ALMA upgrades enhancing kinematic studies at all scales

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Sub-millimeter observations are a key tool for the characterization of winds and outflows at different scales, from Solar-system atmospheres to evolved stars and galactic-scale molecular clouds to quasars. Spectral profile analysis of resolved gas-phase lines (molecular rotational transitions, red-shifted fine-structure lines) allows one to measure projected velocity along the line of sight and to identify velocity components. High-resolution imaging from interferometric observations such as ALMA directly measures the projected velocity field and connects it to spatial features. The next major development of ALMA, the Wideband Sensitivity Upgrade, will improve observing efficiency for all types of observations, and will specifically enhance the scope and accuracy of kinematic studies, opening the way to the exploration of new science cases.

ALMA's Wideband Sensitivity Upgrade

In the next ten years, the highest priority for ALMA's development is a **transformative increase of its instantaneously processed bandwidth, by a factor of 2 initially** (and a factor 4 in a future expansion). The ALMA Wideband Sensitivity Upgrade (WSU, Carpenter at al., 2022) is a partnership-wide initiative that will realize this development across the entire ALMA's wavelength range through a series of major hardware upgrades of the telescope's elements and systems. A core component of the WSU will be the installation of a 2d generation correlator by 2030, with increased bandwidth, digital sensitivity, and vastly more spectral channels and tuning flexibility. Other WSU elements include upgrades to:

- **the receivers**, for wider spectral grasp (IF) and improved receiver temperature (noise). Replacements will happen on a phased schedule between 2025 and 2035, with bands 2, 6 and 8 in the first phase
- the back end components including the digitizers and data transmission system
- the supporting Infrastructure and software

While the 1st generation correlator is hosted in the Array Operations Building at 5000 m of altitude, a new correlator facility to host ALMA-TALON will be set up at 3000m at the Operations Support facility. Carlos Padilla, NRAO/AUI/NSF

Global wind patterns in planetary atmospheres

Molecular rotational lines of common atmospheric species – typically CO, HCN, H_2O and isotopologues – are excellent tracers of wind fields in Solar System atmospheres, and provide a velocity resolution commensurate with the precision needed to characterization the global circulation patterns (~50 m/s). **Using lines of different opacity is a proven technique to sound different pressures** (altitudes) from the ground or troposphere to the stratosphere, helping to determine vertical wind shear and circulation regime transitions.

On some bodies (Venus, Titan), wind variations are present on very short timescales on the order of hours or days, making it hazardous to compare observations of different lines observed at different times. With a wider spectral grasp per receiver, allowing one to observe at once strategic combinations of strong lines even with high spectral resolution, **one can efficiently simultaneously probe a set of altitudes in order to characterize the 3-D wind field at a given moment** in time.

WSU and kinematic studies

The WSU will specifically impact kinematic studies through the following capabilities enhancements:

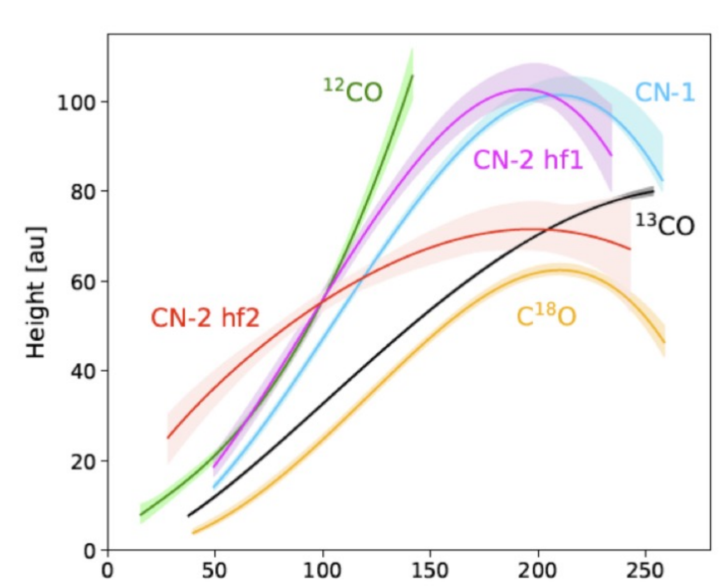
- **line sensitivity** increased across all bands, yielding line imaging speeds improved by at least a factor 2.2
- increase of the receivers' **instantaneous spectral grasp** by a factor 2 (with a goal of 4), translating into more transitions being simultaneously observed
- increase of **instantaneous correlated bandwidth** at any spectral resolution, translating into a 4-68 times larger velocity range at the highest spectral resolution, with the largest gains at low frequency bands. In the vast majority of cases, 100-200 m/s spectral resolution can be achieved over the whole spectral grasp,
- Availability of **ultra-high velocity resolution** of at least 10 m/s at all wavelengths, and down to 1 m/s in narrow zoom windows

Thanks to the significantly enhanced continuum and line sensitivity, the WSU will improve the efficiency of the telescope for all observations.

