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Complex organic molecules tracing the comet-forming zones in protoplanetary disks

Catherine Walsh and John D. Ilee

School of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK
email: c.walsh1@leeds.ac.uk

Abstract. Resolved emission from gas-phase methanol can reveal the abundance and distribution of the comet-forming ice reservoir in protoplanetary disks. ALMA Cycle 4 observations of four transitions of gas-phase methanol in TW Hya allow the first model-independent determination of the rotational temperature of methanol in a prototoplanetary disk. The data confirm that the methanol is rotationally cold ($T_{\rm rot} < 50$ K), and well constrain the column density to 2×10^{12} cm^{-2}. Astrochemical models will constrain the chemical origin of methanol in TW Hya.

Keywords. astrochemistry, planetary systems: protoplanetary disks

1. Introduction

Comets form via the agglomeration of ice-coated dust particles in protoplanetary disks. As comets are warmed upon approach to the Sun, their ices begin to sublimate, allowing remote sensing of the bulk composition. This provides unique insight into the composition of pristine planet-building material in the young disk around the Sun within which the Solar System formed. There is (contested) evidence that comets that impacted the young Earth contributed to the replenishment of water and organic material needed to seed life on the surface. Hence, the degree of chemical complexity reached within comet-building material may determine the propensity for life to develop on terrestrial planets.

ALMA, the Atacama Large Millimeter/submillimeter Array, is the only facility with the sensitivity and resolution to observe complex organic molecules in the comet-forming regions around nearby protoplanetary disks. To date, detected in disks with ALMA are CH_3CN (Ö *et al.* 2015; Bergner *et al.* 2018; Loomis *et al.* 2018a), CH_3OH (Walsh *et al.* 2016; Loomis *et al.* 2018b), and HCOOH (Favre *et al.* 2018). A comparison of the observations with detailed astrochemical models have revealed that ice chemistry combined with some non-thermal desorption mechanism is necessary to explain the line emission (e.g., Walsh *et al.* 2014). However, it has been shown that gas-phase chemistry can also contribute to the observed abundance thus complicating the relation between the abundance measured in the gas phase with that present in the ice reservoir.

2. ALMA observations of gas-phase CH_3OH in TW Hya

Methanol, CH_3OH, is a complex organic molecule that forms in space solely via surface chemistry (e.g., Watanabe & Kouchi 2002). Hence, observations of gas-phase CH_3OH in protoplanetary disk provide insight into the location and abundance of the ice reservoir.

Gas-phase CH_3OH was detected for the first time in a protoplanetary disk with ALMA (in TW Hya: Walsh *et al.* 2016). Four transitions were targeted, spanning upper level energies from 21.6 K to 98.8 K. Detection was confirmed by stacking the emission from the three lowest-lying transitions in the image domain. Analysis using a matched filter technique in the $u-v$ domain confirmed the detection of these three transitions

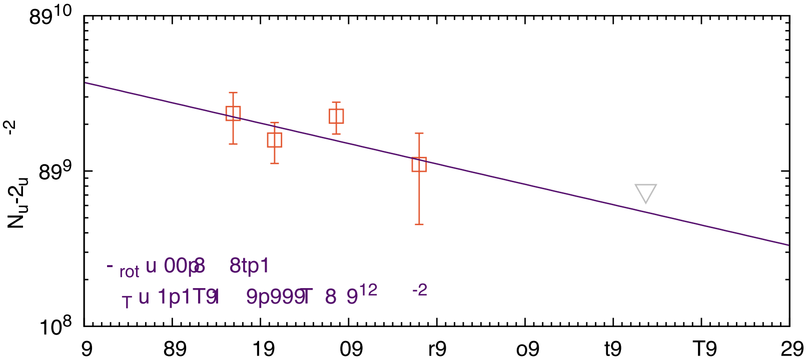

Figure 1. Rotational diagram for gas-phase CH_3OH in TW Hya.

(Loomis *et al.* 2018b). Although the radial distribution of gas-phase CH_3OH was well constrained, the vertical location was not; hence, it was not possible to concretely identify the non-thermal desorption mechanism likely at play in releasing it from the ice reservoir.

Time was thus awarded during ALMA Cycle 4 operations to revisit CH_3OH in the disk around TW Hya. Data was collected at a significantly higher sensitivity (~ 1 mJy beam^{-1} at a velocity resolution of 0.15 km s^{-1}) and spatial resolution ($\approx 0.4 - 0.5$ arcsec or $24 - 29$ au). Five rotational transitions of methanol were targeted, spanning upper level energies from 16.9 K to 63.9 K. Only the four lower-lying transitions were detected.

The detection of four transitions now enables the first rotational diagram for CH_3OH to be made for a protoplanetary disk. Assuming that the emission is optically thin and in local thermodynamic equilibrium, the disk-integrated column density and rotational temperature can be fitted using a simple linear function in log space (see, e.g., Loomis *et al.* 2018a). Figure 1 shows our preliminary results: the gas-phase methanol disk integrated column density is confirmed to be 2×10^{12} cm^{-2}, and the rotational temperature is constrained to $\lesssim 50$ K. This confirms that the gas-phase methanol arises from a cold region in the disk. A comparison with our fitted column densities in Walsh *et al.* (2016) suggests that the methanol is arising from the molecular layer, above the midplane.

3. Future outlook

Next steps will involve azimuthal averaging of the data to increase the signal-to-noise ratio. This will allow the generation of a rotational diagram for gas-phase methanol as a function of radius. Astrochemical models will be used to simulate the gas-ice chemistry in the protoplanetary disk around TW Hya, and the results compared with the data shown here to determine the likely non-thermal desorption mechanism responsible for releasing methanol into the gas-phase. The modelled abundance of methanol ice will then be compared to cometary abundances to determine the role of protoplanetary disks in setting the composition and chemical complexity of comets.

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