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Resolving star and planet formation with ALMA

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Abstract. Disks around young stars are the sites of planet formation. As such, the physical and chemical structure of disks have a direct impact on the formation of planetary bodies. Outflowing winds remove angular momentum and mass and affect the disk structure and therefore potentially planet formation. Until very recently, we have lacked the facilities to provide the necessary observational tools to peer into the wind launching and planet forming regions of the young disks. Within the framework of the *Resolving star formation with ALMA* program, young protostellar systems are targeted with ALMA to resolve the disk formation, outflow launching and planet formation. This contribution presents the first results of the program. The first resolved images of outflow launching from a disk were recently reported towards the Class I source TMC1A (Bjerkeli *et al.* 2016) where we also present early evidence of grain growth (Harsono *et al.* 2018).

Keywords. ISM: jets and outflows, Protoplanetary disks, Stars: winds, outflows, Stars: formation

1. Introduction

The most prominent observational signature of the star formation process are outflows, which remove angular momentum from protostellar systems. Hence, they enhance the ability of stars to grow by accretion (the **why** of outflows). Outflows have in addition been invoked to explain issues such as the low star formation rate, and the low core to star efficiency.

Outflows are closely associated with protostellar disks (Cabrit *et al.* 1990). However, it remains to be understood **where, when** and **how** they are launched. Since the discovery of molecular outflows almost four decades ago (Snell *et al.* 1980), different theories and hypotheses for **how** and **where** they are launched have been presented. These can roughly be divided into three different categories: i) a 'stellar wind' launched from the poles of the protostar (Bouvier *et al.* 2014), ii) An 'X-wind' launching mechanism operating on a fraction of an au from the protostar and where the protostellar and disk magnetic fields interact (Shu *et al.* 1994; Shang *et al.* 2006), iii) the 'disk-wind' scenario where magnetic ejection takes place throughout an extended region of the disk (Blandford & Payne 1982; Königl & Pudritz 2000).

The program *Resolving star formation with ALMA* was initiated in 2015. The first observations were acquired towards the Class I source TMC1A in the Taurus molecular cloud and were published in Bjerkeli *et al.* (2016) and Harsono *et al.* (2018). TMC1A

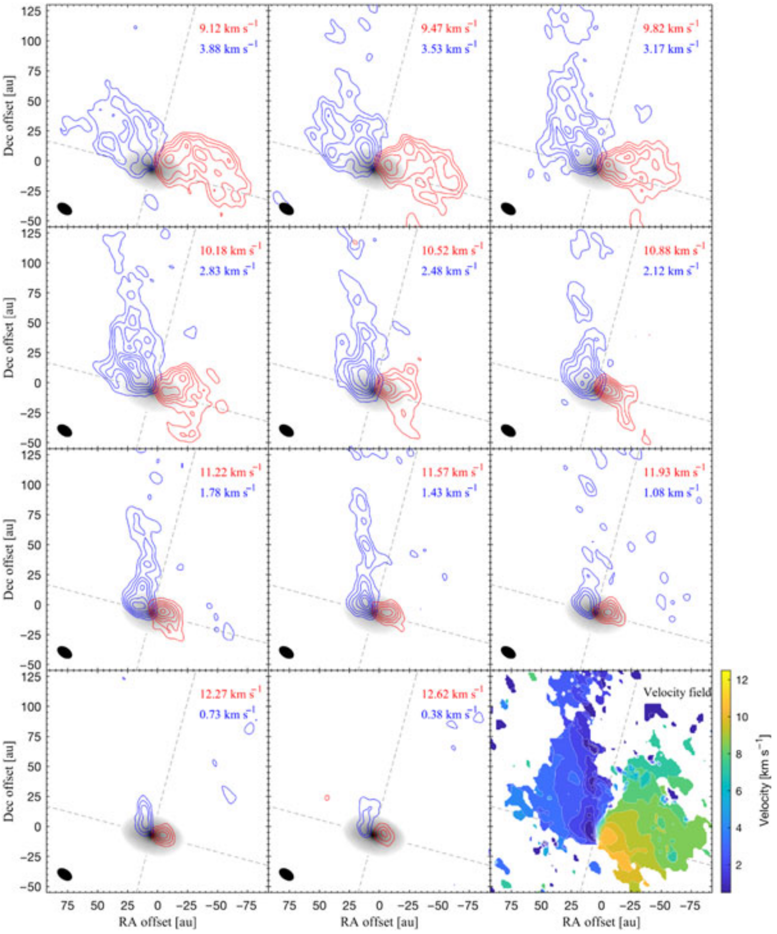

Figure 1. Channelmap of the ^{12}CO emisson in TMC1A Bjerkeli *et al.* (2016). Blue and red-shifted emission is with respect to the source velocity, 6.4 km s^{-1}. The plane of the disk and the outflow axis are indicated with dashed lines. In the lower right panel, the velocity field of the emission is presented.

