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Exocometary Belts Transformed by ALMA

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Exocometary belts are belts of planetesimals lying in the cold outer regions of planetary systems — analogues of our Solar System's Edgeworth–Kuiper belt. Like extrasolar planets, these ice reservoirs are very common in extrasolar planetary systems. In the last 12 years, sensitive, spatially resolved observations enabled by the Atacama Large Millimeter/submillimeter Array (ALMA) have fundamentally transformed our understanding of these belts. ALMA has exposed their exocometary nature with detections of volatile gas linked to exocometary ice compositions and revealed a variety of radial and vertical (sub)structures often linked to ice/gas giants lurking below detectability at tens of au. These ALMA-enabled advances provide new insight into the composition, dynamics and diversity of exocometary belts, and their role in shaping outer planetary systems in the latest stages of planet formation and beyond.

Exocometary belts in outer planetary systems

With the rapid developments in exoplanet discovery in the past three decades, it is now common knowledge that most stars in our Galaxy are surrounded by rich and varied exoplanetary systems. Beyond the vast majority of discovered exoplanets, which lie in the inner ~au region of planetary systems, a significant fraction of stars in our Galaxy (at least ~20%, but potentially up to ~75%; Eiroa et al., 2013; Pawellek et al., 2021) also host belts of small bodies (planetesimals), dust and gas. These belts, commonly also referred to as debris discs, are extrasolar Edgeworth–Kuiper belt analogues (or exoKuiper belts), lying in the frigid outer reaches — at tens of au — of exoplanetary systems. Their widespread presence alone indicates that the planet formation process efficiently produces extrasolar planetesimals as well as planets. These planetesimals give us an insight on their formation, a key intermediate step in the making of planets. By forming at tens of au from their host star, these planetesimals are likely icy analogues of Kuiper Belt Objects and they release dust and volatile gas that makes them observable; this means that they can be viewed as 'exocomets' (Strøm et al., 2020; Fitzsimmons et al., 2024) and their natal belts as 'exocometary belts', the ice reservoirs of planetary systems.

The first landmark detection of dust in a belt was through the unresolved infrared excess it produces around Vega (Aumann et al., 1984); this was quickly followed by the first coronagraphic image of the edge-on belt around beta Pictoris (Smith & Terrile, 1984). The dust observed in these belts (typically ≳ 100 times lower in mass than their young protoplanetary disc counterparts) is short-lived, owing to the outward radiation pressure by photons from the typically intermediate-mass host stars. As such, it must be continuously produced through the collisional destruction of larger and larger solids, within a 'collisional cascade'. This cascade is likely to extend from observable, micron- to centimetre-sized grains to solids as large as about kilometre-sized planetesimals, which are required to sustain dust production over the main sequence age of belt-hosting systems.

One clear consequence of collisional evolution is mass loss from the belt over time, which in turn should cause the belts' infrared (IR) emission, typically peaking in the far-IR given dust temperatures at 10–100s of au around A–G-type stars, to decrease with system age. This is clearly observed in belt population studies in the mid-to-far IR with Spitzer and Herschel space-based surveys, which are most sensitive to the peak brightness of these belts (for example, Wyatt et al., 2007; Sibthorpe et al., 2018), as well as by the pioneering SCUBA-2 Observations of Nearby Stars (SONS) survey with the single-dish James Clerk Maxwell Telescope at submillimetre wavelengths (Holland et al., 2017). This also has the important implication that most of the brightest, well-studied belts are young, in the 10 to few 100 Myr era corresponding to the latest stages of planet formation, following from protoplanetary disc dispersal.

Millimetre/submillimetre-wavelength belt studies are key as they probe ~millimetre-sized, gravitationally bound grains. Contrary to the micron/tens of micron-sized grains probed both in the mid- to far-IR (via thermal emission) and optical/near-IR (via scattered starlight), millimetre-sized grains are large enough not to be affected by radiation forces. This makes them direct tracers of the location and dynamics of larger planetesimals. However, the low dust masses typical of detectable exocometary belts (~1–30 Moon masses) measured at millimetre-wavelenghts, and their relatively large on-sky extent (~1–16 arcseconds in diameter at 150–10 pc for an 80-au belt) result in low-surface-brightness emission which made millimetre-wavelength imaging very challenging with single-dish telescopes or small interferometers; this meant resolved millimetre studies of exocometary belts were limited to a few nearby systems (for example, Greaves et al., 1998; Hughes et al., 2008).

