Review of observations of protoplanetary disks with ALMA

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The Atacama Large Millimeter/Submillimeter Array (ALMA) starated its science operation in 2011. Thanks to its high sensitivity and mapping capability, ALMA has revealed detailed structure of nearby protoplanetary disks, providing us with new informations about the formation of a planetary system in general. In particular, long-baseline campaign observations of HL Tau with ~3au resolution revealed ring-gap structure in the protoplanetary disk, demonstrating that ALMA will be a powerful tool for exploring disks around young stars. Possible origins of the ring-gap struture revealed in the disk associated with HL Tau will be presented in this talk. Observations of disks with deficient emission at near-infrared wavelengths (so called "transitional disks") will also be reviewed. It has been proven that these disks commonly show intriguing features, such as asymmetric distribution of emission and significant spatial variation of gas-to-dust mass ratio. I will discuss the importance of these features when one examines the generalized scenario for planet formation.

Keywords: Atacama Large Millimeter/Submillimeter Array (ALMA), Protoplanetary disks

Observations of volatiles in protostellar cores and protoplanetary disks

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I will review current understanding of composition and evolution of volatiles in star- and planetary system- formation revealed by ALMA and other telescopes, together with theoretical insights and interpretations.
Sun-like stars are formed by gravitational collapse of a dense cloud core. In such cold dense gas, various molecules are formed not only by gas-phase reactions but also by grain-surface reactions. In fact, absorption bands of solid (ice) water, CO_2 and methanol have long been observed in infrared in molecular clouds and protostellar cores. Infrared observation is, however, effective only for ices with relatively high abundance and a clear absorption band. Once the protostar is formed, molecules in ice mantle sublimate and can be observed in radio wavelength. Even in pre-ALMA era, various complex organic species and carbon chains have been detected in the central warm region of protostellar cores (Ceccarelli et al. 2007; Sakai et al. 2008). In ALMA Science Verification Program, Glycolaldehyde, the simplest sugar, is detected towards a protostellar core (IRAS16293) for the first time (Jorgensen et al. 2012). The complex organic species show in general a very compact (< a few 100 AU) emission (Taquet et al. 2015). Quantitative estimates of their abundances, thus requires high-spatial resolution observation by ALMA. Deuterium fractionation of sublimated water is revealed by observations using Herschel and Plateau de Bure interferometer (Coutens et al. 2014). The D_2O/HDO ratio is ~1.2×10^{-2}, which is seven times higher than HDO/H_2O ratio ~ 1.7×10^{-3}. Such fractionation can be naturally explained, if the water ice is formed in two stages; early phase of molecular clouds and dense prestellar/protostellar cores (Furuya et al. 2016). ALMA observations of CO, carbon chains (e.g. C_3H_2)and SO have started to reveal disk formation (Sakai et al. 2014a; 2014b; Ohashi et al. 2014). The position-velocity diagram shows a ring-like distribution of SO emission, which could be tracing the accretion shock.
In Class II objects, i.e. the protoplanetary disks, ALMA clearly revealed spatial distributions of molecular emission lines. Theoretical models of disk chemistry predicted a layered structure of PDR layer, warm molecular layer and freeze-out midplane layer in the vertical direction (Aikawa et al. 1999; Aikawa et al. 2002; Bergin et al. 2007). This layered structure is clearly revealed by the channel map of CO (Rosenfeld et al. 2013). Observations also clearly revealed radial distributions of molecular lines. For example, N_2H^+ and DCO^+ emission shows ring structures, which is considered to correlate with CO snow lines (Qi et al. 2013; Matthews et al. 2013; Oberg et al. 2015; Aikawa et al. 2015). Theoretical models also show that N_2H^+ can be a good probe of ionization rate in the disk midplane (Cleeves et al. 2015; Aikawa et al. 2015). Another highlight is the first detection of complex organic species, CH_3CN, in the disk around MWC480 (Oberg et al. 2015). Although CH_3CN can be formed both in the gas-phase and grain surfaces, the observed abundance ratio of HCN:HC_3N:CH_3CN is better explained by the help of grain-surface reactions. Finally, detailed observations (e.g. CO and HD) and modeling of well-studied disk TW Hya indicates that CO is significantly depleted even in the region warmer than its sublimation temperature; i.e. most CO might be converted to other molecules (Favre et al. 2013). In theoretical models, CO is converted to less volatile species such as CO_2, CH_3OH and hydrocarbon ices (Aikawa et al. 1999; Bergin et al. 2014; Furuya et al. 2014). Since CO is normally the dominant carrier of carbon, depletion of CO, if verified in further observations and analysis, means the conversion of bulk carbon to less volatile molecules.

