation; however, in the parallel case, only a very small disk with a size of $r \lesssim 1$ AU was formed. This suggests that the initial size of the circumstellar disk quantitatively differs depending on the parallel or anti-parallel property of the rotation vector and the magnetic field of the host cloud core. The parallel and anti-parallel property does not changes in time and may last in subsequent evolution. Recent observations of Class 0 young stellar objects (YSOs) seem to support our results. In the large and massive disk, the magnetic flux is largely removed due to the magnetic diffusion, and the magnetic braking becomes unimportant. Alternatively, gravitation instability plays an important role for the angular momentum transfer in the disk. We also show that an envelope with a size of $r > 100$ AU which is anti-rotating against the disk appears in the anti-parallel case, and this anti-rotating envelope may be observable.

The eccentricities and inclinations of planets formed through in situ accretion of protoplanets

Yuji Matsumoto (NAOJ)

Most of super-Earths detected by the radial velocity method have significantly smaller eccentricities than the eccentricities corresponding to velocity dispersion equal to their surface escape velocity (escape eccentricities). If they are formed through in situ accretion in gas free environment, it is considered that the eccentricities of planets are comparable to escape eccentricities by mutual scattering between protoplanets. However, the eccentricity evolution in the in situ accretion model is not studied in detail. We have examined the eccentricity of formed super-Earth in the in situ accretion model through N-body simulations. At first, we investigated processes of the eccentricity evolution in the in situ accretion model of protoplanets. We found that the eccentricities of protoplanets increase by mutual scatterings and they are damped through collisions between protoplanets. In the giant impact stage, protoplanets collide just after the orbital crossing, and this is when the apocenter of the inner protoplanet is on the pericenter of the outer planet. When protoplanets collide in this configuration, since the random velocities are canceled, the eccentricity of the merged planets is significantly smaller than those of colliding bodies. Orbital inclinations are also damped by the same mechanism. These damping processes depend on initial eccentricities and inclinations. We also investigated influence of initial random velocities of the eccentricities of formed planet through accretion of protoplanets. When we change initial eccentricities of protoplanets, the resultant planets are similar. On the other hand, the initial inclinations changed the formed planets. When we start calculations with more inclined protoplanets, the final numbers of planets are smaller, and the final angular momentum deficits are larger.

Subaru/COMICS multicolor mid-infrared imaging of the transitional disk source Oph IRS 48

Kazsushi Okada (the University of Tokyo)

In previous researches, spatially-resolved near-IR, mid-IR and submillimeter observations revealed the asymmetry in the circumstellar disk of Herbig Ae Star Oph IRS 48. In particular, ALMA 0.44mm continuum image shows highly localized emission. It is suggested that these structures are caused by one or more planets in the disk.

In the previous MIR observation with VLT/VISIR, centrally peaked images are obtained in 11.9 μm, while the 18.7 μm image shows an inclined ring-shaped thermal structure with a gap in the center (Geer+2007).

Here we show new images of Oph IRS 48 at 12.8 μm, 17.7 μm, and 24.5 μm using Subaru/COMICS. With these multiwavelength data set, we can derive the emitting dust temperature and discuss the structure of the disk in more detail.

Hydrodynamic Instability in the Similarity Solution of Viscous Accretion Disks

Tomohiro Ono (Kyoto University)

Protoplanetary disks are the birthplaces of planets. Studying structures and evolutions of protoplanetary disks is important for planetary science. It is generally said that the magneto-hydrodynamic instability is a dominant mechanism in disk evolution. However, when we consider the region with steep pressure gradient such as a density bump or gap in disks, or an edge of disks, hydrodynamic instability can be important.

Protoplanetary disks evolve via turbulent viscosity, and their evolution is well represented by the model of Lynden-Bell & Pringle (1974). In this model, the density profile of disks is analytically derived as the similarity solution. The similarity solution has an exponential cut off in surface density at the outermost region, and pressure gradient gets steep in this region. For that reason, we investigate the stability of the similarity solution for hydrodynamic instability.

We first examine the stability of the similarity solution for rotational instability. Rotational instability is local hydrodynamic axisymmetric instability. We find that the similarity solution is unstable against rotational instability (Ono et al., 2014). We also investigate the stability of the similarity solution for Rossby wave instability. Rossby wave instability is global hydrodynamic non-axisymmetric instability. We perform linear perturbation analyses using the same methods as Li et al. (2000). In our poster, we will report these results.