The exocometary (icy) nature of planetesimals in these belts was originally postulated based only on their observed dust temperature, and by association with our Solar System's Edgeworth-Kuiper belt. Evidence for ice was very indirect, through modelling of the belts' spectral energy distribution (for example, Lebreton et al., 2012) and evidence of volatile gas was limited to two systems with CO line detections: 49 Ceti and beta Pictoris (Zuckerman, Forveille & Kastner, 1995; Roberge et al., 2000). For a long time this led to the lack of significant amounts of gas being a defining feature of exocometary belts, in contrast to younger protoplanetary discs.

The Atacama Large Millimeter/submillimeter Array (ALMA) has profoundly transformed our view of exocometary belts and our ability to study them. This contributed significantly to the growth of the wider debris disc community, to the point of sustaining its own yearly/bi-yearly conference series, with its sixth edition since the first 2018 meeting in Victoria, Canada taking place this coming July 2026 at the University of Cambridge, UK[1]. Below, we highlight a few key ALMA-enabled breakthroughs, before reflecting on what the future might hold for this emerging sub-field of exoplanetary system science.

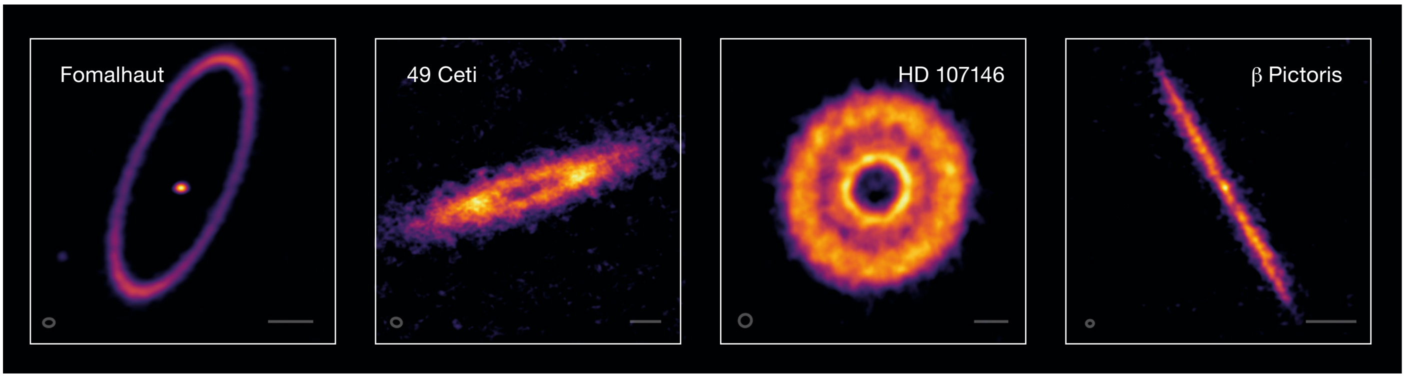

Figure 1. ALMA images of ~mm-wavelength dust emission from the exocometary belts around four nearby stars: Fomalhaut (MacGregor et al., 2017), 49 Ceti (Marino et al., 2026), HD 107146 (Marino et al., 2018) and beta Pictoris (Matrà et al., 2019). These reveal a variety of radial structure, from eccentric narrow rings to broad and gapped belts, to edge-on belts with complex vertical structure. The ellipse in the bottom left represents the spatial resolution of the data and the scale bar indicates a physical distance of 50 au.

Exocometary belt (sub-)structure: dynamical signatures of ice giants at 10s of au

ALMA's key enabling feature for exocometary belt studies has been the major increase in sensitivity it offers thanks to its collecting area, as well as its resolution in the 0.1–1 arcsecond range. A major scientific advance it brought about is the ability to image the dust continuum from millimetre-sized grains, gravitationally bound to the central star at unprecedented resolution, allowing us to detect structure at physical scales of a few to a few tens of au (Figure 1). These physical scales correspond to a few to a few tens percent of a belt's radius (distance from the star); accessing them with ALMA is transformational as these are the scales at which we expect to observe radial and vertical substructure produced by ice and gas giant planets. Following targeted pilot studies, the recently released ALMA Resolved exo-Kuiper belt Substructures (ARKS) ALMA Large Programme presents the most comprehensive view of (sub)structure in belts; we here highlight some of its findings as well as other key ALMA results.