Kinematic telltales of planet formation

By **detecting subtle deviations from the general Keplerian motion in protoplanetary disks,** one can in principle identify signatures of ongoing planet formation, resonances between orbiting planets and gravitational instabilities. Several detections of velocity field 'kinks' have been obtained with ALMA in nearby disks (e.g., Pinte et al., 2018; Perez et al., 2020), providing strong evidence of the presence of embedded planets in disks, and overall constraining the timeline of planet formation. Large scale flows have also been detected, including vertical flows identified through the use of different lines probing different layers (heights) through the disk mid-plane (Teague et al., 2019, 2022).

The increased sensitivity and spectral grasp at 0.1 km/s resolution can be leveraged to expland these experiments towards fainter disks, while providing efficient observations of specific transitions combinations **to better constrain vertical wind structures.** Note that the classic observation setup covering both ^{12}CO and ^{13}CO in Band 6 is expected to be much more sensitive with WSU than with current receivers, reducing the necessary observing time by a factor of 4.

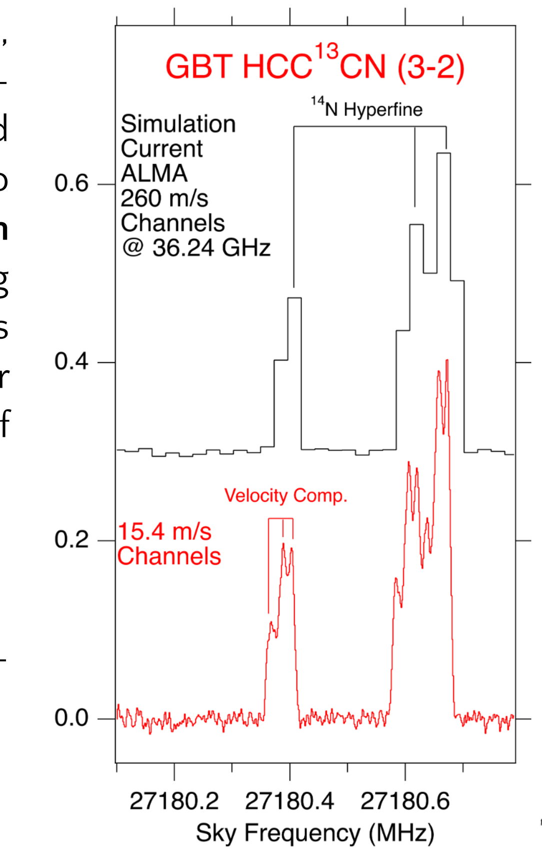


Adapted from Paneque-Carreno et al., 2022: location of the emission level probes by ^{12}CO, ^{13}CO and $C^{18}O$ lines in the disk Elias 227.

Infall signatures in cold galactic environments

Direct evidence of the kinematics in dark and cold molecular clouds was only recently explored thanks to new high velocity resolution capabilities on single-dish mm-wave telescopes, revealing from spatially unresolved spectra the **unexpected complexity in the way gas accretes to form protostars.**

On this emerging field of investigation, the combination of ALMA-WSU's ultra-high velocity capabilities (~10 m/s) and angular resolution is necessary to **connect low-velocity components in narrow lines to spatial features**, allowing a powerful exploration of the kinematics in cold regions such as dark molecular clouds and molecular envelopes of protostars.



GBT HCC^{13}CN J = 3 – 2 spectrum from the GOTHAM survey (Mc Guire et al., 2020) toward the cold dark molecular cloud TMC-1 with a spectral resolution of 15.4 m/s; the black spectrum shows a simulation at ALMA's current best resolution. Adapted from Carpenter et al., 2022

