Onsala Proposal

Roth 0108.F-9322

Unraveling Comet Photochemistry in Oort Cloud Comet C/2021 A1 (Leonard)

Semester: may2021 **Science Cat.: Solar system**

Abstract

We propose an APEX molecular survey of multiple volatile species toward Oort cloud comet C/2021 A1 (Leonard) as part of a multi-wavelength effort to measure its coma composition and photochemistry. These observations will help constrain the origin of C/2021 A1 in the protosolar nebula, establish molecular abundances, and provide insight into comet chemistry. We will target C/2021 A1 in early December, coinciding with maximum brightness, near its closest approach to Earth, and in coordination with approved NOEMA and proposed ALMA observations. Data obtained with APEX will be complementary to the ALMA and NOEMA observations aiming to measure the temperature, activity, and extended flux of the targeted molecules. Such complementary observations have recently proven successful in observations of comets K1/PanSTARRS, Q2/Lovejoy, and ER61/PanSTARRS.

Applicants

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Is this a long term proposal: No

No overall scheduling requirements

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
A	APEX	SEPIA345 (277-371 GHz)	1h (1h)	353	any	10-20	This configuration will target the HCN (4-3) and H2CO (5_15 - 4_14) transitions. We request observations of the comet in one or more observing blocks between December 5 and December 10. This will coincide with our observations of the comet at other facilities, maximize comet brightness, and maintain sufficient solar elongation.
B	APEX	SEPIA345 (277-371 GHz)	5h (5h)	338	any	10-20	This setting will target multiple strong transitions of CH3OH near 338 GHz to measure the coma temperature along with the CS (7-6) transition. We request observations of the comet in one or more observing blocks between December 5 and December 10. This will coincide with our observations of the comet at other facilities, maximize comet brightness, and maintain sufficient solar elongation.

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
C/2021 A1	14:50:00.00	+20:48:00.0	J2000	0.0	360	A B	The exact LST interval and VLSR will be determined when the observations are scheduled. We request observations over one or more blocks between December 5 and December 10. A detailed ephemeris will be uploaded daily.

Scientific Rationale

Comets are among the most primitive remnants of solar system formation, and are composed of molecular ices along with crystalline silicate dust. Their ices have undergone relatively little processing since their formation [14], and characterizing their native ice composition may provide important clues to the chemistry present in the protosolar nebula where (and when) they formed. The composition of the comet nucleus is inferred predominantly through remote sensing of coma gases. These observations are interpreted using a simple Haser model [11], with species being separated into "parent" (i.e., subliming directly from the nucleus) or "product" (being produced by photolysis or other processes in the coma). However, the observed distributions of some molecules (e.g., H_2CO, HNC, CO) are inconsistent with production by direct sublimation alone and indicate production by unknown parents in the coma ("distributed" sources) [6]. Discerning the coma distributions of these species in a large number of comets will enable us to better understand which molecules are truly "parent" vs. "product" in comets, and in turn better our understanding of the formation of the solar system.

H_2CO: Millimeter studies of bright comets have indicated H_2CO production from an unknown parent source with a scale length of 7000 km at 1 AU [1, 3, 13], whereas ALMA studies of the inner coma suggest a scale length of 1000 - 5000 km [4]. In contrast, near-IR observations indicate H_2CO production from both nucleus ices and coma sources, including increased production from extended sources at small heliocentric distance (r_H) [8]. Polyoxymethylene (POM), the H_2CO polymer, has been suggested as a likely parent based on the comparison of laboratory studies with the r_H-dependence of H_2CO production in Hale-Bopp [1, 10]. However, few comets have been imaged in H_2CO and more observations are needed to understand how this species is produced from comet-to-comet, its production dependence on r_H, and the identity of its parent.

CS: Previous work for other comets has indicated that CS is a product species produced in the inner coma.. Although short-lived CS_2 has been suggested, a precursor has never been conclusively identified [9]. Recent work [15] has suggested distributed source CS production. Coupled with an observed r_H-dependence of CS production in other comets [6] which cannot by explained by CS_2 photolysis, this emphasizes that the source of cometary CS is still not understood. Similar to H_2CO, more imaging of cometary CS is required to constrain its production from comet-to-comet and its origin.