Radial structure

ALMA moderate-resolution observations of 74 belts uniformly analysed as part of the REsolved ALMA and SMA Observations of Nearby Stars (REASONS) study show that a significant fraction of belts defies the classical picture of being a narrow ring such as Fomalhaut (Figure 1), instead being broad discs with a width more than half their radius (Matrà et al., 2025). Targeted studies of iconic systems such as HR8799 and Vega showed that at least some broad discs remain broad and smooth when imaged at higher resolution (Faramaz et al., 2021; Matrà et al., 2020); this is confirmed in around 40% of 24 systems in the ARKS Large Programme (like 49 Ceti; Figure 1 and Han et al., 2026). These broad belts are challenging to explain given the narrowness of rings observed in most young protoplanetary discs (Bae et al., 2023). The connection between the two evolutionary stages is therefore not as simple as one might expect, and other processes need to be invoked, such as migrating planets moving dust traps/rings and forming planetesimal discs across a wide range of radii (Miller et al., 2021) or scattering of planetesimals by a planet interior to the belts (Geiler et al., 2019).

On the other hand, the ARKS programme has established that about 50% of bright belts, when observed at sufficiently high resolution, show substructure in the form of multiple rings with gaps (for example, Marino et al., 2018), or bright rings on top of low-amplitude broad emission (Han et al., 2026). If interpreting gapped belts in the simple picture of a single static planet on a circular orbit carving the gap, the gap width measured by ALMA implies the presence of ~Neptune- to super-Jupiter-mass planets at 20–80 au in mature planetary systems. The vast majority of these remain below detectability with direct imaging (Milli et al., 2026; Bendahan-West et al., 2026), highlighting the role of belt substructure in revealing the influence of otherwise undetectable, long-period planets.

It is important, however, to recognise that these substructures may simply be inherited from protoplanetary discs (Marino et al., 2019), or created by alternative dynamical processes such as multiple planets, planet migration, mean motion resonances and secular interactions (for example, Pearce & Wyatt, 2015; Friebe, Pierce & Löhne, 2022). ALMA measurements of the sharpness of the inner and outer edges of planetesimal belts are a further indication of present or past interaction with planets (Pearce et al., 2024, Marino, 2021), though a fraction of the belts show shallow inner edges consistent with being produced by collisional evolution alone (Imaz-Blanco et al., 2023).

Vertical structure

A long-standing, fundamental challenge in the field has been weighing the mass in solids present within the belts; as mass is dominated by the largest objects in the collisional cascade, which are not observable directly, this is the same as asking how large the biggest planetesimals are — a key constraint for planetesimal formation models. ALMA has shed new light on this by allowing measurements of the belts' vertical structure, which can be linked to the velocity dispersion of dust particles imparted by the gravitational effect and therefore the mass/size of the largest solid bodies within the belts (for example, Quillen, Morbidelli & Moore, 2007). The first two pilot ALMA studies of edge-on belts discovered, on the one hand (Daley et al., 2019) that the largest bodies in the AU Mic belt must be less massive than ~1.8 $M_\oplus$. On the other hand, in the case of beta Pictoris (Figure 1; Matrà et al., 2019) ALMA revealed a complex vertical structure analogous to the two-component (dynamically hot and cold) population of classical Kuiper Belt Objects (for example, Brown et al., 2001). This points to the potential of planets interior/exterior to the belts to also contribute to the belt's vertical structure, as Neptune would have done by migrating outwards in our Edgeworth-Kuiper belt (for example, Nesvorný, 2015).

We now know from the ARKS programme (Zawadzki et al., 2026) — vertically resolving 13 systems — that belts show a wide variety of vertical thicknesses, with aspect ratios of ~0.003 to ~0.2 indicating that the largest bodies within the belts have radii in the range ~30–3000 km (between a large comet and Mars). However, ARKS has also shown complex structure similar to beta Pictoris for 10/13 belts, indicating that interaction with interior/exterior planets may be a common feature of exocometary belts. This corroborates the radial structure results, with ALMA showing overall that ice giants at tens of au commonly form in systems with bright belts, dynamically shaping planetary systems and likely producing volatile transport from these icy belt reservoirs.

