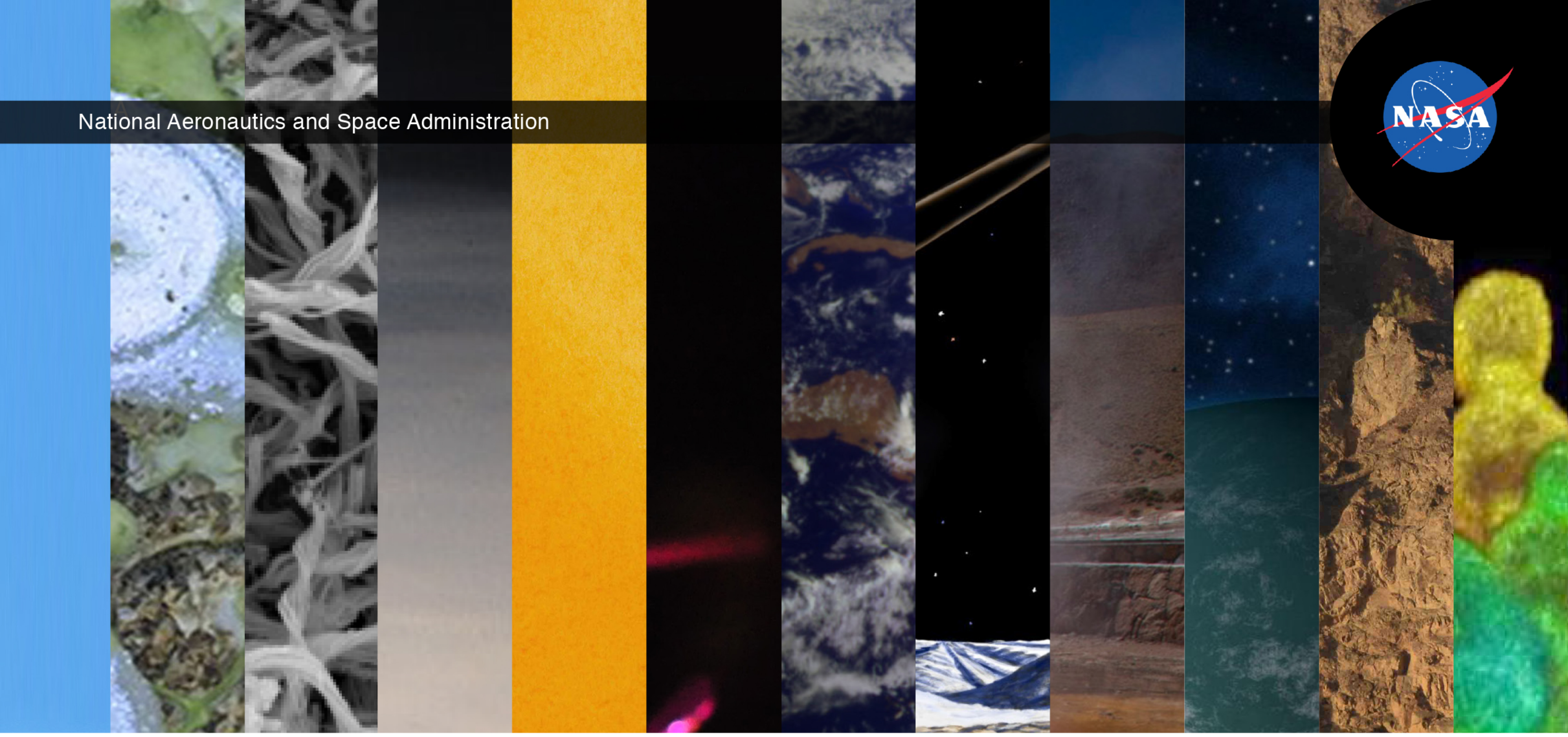
National Aeronautics and Space Administration