Disk Formation and Jet Driving in Collapsing Cloud Cores

Masahiro Machida (Kyushu University)

In the star formation process, the magnetic field and its dissipation process play an important role. The magnetic field effectively dissipates and the rotation-supported disk forms inside the first core, while the magnetic field coupled with the neutral gas again around the protostar and can drive high-velocity jet. Non-axisymmetric structure develops in the disk due to gravitational instability and induces episodic accretion onto the protostar. With the non-steady accretion, high-velocity jets show significant time variability. I will talk about the disk formation and jet driving processes investigated by numerical simulations.

Pre-main sequence evolution of low-mass stars: Effects of planet formation on stellar composition

Masanobu Kunitomo (Nagoya University)

Recent spectroscopic observations have revealed that the solar surface composition is peculiar compared to most of solar-type stars. Refractory elements are scarce in the solar surface and this feature would be related to planet formation process and pre-main sequence (PMS) evolution. One possible scenario is that rocky planet formation removes them from accreting materials in the protosolar nebula and the accretion pollutes the solar surface composition. However, if PMS stars are fully convective as in classic studies, the effect of pollution is negligible.

In this study, we revisit the PMS evolution with the disk accretion, which is suggested by recent multidimensional hydrodynamic simulations. Since the entropy of accreting materials in the disk accretion can be much lower than that of the spherically symmetric accretion assumed in classical studies, the internal structure of PMS stars in the disk accretion can be different.

We calculated the PMS evolution using a one-dimensional stellar evolution code MESA with modeling the entropy of accreting materials. We found that the PMS evolution is greatly affected by the accreting material's entropy and the deuterium content. The surface convective zone (CZ) of PMS stars formed by the low-entropy accretion can become shallow at 3 Myr, which is one order of magnitude faster than the classical theory. Since this is faster than the typical disk lifetime (~6 Myr), we conclude that the stellar surface composition can be affected by the formation of rocky objects (e.g., planetesimals, terrestrial planets) in protoplanetary disks, if the accreting materials' entropy and the deuterium content are low. Finally, we discuss that the shrink of CZ is also important for the orbital evolution of close-in planets via tidal interaction and the updated PMS evolutionary tracks have a potential to change the estimated stellar age and mass.

Protoplanetary Disk Observations at Radio Wavelengths

Laura Perez (NRAO)

Protoplanetary disks surrounding young stars are the birthplaces of planets. With the advent of sensitive observations and together with developments in theory, our field is making rapid progress in understanding the process of planet formation. In this review, I will describe how the evolution of protoplanetary disks is traced by observations of their dust and gas components, and I will present recent observational results that elucidate key aspects of the planet formation process, particularly focusing on observations at the sub-mm, millimeter, and centimeter-wave regime. This wavelength range is already providing a plethora of new results, thanks to improvements in sensitivity brought forward by VLA and ALMA.

Chemical Processes in Protoplanetary Disks

Hideko Nomura (Tokyo Institute of Technology)

Thanks to recent development of infrared and radio observations, it has become possible to detect various kinds of molecular lines from protoplanetary disks. These lines give us information of the physical and chemical structure of the disks. Statistical studies of molecular line observations from disks will help us to understand the origin of the diversity in exoplanetary systems. In this talk I will review recent observations of molecular lines and chemical modelling of protoplanetary disks, focusing on some topics related with planet formation process and chemical evolution. For example, observations of molecular lines are useful to understand gas motion in the disks, which affects chemistry and line spectrum of molecules. Also they can be a tracer of ionization degree as an indicator of magnetorotational instability in the disks. Studies of environmental effects on chemistry in disks, such as inner holes and irradiation from nearby massive stars, will be useful for analysing varieties of disks which will lead to varieties of planetary systems formed in the disks. Also, understanding distribution and formation processes of water and organic molecules in the disks will be practical to understand the origin of materials in our Solar System and other planetary systems.