harbors an outflow that is 6000 au long and a disk that is 200 au in size. Surrounding the system is a ∼10 000 au diameter envelope that is collapsing towards the central star and disk. TMC1A is located sufficiently nearby (∼140 pc) allowing for resolved observations of both the outflow and disk. ALMA was used for approximately four hours, in its most extended configuration (∼6 au spatial resolution), to observe ^{12}CO (2–1), ^{13}CO (2–1), C^{18}O (2–1) and 1.3 mm continuum.

In addition to the TMC1A results presented in this contribution, we are now also including other targets in our study. The objectives of the program are not only to constrain the **when, where** and **how** of outflows that are responsible for mass-loss during early star formation but also to constrain the initial conditions for planet formation.

2. Resolved images of a disk wind in TMC1A

The ^{12}CO channel map (Fig. 1) shows integrated blueshifted and redshifted emission from the outflow in TMC1A, revealing substantial morphological changes with increasing velocity. The northeastern cavity wall is detected above 3σ and at velocities greater than 2 km s^{-1} with respect to $\upsilon_{\rm LSR}$. Outflowing gas is detected out to a distance of more than 100 au from the central source. Already from visual inspection it is clear that there is

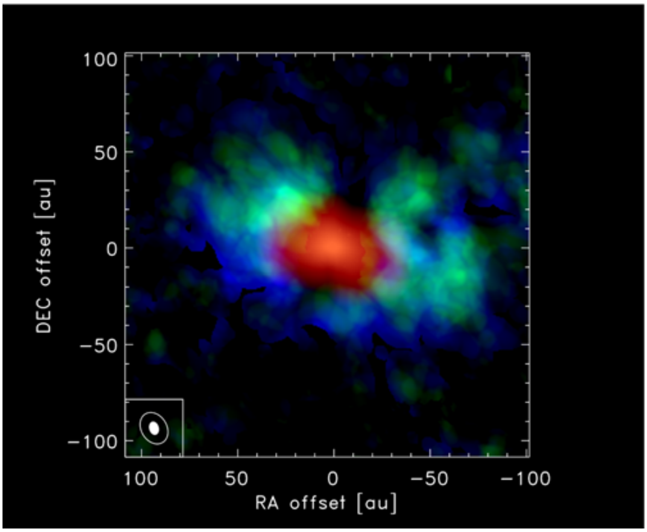

Figure 2. Colours represent integrated ^{13}CO (green) and C^{18}O (blue) emission and dust continuum (red) towards TMC1A (Harsono *et al.* 2018). There is a lack of emission from CO isotopologues and a supression in the continuum emission inside 20 au.

emission close to the disk surface at large radii, which suggests the bulk of the emission can not be of ‘X-wind’ origin. Meanwhile, only one side of the blueshifted outflow cavity wall and only fractions of the redshifted component to the south are visible. We believe the absence of emission from the north-western and south-eastern cavity walls is a result of the emission from these components coinciding with the velocity of the foreground cloud absorption. The velocity map of the outflow shows an ‘onion-layered’ pattern, where the highest velocities are found close to the outflow axis. From a careful comparison between the emission from the different CO isotopologues we conclude that the emission from ^{12}CO is from the outflow.

Two different methods are used to determine the outflow launching radii. First, launching radii are fit from the geometry of the emission, yielding launching radii between 5 and 25 au on the disk. The second method is to use magnetohydrodynamic wind theory following Anderson *et al.* (2003). Using this method, we derive launching radii between 1 and 19 au, i.e. consistent with the geometric calculation. Hence we conclude that at least some of the outflow is launched from the disk at radii sufficiently large to be directly resolved in our observations. It is important to point out that this does not rule out the possible existence of a co-eval ‘X-wind’ operating on smaller scales than probed by these observations.

Since the discovery of the extended disk wind in TMC1A in 2016, similar observations toward other protostellar systems have been presented by other groups. For example HH 212 is particularly interesting since the SiO emission hints that launching takes place very close to the central protostar, i.e. within 0.05 au (Lee *et al.* 2017).