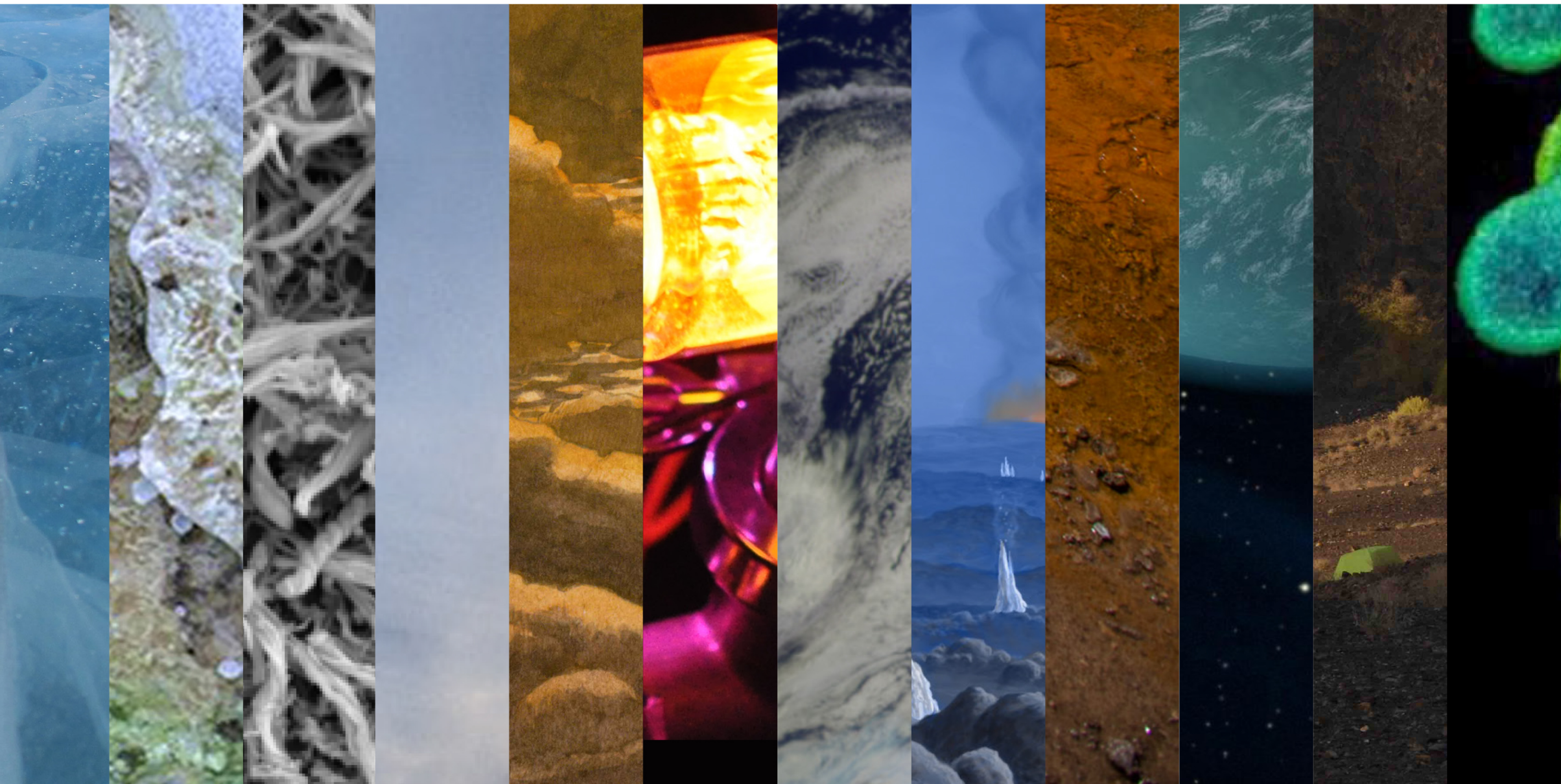


NASA Astrobiology Institute

2017 Annual Science Report

Origin and Evolution of Organics and Water in Planetary Systems

NASA Goddard Space Flight Center



Origin and Evolution of Organics and Water in Planetary Systems

Lead Institution:
NASA Goddard Space Flight Center

Principal Investigator:
Michael Mumma

Team Overview

The Goddard Team targets the Origin and Evolution of Organics and Water in Planetary Systems, in short – Why is Earth Wet and Alive? We address this central question through an integrated program of (a) pan-spectral astronomical observations of comets, circumstellar disks, and exoplanet environments, (b) models of chemical evolution and dynamical transport in the early Solar System, (c) laboratory studies of extraterrestrial samples, and (d) realistic laboratory and numerical simulations of inaccessible cosmic environments.

Synergistic integration of these areas is essential for testing whether delivery of life's building blocks – exogenous water and prebiotic organics – enabled the emergence and development of the biosphere. As humankind plans searches for life elsewhere in the Solar System, our Team develops (e) instrumental protocols to search for life's fundamental molecules – the informational polymers without which "life as we know it" would not exist.

- From Comets and Asteroids to Planets: Organics as a Key Window into Emergent Earth
- Organic Compounds in Authentic Extraterrestrial Materials: The Ultimate Rosetta Stones
- Laboratory Simulations of Formative Processes in Cosmic Ice and Dust Analogues
- From Molecular Cores to the Protoplanetary Disk: Our Interstellar Organic Heritage
- Analytical Protocols for Detection and Diagnosis of Life's Molecular Compounds

Team Website: https://astrobiology.gsfc.nasa.gov

2017 Executive Summary

Team members pursued a vigorous and highly productive research program in all five topical areas, conducting many investigations in the laboratory and in the field (mainly astronomical).

What material was delivered to "barren" Earth? We sampled material in/from additional primitive bodies identified as plausible "carriers", and established their compositional diversity–including chemical, isomeric, isotopic, chiral, and nuclear-spin signatures. We quantified volatile composition and isotopic ratios in four comets, and expanded to 34 comets our taxonomy based on composition. In depth analysis of 23 comets revealed evidence of a new class of material in the cometary nucleus, with astrobiological significance (Mumma et al., in prep.). Compared with 'normally-active' comets in this group, disrupting comets were found to be enriched in HCN and NH_3 relative to ethane.

From ALMA observations of disrupting comet C/2012 S1 (ISON), GCA scientists produced time-sequenced emission maps for HNC, HCN and H_2CO (Cordiner et al. 2017b). While HCN was released directly from the nucleus of comet ISON, HNC originated in the coma from decomposition of nitrogen-rich refractory organic material. This finding addresses a 30-year puzzle on the ratios of isomers HNC and HCN in comets. We published new results for deuterium enrichment in cometary water, showing that in C/2014 Q2 (Lovejoy) the D/H ratio was enriched by a factor of 1.9 relative to Earth's oceans. We initiated a search for hydrogen deuterium oxide (HDO) in comets using the newly commissioned iSHELL at NASA's Infrared Telescope Facility on Maunakea, an advanced IR spectrometer that should make such detections routine. Using now-mature procedures for molecular fluorescence in comets, we initiated a program to re-analyze data for all comets in our 30-year database, to eliminate systematic uncertainties that may have been introduced by changing molecular models.

We continued to focus on better understanding the origin of meteoritic amino acids and their chiral excesses, as well as potentially related organic compounds. We identified potential pathways for formation of glycine and methylamine – the simplest amino acid and its related amine (Aponte, Elsila, et al. 2017). We expanded our previous investigations into the correlation between amino acids and amines, publishing results from the analysis of a series of CV, CO, and CK chondrites (Aponte, Abreu, et al. 2017). With large consortia, we participated in analyses of recently discovered meteorites, including the Sariçiçek Howardite. We continued to develop new work exploring amino acid correlations with structurally related species and other organic compounds, such as hydroxy acids, ketones, aldehydes, carboxylic acids, and aromatic hydrocarbons.

Did Earth Receive its Water and Pre-biotic Organics from Comets? From Asteroids?
Background image credit: NASA/JPL/USGS

Fig. 1. The nucleus of comet 67P/Churyumov-Gerasimenko, revealing its primordial nature. Image credit: ESA / Rosetta / MPS for OSIRIS Team

How was prebiotic matter synthesized and processed in the solar nebula, prior to being incorporated into such carriers? Scientists in the Nucleation and Dust Chemistry Laboratory investigated organic molecule formation on dust grains by surface-mediated reactions, and their implications for incorporating carbonaceous materials into planetesimals. They demonstrated that CO's efficient conversion into solid forms solves a conundrum about "trapping" gaseous carbon in the early solar nebula, and that growth of carbon deposits on mineral surfaces may increase the efficiency of coagulation in the hot inner nebula. In 2017, they continued investigations on the rates and products of such reactions over a large range in time, temperature, pressure, catalyst composition and secondary reactions, simulating processes that could have occurred in the solar nebula. Visiting scientist Chaitanya Giri (ELSI Tokyo Tech) investigated surface mediated reactions using SiC, FeS, and Fe_3P. In particular, the goal was to examine the resulting coating for possible incorporation of the anion into the organics.

