Protoplanetary Disks: ALMA's Recent Discoveries

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Abstract

Since its launch in 2011, ALMA (Atacama Large Millimetre/Submillimetre Array) has revolutionised theories of circumstellar disk evolution and planetary formation. Vast protoplanetary disk surveys reveal that these disks exhibit a wide variety of patterns, and that the panoply of exoplanets obey no set trend in terms of formation and composition. The main point of focus here are discoveries and subsequent research which reveal that we are on the cusp of the answer to the long-standing question of angular momentum transport within circumstellar disks. Highlighted, are just three of a multitude of ALMA discoveries which, when combined with computer modelling, exhibit the dynamic nature of each disk, challenge our current understanding of their evolution and enlighten us as to the formation of planets which may host life.

1 Introduction

Availing of the exceptionally clear Chilean skies offered by the 5,000-metre-high vantage point of Chajnantor plateau in the Atacama Desert, the largest radio interferometer in the world has broken ground in protoplanetary disk observations. [**1**] ALMA is an assembly of 66 parabolic dishes, which can be separated by up to 16km. [**2**] 12 of the antennae in the array were operational in 2011, and an image, of the highest quality to date, was taken in sub-millimetre wavelength of the Antennae Galaxies. Then in 2014, when the array was in its near-final configuration, of a 15km baseline, ALMA captured the sharpest submillimetre wavelength image of a protoplanetary disk surrounding the young star HL Tauri, 450 light-years away [**3**]. The result defied expectations, detailing a well-defined disk structure, with narrow rings and concentric gaps indicative of planets accreting mass.

To appreciate the significance of ALMA's recent discoveries, it is important to highlight areas of protoplanetary disk evolution of which we are uncertain. [**7**] The fragmenting cloud of gravitationally infalling interstellar gas and dust, which forms a planetary system, rotates with a tangential velocity, $v_\phi \sim r^{-1}$, where r is the radial distance, thus conserving angular momentum. Inflow perpendicular to the axis of rotation experiences rotational support and the motion of this material will approach Keplerian (whereby $v_\phi \sim r^{-1/2}$), forming a disk.

[**9**] The evolutionary stages of circumstellar disks are inferred from the infrared spectral energy distributions, and define the "classes" of the stellar object, ranging from the youngest, Class 0 (a deeply embedded proto-star) to the eldest phase, Class III (a fully formed star with a non-accreting disk).

[**10**] Stellar and disk accretion is well documented in protoplanetary disks hosted by stars of Class 0 to Class II. However, understanding the precise angular momentum transport mechanisms, which allow accretion to occur, has proved a challenge. If the disk were inviscid, then accretion would not occur, due to lack of torque. Assuming the motion of the disk is Keplerian, such that the angular velocity, Ω, varies as $r^{-3/2}$, then one can attribute the viscosity component to the shear between fluid elements at various radii. [**11**] The radial velocity, directed inwardly to the central mass, is related to the viscosity, ν, as $v_R \sim \frac{\nu}{r}$. [**12**] A typical accretion timescale varies as $t_\nu \sim \frac{r}{v_R} \sim \frac{r^2}{\nu}$. If the viscosity is only molecular, then $\nu \sim v_T\lambda$ where v_T is the thermal velocity and λ is the mean free path. For astrophysical fluids, the mean free path is much smaller than the radial distance, and so the inward velocity is extremely small, and the accretion timescale very large (much larger than the lifetime of a proto-stellar accretion disk). Thus another viscosity contribution, of much greater magnitude, must be at play.

Without resolved observational data, [**15**] Shakura Sunyaev (1973) proposed a general "α-disk" model by which to solve for the structure of any disk without an identified viscosity attribution. In short, they derived the viscosity relation (assuming that the source is a turbulent process), $\nu \sim \alpha c_s^2 \Omega^{-1}$ where c_s is the local sound speed and α is the a constant, determined by the turbulent viscosity effect present in the disk. [**10**] It has been hypothesised that MRI (magnetorotational instability) is the source of this turbulent viscosity, and thus drives the large accretion rates inferred for the disks. [**14**] Briefly, this is an effect of magnetic torque experienced by adjacent particles at different radii, which are connected by a magnetic field line. The inner element will have a greater angular velocity and thus the particles separate, increasing the magnetic torque. The torque acts to reduce the inner element's angular momentum (so its radial distance will decrease), and increase that of the outer element, thus the magnetic torque increases again. This feedback results in an outward distribution of angular momentum.