Analytical Formulas of Molecular Ion Abundances and N_2H^+ Ring in Protoplanetary Disks

Yuri Aikawa (University of Tsukuba)

We investigate the chemistry of ion molecules in protoplanetary disks, motivated by the detection of N_2H^+ ring around TW Hya. While the ring inner radius coincides with the CO snow line, it is not apparent why N_2H^+ is abundant outside the CO snow line in spite of the similar sublimation temperatures of CO and N_2. Using the full gas-grain network model, we reproduced the N_2H^+ ring in a disk model with millimeter grains. The chemical conversion of CO and N_2 to less volatile species (sink effect hereinafter) is found to affect the N_2H^+ distribution. Since the efficiency of the sink depends on various parameters which are not well constrained, we also constructed the no-sink model; the total (gas and ice) CO and N_2 abundances are set constant, and their gaseous abundances are given by the balance between adsorption and desorption. Abundances of molecular ions in the no-sink model are calculated by analytical formulas, which are derived by analyzing the full-network model. The N_2H^+ ring is reproduced by the no-sink model, as well. The 2D (R-Z) distribution of N_2H^+, however, is different among the full-network model and no-sink model. The column density of N_2H^+ in the no-sink model depends sensitively on the desorption rate of CO and N_2, and the flux of cosmic ray. We also found that N_2H^+ abundance can peak at the temperature slightly below the CO sublimation, even if the desorption energies of CO and N_2 are the same.

Non-equilibrium Ionization Degree and MRI in Protoplanetary Disks

Yuri Fujii (ELSI)

The magnetorotational instability (MRI) is thought to be the main mechanism of angular momentum transport in protoplanetary disks. Also, a disk wind caused by an MRI turbulence is expected to play important roles in disk evolution. When a disk has plenty of dust grains, in general, the timescale of chemical reactions governing MHD effects is much smaller than the dynamical timescale, so we can use the equilibrium ionization degree for MHD simulations. However, when the abundance of tiny dust grains is small or near the disk surface, the chemical timescale could be longer than the dynamical timescale. Thus, it is important to consider the non-equilibrium ionization degree in those cases.

We implemented the calculation scheme for time-dependent ionization degree that is developed by Fujii et al., (2011) into the Athena MHD code and performed three dimensional local shearing box simulations. When the disk has mostly dissipated, we find that the ionization degree in the surface layer becomes smaller than the equilibrium solution. This is because the disk wind lifts the poorly ionized gas in the lower layers to the surface layers. This effect may be important in the MHD and chemical evolution of protoplanetary disks.

Gas dynamics in disks: planet signatures and dynamical instabilities.

Wladimir Lyra (Caltech/JPL)

Recently, high angular resolution images obtained with the Combined Array for Research in Millimeter-wave Astronomy (CARMA) and with the Atacama Large Millimeter Array (ALMA) have become available, showing a plethora of puzzling asymmetries in the outer reaches of protoplanetary disks that beg for explanation. The presence of planets is a particularly attractive interpretation for explaining these asymmetries, since they generally match the range of structures predicted by hydrodynamical models of planet-disk interactions, namely, gaps, vortices and spirals. If that is indeed the case, the observed asymmetries would provide a tantalizing laboratory to study planet-disk interaction and planet formation. On the other hand, circumstellar disks are home to a myriad of hydrodynamical processes, which bring about turbulence and structure formation, generally also matching those predicted by the presence of planets. In this talk I will review the state of the art and recent advances in gas dynamics in disks with and without planets, and examine the observational evidence under the light of our current theoretical understanding to help decide between the competing interpretations.

The Origin and Fate of Rings in HL-Tau: Diversity of Planet Formation Mechanisms

Shu-ichiro Inutsuka (Nagoya University)

Protoplanetary disks are supposed to be the sites of planet formation, and thus, understanding of the evolution of the disk is crucial in understanding of the planet formation. Recent ALMA observation revealed a remarkable multiple ring structure in a protoplanetary disk around HL Tau. Prior to this observation, Takahashi & Inutsuka (2014) proposed a possible formation of multiple ring structures by secular gravitational instability in the case of weak turbulent diffusion. This talk describes the condition for this to occur in detail and discuss the further evolution of the rings. A possible scenario for the formation of rocky objects at outer regions of the disks is outlined and contrasted with the other formation scenarios.

