Abstract Submillimeter observations with ALMA will be the essential next step in our understanding of how stars and planets form. Key projects range from detailed imaging of the collapse of pre-stellar cores and measuring the accretion rate of matter onto deeply embedded protostars, to unraveling the chemistry and dynamics of high-mass star-forming clusters and high-spatial resolution studies of protoplanetary disks down to the 1 AU scale.

Keywords Star formation · Protoplanetary disks

1 Introduction

The formation of stars and planets occurs deep inside clouds and disks of gas and dust with hundreds of magnitudes of extinction, and can therefore only be studied at long wavelengths. In the standard scenario for the formation of an isolated low-mass star, a cold core contracts as magnetic and turbulent support are lost and subsequently collapses from the inside out to form a protostar with a surrounding disk. Soon after formation, a stellar wind breaks out along the rotational axis of the system and drives a bipolar outflow entraining surrounding cloud material. The outflow gradually disperses the protostellar envelope, revealing an optically visible pre-main sequence star with a disk. Inside this disk, grains collide and stick owing to the high densities, leading to pebbles, rocks and eventually planetesimals which interact to form planets. The original interstellar gas and dust is gradually lost from the disk through a combination of processes, including accretion onto the new star, formation of gas-rich planets, photoevaporation and stellar winds.

These different evolutionary stages in star- and planet formation are traditionally linked to their Spectral Energy Distributions (SEDs) (Lada 1999), which illustrate how the bulk of the luminosity shifts from far- to near-infrared wavelengths as matter moves from envelope to disk to star. So far, most tests of this scenario have been done using spatially unresolved data which encompass the entire star-disk-envelope system in a single beam. ALMA will be the first telescope capable of spatially and spectrally resolving the individual components and tracing the key physical and chemical processes on all scales.

The strengths of ALMA are (i) its high angular resolution, combined with enough sensitivity to image continuum and lines down to 0.01″ (~1 AU = terrestrial planet-forming zone at 150 pc, 30 AU = disk of high-mass YSO at 3 kpc); (ii) its high spectral resolution down to 0.01 km s\(^{-1}\) so that the details of the dynamics and kinematics can be probed; (iii) access to thousands of lines from hundreds of species allowing a wide variety of physical and chemical regimes to be probed; and (iv) its ability to detect optically thin dust emission and thus directly derive dust masses.

ALMA probes the wavelength range of 0.3–9 millimeter, which is on the Rayleigh–Jeans tail of the SEDs of young stellar objects. For a complete picture of these sources complementary space and ground-based observations at shorter wavelengths are necessary. Compared with other missions, ALMA is less well suited for large area surveys because of its small field of view. Mid-infrared observatories such as the Spitzer Space Telescope at 3–70 µm probe the peak...
of the SED for low-mass YSOs and can scan large areas much more rapidly, albeit at lower spatial and spectral resolutions. Near-infrared imaging is a powerful tool to characterize the stellar component, whereas the Herschel Space Observatory and ground-based single-dish submillimeter telescopes equipped with large format bolometers can rapidly search large areas for cold dust emission. These missions will provide complete unbiased catalogs with thousands of sources covering all the nearby molecular clouds and star-forming regions within a few hundred pc (contained within Gould’s Belt), many of the young clusters and associations within 1 kpc, and most of the prominent high-mass star-forming clouds to the outer edge of the Galaxy. Thus, the primary source lists for ALMA will come from these missions. They will also provide the main statistical results from which, for example, timescales for the different phases can be derived.

This paper outlines a number of key questions for each evolutionary state where ALMA can make a major contribution. It focuses mostly on low-mass star formation and protoplanetary disks, but many of the same arguments are also valid for high-mass star formation. Inspiration for this review was provided by the many beautiful paintings by Juan Miró displayed in Madrid and elsewhere around the world. Most appropriate for this topic are ‘Birth of the world’, ‘Chiffres and constellations’, ‘Red disk’ and ‘Serpent looking at comet’. A challenge for the reader is to find the relations between these paintings and the topics described here.

2 Low-mass star formation

2.1 Pre-stellar cores

**Question 1** What are the initial conditions for low-mass star formation, in particular the physical structure and kinematics of the densest part of the core?

In recent years, a number of cold, highly extincted clouds have been identified which have a clear central density condensation. These so-called pre-stellar cores are believed to be on the verge of collapse and thus represent the earliest stage in the star-formation process (e.g., Tafalla et al. 1998). The physical and chemical state of these clouds is now well established on scales of few thousand AU by single dish millimeter observations combined with extinction maps. The cores are cold, with temperatures varying from 10–15 K at the edge to as low as 7–8 K at the center, and have density profiles that are well described by Bonnor–Ebert profiles. It is now widely accepted that most molecules are highly depleted in the inner denser parts of these cores (Caselli et al. 1999; Bergin et al. 2002). Images of clouds such as B68 show only a ring of C$^{18}$O emission, with more than 90% frozen out toward its center.

ALMA will be particularly powerful in probing the central part of the core on scales of 100 AU and search for signs of collapse in the very earliest stages. Important probes are the lines of N$_2$H$^+$ and H$_2$D$^+$ at 372 GHz, with the latter line a unique probe of the kinematics in regions where all heavy molecules are depleted (van der Tak et al. 2005).

2.2 Very low luminosity objects and formation of brown dwarfs

**Question 2** What prevents some clouds from collapsing? Why do some low-luminosity sources have such a low accretion rate in spite of the much larger reservoir of gas and dust?

About 75% of so-called ‘starless’ cores (i.e., dark cores with no IRAS source) remain starless down to 0.01$L_{\odot}$ or less even after deep surveys with Spitzer (Kirk et al. 2007). However, Spitzer has revealed a small set of cores with so-called Very Low Luminosity Objects (VeLLOs). Examples include L1014 (≈0.1$L_{\odot}$, Young et al. 2004), L1521F (≈0.05$L_{\odot}$, Crapsi et al. 2005; Bourke et al. 2006), and IRAM 04191 (≈0.08$L_{\odot}$, Dunham et al. 2006). These VeLLOs are embedded in cores with typical masses of 1M$_{\odot}$, but their low luminosities suggest that their central stellar masses are low and that they (currently) have low accretion rates. They also show very different outflow properties ranging from a large well developed outflow in IRAM 04191 to a miniscule outflow in L1014 only detectable through high angular resolution millimeter observations (Fig. 1). This suggests that accretion in these cores may be episodic. It remains an interesting question whether these VeLLOs constitute a separate stage in the evolution of low-mass protostars or are precursors of substellar objects, but without a better handle on their dynamical structure it is difficult to predict the “end result” of the ongoing star formation in these cores. ALMA will be able to zoom in on these sources, image their disks (whose presence is inferred from the SEDs) and small scale outflows and furthermore constrain the kinematics of their envelopes.

![Fig. 1](image-url) The VeLLO L1014-IRS. Left: optical image with 1.2 mm dust continuum emission overlayed. Middle: Spitzer mid-infrared image with 4.5 μm (blue), 8.0 μm (green) and 24 μm (red). Right: CO 2–1 map of the innermost region of the core from the SubMillimeter Array (SMA). Images from Young et al. (2004) (left, middle) and Bourke et al. (2005) (right)