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

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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 $\sim 1.2\times10^{-2}$, which is seven times higher than HDO/H_2O ratio $\sim 1.7\times10^{-3}$. 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.

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

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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

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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

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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

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obtained from the ALMA Band-9 observations.

Keywords: Venus, Planetary Atmosphere, ALMA

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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

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Invitation to ALMA and exciting research with it

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ALMA telescope (Atacama Large Millimeter/submillimeter Array) is an international facility built and operated by Europe (ESO with its 16 member countries), North America (USA and Canada) and East Asia (Japan, Taiwan and Korea), in cooperation with Chile. It is located at the 5000-m site in the Atacama altiplano in the Andes in northern Chile, and has an extremely high performance in observing millimeter and submillimeter waves (wavelengths from 3.5 mm down to 0.32 mm). It is an aperture synthesis telescope consisting of 54 12-m parabolic antennas and 12 7-m parabolic antennas, and can adjust its spatial resolution by changing the antenna array configuration.
In the long baseline campaign in 2014, ALMA demonstrated its maximum baseline of 15 km to reveal multiple ring/gap structure in the protoplanetary disk around HL Tau by the spatial resolution as high as 0.025" (3.5 AU) at the observing wavelength of 0.87 mm (ALMA Partnership et al. 2015, ApJL 808, L3). By observing protoplanetary disks around young stars with various characters and various stages, ALMA is revolutionalizing our understanding of the earlier stages of planetary formation.
East Asia, who contributes 25% of the construction and operation of ALMA, has a 22.5% share of the observing time (= 25% x 0.9, because 10% goes to Chile). This presents a great opportunity for researchers in Japan, Taiwan and Korea to join and drive the exciting research.
ALMA Regional Centers (ARCs) have been established in Europe, North America and East Asia as interface points between ALMA and research community. The East Asian ALMA Regional Center (EA-ARC) is located in the Mitaka headquarter of National Astronomical Observatory of Japan. ARCs take care of the call for proposal, preparation of the observing script for accepted proposal, quality assurance and delivery of observed data, and updates and maintenance of the data archive. ARCs are answering users' consultations on, e.g., proposal preparation and data analysis through a helpdesk and support astronomers.
In the present paper, I introduce how the observations with ALMA are made and how we support the researchers. I hope more and more researchers join in the exciting and revolutionary science using ALMA and its archival data.
National Astronomical Observatory of Japan/ALMA
http://alma.mtk.nao.ac.jp
East Asian ALMA Regional Center
http://alma.mtk.nao.ac.jp/e/forresearchers/ea-arc/
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Keywords: Planet formation, Protoplanetary disks, Radio astronomy observations, Millimeter and submillimeter waves

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Sintering-induced dust ring formation in protoplanetary disks

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The latest ALMA observation of HL Tau revealed spectacular concentric dust rings in its circumstellar disk. We propose the hypothesis that the multiple rings resulted from the sintering of icy aggregates in the disk. Sintering is the process that fuses particles consisting of an aggregate at temperatures slightly below the melting temperature of the particles. Sintering makes aggregates harder but less sticky (Sirono 1999; Sirono & Ueno 2008), thereby suppressing their growth through coagulation. In a protoplanetary disk, icy aggregates are thought to contain various volatiles such as CO and CH_4, each of which may cause the sintering of the aggregates in the vicinity of its snow line (Sirono 2011). We construct a simple model that takes into accout sintering, coagulation, and radial drift (Adachi et el. 1976; Weidenschilling 1977) of composite ice aggregates in a protoplanetary disk. We find that the aggregates pile up in the sintering zones near the snow lines because smaller aggregates drift toward the central star more slowly. At millimeter wavelengths, the sintering zones are seen as bright, optically thick rings with a spectral slope of 2, whereas the non-sintering zones are seen as as dark, optically thin rings of a spectral slope of 2.3-2.5. The observational features of the sintering and non-sintering zones are consistent with those of the major bright and dark rings found in the HL Tau disk, respectively. We also apply our model to the protoplanetary disk of TW Hya, for which latest ALMA observations suggest the presence of a pileup of dust near the CO snow line (Nomura et al. 2016).