Scientists in the Cosmic Ice Laboratory emphasize the identification and quantification of organic molecules known or suspected to be of astrobiological significance, or related to molecules that are of such significance. They quantified infrared (IR) spectral assignments, band strengths, and structural changes for ethanol ice, over temperatures relevant to the interstellar medium (ISM) (Hudson 2017a). They reported the first ever IR band strengths for solid acetone, the simplest ketone (Hudson et al. 2017), and explored its radiation chemistry, showing its decomposition into ketene from which a number of other products can form (Hudson 2017b). With URAA summer Fellow Sarah Frail (Univ. MD), Gerakines and Hudson carried out experiments on the radiolytic destruction of uracil (an RNA nucleobase) at 10-150 K. These were the first *in situ* experiments of their type and are now being prepared for publication.

How was prebiotic matter synthesized and processed in the interstellar medium prior to being carried into the solar nebula? A major focus of this work is to connect interstellar organic chemistry, protoplanetary disk chemistry, and the composition of Solar System bodies. Observational and theoretical studies can elucidate the range of compounds possibly available for prebiotic chemistry or central to it. In the dark molecular cloud TMC-1, Cordiner et al. (2017a) detected a new interstellar molecule, HC_7O (1-oxo-hepta-2,4,6-triynyl), as predicted by theoretical models of interstellar anion chemistry.

The Blake group (CalTech) followed up its detection of the first chiral species in the interstellar medium with an extensive survey of propylene oxide rotational lines, detecting several new lines using the Effelsberg and Green Bank telescopes. They also advanced the measurement of the cm- and mm-wave analog of Circular Dichroism, which may ultimately enable remote studies of enantiomeric excesses of chiral compounds in molecular clouds and disks. Success would profoundly affect our ability to relate the chirality of amino acids measured in primitive meteorites in our Astrobiology Analytical Laboratory to their potential chemical origin in the Solar System's natal interstellar cloud core. For unknown reasons, the amino acids used by life are L-type only while both L- and D-type are found in primitive meteorites.

Blake's work on the water snow line in proto-planetary disks has used both infrared observations with CRIRES and NIRSPEC (Banzatti et al. 2017) and Herschel (Du et al. 2017). Related work on snow lines involving carbonaceous molecules has focused on an extensive theoretical analysis of the destruction of refractory carbon grains in the upper layers of disks (Anderson et al. 2017). Snow lines may strongly

Fig. 2. The Rosetta Stone, British Museum. Credit: Bettmann/CORBIS

influence the composition of ices that accumulate into icy cometesimals formed within/beyond individual snowline locations, and thus may affect the heterogeneity of cometary nuclei.

Can we provide new tests of conditions amenable to life elsewhere in our Planetary System? We also obtained revolutionary new results on the biological potential of Titan. The prospect of life on Titan has engaged many authors, leading to a thorough study of chemicals that could fulfill the role of lipids in forming membranes at temperatures where methane is liquid but water is 'rock'. Of 10,000 compounds considered, Stevenson et al. (*Sci. Adv.* 2015;1:e1400067) showed, that acrylonitrile (aka vinyl cyanide) is one of the most favored to form thermodynamically stable membranes (azotosomes) in liquid methane at the surface temperature of Titan (approximately 94 K). In Palmer et al. (2017), we reported the discovery of acrylonitrile (C_2H_3CN) in the atmosphere of Titan. Palmer et al. demonstrated that very high concentrations could result if acrylonitrile rained out into Titan's second largest lake, Ligeia Mare. Thus, the feedstock for azotosome formation is present on Titan in adequate amounts, a finding with important implications for Titan's astrobiological potential. Our subsequent study (Lai et al., 2017) found even more spectral lines, and mapped the spatial distributions of C_2H_3CN and other major nitriles in Titan's atmosphere.

Paganini, Mumma, and collaborators conducted a deep survey at IR wavelengths seeking spectral signatures of H_2O plumes on Europa. A total of 20 half-nights were awarded at Keck-2 for this study; the observations and analysis are complete and the results are being prepared for publication. Mumma, Villanueva, Faggi, and Novak conducted a deep search for methane, H_2O, and HDO on Mars using iSHELL at NASA's IRTF, during early summer in the North (L_s ~120). Analysis is in progress.

Can we define new instrument protocols to extend our knowledge of the complexity of organic compounds in mission targets relevant to astrobiology? We continue to explore the potential application of novel nanopore-based detection and sequencing of informational biopolymers for future missions to Mars and ocean worlds such as Europa or Enceladus. In 2017, we contributed to the development and testing of DNA-sequencing capabilities carried out on the International Space Station, with co-authorship (Dworkin, Burton) on a resulting paper (Castro-Wallace et al. 2017).

Project Reports

From Comets and Asteroids to Planets: Organics as Key Windows into Emergent bio-Earth

GCA scientists quantify the diversity of chemical composition among comets, to assess their potential for delivering pre-biotic organic materials and water to young (barren) planets.

2017 was a banner year, with apparitions of three long period comets from the distant Oort Cloud reservoir and four ecliptic comets from the Kuiper Belt. GCA scientists led or participated in multiple investigations, and results were submitted and/or published during 2017 for one comet from each reservoir. Results from these seven comets extend our 30-comet taxonomy very considerably.

Using the recently commissioned high-resolution IR spectrograph (iSHELL) at NASA's Infrared Telescope facility on Maunakea, HI, DiSanti et al. (2017) measured production rates for H_2O and eight trace gases (CO, CH_4, C_2H_6, H_2CO, CH_3OH, C_2H_2, HCN, NH_3) in ecliptic (Jupiter-family) comet 45P/Honda-Mrkos-Pajdušáková shortly after its perihelion passage (Fig. 3A). In an independent study, Mumma, Villanueva, Paganini, and Postdoctoral Fellow Sara Faggi acquired IR spectra of three Oort cloud comets with iSHELL, including C/2017 E4 (Lovejoy) which appeared unexpectedly during observations of two other Oort Cloud comets at the NASA-IRTF (Fig. 3B).

In 45P, DiSanti et al. emphasized measurement of CO and CH_4, the two most volatile ices systematically measured in comets entering the inner solar system from the Oort cloud. Owing to limitations in sensitivity and observational circumstances, statistics on their abundances in ecliptic comets are severely lacking. This work provided the most robust values to date for both these "hyper-volatiles" in an ecliptic comet, and so laid a foundation for building meaningful statistics regarding their abundances. Relative to H_2O, CO was severely depleted in comet 45P compared with its median value among Oort cloud comets, whereas CH_4 was consistent with its median value (Fig. 4). This supports retention of a significant primitive record in a comet experiencing repeated passages to within 0.6 AU of the Sun.