[Reference]

"Two-component Secular Gravitational Instability in a Protoplanetary Disk: A Possible Mechanism for Creating Ring-like Structures"
Sanemichi Z. Takahashi & Shu-ichiro Inutsuka (2014)
The Astrophysical Journal Vol. 794, 55 (arXiv:1312.6870)

Collsion simulation of sintered icy aggregates

Sin-iti Sirono (Nagoya University)

In the outer part of a protoplanetary nebula, the main component of solid is ice. Major species of ices are H2O, CO, CO2, CH4 and NH3. Grain aggregates are formed from these ices and cores of Jovian planets are eventually formed from the icy aggregates. Because the ices are volatile, slight temperature increase is enough to lead to sublimation. Sublimed ice molecules preferentially recondense on the neck between adjacent grains. This process is called sintering. Mechanical properties of an icy grain aggregate substantially changes due to condensed ice molecules. Without sintering, two icy grains are connected by surface adhesion. In this case, a grain can freely roll on another grain without breakup of the connection between grains. On the other hand, free rotation of a grain is hindered by the condensed molecules, and breakup of a neck is required to rotate a grain.

We performed 2-D numerical simulations of collisions between sintered grain aggregates and found that the critical collision velocity, below which the growth of an aggregate is possible, decreases to 20 m/s from 50 m/s without sintering. This decrease can be attributed to the change of the deformation mode of an aggregate. Ductile deformation of an aggregate is possible because of the free rotation of grains. For the sintered case, the deformation becomes brittle, leading to easy disruption of an aggregate.

Sublimation temperature depends on the ice species. Therefore, there are several distinct sintering regions in a protoplanetary nebula. Necks grow in the sintering regions due to sublimation + condensation of corresponding icy spices. This simulation result indicates that there are several regions inside which the growth of grain aggregate is difficult and aggregate growth is only possible outside these regions.

Electron Heating and Suppression of Magnetorotational Turbulence in Protoplanetary Disks

Shoji Mori (Tokyo Institute of Technology)

Turbulence plays an essential role in both the disk evolution and dust dynamics. One of promising mechanism for generating vigorous turbulence is magnetorotational instability (MRI) whose activity depends largely on the ionization fraction of the disk gas. It has recently been shown that the electric field induced by the MRI turbulence can heat up electrons (electron heating) and thereby affect the ionization balance. Especially, in a disk where dust grains are abundant, the electron heating decreases the electron abundance and hence prevents further growth of MRI.

We investigate the actual distribution of the region in protoplanetary disks for the electron heating to occur. We find that the "e-heating zone," the region where the electron heating limits the saturation of the MRI, extends out to 80 AU in the minimum-mass solar nebula with abundant submicron-sized grains. This region is considerably larger than the conventional dead zone whose radius is ~ 20 AU in the same disk model. We also estimate the MRI turbulent strength in the e-heating zone and find that the strength at the midplane is suppressed down to ~ 10^{-5} and 10^{-3} at the inner and outer edge of the e-heating zone, respectively. This implies that the MRI should be "virtually dead" in the e-heating zone. We will also discuss the possibility of secular gravitational instability caused by the suppression of the MRI turbulence, which may explain the multiple stripe structure observed in HL Tau.

Observational Signatures of Planets in Protoplanetary Disks

Robin Dong (UC Berkeley)

It has been suggested that the spiral arms, gaps, and cavities recently discovered in protoplanetary disks are produced by planets. To explore this scenario, we combine hydrodynamical calculations with three-dimensional Monte Carlo Radiative Transfer simulations to study the observational signatures of features produced by planets, as well as disk activities, to check if they are consistent with observations. We find that common gap opened by multiple planets can explain the observations of transitional disks. Both the contrast ratio of the gaps and the wavelength dependence of the gap sizes are broadly consistent with data. Planet-induced spiral density waves, however, do not appear to resemble the morphology of the directly imaged spiral arms at NIR wavelengths, and observations call for alternative explanations. Finally, inspired by the recent ALMA release of the image of the HL Tau disk, we show that multiple narrow gaps, well separated by bright rings, can be opened by 0.2MJ planets soon after their formation in a relatively massive disk.

Disk-planet interaction and gap formation induced by a giant planet in protoplanetary disks

Kazuhiro Kanagawa (Hokkaido University)

A large planet is able to create a density gap along the planet's orbit in protoplanetary disks, due to the disk-planet interaction. This gap formation significantly influences not only the orbital evolution of planet, e.g., transition from type I to slower type II migration, but also the mass growth of the planet. In addition, the gap formation induced by a giant planet possibly explains the formation of the so-called pre-transition disc with a ring gap. Hence, it is important to determine the relation between the planet mass and the gap depth and width.