However, in recent years, this theory has come into question. [**12**] MRI is plausible in hot, ionised accretion disks, but in cold, poorly ionised disks the cause of angular momentum transport is less clear. Other turbulent effects (which I will not detail here), such as gravitational instability [**13**], have been posed as viscosity contributors. Even non-viscous angular momentum transport mechanisms, such as magnetothermal winds (MTW) have been suggested. MTW remove angular momentum from the disk, but as investigated by Najita et al. (2018), if this were in effect, "in-disk" transport of angular momentum would be negligible. They found, when comparing Class I and II disks and applying the α-disk prescription, disk sizes increased during the Class II phase, a result consistent with the expectations of viscous spreading. However, with no direct observation of MRI nor any angular momentum redistribution mechanism, the exact processes of planetary formation are still to be identified.

Rafikov, R. (2017) utilised ALMA survey data of 26 protoplanetary disks, also prescribing the α-disk model, and found that the dimensionless viscosity parameter, α, ranged in value by over 2 orders of magnitude and showed no obvious value preference. The data also showed no correlation between α and any global disk parameter (such as mass, size, surface density), nor any stellar parameter (such as mass, radius, luminosity). He concluded that the picture of viscous evolution being driven by a process with a single, well-defined α value (which countless researchers have adopted since its proposal) is too simplistic. With the emergence of larger, high-resolution surveys from ALMA at our disposal, the data will reveal frequencies, correlations and the full diversity of disk morphology, so we can identify the exact processes of angular momentum transport, disk evolution and planetary formation.

1.1 Discovery 1: 3D Gas Velocity Observations

[**16**] In 2018, an ALMA survey (known as DSHARP) resolved 20 protoplanetary disks with a resolution of 0.035" (5AU) of 1.25mm dust continuum emission. The survey found all the disks demonstrate small-scale sub-structures, the most common of which were concentric, narrow emission rings and gaps.

[**17**] Subsequent research of a disk of particular interest, surrounding the star HD 163296, found that the gaps in the emission spectrum are at 48, 86, 131 and 237AU from the central star. Comparing the observations to planet-disk interaction models suggests that these gaps are the result of 4 planets. [**18**] However, the results are also consistent with gravitational perturbations caused by just one planet orbiting at 100AU, [**19**] and potentially with MRI effects responding to variations in the density.

In 2019, researchers availed of the unprecedented resolution of the ALMA DSHARP data and applied a new technique for analysing the ring morphology of this disk. Teague et al. measured the velocity structure of the gaseous molecule, CO. [**20**] CO is a highly abundant molecule, whose isotopologues (molecules of different neutron numbers) emit mainly in the microwave region during rotational transitions. It is thus a commonly used gas tracer for protoplanetary disks, and ALMA can observe the emitted light in considerable detail. [**21**] For the first time, observations of the ALMA data revealed ^{12}CO gas motions in 3 directions: azimuthally, radially and *vertically*. [**22**] The line emission of this gas was analysed by interpreting Doopler-shift deviations from the line centres. Once this shift is determined in the radial and azimuthal directions, any unexpected digression from the line centre is interpreted as a vertical velocity component. They determine the local sound speed variations over the disk and subtract a "baseline model" for the azimuthal velocity to highlight strong deviations, which they then plot in the (radial, azimuthal) plane and the (radial, vertical) plane, shown in the first and second panels of Figure 1.

One can see that the azimuthal velocities (shown in the first panel) are slower at the interiors of the vertical velocity maxima (second panel), and faster at the exteriors. The vertical velocity maxima are virtually coincident with the dust emission gaps of **[17]** at radial distances of 87, 140 and 237AU, indicative of meridional flows created by planets of 0.5, 1 and $2M_J$ respectively. Such flows are expected to feed material from the upper layer of the disk to the cooler midplane and form planetary atmospheres.
One will also note that beyond 300AU, there appears to be a "radial outflow" as marked by the blue, dashed box. The velocities in this region are much too high ($\sim 30ms^{-1}$) to be attributed to viscous spreading (**[10]** which results in outflows of $\sim 1ms^{-1}$). This finding thus contradicts that of **[10]**, as Teague et al. hypothesise that this outflow could be the result of the disk wind, removing angular momentum, rather than a turbulent viscosity re-distributing it. **[22]** However, this very recent research, made possible by the resolving power of ALMA, demonstrates that we can infer large-scale 3D velocity flows of protoplanetary disks and presents the possibility of understanding angular momentum transport mechanisms which allow for planetary formation.