Mumma et al. used both scheduled and Director's time to observe long period comet E4 Lovejoy in April 2017, soon after its discovery, and fortunately so – the comet disrupted completely several weeks later, near 0.5 AU heliocentric distance. Nine primary volatiles

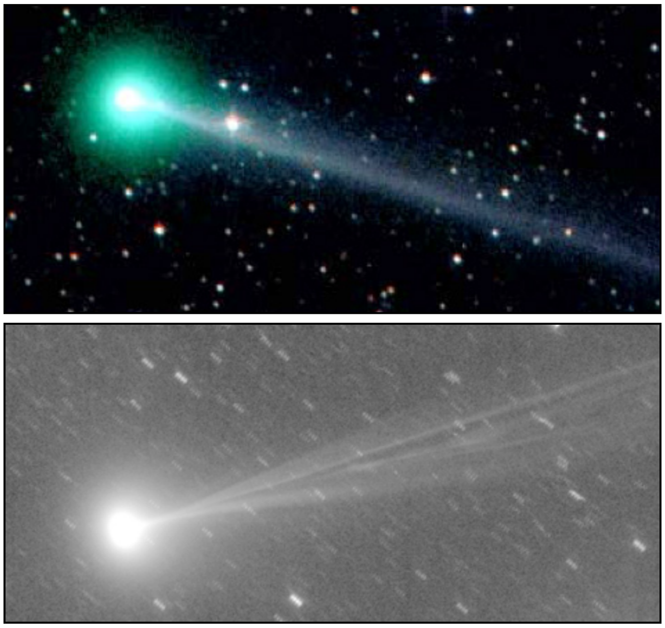


Fig. 3. Optical images of recent comets. ***A)*** *Ecliptic comet, 45P/H-M-P.* ***B)*** *Oort Cloud comet, C/2017 E4 (Lovejoy). Both comets show long narrow tails from ionized gases but dust tails are missing, reflecting their gas-rich and dust-poor nature. Image credits: galeriadometeorito.com/ GianLucaMasi-VTP/Michael Schwartz-TO*

(same as for 45P, Fig. 4) and three product species were quantified (Faggi et al. (accepted). HCN and NH_3 were enriched significantly relative to ethane, placing E4 among the group of disrupting comets that display this property. Mumma et al. (in prep.) suggest that this behavior stems from disruptive ejection of a previously unrecognized fraction of the cometary nucleus that is thermally activated in the coma. If delivered intact to young planets the proposed fraction has major implications for astrobiology.

GCA scientists continued their pioneering leadership of cometary molecular astronomy with the Atacama Large Millimeter/submillimeter Array (ALMA). They addressed a 30-year puzzle in cometary chemistry – accounting for the presence of HNC, the metastable isomer of HCN. The abundance ratio HNC/HCN is very small in comets beyond 2 AU heliocentric distance but increases dramatically (to ~0.2-0.3) for comets within 0.5 AU of the Sun; the explanation eludes current models. Revisiting ALMA observations of comet C/2012 S1 (ISON), Martin Cordiner and colleagues produced time-sequenced emission maps (Fig. 5) for HNC, HCN and H_2CO (Cordiner et al. 2017b). While HCN was released directly from the nucleus of comet ISON, HNC originated in the coma from decomposition of nitrogen-rich refractory organic material.

Making accurate measurements of molecular abundances requires an understanding of thermal structure in cometary comae, including spatial variations in the rotational temperatures. Until now, only stepped maps with single aperture telescopes were feasible and spatial resolution was severely limited by telescope size. With ALMA, GCA scientists simultaneously mapped many methanol emission lines over the inner coma of comet C/2012 K2 (PanSTARRS), and so derived a map of the CH_3OH rotational temperature (Cordiner et al. 2017a). Detailed modeling of these results suggests the presence of a previously-unknown heat source in the inner coma.

The (D/H) isotopic ratio in cometary water is often compared with ocean water (VSMOW), to assess the possible role of comets in delivering water to Earth. Among 13 comets with detected HDO since 1986, the D/H ratio ranged from one to four times VSMOW. For the 14th comet, Paganini et al. (2017) reported HDO and H_2O in C/2014 Q2 (Lovejoy) at 1.9 VSMOW -

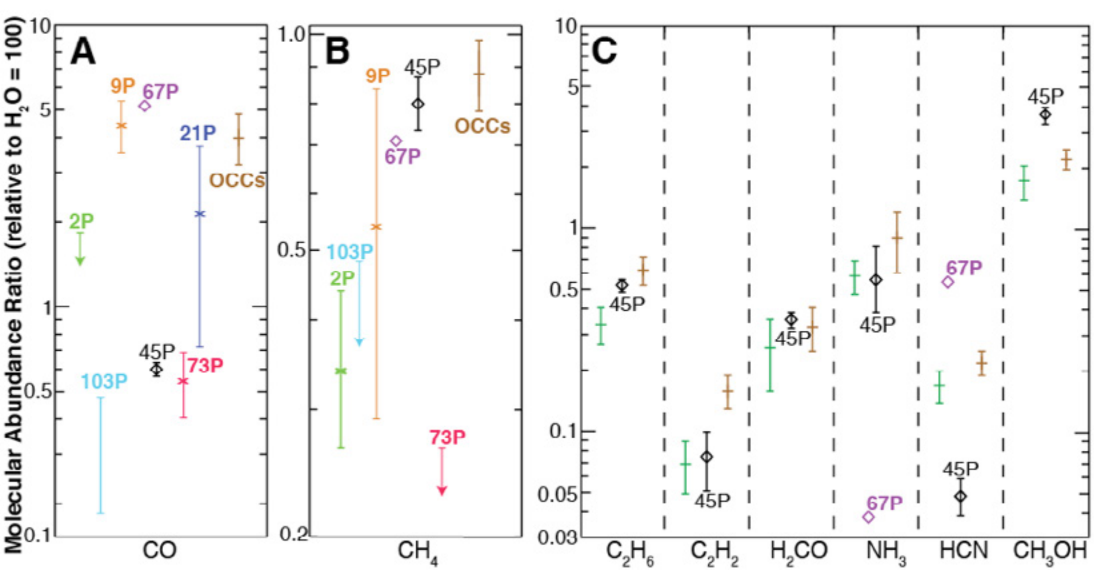


Fig. 4. ***A, B)*** *Abundance ratios of CO and CH_4 in 45P (with ±1σ error bars) and in previously measured ecliptic comets (ECs; upper limits are 3σ) and median values among Oort cloud comets (OCCs; in brown). Given the paucity of previous measurements of these species in ECs, no meaningful statistics exist, and 45P lays a foundation.* ***C)*** *Abundances for additional trace volatiles in 45P, and median values among ECs (green) and OCCs (brown). Abundance values for the inner coma of 67P were measured in situ with the ROSINA mass spectrometer aboard Rosetta (Gasc et al. 2017, MNRAS, 469, S108). From DiSanti et al. 2017.*