According to our analysis with the one-dimensional model, the propagation and damping of the density wave excited by the planet is closely related to the gap depths and widths (Kanagawa et al 2015). We performed a numerical simulation for a disk structure with a planet using FARGO, which is well-known hydrodynamic code. Our results of the simulation indicate that a disk-planet interaction in the case of the large planet (such as Jupiter) is quantitatively different from the interaction in the case of the small planet. In the large planet case, low-mode interactions (in particular m=1 and 2) become larger than high-mode interactions, whereas the high-mode interactions dominate the interaction in the small planet case. The waves excited by a giant planet were thought to be instantly damped due to the non-linear dissipation. However, as the same as the disk-planet interaction, we find that in the large planet case, the low-mode waves becomes stronger than high-mode waves and are able to carry an amount of angular momentum to an outside of a gap region. This result might indicate a wide-gap formation induced by a planet.

In this talk, I will illustrate our results and discuss the disk-planet interaction and wave propagation with the deep gap created by the giant planet. I will also talk about observational applications of our results.

SEEDS : Review of direct imaging explorations of exoplanets/disks with Subaru

Nobuhiko Kusakabe (NAOJ)

SEEDS, Strategic Explorations of Exoplanets and Disks with Subaru, is the first "Subaru Strategic Program". We have 120 nights from 2009 and finished in January 2015. This project aims are (1) NIR direct imaging and census of giant planets in the outer regions (10-100AU) around about 500 solar-type and massive stars, (2) Exploring protoplanetary disks and debris disks for the origin of their diversity and evolution at the same radial regions, (3) Direct linking between planets and protoplanetary disks. In this talk, I will review mainly direct imaging of the giant planets result.

Probing the Dynamical History of Exoplanets: Spectroscopic Observations of Transiting Systems

Teruyuki Hirano (Tokyo Institute of Technology)

The origin of close-in giant planets is an enduring problem in the exoplanetary science. The key process is the planet “migration” from their birth-places. Many migration scenarios have been proposed and investigated both observationally and theoretically. One promising observational approach to probe their dynamical history is to measure the obliquity of planet-hosting stars with respect to planetary orbits. This is because different migration scenarios predict different outcomes for the stellar obliquity, and its observations in the past have revealed that there are likely more than one migration channel that close-in giant planets have experienced (e.g., Hebrard et al. 2010, Hirano et al. 2012). With the growing number of systems characterized in term of stellar obliquity, our understanding on the dynamical history of exoplanets has made significant progress. In this talk, I will present some of the key observational techniques to measure the stellar obliquity, and review their observational status.

Occurrence rate of giant planets around massive stars

Masashi Omiya (NAOJ)

The occurrence rate of giant planets would depend on the stellar mass. In particular, only a few giant planets are found around stars with masses of more than 3 solar masses by the radial velocity method and the rate around massive stars seems to be low. However, the lack of giant planets may be caused by an observational bias because of small number of sample stars in radial velocity surveys. To clarify the stellar mass dependence of planetary systems and frequency around massive stars, we have been carry out a radial velocity survey of giant stars with stellar masses of more than 3 solar masses. Based on our survey over 3 years and results of other radial velocity surveys, we estimated occurrence rate of giant planets around massive stars and discuss a relationship between the stellar mass and the occurrence rate of giant planets.

Re-characterization a gravity-darkened and precessing planetary system PTFO 8-8695

Shoya Kamiaka (The university of Tokyo)

We reanalyse the time-variable lightcurves of the transiting exoplanetary system PTFO 8-8695, in which a planet of 3 to 4 Jupiter mass orbits around a rapidly rotating pre-main-sequence star.
Both the planetary orbital period of 0.45 days and the stellar spin period less than 0.67 days are unusually short, which makes PTFO 8-8695 an ideal system to check the model of gravity darkening and spin-orbit nodal precession.
The previous analysis of PTFO 8-8695 assumed that the stellar spin and planetary orbital periods are the same, but this condition is unlikely to hold in the actual system from the viewpoint of the long-term stability of the system.
Therefore we extend the analysis by discarding the spin-orbit synchronous condition, and find three different classes of solutions roughly corresponding to the spin-orbit nodal precession period of 200, 470, and 830 days that reproduce the transit lightcurves observed in 2009 and 2010.
We compare the predicted lightcurves of the three solutions against the photometry data of a few percent accuracy observed at Koyama Astronomical Observatory in 2014 and 2015, and find that the solution with the 200 precession period is preferred even though preliminary.
Future prospect and advantages of this methodology to characterize the transiting exoplanetary systems are also briefly discussed.