3. Evidence for the start of planet formation in TMC1A

Dust growth is the first step toward planet formation. Such growth has been inferred previously through dust spectral index observations, but only towards systems older than a few million years (Testi *et al.* 2014; Miotello *et al.* 2014). Meanwhile, most observed exoplanets have masses larger than the mass reservoir available in such disks. This alone suggests that grain growth should start very early in protoplanetary disks.

In the case of TMC1A, dust continuum observations do not reveal any gaps or rings, e.g., like the case of HL Tau (ALMA partnership *et al.* 2015). However, a shoulder is clearly visible in the flux density distribution (Supplementary Fig. 1 of Harsono *et al.* 2018). This shoulder was detected already in the initial reduction of the dataset, but the unknown nature of it motivated us to improve the calibration procedure and to include a dataset that was previously omitted due to bad weather. The strength of the shoulder varies slightly in azimuth angle but remains at a fairly constant radius of ∼20 au. Inside 20 au, there is, in addition, a striking lack of CO isotopologue emission (Fig. 2). To analyze the lack of emission, we compare the observations to several different disk models. We find that a canonical model with micron sized grains can not reproduce the observed lack of emission, because optical depths would not be high enough. We also conclude that a very massive disk (that could reproduce the hole in emission) is very unlikely because such a disk would be dynamically unstable on short timescales. Deep continuum observations of TMC1A do not show any azimuthal or radial variations consistent with a gravitationally unstable disk. An unusually flat and cold disk structure does produce a lack of emission in the central regions, but this is in contrast with the temperature structure of a disk like TMC1A. We find, that the only way to reproduce the lack of emission is instead to include a population of larger grains in the models that are at least 1 mm in size. This finding is important, since the TMC1A disk is sufficiently young and massive enough to form multiple Jupiter sized planets. This evidence for a substantial reservoir of larger grains in such a young disk therefore implies that planet formation starts very early.

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References

ALMA partnership, *et al.* 2015, *ApJL*, 808, 3
Anderson, J. M, Li, Z. Y., Krasnopolsky, R., *et al.* 2003, *ApJL*, 590, L107
Bjerkeli, P., van der Wiel, M. H. D., Harsono, D., *et al.* 2016, *Nature*, 540, 406
Blandford, R. D. & Payne, D. G 1982, *MNRAS*, 199, 883
Bouvier, J, Matt, S. P, Mohanty, S., *et al.* 2014, *Protostars and Planets VI*, 433
Cabrit, S., Edwards, S., Strom, S. E, & Strom, K. M 1990, *ApJ*, 354, 687
Harsono, D., Bjerkeli, P., van der Wiel, M. H. D., *et al.* 2018, *Nature Astronomy*
Lee, C. F., Ho, P. T. P, Li, Z. Y., *et al.* 2017, *Nature Astronomy*
Königl, A. & Pudritz, R. E 2000, *Protostars and Planets IV*, 759
Miotello, A., Testi, L., Lodato, G, *et al.* 2014, *A&A*, 567, 32
Shang, H., Allen, A., Li, Z. Y., *et al.* 2006, *ApJ*, 649, 845
Shu, F., Najita, J. Ostriker, E., *et al.* 1994, *ApJ*, 429, 781
Snell, R. L, Loren, R. B, & Plambeck, R. L 1980, *ApJL*, 239, L17
Testi, L., Birnstiel, T., Ricci, L., *et al.* 2014, *Protostars and planets VI*, 339

Discussion

Pérez: Was the spectral line data processed with continuum subtraction? Because the dust emission is optically thick and bright, if you subtract it from the line it may artificially create a hole.

Bjerkeli: We explored different baseline subtraction methods (both in the uv domain and in the image domain) applied to different spectral windows. In all cases we see the ^{13}CO/C^{18}O hole, and for ^{12}CO we see the same morphology.

Waller: What is the status + prospects for observing rotation in the outflows?

Bjerkeli: Tentative measurements of rotation has been observed towards outflows for more than a decade. The situation has, however, changed dramatically in recent years, thanks to ALMA. Some recent examples where jet rotation is claimed are: HH212 (Lee *et al.* 2017), IRAS4C (Zhang *et al.* 2018).

Wandel: The axis of the large scale Cycle 0 observation seems to be different from your small scale outflow. Is this real?

Bjerkeli: The position angle of the flow axis is the same in both Aso *et al.* 2015 and Bjerkeli *et al.* 2016. The reason that they look different is that we only see one side of the outflow towards TMC1A, the part of the flow that is rotating towards us.