a factor of 2 larger than that measured by radio astronomers several weeks earlier (Biver et al. 2016), questioning whether Lovejoy 'aged' as it passed through perihelion or if the measurements were imperfect. Diversity is expected–and seen–amongst the comet population, but convergence and interpretation requires that many more comets be sampled. The new generation of IR spectrometers (e.g., iSHELL) promises to enable regular high-confidence measurements of D/H in cometary water.

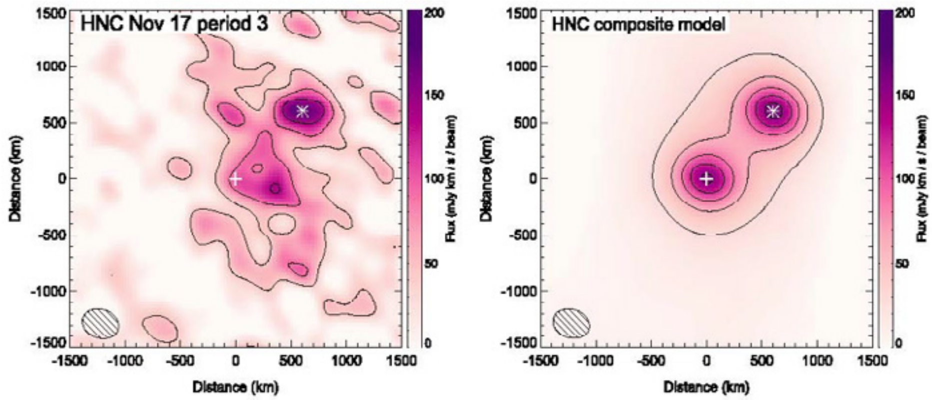


Fig. 5. ALMA map of HNC in C/20112 S1 (ISON), showing extended production in the coma (x) and offset from the nucleus (+). Left: integrated flux map for HNC on November 17, period 3. Right: best-fitting two-component (composite) HNC production model. After Cordiner et al. 2017b.

Analysis of Prebiotic Organic Compounds in Astrobiologically Relevant Samples

We continued to focus on better understanding the origin of meteoritic amino acids and their chiral excesses, as well as potentially related organic compounds. This year, we published a manuscript describing potential formation pathways for glycine and methylamine – the simplest amino acid and its related amine (Fig. 6; Aponte, Elsila et al. 2017). We expanded our previous investigations into the correlation between amino acids and amines, publishing a paper on the analysis of a series of CV, CO, and CK chondrites. We contributed to the development and testing of DNA-sequencing capabilities carried out on the International Space Station, with co-authorship on a resulting paper (Castro-Wallace et al. 2017). We participated in analyses of recent meteorite discoveries with large consortia. We continued to develop new work exploring amino acid correlations with structurally related species and other organic compounds, such as hydroxy acids, ketones, aldehydes, carboxylic acids, and aromatic hydrocarbons (Fig. 7; Aponte, Abreu et al. 2017). We also continued a variety of collaborations, including one using NASA high-end computing models to explore the degradation of amino acids under meteoritic conditions and another aimed at studying organic compounds in micrometeorites. We hosted an Undergraduate Research Associate in Astrobiology (URAA) summer Fellow, who studied meteoritic monocarboxylic acids, while two previous URAA Fellows presented research results at conferences.

We led the authorship of a book chapter on the origin and evolution of prebiotic organic compounds in meteorites (Glavin et al. 2017), and also participated in workshops and conferences related to this theme. We continue to leverage our expertise and facilities to develop novel instrumentation for future spaceflight.

We continue involvement in multiple NASA flight missions and mission proposals, with key involvement in the CAESAR comet sample return mission that was selected for Phase A study in the New Frontiers 4 competition. We also continue to support the Sample Analysis at Mars (SAM) instrument on the Curiosity rover via laboratory instrument analogs.

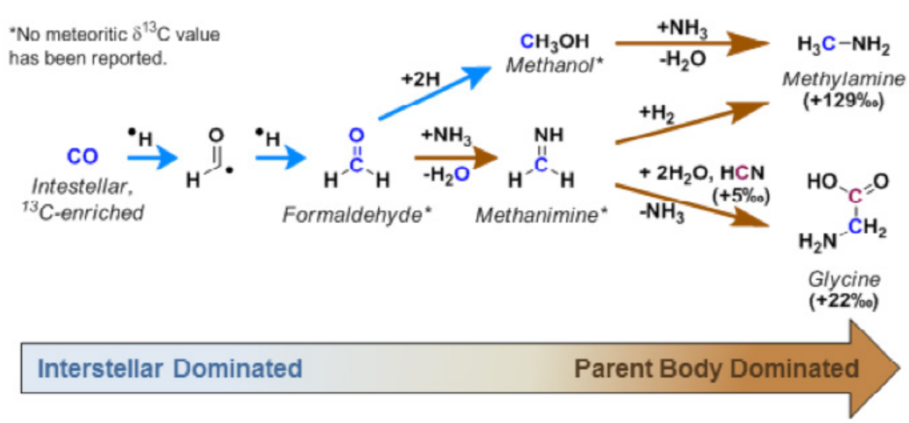


Fig. 6. Possible pathways to the formation of meteoritic glycine and methylamine (from Aponte, Elsila, et al. 2017).