High-resolution, global N-body similaton of planetary formation: Outward migration of a protoplanet

Junko Kominami (Tokyo Institute of Technology)

We performed N-body simulations of planetesimal disk ranging from 0.7 AU - 4.0 AU which includes the ice line. Runaway bodies form at the ice line first, where the solid surface density increases, as well as at the inner edge. It is likely that the planetesimals around the runaway bodies accrete and a gap in the planetesimal disk forms. We let the runaway bodies to grow to 0.1 M_Earth and restarted the simulations. Full gravity calculation is included in the simulations. The runaway body moves outward trasfering angular momentum of the planetesimals right outside the gap to its inside causing planetesimal driven migration. The viscous stirring among the planetesimals increases the random velocity of the planetesimals which the protoplanet encounters. The increase of the random velocity stops the migration. However, if we consider more realistic model which includes gas drag, the random velocity would decrease and the migration would continue. We present a model that forms the gas giant cores around the ice line and make them migrate outward.

Constraints on planetesimals implying from Itokawa dust particles

Shigeru Wakita (NAOJ)

Planetesimals are primordial bodies in the solar nebula, and the formation process of them has not been established. We performed the thermal modelling of the parent asteroid of Itokawa, which would be originally a planetesimal. The mineralogic studies of Itokawa dust particles revealed that those dust particles resemble LL5 and/or LL6 type ordinary chondrites (Nakamura et al. 2011; Yurimoto et al. 2011). There are constraints from these particles: they experienced thermal metamorphism at a peak temperature of 800 degree Celsius but did not experienced > 1000 degree Celsius. The radiogenic and isotopic studies indicate that the parent asteroid of Itokawa kept at 700 degree Celsius or higher at 7.6 Myr after Ca-Al rich inclusions (CAI) formation. We assumed the parent body of Itokawa is the instantaneously-accreted spherically symmetric one and the physical properties of the body are the same of those of LL6 chondrites. The one-dimensional heat conduction equations were solved numerically using a finite difference method, with a main heat source of the decay energy of short-lived radionuclide (aluminum-26). We performed numerical simulations for the parent bodies which have variable sizes and accretion times. Our results showed that the parent bodies of Itokawa would have been larger than 20 km in radius at least to satisfy evidences from dust particles of Itokawa. The current Itokawa, which size is about 0.5 km, originated in larger bodies, which was once disrupted and reaccumulated. We also found that the parent bodies of Itokawa accreted at a period between 1.9 and 2.2 Myr after CAI formation. These values of Itokawa parent asteroids would constrain the size and accretion time of planetesimals.

Dynamical Evolution of Planetary Systems:

Sourav Chatterjee (Northwestern University)

Following formation and gas disk dispersion, planetary systems can evolve through several dynamical processes over billion year timescales, the age of typical planet host stars. These processes alter the orbital properties of these planets. Under certain configurations, dynamical processing of orbits may also result in changes in the planets' structural properties via tidal evolution and physical collisions. In my talk I will review these processes with a focus on specific classes of observed planetary systems, different from each other through their orbital properties, and how dynamical processes could have created them.

Impact of stellar encounters on planetary systems

Steven Rieder (RIKEN)

Stars and planets generally form in large groups: star clusters and associations. In this birth environment, the density of stars is much larger than in the later stages of a star's life, when the cluster has evaporated. This also results in a much higher chance of encounters between stars.

When in such an encounter the distance between stars is small enough, it can have a strong impact on planets and circumstellar disks: possibly leading to migration of planets or even the disruption of the system. To quantify the importance of encounters on the final appearance of planetary systems, we need to study the effect of stellar encounters of various parameters (mass ratio, closest approach). Also, we need to know how often such encounters occur, by investigating different birth conditions for the stars (e.g. number of stars in the star cluster, initial density and survival time of the cluster).

I study these aspects by means of simulations. The Astrophysical Multipurpose Software Environment AMUSE (www.amusecode.org) can combine different physical aspects (e.g. gravity, gas dynamics and stellar evolution) over the different physical scales relevant to this problem. In my current model, I include gravity on the scale of planetary systems, star clusters and the galaxy, as well as stellar mass loss.