ALMA discovers volatile gas: exocometary release or planet formation leftover?

A key discovery enabled by the sensitivity of ALMA has been the detection of gas in the form of carbon monoxide (CO) and/or atomic carbon (CI) in around 25 exocometary belts, or about 30% of the ALMA resolved exocometary belt population. Small ALMA surveys focused so far on stars with belts known to be bright in dust emission. These show that the detectability of gas correlates with 1) age, in all but two CO-bearing belts in systems <50 Myr old (for example, Mac Manamon et al., 2026), and 2) luminosity of the central star, with around a 70% CO detection rate around A stars with bright exocometary belts (Moór et al., 2025). Amongst the detections, a dichotomy has arisen between CO-poor belts, with optically thin ^{12}CO and masses $< 10^{-3}\ M_\oplus$ and CO-rich belts with CO masses $> 10^{-3}\ M_\oplus$ (for example, Cataldi et al., 2023).

CO-rich belts tend to be bright and are amenable to high-resolution studies, with five of them observed at unprecedented spectrospatial resolution through the ARKS programme (Figure 2). ARKS confirmed that ^{12}CO emission is very optically thick (Brennan et al., 2026) and that it is typically broader than the belt as traced by dust (Mac Manamon et al., 2026); it also showed that dust may be significantly affected by gas drag in CO-rich systems (Marino et al., 2026; Weber et al., 2026; Milli et al., 2026).

The origin of this gas has been a matter of intense debate over the past decade. On the one hand, CO-poor systems like beta Pictoris have insufficient gas to shield themselves from the stellar and interstellar UV radiation field, leading to ~100-yr destruction timescales. This means that, like the dust, CO must be continuously replenished (Zuckerman & Song, 2012; Matrà et al., 2015) by exocomets within the belt. This led to the realisation that ALMA allows us to access the volatile component of exocomets released from exocometary ice. Assuming gas release over time through the same collisional cascade producing the dust, a CO+CO$_2$ mass fraction may be derived from the observed CO gas mass, revealing exocometary CO+CO$_2$ compositions similar to those of Solar System comets (Matrà et al., 2017, 2019). Rapid UV photodissociation unfortunately hinders a broader compositional comparison, as other molecules are typically much shorter-lived than CO, explaining non-detections in millimetre molecular surveys so far (Matrà et al., 2018; Klusmeyer et al., 2021).

The picture remains complicated, on the other hand, for CO-rich belts, as the CO exocometary production rates required to explain the observed high masses would be unreasonably high (Kóspál et al., 2013), implying that the CO must be shielded from photodissociation by itself or other species. In an exocometary release scenario, it is possible that CO gas released fast enough would produce enough atomic carbon to shield the CO itself, allowing it to accumulate and explaining observed CO-rich belts (Kral et al., 2019; Marino et al., 2020). However, the low CI/CO ratios recently measured by ALMA and