CH_3OH and HCN: In contrast, previous work has shown that HCN and CH_3OH are associated with nucleus sources in many comets [e.g., 4]. CH_3OH can also be used to characterize the physical properties of the coma such as temperature [5]. Characterizing the spatial distributions of HCN, CH_3OH, H_2CO and CS in a comet can therefore provide strong evidence regarding the nature of H_2CO and CS production in comets, including whether they are released from nucleus sources and how their parent scale lengths varies with overall comet activity and r_H.

APEX observations of these molecules in comets are highly complementary to those of ALMA, which provides detailed maps yet resolves out extended flux. Only combined single dish and interferometry observations can provide a comprehensive characterization of the origins, distributions, and abundances of these molecules in comets. APEX is uniquely suited to complement our ALMA observations owing to its similar frequency ranges and close proximity to ALMA. Analysis of these observations will enable us to determine to what extent the targeted species are produced from nucleus or coma sources (or both), to examine how their spatial and velocity distributions compare, and to compare our results with laboratory measurements in order to identify possible parents for molecules originating from distributed sources.

Facilities Requested

The powerful capability of APEX to sensitively measure these molecules has been demonstrated repeatedly through our recent observations of comets C/2012 F6 (Lemmon) (Figure 1), C/2012

K1 (PanSTARRS), C/2012 S1 (ISON), C/2015 ER61 (PanSTARRS), and C/2014 Q2 (Lovejoy) [7]. Our observations of C/2014 Q2 formed part of a large campaign with ALMA, APEX, JCMT, IRAM 30m, and PdBI. The APEX observations precisely measured production rates for HCN, CH_3OH, H_2CO, and CO and provided stringent upper limits for acetaldehyde (CH_3CHO) and formamide (NH_2CO) [7], while our IRAM 30m observations produced the first detections of ethyl alcohol and glycoaldehyde in a comet [2]. APEX is uniquely situated as the only single dish facility that can observe targets at the same time and frequencies as ALMA, as other observatories (e.g., JCMT) are further north. Furthermore, the APEX receivers allow sampling multiple strong transitions of our targeted coma molecules, making it an ideal facility for this study. It is important to note that similar ALMA ACA observations are not guaranteed to be carried out simultaneously with more extended array observations; thus, APEX plays an integral part in fully sampling the millimeter chemistry present in comets.

Observing Requirements

We propose to use the APEX 12m telescope with SEPIA345 to measure production rates of HCN, CS, H_2CO, and CH_3OH in Oort cloud comet C/2021 A1 (Leonard; hereafter Leonard). Leonard will be available from APEX in late November – early December, near closest approach to Earth and maximum brightness. We will conduct our observations simultaneously with ALMA if possible in order to fully sample the production mechanisms and coma distributions of our targeted molecules. We have been awarded time at NOEMA (S21AA, PI Roth) in support of this effort, and have submitted two relevant ALMA proposals for the upcoming Cycle 8: one targeting HDO in Leonard (PI Cordiner) and another targeting sulfur-bearing molecules (e.g., CS, OCS, H_2CS) in a bright comet (PI Roth) for which Leonard is a potential candidate.