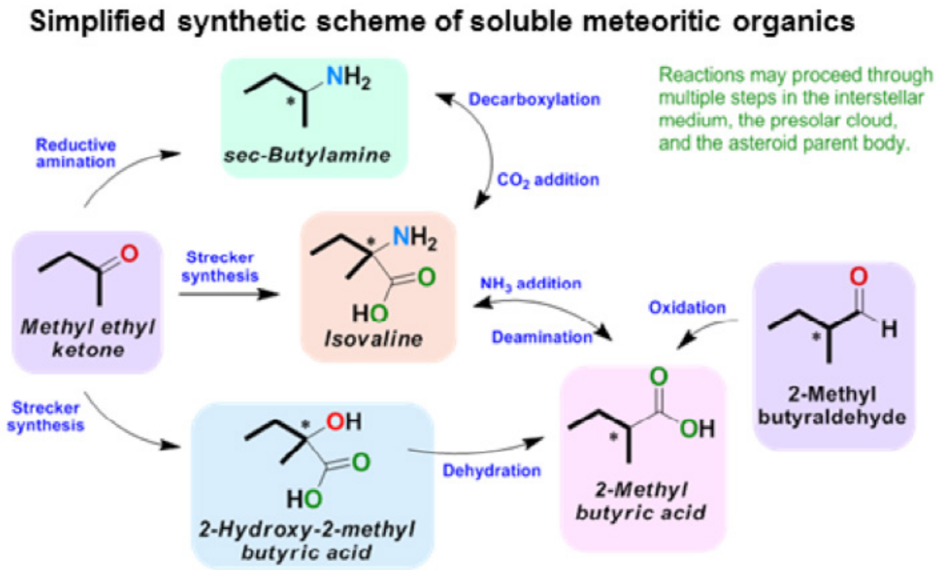


Fig. 7. Potential synthetic connections among meteoritic organic compounds. After Aponte, Abreu et al. (2017).

Surface Mediated Reactions in the Primitive Solar Nebula

In our Nucleation and Dust Chemistry Laboratory, Natasha Johnson and Joseph Nuth investigated the formation of complex hydrocarbons from gas-phase CO via surface-mediated reactions using simple gases (CO, N_2, and H_2) on almost any grain surface. Hydrogen, carbon monoxide and nitrogen were abundant in the primitive solar nebula. If absorbed on the surfaces of silicate dust and metallic grains, they can react and produce an abundance of carbon-bearing products including volatile hydrocarbons, amines, alcohols, aldehydes, and acids as well as more complex, less volatile species such as carbon nanotubes. For the primitive solar nebula, surface mediated reactions might provide a solution for a problem that modern chemical models of nebular processes do not address; namely, the conversion of large quantities of CO and carbon dioxide generated by high temperature reactions under oxidizing conditions back into solid carbonaceous species that can be more easily incorporated into planetesimals. We also determined that refractory carbonaceous deposits catalyze additional surface reactions. We are working to understand the rates and products of such reactions given the large range in time, temperature, pressure, catalyst composition and secondary reactions that could occur in nebular environments.

Higher temperature experiments are also being explored using a dedicated system to further investigate the CO loss using different Fe-based substrates. We are also looking into the 'dusting' or sequestering of iron into the hydrocarbons and the possible formation of iron carbides. These reactions appear to occur over a much wider temperature range than expected (Fig. 8).

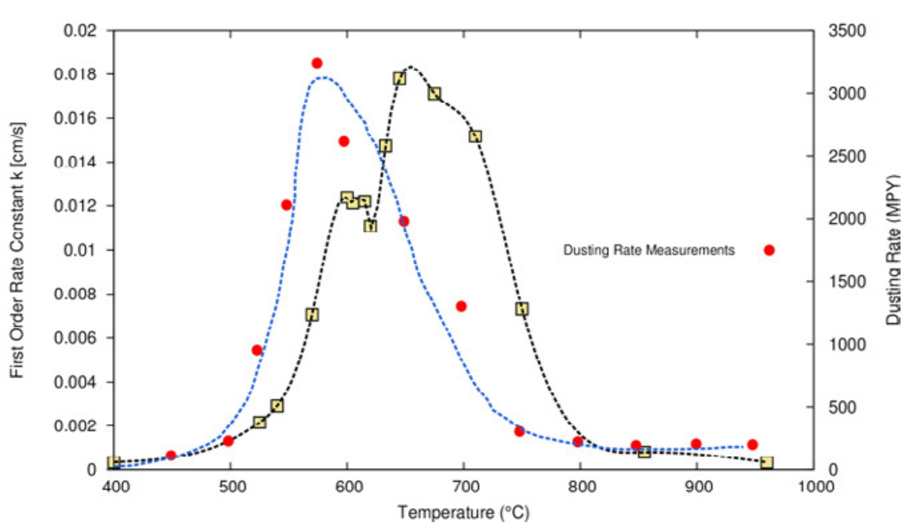


Fig. 8. The rate of CO loss as a function of temperature in our experiments is compared to those measured for production of Fe carbides in "Mechanisms of Metal Dusting Corrosion of Iron" C.M. Chun, J.D. Mumfort, and T.A. Ramanarayanan, Journal of the Electrochemical Society 149 (7) B348-B355 (2002), demonstrating that at least two chemical processes are occurring in our experiments. Note that the Fischer-Tropsch process primarily occurs below 500 C, producing volatile hydrocarbons: the higher temperature processes produce solid carbon or carbides.

We hosted a colleague this summer, Chaitanya Giri – from ELSI Tokyo Tech – who was co-located with us and Carnegie. He ran surface mediated reactions using SiC, FeS, and Fe_3P. In particular, the goal was to examine the resulting coating for possible incorporation of the anion into the organics. These experiments were completed and the analyses are beginning. These experiments will be continued and the necessary characterization of the resulting products will allow us to renew collaborations with DTM colleagues. We are also continuing our recent collaborations with the Rosetta COSIMA team using our carbonaceous products to understand their measurements of C-rich comet dust. A collaborative review was completed during this period with Tim McCoy (NMNS) (Nuth, McCoy, & Johnson 2017).

Interstellar Chemistry, Protoplanetary Disks and Early Solar System Processes

A major focus of this work is to connect interstellar organic chemistry, protoplanetary disk chemistry, and the composition of Solar System bodies. Observational and theoretical studies can elucidate the range of compounds possibly available for prebiotic chemistry or central to it.

Expanding the known inventory of interstellar molecules is a fundamental goal for astrobiology since these molecules can eventually become incorporated into planet-forming disks. Cordiner et al. (2017c) used the 100m Green Bank telescope to search for many new organic molecules in the dark molecular cloud TMC-1. A new molecule, HC_7O (1-oxo-hepta-2,4,6-triynyl), was detected, as predicted by theoretical models of interstellar anion chemistry. Upper limits were also obtained for related carbon chains, as well as prebiotically-interesting species such as pyrimidine, quinoline and isoquinoline.