Keywords: HL Tau, TW Hya, sintering, ALMA

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Modeling of Dust Emission from Disk Surrounding HD 142527

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We model the 870 μm dust continuum emission from the azimuthally-asymmetric disk around HD 142527 based on ALMA Cycle 0 observation. The disk is inflated, inclined by 27° to the line of sight, and its major axis is along PA = 341°. High resolution images in NIR scattered light (Fukagawa et al. (2006)) and MIR thermal radiation (Fujiwara et al. (2006)) indicate that the eastern side (PA = 341° −161°) of the disk is farther whereas the western side (PA = 161° −341°) is closer to us. In our model, we assume the radial surface density distribution of the dust disk to be gaussian, and the dust size distribution follows $a^{-3.5}$, where a_{max} = 1 mm. At the observation wavelength, scattering opacity is 10 times larger than absorption opacity in our model (Aikawa & Nomura (2006)). Dust density, temperature, and radiative energy density of the disk are determined by M1 approximation method (Kanno, Harada, Hanawa (2013)).
The peak surface densities of dust, Σ_0, at PA = 21° (the brightest region) and PA = 221° (the faintest region) are 0.8 g cm^{-2} and 0.008 g cm^{-2}, which are consistent with Muto et al. (2015). We cannot reproduce, however, the observed surface brightness in the northwestern region (PA = 291° − 351°), i.e., the near side with about 80% brightness of PA = 21°, even with Σ_0 = 1.25 g cm^{-2}. This is due to: (i) the heavy scattering; (ii) the dependence of the disk surface brightness on the veiwing angle. We solve the problem by reducing the scattering opacity to 10% of its original value. Subsequently, the Σ_0 values for the brighter lopsided region (PA = 291° −71°) become about 50% lower than their original values, while for the remaining optically thin regions Σ_0 values do not change significantly. We will also discuss how such a scattering opacity can be realized.

Keywords: HD 142527, Dust emission, Modeling

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Quantitative Modeling of the Gap Induced by a Planet in a Protoplanetary Disk

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Recent high resolution observations have revealed that protoplanetary disks are rich in structures. Especially, multiple ring-like structures are discovered in the disk around HL Tau by the long baseline campaign observations of ALMA.

Such structures may be connected to the dynamical processes that occur in the disks. One interesting processes that occur in protoplanetary disks is the gravitational interaction between a (already formed) planet and the disk. As a result of disk-planet interaction, planets induce gap and spirals in the disk. If such structures are found in real observations, they strongly indicate the existence of a planet embedded in the disk. The shape of the gaps and spirals can be used to infer the physical properties of the disk and the planet. The physical parameters of disks and planets that are derived based on the disk morphology are independent from those derived from other methods. It is therefore important to understand and model the disk-planet interaction quantitatively.

In this poster, we present a series of numerical simulations and analytical theory of the gap formation by a single planet embedded in a protoplanetary disk. We quantify the shape of the gap structures in terms of the planet mass, disk scale height and disk viscosity. We first present the depth and the width of the gap can be determined by these three quantities. We have found that the gap depth is determined by a single parameter $K = q^2 / (h^5 * alpha)$, where q is the mass ratio between the planet and the central star, h is the disk aspect ratio, and alpha is the disk viscosity parameter. We have also found that the gap width is determined by $K' = q^2 / (h^3 * alpha)$. We have derived a simple formula that describes the gap depth and width in terms of K and K'. We apply our results to the ALMA long baseline campaign observations of the disk around HL Tau, and suggest that the planet mass is <~ 1 MJ, if the observed gap is induced by (unseen) planets in the disk. We also present the model for the detailed profiles of the gap induced by a planet, which can be compared to observations if detailed gas structures are revealed in the near future.

Keywords: Protoplanetary Disks, Disk-planet Interaction, Direct Imaging Observations of Disks

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ALMA Observation of Gas and Dust in Debris Disks

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The evolution from protoplanetary disks to debris disks is very important for understanding planet formation. Infrared emissions from debris disks observed by AKARI imply that the debris disks have gas components. The archive data of ALMA cycle1 include the samples of the debris disks found by AKARI. Therefore, we analysed the data and then found CO detections in 5 of 10 samples.

