FIRST COMETARY OBSERVATIONS WITH ALMA: C/2012 F6 (LEMMON) AND C/2012 S1 (ISON)

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Introduction: Cometary ices are believed to have aggregated around the time the Solar System formed (c. 4.5 Gyr ago), and have remained in a frozen, relatively quiescent state ever since. Ground-based studies of the compositions of cometary comae provide indirect information on the compositions of the nuclear ices, and thus provide insight into the physical and chemical conditions of the early Solar Nebula. To realize the full potential of gas-phase coma observations as probes of solar system evolution therefore requires a complete understanding of the gas-release mechanisms. However, previous observations have been unable to ascertain the precise origin of fundamental coma species including H_2CO, HCN and HNC, and details regarding the possible formation of these species in the coma are not well understood. Here we report results from the first cometary observations made using the Atacama Large Millimeter Array (ALMA).

We have measured spatially and kinematically-resolved structures in submm emission lines of HCN, CH_3OH and H_2CO from the comae of two bright comets: C/2012 F6 (Lemmon) and C/2012 S1 (ISON). Our observations reveal an unprecedented level of detail in the distributions of these fundamental coma constituents, and address long-standing questions concerning the production/release mechanisms of these species.

Method: Observations of comets F6 (Lemmon) and S1 (ISON) were made using ALMA Band 7 in Cycle 1 (Early Science) mode. Two correlator settings were used per comet to cover spectral lines in the frequency range 339-364 GHz. Comet Lemmon was observed on 2013 May 31 – June 2 (at heliocentric distance r_H = 1.45 AU and geocentric distance Δ = 1.75 AU) with 28-31 antennae; ISON was observed on 2013 November 15-17 (at r_H = 0.54-0.61 AU and Δ = 0.9 AU) with 25-29 antennae. Phase calibration was performed using nearby quasars. Weather conditions were excellent for all observations, with good atmospheric phase stability and low zenith precipitable water vapor (0.5-1.0 mm). The spatial resolution was c. 0.4-0.5'' (with maximum recoverable angular scales c. 5-10''), and the spectral resolution was c. 0.4 km s^{-1}.

The observed visibilities were flagged, calibrated and imaged using standard routines in the NRAO CASA software (version 4.1.0). Image deconvolution was performed using the Hogbom algorithm with natural weighting and a threshold flux level of twice the RMS noise.

Results: The data cubes show spectrally and spatially-resolved structures in HCN, CH_3OH and H_2CO emission in both comets, consistent with anisotropic outgassing from their nuclei. Clear 0.9 mm continuum emission was detected in both comets, showing (unresolved) central peak and (slightly extended) coma/tail components, consistent with nuclear and dust thermal emission, respectively.

Integrated molecular line flux maps (Figure 1) show dramatic differences between the distributions of HCN, CH_3OH and H_2CO emission in comet Lemmon. The HCN and CH_3OH maps are relatively symmetric and peak very close to the origin of the continuum emission (which is assumed to represent the location of the cometary nucleus). H_2CO, on the other hand, shows a remarkable, distributed structure, with multiple peaks at large distances (~ 1000 km) from the continuum peak. Comet ISON, by comparison, shows an H_2CO distribution dominated by a centrally-peaked source, with evidence for a weaker, distributed component at a distance ~ 500 km.

We deduce that HCN and CH_3OH originate from (or very close to) the nucleus (within a few hundred km), whereas H_2CO (in comet Lemmon) is released predominantly in the coma (at nucleocentric distances up to ~ 1000 km). Our ISON observations show that H_2CO can be released both in the coma and from the region of the nucleus. The stark difference between the H_2CO distributions observed in ISON and Lemmon could be a consequence of differing compositions and/or thermal histories of the cometary ices, or differences in the heating rates of the cometary matrial. Preliminary LTE analyses of the CH_3OH line strengths indicate a kinetic temperature of 41 K for Lemmon and 170 K for ISON.

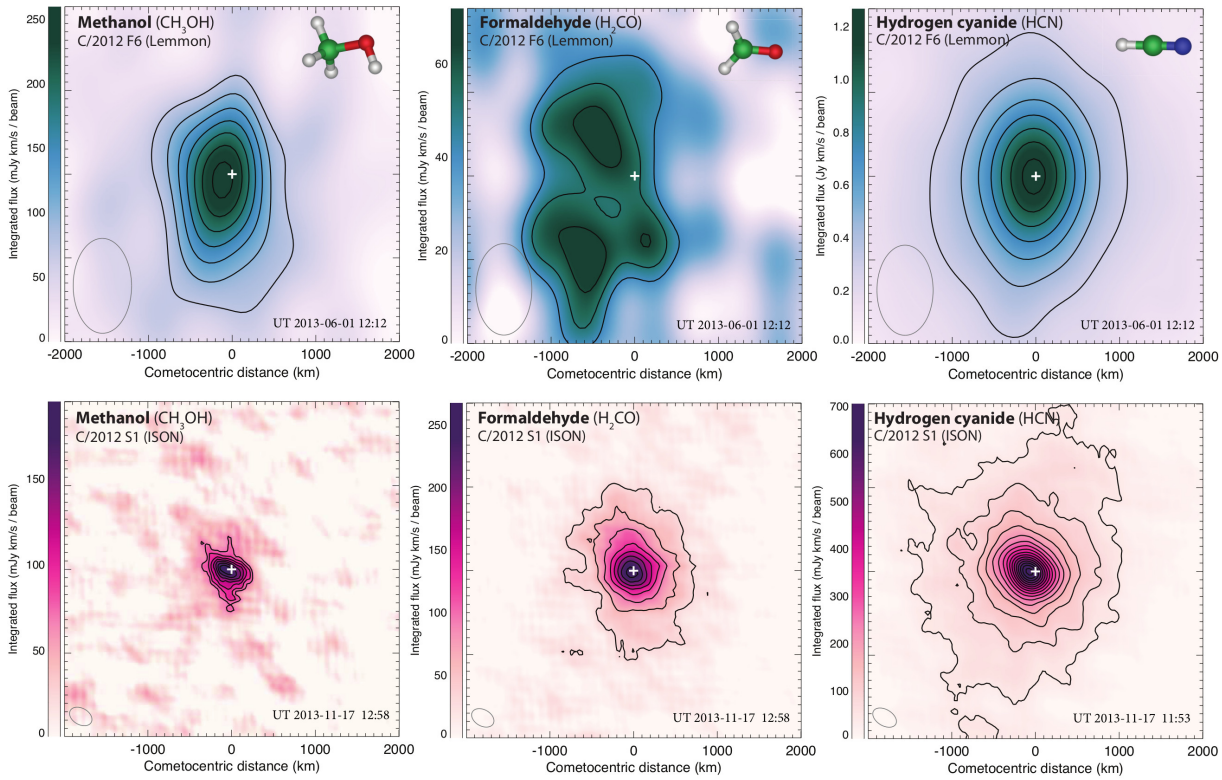

Figure 1. ALMA Band 7 integrated flux maps of molecular lines observed in comets F6 Lemmon (top/blue-green) and S1 ISON (bottom/pink-purple). Spatial resolution (half-power) ellipse dimensions are indicated in lower-left; observation dates and times are given lower-right. White cross denotes the 0.9 mm continuum peak. Formaldehyde and HCN maps are of the $5_{15} - 4_{14}$ and 4 – 3 transitions (with upper-state energy levels E_u = 63 K and 43 K), respectively. Methanol maps are the sum of multiple lines (with E_u = 17-80 K).