We find that the intensity of cometary rotational transitions scales with a Figure-of-Merit (FoM = $Q(H_2O[10^{28}])\Delta^{-1}$), where Q is the H_2O production rate (s^{-1}) and Δ is geocentric distance (au). We request approximately 6 hours of observing time over 1 or more transits of the comet in coordination with ALMA. Optimal dates are December 5 – December 10, when the comet will be near FoM = 20 yet sufficiently far from the sun ($\geq 30°$) for APEX solar elongation constraints. Data will be taken in position switching mode and employ a spectral resolution of 0.20 km s^{-1}, providing sufficient resolution to characterize the activity of coma gases. We will upload a comet ephemeris daily. The APEX observing time calculator (V 7.3) was used to calculate observing time estimates for the targeted species (Table 1), including overhead. We assumed a nominal $Q(H_2O)$ of 6E28 s^{-1} at $r_H = 0.8$ au and $\Delta = 0.3$ au, corresponding to FoM = 20, along with abundances (%) of 0.1 for HCN, 0.3 for H_2CO, and 2 for CH_3OH. We predicted $Q(H_2O)$ using an empirical relationship between Q and heliocentric magnitude (m_H), where $m_H = m_V - 5 \log \Delta$ [12]. Predicted abundances are averages among measured Oort cloud comets such as Leonard [8]. Exact abundances of each species are not known in advance and have been shown to vary from comet-to-comet, as well as from day-to-day within a particular comet. Our estimated total observing time of $\sim$6 hours (including overhead) is for 1.5 mm pwv, 5σ rms levels, and an average elevation of 40°.

Observing Plan and Scheduling Requirements

We will sample the HCN (4–3) and H_2CO ($5_{1,5}$–$4_{1,4}$) transitions in a single spectral setup, followed by the CS (7–6) and multiple CH_3OH = (7_K–6_K) transitions near 335–338 GHz in a second spectral setup, using 0.2 km s^{-1} spectral resolution in both instances. The HCN measurement will provide an overall gauge of cometary activity and the CH_3OH measurements will provide a measure of the coma temperature. We request 1 or more observing blocks between December 5 – December 10 to complement our observations of Leonard at other facilities while maximizing comet brightness and maintaining sufficient solar elongation.

Figures

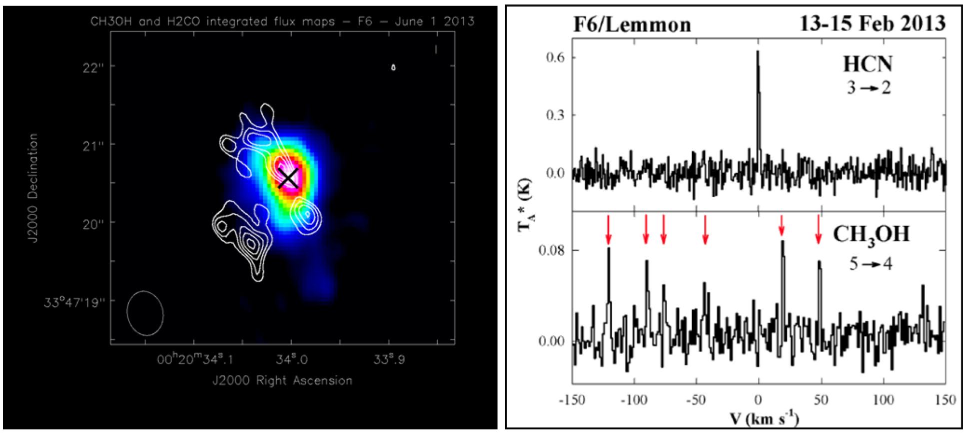

Figure 1: (left): ALMA Band 7 maps of CH_3OH (color map) and H_2CO (white contours) observed in comet F6 (Lemmon) on June 1st 2013. These show a compact 'primary' source for CH_3OH and an extended/distributed source with scale-length ∼1000 km for H_2CO. A black cross denotes the 0.9 mm continuum peak. All observations were performed simultaneously and the on-source integration time was 22 min. The lowest flux levels displayed are 3:5σ. (right): Sample spectra recently obtained for Comet C/2012 F6 (Lemmon) from APEX in February 2013, FOM=28, of HCN (3-2) (18 min integration time) and multiple lines of CH_3OH near 242 GHz (47 min integration time) used to determine the comet's volatile composition and probe the temperature in the coma.