Keywords: protoplanetary disk, debris disk, gas/dust

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The Spatially-resolved HCN(J = 4-3) Interferometric Observation on Neptune's Stratosphere with ALMA Array

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ALMA array is a powerful tool to illustrate both the photochemistry and dynamics of gas giants' stratosphere thanks to its high spatial resolution and sensitivity. We have constructed the spatially-resolved HCN(J=4-3) map of Neptune with archived ALMA data obtained during Cycle-0 season. From the doppler-shift analysis, stratospheric dynamics of Neptune's stratosphere showing the spatial difference is illustrated clearly. In this presentation, obtained result and possible driving mechanism of the dynamics will be discussed.

Keywords: ALMA array, Planetary atmosphere, Radio astronomy

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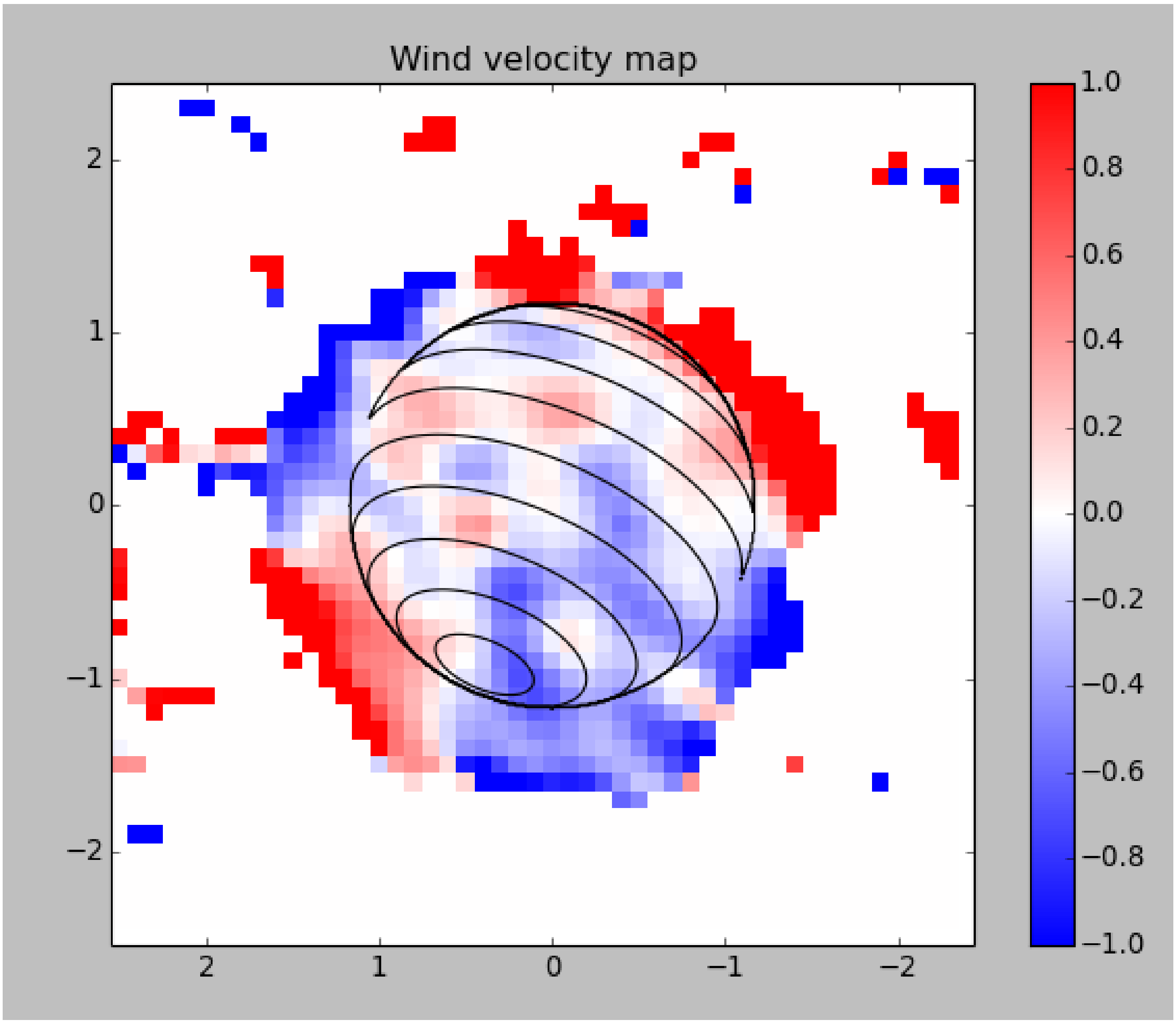

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