The Blake group (CalTech) followed up its detection of the first chiral species in the interstellar medium with an extensive survey of propylene oxide rotational lines using the Effelsberg and Green Bank telescopes. Several new detections were made, and are presently being written up for publication. And, laboratory work is proceeding on the measurement of the cm- and mm-wave analog of Circular Dichroism, which may ultimately enable remote studies of enantiomeric excesses of chiral compounds in molecular clouds and disks. Success would profoundly affect our ability to relate the chirality of amino acids measured in primitive meteorites in our Astrobiology Analytical Laboratory to their potential chemical origin in the Solar System's natal interstellar cloud core. For unknown reasons, the amino acids used by life are L-type only while both L- and D-type are found in primitive meteorites.
In protoplanetary disks, we have continued our extensive observational and theoretical analysis of their chemical composition and snow lines. Our work on the water snow line in disks has used both infrared observations with CRIRES and NIRSPEC (Banzatti et al. 2017) and Herschel (Du et al. 2017). Related work on snow lines involving carbonaceous molecules has focused on an extensive theoretical analysis of the destruction of refractory carbon grains in the upper layers of disks (Anderson et al. 2017). Snow lines should strongly influence the composition of ices that may accumulate into icy cometesimals formed within/beyond their locations, and thus the heterogeneity of local cometary nuclei.

We also obtained revolutionary new data on the atmospheric chemistry of Solar System planets and moons, with ALMA. In Science Advances, we reported the discovery of vinyl cyanide (C_2H_3CN) in the atmosphere of Titan, Saturn's largest moon (Palmer et al. 2017). Palmer et al. also explored the plausibility that C_2H_3CN on Titan could spontaneously form membrane-like vesicles ("azotosomes") analogous to the lipid membranes fundamental to cellular life on Earth. We found that there may indeed be sufficient C_2H_3CN present such that rainout into Ligeia Mare (Titan's second largest lake) could result in very high azotosome concentrations, a finding with important implications for Titan's astrobiological potential. A subsequent study by Lai et al. (2017) found even more C_2H_3CN lines and allowed mapping of the spatial distributions of C_2H_3CN and other major nitriles present in Titan's atmosphere (Fig. 9).

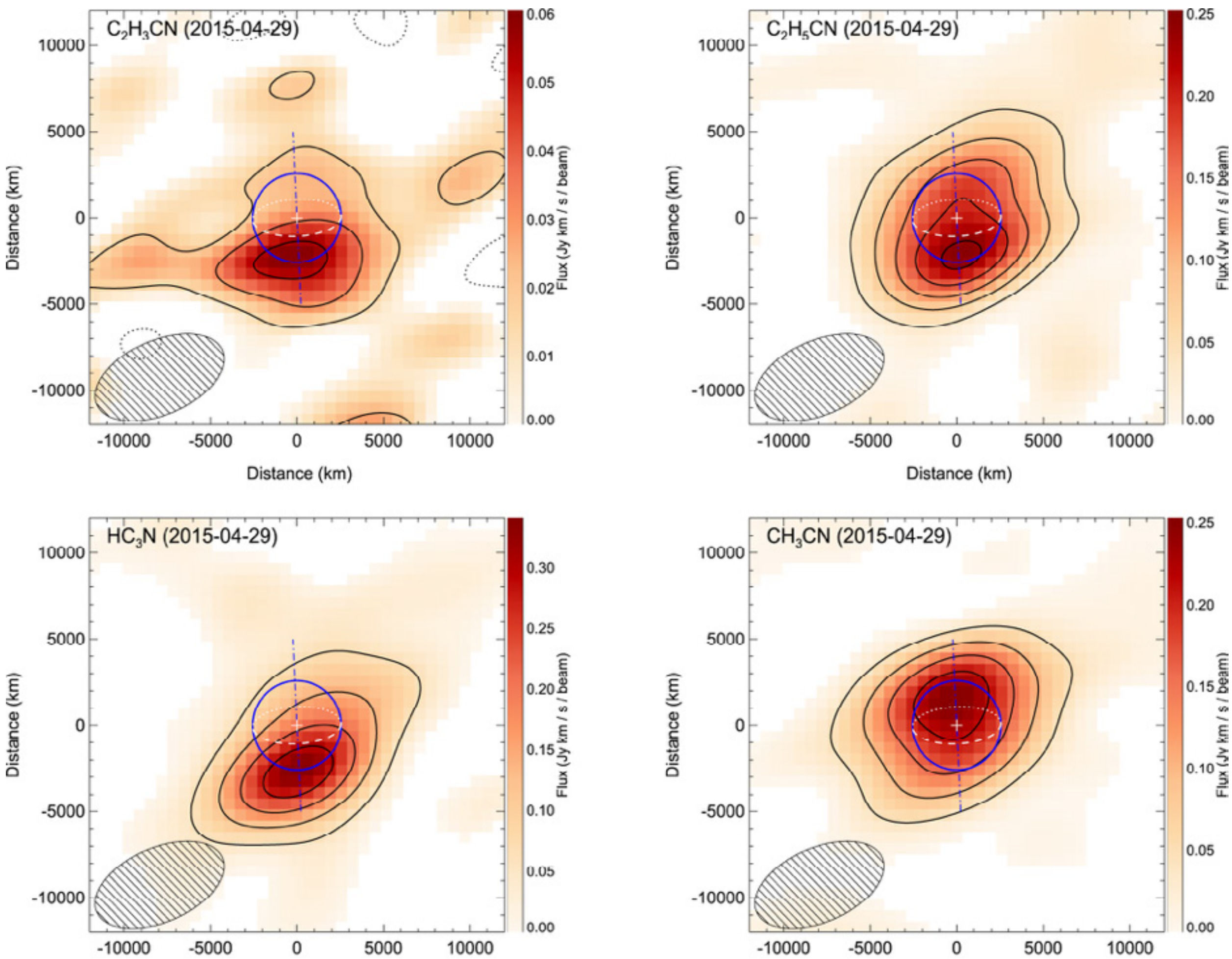


Fig. 9. ALMA images of the nitrile molecular distributions on Titan. The contour maps of integrated emission show (clockwise from upper left): vinyl cyanide, ethyl cyanide, cyanoacetylene and methyl cyanide. Titan's surface is shown as a blue circle and the size of the telescope beam is the hatched ellipse. Three species are enhanced in the South polar region during his season, while methyl cyanide is enhanced in the North. With the demise of Cassini, ALMA is the sole means to extend these studies throughout the Jovian year, permitting detailed investigation of the seasonal changes in atmospheric chemistry on Titan and their possible significance for variations amenable to life. From Lai et al. (2017).