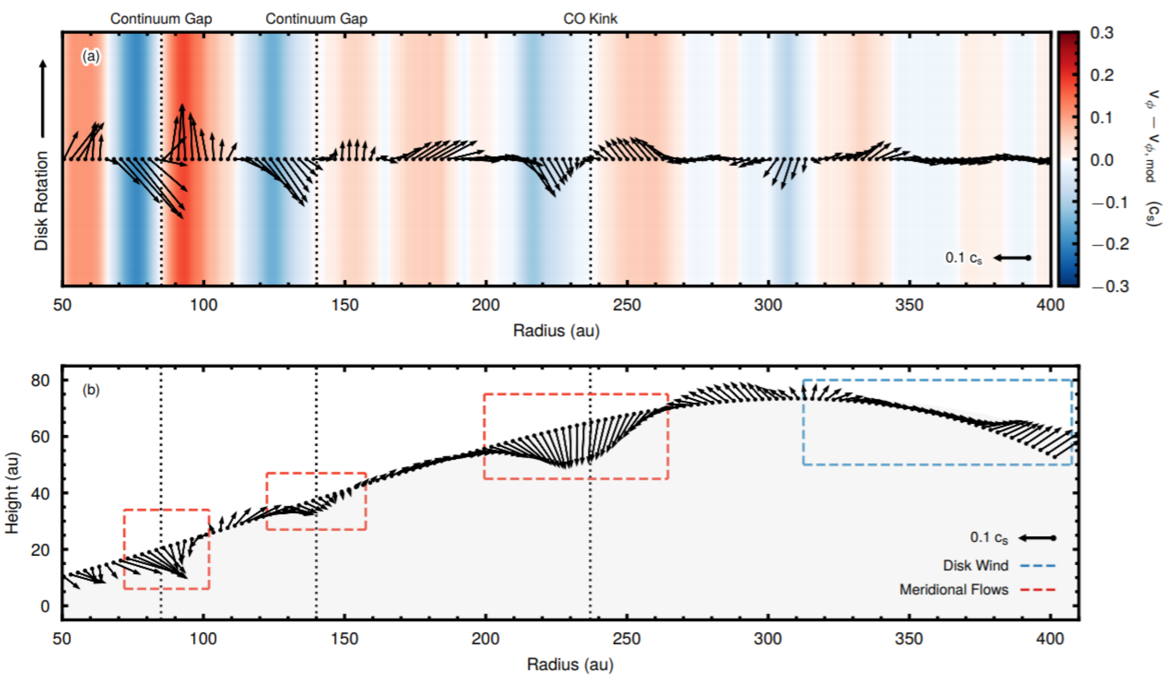

Figure 1: **[22]** 3D gas velocity structure of the disk of HD163296 in the (r, ϕ) plane and (r, z) plane respectively. The vertical dashed lines indicate the gaps in the dust continuum emission found by **[17]** and local velocity disturbances of the CO. The colour bar indicates the deviation of azimuthal velocity. The arrow vectors indicate velocity where, if pointing in the positive y-direction, is faster rotating material, and slower if in the negative y-direction. The blue dotted box is the region of radial outflow.