Planet Formation and Debris Disks

Hiroshi Kobayashi (Nagoya University)

The circumstellar disks observed around several hundred main sequence stars are mainly gas poor, faint disks, which are called debris disks. They are mostly revealed by excess infrared emission around the stars. In a planetesimal disc, collisional coagulation of kilometer or larger planetesimals produces a small number of large bodies, oligarchies. Leftover planetesimals are strongly stirred by oligarchies, resulting in the violent collisions between planetesimals. The collisional fragmentation of planetesimals may form a debris disk. We aim to determine the properties of the underlying planetesimals in debris disks by numerically modelling the coagulation and fragmentation of planetesimal populations. We find that a radially narrow planetesimal disc is most likely to result in a debris disk that can explain the trend of observed infrared excesses of debris disks around G-type stars, for which planet formation occurs only before 100 million years. Planetesimal disks with underlying planetesimals of radii ~100 km at ~ 30 AU most readily explain the Spitzer Space Telescope 24 and 70 micron fluxes from debris disks around G-type stars.

Gravitational Instability in Early Disk Evolution and the Formation of Clumps, Companions, and Free Floating Objects

Basu Shantanu (University of Western Ontario)

I review a series of works that solve the problem of protostellar disk formation and evolution self-consistently from the collapse of a prestellar core. At early times the disk may be massive and driven episodically into gravitational instability due to infall from the parent cloud core.
Instability leads to the formation of gaseous clumps, essentially first cores, that can continue to accrete matter but generally also migrate inward. This leads to a migrating embryo scenario for early disk evolution. Most clumps migrate to the center and are sheared apart, leading to luminosity bursts from the central young stellar object. However, some clumps can carve out a gap in the disk and survive in stable orbits. Others may be ejected from the system through interaction with other clumps. I also discuss observability of clumps in disks with ALMA.

The revised criterion for the self-gravitational fragmentation of protoplanetary disks

Sanemichi Takahashi (Tohoku University)

Recent direct-imaging observations of planetary-mass objects far away from the central stars are supposed to be emphasizing the importance of the self-gravitational fragmentation in the early evolutionary phase of protoplanetary disks. This process may provide a formation mechanism of binary stars, brown dwarfs, and gaseous giant planets. Thus it is important to investigate the detailed condition for the fragmentation of the protoplanetary disks. So far, the condition for the fragmentation has been thought that the disk cooling timescale is comparable to its dynamical timescale. Gammie (2001) firstly showed this condition, and many subsequent works (e.g., Rice et al. 2005, Stamatellos and Whitworth 2009) seem to advocate this fragmentation condition. Since this condition is simple and useful, many theoretical works (e.g. Rafikov 2005) on the evolution of the protoplanetary disks have used this condition.

However, there are the several works that seem to contradict the fragmentation criterion. For example, Kratter et al. (2010) or Tsukamoto et al. (2015) shows the cases in which the fragmentation does not occur even if the cooling time is small enough. On the other hand, Machida et al. (2010) shows that the fragmentation can occur even when the cooling is inefficient. Therefore, the simple cooling criterion for the disk fragmentation is not reliable for the realistic condition for the fragmentation of protoplanetary disks.

In this work, using the two-dimensional numerical simulation and the linear stability analysis of the spiral arms, we propose a new, reliable condition for the fragmentation of the protoplanetary disks. We perform two-dimensional numerical simulations that take into account the effect of the irradiation of the central star and radiation cooling of the disk, and precisely investigate the structure of the spiral arms formed in the protoplanetary disks. As a result, we find that the Toomre's Q parameter "in the spiral arms", Q_spiral is the important parameter for the fragmentation. The new condition for the fragmentation is that ""the spiral arm fragments when Q_spiral < 0.6 is satisfied in the region two times as long as the width of the spiral arms"".

We confirmed this fragmentation condition found in the numerical simulations can be obtained from the linear stability analysis of the self-gravitating spiral arms. We will discuss the relation between our new criterion and the previous cooling criterion and clarify the shortage of the previous cooling criterion

Understanding Kepler's Super-Earth's & Sub-Neptunes

Eric Lopez (University of Edinburgh)

Recent surveys have uncovered a large new population of super-Earth and sub-Neptune sized planets. Understanding these planets poses a fundamental test for models of planet formation and evolution. I will review the possible origins and compositions of these planets and the constraints that can be provided by models of planetary structure and evolution. I will discuss the transition between rocky super-Earths and gaseous sub-Neptunes, the possible compositions of the sub-Neptunes, and the role that atmospheric photo-evaporation plays in sculpting these populations.