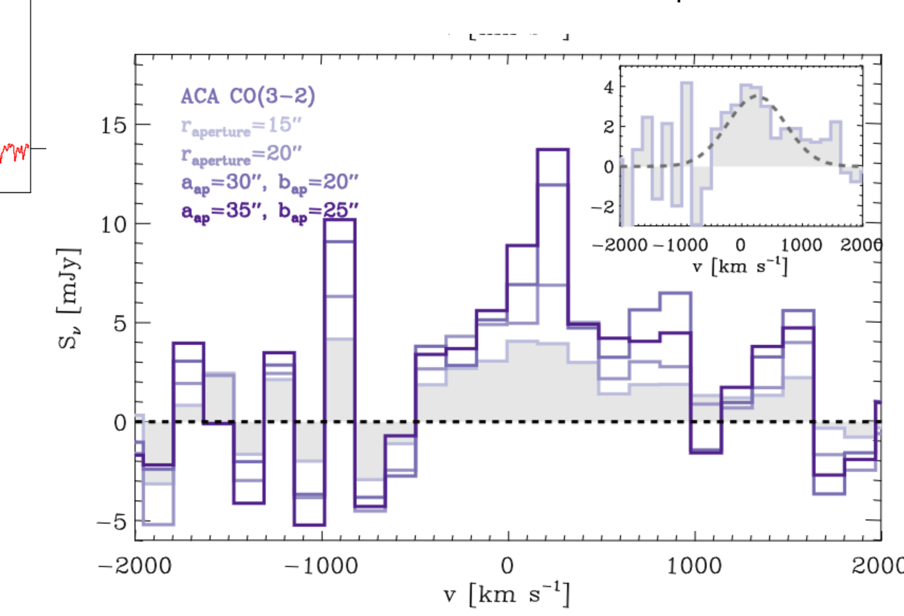
Winds in high-density sources through the SZE effect

Local modifications of the cosmic microwave background emission ca convey unique information about foreground sources. The Sunyaev-Zeldovich Effect (SZE) is a distortion of the CMB's spectrum in the 80-300 GHz range that happens when the line of sight goes through a very dense and hot environment, due to inverse Compton scattering by energetic electrons. One of the components of the SZE **– the kinetic SZE – is indicative of the line of sight bulk velocity of the electrons in the foreground source**. Outflows and expanding bubbles of overpressurized shocked hot gas or plasma from AGNs and starbursts, where wind speeds could be on the order of thousands of km/s, are a prime type of environment where the kinetic SZE should be measurable. Only one instance of kinetic SZE identification on a quasar has been reported (Lacy et al., 2019).

With ALMA's WSU, the significant increase in continuum sensitivity and the wide instantaneous bandwidth of at least 16 GHz per band (and up to 32 GHz), will greatly facilitate **the study of the wide and smooth spectral signature of the SZE on a larger number of sources**, and provide the necessary angular resolution. Considering that the SZE signature is redshift-independent, this technique could in principle be applied to study the intergalactic medium across cosmic times..

Extragalactic high-velocity outflows

The identification and characterization of galactic scale outflows is essential to understand the role of AGN and starburst feedback in shaping galactic halos and feeding the circumgalactic and intergalactic medium. Outflows can present with velocities reaching up to several 1000s of km/s (Salak et al., 2023). High-velocity components can also be found on water maser satellites lines (Yang et al., 2023), which may originate from spots on the central accretion disk of a quasar, and provide direct constraints on the mass of the supermassive black hole. **ALMA's general wavelength range is ideally placed to identify velocity components for sources over a large range of redshifts**, using tracers such as ionized and atomic carbon lines, CO or OH lines. However the current available instantaneous contiguous spectral grasp (corresponding at most to a velocity range of ~2400 km/s at Band 9 or ~5000 km/s at Band 6) is not well suited to effectively search for high-velocity components, In addition, these lines can be very broad (upwards of 1000 km/s) leaving insufficient line-free spectrum available to determine the continuum component.



Adapted from Cicone et al., 2021: CO(3-2) spectrum of quasar cid_346 (z~2), with different extraction methods, observed with a single 2GHz baseband in Band 3 with the ALMA ACA array. A faint component is identified at ~-1500 km/s.

By doubling or quadrupling the instantaneous spectral grasp, **a comprehensive outflow/velocity structure characterization on extra galactic sources can be obtained in a single spectral setting**, opening the way to a number of serendipitous discoveries of high-velocity components, Also note that the upgraded Band 8 will have a 12 GHz spectral grasp which will allow for the first time with ALMA to observe both the [CI] and CO(4-3) lines, for effective comparison of the velocity structure of the atomic and molecular components.

References

Carpenter et al., ALMA Memo 621, arXiv:2211.00195, 2022; Pinte et al., ApJL 860, 2018; Perez et al., ApJL 889, 2020; Teague et al., Nature 574, 2019; Teague et al., ApJ 936, 2022; Paneque-Carreno et al., A&A 606, 2022; McGuire et al., ApJL 900, 2020; Lacy et al., MNRAS 483, 2019; Salak et al., arXiv:2307.02104, 2023; Yang et al., ArXiv:2308.07368, 2023; Cicone et al., A&A 654, 2021.