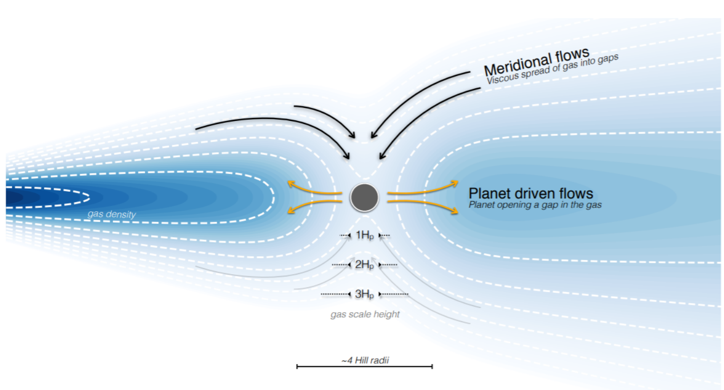

Figure 2: **[22]** Schematic of the meridional flow around a forming planet

1.2 Discovery 2: Youngest Proto-star Ever Imaged

[**23**]Amongst the ground-breaking observations of protoplanetary disks within its first year of launch, ALMA also imaged the disk of the youngest proto-star captured to date. The star VLA 1632A (one of a triple proto-stellar system $\sim$ 120pc away) is a Class 0 star, thus expected to be embedded in the molecular envelope and display no evidence of Keplerian rotation.
[**24**] However, research utilising the ALMA data found evidence for a rotationally supported disk within the infalling envelope. By measuring the emission of CO isotopologues (within the disk, where the molecule is still gaseous and emitting) and the molecule DCO^+ (which has a lower condensation temperature and so is abundant in the cold molecular envelope), researchers Murillo et al. developed the emission velocity diagrams (Figure 3), and fitted models for disks of Keplerian rotation. They conclude that both species have line emissions which are well described by Keplerian rotation, indicating the disk edge may be dragging envelope material, causing both regions to rotate in this fashion.
[**25**] A 2020 study of 16 Class 0 proto-stars found that large Keplerian disks are rare, observing only 2 said disks in the sample. They hypothesise that MRI effects hamper the formation of these disks, whereas varying initial conditions (such as a misalignment of the rotational axis and the magnetic field) can promote the early formation of Keplerian disks. With ALMA's high resolution, observations of this evolutionary phase will be much more common, allowing for the study of the disk-envelope boundary kinematics, and its influence on stellar and planetary formation.

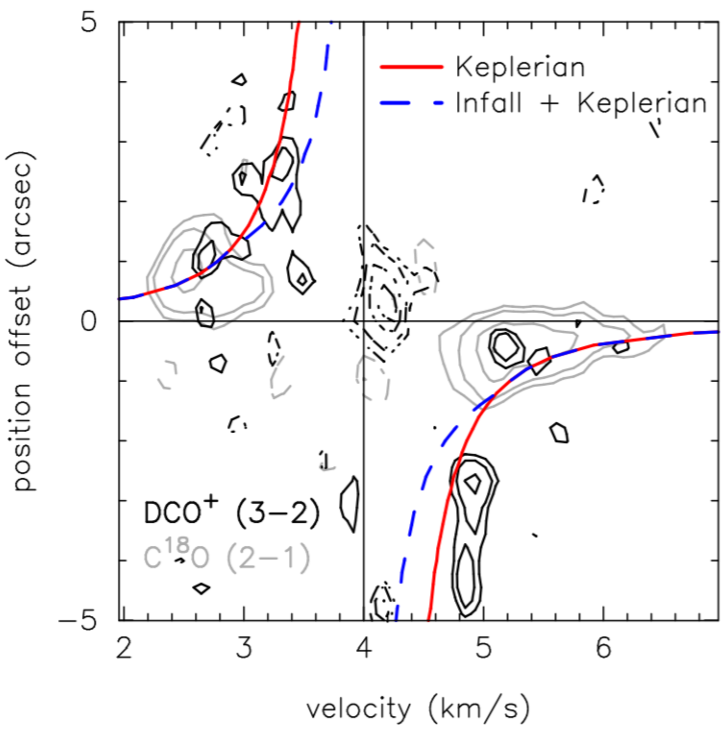

Figure 3: [**24**] Velocity diagram for the line emission of the CO isotopologue (grey) and DCO^+ (black). The Keplerian rotation fit ($v_\phi \sim r^{-3/2}$) is over plotted as a solid red line, and the total velocity relationship for Keplerian motion and radial infall motion is over plotted as a dashed blue line.