Atmospheric Study of Exoplanets by Transmission Spectroscopy

Akihiko Fukui (NAOJ)

Atmospheric composition of exoplanets can provide an important clue to the planetary formation histories. Planetary atmospheres can be probed by means of transmission spectroscopy, which measures the transit depth of a transiting planet as a function of wavelength. So far, several atoms (Na, K) and molecules (H2O, CO) have been detected by this technique in a number of exoplanets. On the other hand, flat or smooth transmission spectra have also been observed in some planets, which indicates that these planets are probably covered by a cloud or haze layer. Studying the nature of cloudy and hazy atmosphere has become an important topic aiming at detecting the molecular features buried under the clouds and haze and understanding the condition of cloud/haze formation. In this keynote talk, I review the atmospheric study of transiting planets focusing on the latest results including our works.

Future Missions of Transit Surveys and Characterizations

Norio Narita (NAOJ)

Thanks to previous planet surveys, we have learned that there are diverse planets. Especially NASA's Kepler mission discovered thousands of planet candidates and revealed that small sized planets are quite common in the Universe. One weakness of the Kepler mission was it mainly targeted stars too far away for further characterization studies. Future transit survey missions thus aim to find transiting planets orbiting solar neighbor stars. Such planets are suitable for further characterization studies, such as atmospheres, orbits, and so on. One already ongoing transit survey mission is K2, which is 2nd epoch mission of the Kepler. And the next flagship mission will be Transiting Planet Survey Satellite (TESS), led by MIT and NASA. Ground-based facilities are preparing various instruments for follow-up observations for those planets which will be discovered by K2 and TESS. In this talk, I will summarize the future transit survey missions and ongoing efforts for ground-based follow-up observations.

Infrared Doppler planet search for Earth-mass planets

Bun'ei Sato (Tokyo Institute of Technology); Masashi Omiya (NAOJ)

To detect Earth-mass planets using the Doppler method is expected as a future step for understanding the planetary systems and planet formation mechanisms in the universe. However, because of tiny signal (0.1m/s) caused by Earth-mass planets around solar-type stars compared with the stellar noise (~1m/s) in radial velocity variations, it is very difficult to confirm the existence of such planets using optical Doppler instruments with current technologies. On the other hand, new infrared Doppler instruments optimized to precise radial velocity measurements have been planed and constructed to search for Earth-mass planets around low-mass stars. The infrared Doppler planet searches using the infrared instruments are able to perform more efficient radial velocity surveys of M-type main sequence stars and thus choose very low-mass stars as targets of the their observations, and also can reduce the stellar noise in the radial velocity variations. Moreover, low-mass stars are attractive targets to detect Earth-mass planets in the habitable zone, because the habitable zone of low-mass stars is located at close-in orbits and Doppler signals from the planets are relatively large (>1m/s). Thus, infrared Doppler planet searches have useful and interesting advantages for detecting Earth-mass planets.

On these background, we are planning to conduct a new planet search of low-mass stars using a new infraRed Doppler instrument for the Subaru telescope (IRD). The IRD is composed of a very stable near-infrared high dispersion spectrograph and a precise wavelength (Doppler-shift) calibrator using a laser-frequency comb. IRD is installed on the telescope in 2015 and observations of our planet search using IRD will be started in 2016. The main goals of the planet search are to detect Earth-mass planets in the habitable zone and to understand statistical properties, formation and habitability of extrasolar planetary systems around low-mass stars.

Based on our suitable observing plan and results of theoretical population synthesis, we performed a observing simulation of our planet search and estimated expected numbers of detectable planets in our observation. For a five year observation, we expect discoveries of more than 50 planets including more than 30 planets with 1-5 Earth-masses and ten Earth-like planets in the habitable zone. In this talk, we introduce IRD, our observing plan and simulation, and also expected scientific results to all participants.

Exoplanet Researches at the NINS Astrobiology Center (ABC)

Motohide Tamura (UTokyo & NAOJ)

I will introduce the roles and researches at the Astrobiology Center of NINS, which has been just founded in this April.

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