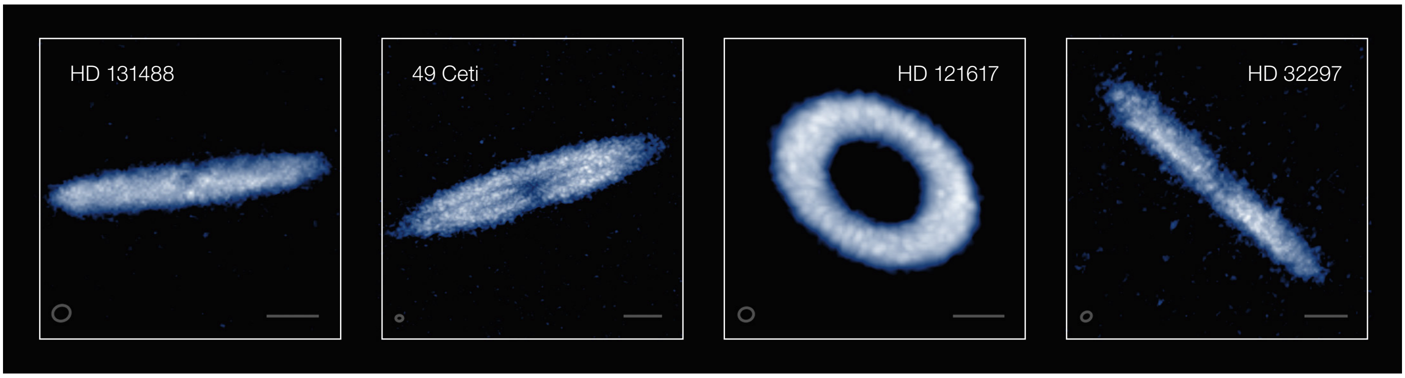

Figure 2. ALMA ARKS Large Programme images of ^{12}CO J = 3–2 (peak) line emission from the CO-rich exocometary belts around HD 131488, 49 Ceti, HD 121617 and HD 32297 (Mac Manamon et al., 2026), showing abundant optically thick emission co-located with, but typically more radially extended than, the belts traced by the millimetre dust. The ellipse in the bottom left represents the spatial resolution of the data and the scale bar indicates a physical distance of 50 au.

the Hubble Space Telescope (Cataldi et al., 2023; Brennan et al., 2024) are challenging to explain in this exocometary production scenario.

This leads to the possibility that, instead, enough (undetectable) H_2 could be present as a shielding agent, raising the possibility that CO-rich belts may be long-lived remnants of Herbig Ae protoplanetary discs (Kóspál et al., 2013), with the gas therefore primordial in origin. This is supported by theoretical work indicating that the dispersal of protoplanetary discs around intermediate mass stars may take much longer than previously believed, and up to tens of Myr (Nakatani et al., 2021, 2023). However, the primordial H_2 scenario for CO-rich belts is also challenged by the high mean molecular weights derived by modelling high-resolution gas observations (Figure 2; Hughes et al., 2017; Brennan et al., 2026), and now by absorption observations with the upgraded CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES$^+$) at the Very Large Telescope that show a CO/H_2 ratio $> 10^{-3}$ in a CO-rich belt, significantly higher than expected from protoplanetary disc or interstellar medium gas (Smith et al., 2026).

ALMA's key role for the community and the future quest for sensitivity

ALMA has enabled transformational progress in our understanding of exocometary belts in the outer regions of planetary systems; detailed targeted studies, the REASONS population study and now the ARKS Large Programme have given us access to key angular scales at sufficient sensitivity to meaningfully constrain exocometary belt physics, dynamically revealing interaction with otherwise undetectable ice and gas giant analogues at tens of au. ALMA has also opened a completely new direction and challenged the very definition of belts by discovering volatile CO and CI gas, verifying their exocometary nature and allowing us to access exocometary compositions.

Many mysteries remain, such as the origin of the CO-rich belts discussed here, as well as many unanswered questions, such as the occurrence and nature of belts closer to the star (potentially undetectable because they are faint) and those around low mass stars. Despite being the most common planetary systems in the Galaxy, their outer planetary systems remain completely unexplored (only one belt resolved by ALMA around $< 0.1\ L_\odot$ stars, with most studied belts in the A–F-type range). ALMA has characterised the brightest, largest and most massive belts, the tip of the iceberg and around 3–5 orders of magnitude more massive than our Solar System's Asteroid and Edgeworth-Kuiper belts.

The key need of the community is more surface brightness sensitivity for both continuum and line observations, as making progress from the current state of the art is not limited by ALMA's highest achievable resolution, but rather by its sensitivity. In the short term, deeper integrations and further characterisation of bright systems with current ALMA, as well as the moderate continuum sensitivity advance brought by the Wideband Sensitivity Upgrade will be beneficial to the community and will continue to provide interesting insights into exocometary belts as the ice reservoirs of planetary systems. These ALMA results will be enhanced by complementary observations at other wavelengths. JWST will lead the quest for directly imaged planets, but also for warmer dust and solid-state ice features (for example, Su et al., 2024; Xie et al., 2025), whereas the Extremely Large Telescope's Mid-infrared ELT Imager and Spectrograph (METIS) and Multi-AO Imaging CAmera for Deep Observations (MICADO) instruments will soon enable high-contrast imaging in the *M/N* band and for more compact/distant belts. In the longer term, however, moving from the tip of the iceberg to studying the most common exocometary belts requires a significant improvement in sensitivity as well as flexible resolution from a few milliarcsec to ~1 arcsec, making a next generation millimetre interferometer with a transformational increase in collecting area best placed to enable the next big leaps in exocometary belt science.

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Links

[1] Debris Disk Connections conference 2026: https://www.ast.cam.ac.uk/debris-disk-connections