

Chemical and Kinematic Stratification of the HL Tau Outflow seen by ALMA and JWST

T. Nony, F. Bacciotti, C. Dougados, G. Navarro, B. Nisini, P. Kavanagh, A. Banzatti, S. Cabrit, L. Podio, J. Ferreira

Investigating ejections from protostellar systems is crucial for understanding the formation of stars and planets. HL Tau, a Class I/II star with a mass of 2.1 Msun, stands out as a benchmark system, as it offers a unique opportunity to trace the origin of a prominent bipolar outflow associated with a well-studied ringed disk.

Our studies of HL Tau using ALMA at 1.3 mm and JWST (1.6 – 26 μm) reveal a clear chemical and kinematic stratification in the HL Tau outflow, organized into three main nested components. The innermost component is the atomic jet, detected at radial velocities of about 160 km/s in numerous infrared transitions of [Fe II] and other species. It displays a knotty structure indicative of a possible temporal variability in the ejection of a few years. Surrounding the jet, H₂ lines trace a wide-angle outflow, with velocities of 45 km/s and a complex arc-like substructure. The rovibrational transitions of CO($v=1-0$) at 4.7 μm appear as an external cocoon around the H₂, co-spatial with the cooler gas emitting in the rotational transitions of CO($J=2-1$). Our ALMA study of the CO($J=2-1$) outflow in HL Tau shows that it is itself structured into distinct nested, layered shells with velocity decreasing with distance from the axis, from 20 to 2 km/s. Comparison with theoretical models show that this distribution is compatible with the CO($J=2-1$) flow being a wide, inhomogeneous magnetized wind launched from an extended region of the disk, possibly up to 90 au from the star.

These findings pave the way for a detailed comparison with MHD models of disk, jets and wind systems, to shed light on the physical mechanisms driving the formation of young stars