Keywords: astrochemistry, protoplanetary disks, star- and planetary system-formation

Signs on Protoplanetary Disks Created by Planet Fomation Processes

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Planet formation theories predict various observable structures created in protoplanetary disks. It is strongly expected that each high-resolution images of protoplanetary disks obtained by ALMA should give us vital information on building sites of extrasolar planets.
In the early stage of planet formation, dust growth considerably alters temperature and radiation in the disks. It is because dust growth significantly reduces the opacity for radiation. The time scale of dust growth is generally given by several hundreds of the Keplerian period, independently of the disk mass and temperature. In an inner disk region where the Keplerian period is short, dust grains grow quickly whereas their growth is relatively slow in the outer regions. We examined the evolution of disk radiation and temperature due to dust growth, by performing numerical simulations of radiative transfer. The simulations shows that a high-temperature ring-like region is created at the boundary between the inner disk with largely grown dust and the outer disk with primitive small dust. If such a ring region is observed in a protoplanetary disks, we can estimate the age of the disk accurately, using the universal dust growth time.
When a gas giant planet forms in the later stage, on the other side, it create a low-density gap structure along its orbit. We obtained an empirical relation between the planet mass and the gap width from many hydro-dynamical simulations. Hence, from the width of an observed gap, we can estimate the mass of an embedded planet, by using the empirical relation.
Since the degree of progress in planet formation depends on the radial location in disks, both the high-temperature ring region and the gap structure can exist simultaneously in a protoplanetary disk. If such a disk is observed, it enables us to measure the planet mass and age, which gives a crucial constraint on planet formation theories.

Keywords: ALMA, protoplanetary disk, dust, giant planet

ALMA Observations of a Gap and a Ring in the Protoplanetary Disk around TW Hya

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We report the first detection of a gap and a ring in 336GHz dust continuum emission from the protoplanetary disk around TW Hya, using the Atacama Large Millimeter/Submillimeter Array (ALMA). The gap and ring are located at around 25 and 41 AU from the central star, respectively, and are associated with the CO snowline at ~ 30AU. The gap has a radial width of less than 15AU and a mass deficit of more than 23%, taking into account that the observations are limited to an angular resolution of ~ 15AU. The observed gap could be caused by gravitational interaction between the disk gas and a planet with a mass less than super-Neptune ($2M_{Neptune}$), or result from destruction of large dust aggregates due to the sintering of CO ice.

Keywords: protoplanetary disks, dust continuum emission, gap and ring

Solar system observations with ALMA: Understanding the dynamics and chemistry of Venus atmosphere

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Venus, a neighbor planet of the Earth, has atmosphere significantly different from that of our planet. It is covered by a dense CO2 atmosphere and thick H2SO4 clouds. Although the planet itself rotates with a very slow speed (1.4 m/s), the Venus atmosphere moves about 60 times faster than the surface. Such a zonal wind (a.k.a. “super-rotation”) governs the dynamics of Venus atmosphere below the cloud layer. On the other hand, different characteristics in the wind pattern appear in the upper atmosphere. One of the most predominant components of the atmospheric dynamics in the upper atmosphere is the sub-solar-to-anti-solar (hereafter, “SSAS”) flow, driven by the thermal gradient between the dayside and nightside. It is considered that the superimposition of these two (zonal and SSAS) wind patterns is the key to describe the dynamics in the middle atmosphere (mesosphere) of Venus [Lellouch et al., 1997].