1.3 Discovery 3: First Resolved Image of Water Snow Line

[**27**] A snow line of an element or molecule marks the point, beyond which the molecule has condensed and forms ice. [**26**] Beyond the water snow line, extremely low pressures mean water transitions directly from the gaseous state to solid state, corresponding to an abrupt increase in solid density and thus grain coagulation, sparking planetary formation. [**27**] Water has a relatively low condensation temperature ($\sim$100K) and its snow line lies $\sim$5AU from the central star. This short distance means the water snow line had never before been resolved, that was until 2016, where the $1.3M_\odot$ star V883 Ori was observed to be in a state of "outburst"

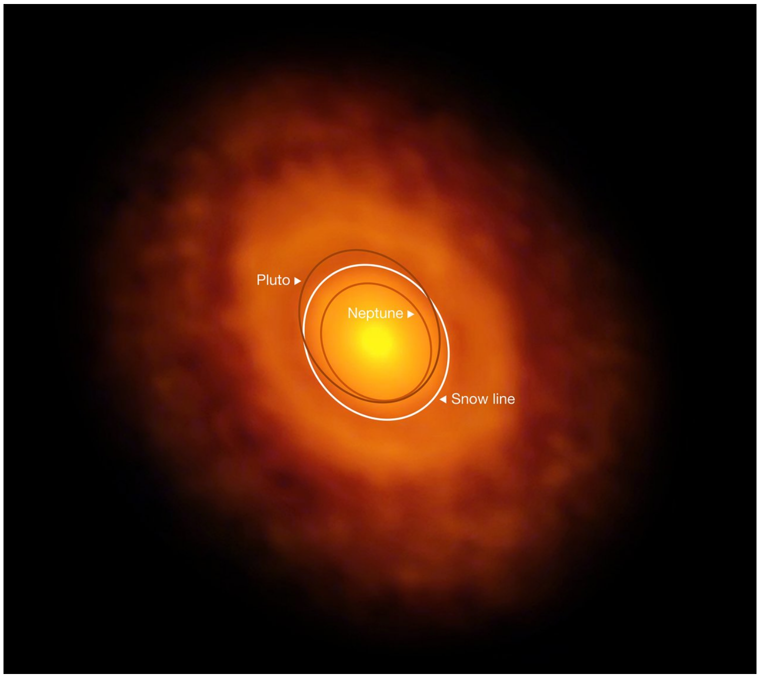

Figure 4: [**30**] Long baseline ALMA image of the region around proto-star V883 Orionis. The orbits of Neptune and Jupiter are shown for scale.

with a luminosity of over $400L_{\odot}$. [**29**] This is attributed to a temporary increase in the stellar accretion rate by over 3 orders of magnitude, from 10^{-7} to $10^{-4}M_{\odot}yr^{-1}$. Owing to ALMA's remarkable resolution of 0.03" (around 12AU for the star's distance of 414pc), and the fact that this outburst pushed the water snow line to a distance of about 42AU, we now have the first ever resolved image of a water snow line in a protoplanetary disk. This was interpreted as an intensity break (where the opacity transitioned from the optically thick to thin regime) at 0.1", coinciding with a temperature decrease to 105±11K.
[**30**] Then, in 2019, further research revealed within this extended water snow line, the sublimation of Complex Organic Molecules (COMs). COMs, which form the basis of prebiotic material, amino acids and sugars, are usually spatially unresolvable due to the fact they are only in gaseous form within the radially close water snow line, and beyond this point, they are in non-emissive ice form. [**31**] However, the now 10 times larger radial extent of the water snow line, allows for the line emission of the fresh sublimates methanol, acetone, acetonitrile, acetaldehyde, and methyl methanoate to be spatially resolved in the sub-millimetre regime, with a resolution of 0.2". COM cometary abundances in our Solar System and the abundances of V883 Ori are in reasonable agreement, suggesting that this data could be utilised to reconstruct organic molecule evolution of our own Solar System.
[**27**] Outbursts are believed to be an evolutionary stage for most Class I systems, but last < 100 years. The gas emission of the fresh COM sublimates directly traces their abundances which were in ice phase pre-burst. Post-burst, however, the grains cool so quickly that the freeze-out timescale for COMs is less than a year. Thus, ALMA has provided a unique probe of chemical evolution and its imprint on formed planets. More observations of this epoch will develop our modelling of protoplanetary disk evolution, accounting for the highly dynamical snow lines, and perhaps solving the long-standing puzzle of angular momentum transport.

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