Table 1: Target Molecules and Transitions in C/2021 A1 Leonard

Setting 1: HCN and H_2CO			Setting 2: CH_3OH, CS, and $T_{\rm kin}$		
Transition	$\nu_{\rm rest}$ (GHz)	Time (hr)	Transition	$\nu_{\rm rest}$ (GHz)	Time (hr)
HCN(4–3)	354.505	0.13	CS(7–6)	342.882	0.50
H_2CO ($5_{1,5}$-$4_{1,4}$)	351.768	0.92	CH_3OH (multiple)	335–338	4.7

Note: Estimated total integration times for 5σ detections. (a) All estimates assume a nominal water production of 6E28 s^{-1} at $r_{\rm H}$=0.8 au, Δ=0.3 au, gas expansion velocity $v_{\rm exp}$=0.87 km s^{-1} and $T_{\rm kin}$=75 K, corresponding to FoM=20 on a representative date of UT 2021 Dec. 7. (b) The total time includes ON+OFF time with observational overheads (setup and calibration). We assumed a water column of 1.5mm for all species.

References

REFERENCES: [1] Biver, N., et al. 1999, AJ, 118 1850 [2] Biver, N., et al. 2015, Sci. Adv., 1, 1500863 [3] Bockelée-Morvan, D., et al. 2000, A&A, 353, 1101 [4] Cordiner, M., et al. 2014, ApJL, 792, L2 [5] Cordiner, M., et al. 2017, ApJ, 837, 177 [6] Cottin, H. & Fray, N. 2008, SSRv, 138, 179 [7] de Val-Borro, M., et al. 2018, MNRAS, 474, 1099 [8] Dello Russo, N., et al. 2016, Icarus, 278, 301 [9] Feldman, P., et al. 2004, in Comets II, U. of A. press, 425 [10] Fray, N., et al. 2006, Icarus, 184, 239 [11] Haser, L. 1957, Bull. Classe des Sciences Aca. Roy. Belgique, 43, 740 [12] Jorda, L. et al. 2008, in ACM Book of Abstracts, Baltimore, MD 8046 [13] Milam, S., et al. 2006, ApJ, 649, 1169 [14] Mumma, M. & Charnley, S. 2011, ARA&A, 49, 471 [15] Roth, N., et al. 2021, arXiv, https://arxiv.org/abs/2104.03210

No PhD Students involved

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Relevant previous Allocations: Yes

"A Search for Distributed Sources in a Target of Opportunity Comet" designated 0107.F-9314. Not triggered due to lack of suitable target within the semester.

"A Search for Distributed Sources in a Target of Opportunity Comet" designated 0105.F-9315. All observing time lost due to APEX COVID shutdown.

"Determining the HDO/H2O ratio and chemical composition in a ToO comet" designated 100.F-9320(A,B), publication in progress

"Investigating isotopic composition and chemistry in a ToO comet", 099.F-9323, publication in progress

"Complementary Multiwavelength studies of comet C/2012 K1 (PanSTARRS) designated 094.F-9321, publication in preparation

"Constraining Comet Chemistry in a New Dynamic Comet: A Target of Opportunity Proposal" designated 094.F-9307, 5 hours, not triggered

"Multiwavelength Observations of the 'Comet of the Century': Comet C/2012 S1 (ISON)" designated 092.F-9321(A), 4 hours, in preparation

"Multiwavelength Observations of the Oort Cloud Comet C/2011 L4 (PanSTARRS)" designated 091.F-9324(A), 18 hours, time reallocated to F6 Lemmon. Publication in preparation.

"APEX observations of comet C/2012 F6 (Lemmon) in support to Open-Time Herschel measurement of the D/H ratio in water" designated 091.F-9331(A), 16 hours, complete. Publication in preparation.

"Determining the Origin and Composition of Oort Cloud Comet C/2010 X1 (Elenin)" designated 088.F-9312(A), 25 hours, not observed due to no comet activity

"A Multiwavelength Effort to Determine Comet Taxonomy: A Target of Opportunity Proposal" designated 093.F-93016(A), 5 hours, not triggered.

Additional remarks

ESO = nxrq67

Observing run info :