The wind in the Venus middle atmosphere has been investigated through the Doppler shift measurements of submm/mm CO absorption lines. Recent observations [e.g., Clancy et al., 2010, Moullet et al, 2012] revealed that the strengths of the zonal and SSAS flows (in a global scale) are highly time variable, and also localized significant inhomogeneity exists. Such temporal and spatial variability may be induced by activities of waves (gravity wave, for example), as predicted by GCM numerical simulations [e.g., Hoshino et al., 2012]. To advance the understanding on Venus dynamics, observational information with “high spatial resolution” and “high temporal resolution” are most required. Using single-dish submm/mm telescope often has a limitation in the spatial resolution (~10 arcsec, typically). Some improvement in the spatial resolution has been achieved by previous submm/mm interferometric observations but at the expense of the time resolution (~one day). Considering these facts, it can be said that ALMA is one of the most favorable facilities to study the atmospheric dynamics in Venus: ALMA provides a spatial resolution of sub-arcsec level with only a couple of minute’s data integration, i.e., “snap-shot” of Venus map in submm/mm wavelengths.

In addition to the scientific interest on the atmospheric dynamics, understanding the chemistry (including the chemistry related to H2SO4-cloud formation) in the Venus atmosphere is also a scientific subject which has been debated for years. ALMA can be a very powerful tool for this scientific interest as well. Its high sensitivity enables the observations of minor species such as SOx and HDO, and also its capability of observing at higher frequencies opens a door to the mapping of newly observed species such as HCl. HCl is an important reservoir for highly reactive chlorine (ClO*x*) species. While HCl was detected from ground for the first time in 2010 at 625 GHz [Sandor and Clancy, 2012], its spatial and diurnal variations are still left unrevealed.

In this study, we review the new findings with respect to the atmospheric dynamics and chemistry of Venus during the ALMA early science operations. Encrenaz et al. (2015) successfully observed Venus with ALMA in the Cycle-0 semester. They obtained the distribution maps of CO, SO, SO2, and HDO. The SO and SO2 maps showed significant local variations and also day-to-day temporal variation. From their CO data, the wind map can be also derived [Encrenaz, in private communications].

Subsequently, in the Cycle-2 semester, we challenged Venus HCl mapping using Band-9 (625 GHz) configuration. Unfortunately the quality of observation was severely limited due to the very low elevation angle of Venus. Careful data reduction is on-going, and we will present the first results

obtained from the ALMA Band-9 observations.

Keywords: Venus, Planetary Atmosphere, ALMA

The vertical distribution of CH_3CN in Titan's atmosphere by the ALMA archive data analysis

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We report the analysis of CH_3CN (metyl cyanide) in Titan’s atmosphere using the Atacama Large Millimeter/submillimeter Array (ALMA) archive data ranging from 275 to 350 GHz. We developed a radiative transfer code for the multiple emission lines of CH_3CN in spherically symmetric distribution within the synthetic beamshape of ALMA, and derived the optimized vertical abundance profile for CH_3CN by the fittings of spectral line shapes. It was found that the abundance of CH_3CN readily increases around 200 km altitude, and then decreases along with the higher altitude. This result disagrees with various photochemical calculations for Titan’s atmosphere, showing that the mole fraction of CH_3CN has a peak around 1000 km altitude. In contrast, our result is in reasonable accordance with that observed by the Cassini/Composite Infrared Spectrometer (CIRS) for the vertical distribution of HCN, which is as stable as CH_3CN from a chemical point of view. Our results also suggest the effect of Titan’s atmospheric dynamics and seasonal change on the vertical profile of CH_3CN.

Keywords: ALMA, Titan