Investigations of Cosmic Ice Analogues and Processes

In the Cosmic Ice Laboratory, we continued to emphasize the identification and quantification of organic molecules known or suspected to be of astrobiological significance, or related to molecules that are of such significance. Our study of ethanol established infrared (IR) spectral assignments, band strengths, and structural changes over temperatures relevant to the interstellar medium (ISM) (Hudson 2017a). The results were compared to earlier work on methanol, still the only alcohol ice identified in the ISM, and to a new study of ethanethiol, a possible biomarker. Two other studies focused on acetone, the simplest ketone. The first explored its radiation chemistry, showing how it can be decomposed into ketene, from which a number of other products can form (Hudson 2017b). The second reported the first ever IR band strengths for solid acetone (Hudson et al. 2017). Each publication included corrections to errors in the literature, and established rigorous parameters for use in astrobiological and astrochemical applications.

A second line of work involved an astrobiology (URAA) summer Fellow, Ms. Sarah Frail of the University of Maryland. Together with co-investigators Gerakines and Hudson, she carried out experiments on the radiolytic destruction of uracil (an RNA nucleobase) at 10-150 K. These were the first in situ experiments of their type and are now being prepared for publication.

Origin and Evolution of Organics and Water in Planetary Systems: 2017 Publications

Anderson, D. E., Bergin, E. A., Blake, G. A. et al. (2017). Destruction of Refractory Carbon in Protoplanetary Disks. *The Astrophysical Journal* 845, Issue 1, article id. 13, 14pp. DOI: 10.3847/1538-4357/aa7da1.*

Aponte, J. C., Abreu, N. M., Glavin, D. P, Dworkin, J. P., Elsila, J. E. (2017). Distribution of aliphatic amines in CO, CV, and CK carbonaceous chondrites and relation to mineralogy and processing history. *Meteoritics & Planetary Science* 52 (12): 2632-2646. DOI: 10.1111/maps.12959.

Aponte, J. C., Elsila, J. E., Glavin, D. P., Milam, S. N., Charnley, S. B, Dworkin, J. P. (2017). Pathways to Meteoritic Glycine and Methylamine. *ACS Earth and Space Chemistry* 1 (1): 3-13. DOI: 10.1021/acsearthspacechem.6b00014.

Banzatti, A. Pontoppidan, K. M., Salyk, C. et al. (2017). The Depletion of Water During Dispersal of Planet-Forming Disk Regions. *The Astrophysical Journal* Volume 834, Issue 2, article id. 152, 23pp. DOI: 10.3847/1538-4357/834/2/152.*

Bonev, Boncho P., Villanueva, G.L., DiSanti, M. A., Böhnhardt, H., Lippi, M., Gibb, E. L., Paganini, L., Mumma, M. J. (2017). Beyond 3au from the Sun: The Hypervolatiles CH_4, C_2H_6, and CO in the Distant Comet C/2006 W3 (Christensen). *The Astrophysical Journal* Volume 153, Issue 5, article id. 241, 12pp. DOI: 10.3847/1538-3881/aa64dd.

Castro-Wallace, S. L. et al. (including Dworkin, J. P. and Burton, A. S. (2017). Nanopore DNA Sequencing and Genome Assembly on the International Space Station. *Nature Scientific Reports* 7 (1), 18022. DOI: 10.1038/s41598-017-18364-0.

Cordiner, M. A., Biver, N., Crovisier J., Bockelée-Morvan, D., Mumma, M. J., Charnley, S. B., Villanueva, G., Paganini, L., Lis, D. C., Milam, S. N., Remijan, A. J., Coulson, I. M.,Kuan, Y.-J. Boissier, J. (2017a). Thermal Physics of the Inner Coma: ALMA Studies of the Methanol Distribution and Excitation in Comet C/2012 K1 (PanSTARRS). *The Astrophysical Journal* Volume 837, Issue 2, article id.177, 10pp. DOI: 10.3847/1538-4357/aa6211.*

Cordiner, M. A., Boissier, J., Charnley, S. B., Remijan, A. J., Mumma, M. J., Villanueva, G. L., Milam, S. N., Paganini, L., Crovisier, J., Bockelée-Morvan, D., Kuan, Y.-J., Biver, N., Coulson, I. M. (2017b). ALMA Mapping of Rapid Gas and Dust Variations in Comet C/2012 S1 (ISON): New Insights into the Origin of Cometary HNC. *The Astrophysical Journal* Volume 838, Issue 2, article id. 147, 10 pp. DOI: 10.3847/1538-4357/aa6590.

Cordiner, M.A., Charnley, S.B., Kisiel, Z., McGuire, B.A., Kuan, Y.-J. (2017a). Deep K-band Observations of TMC-1 with the Green Bank Telescope: Detection of HC_7O, Nondetection of $HC_{11}N$, and a Search for New Organic Molecules. *The Astrophysical Journal* Volume 850, Issue 2, article id. 187, 7pp. DOI: 10.3847/1538-4357/aa970c.

DiSanti, M. A., Bonev, B. P., Dello Russo, N., Vervack, R. J., Gibb, E. L., Roth, N. X., McKay, A. J., Kawakita, H., Feaga, L. M., Weaver, H. A. (2017). Hypervolatiles in a Jupiter-family Comet: Observations of 45P/Honda-Mrkos-Pajdušákova Using iSHELL at the NASA-IRTF. *The Astrophysical Journal* Volume 154, Issue 6, article id. 246, 17pp. DOI: 10.3847/1538-3881/aa8639.

Du, F., Bergin, E.A., Hogerheijde, M. et al. (2017). Survey of Cold Water Lines in Protoplanetary Disks: Indications of Systematic Volatile Depletion. *The Astrophysical Journal* Volume 842, Issue 2, article id. 98, 16pp. DOI: 10.3847/1538-4357/aa70ee.*

Glavin, D. P., Alexander, C.M.O'D., Aponte, J. C., Dworkin, J. P., Elsila, J. E., Yabuta, H. (2017). The Origin and Evolution of Organic Matter in Carbonaceowus Chondrites and Links to their Parent Bodies. In *Primitive Meteorites and Asteroids*, (ed. N. Abreu), Elsevier, Cambridge. ISBN: 9780128133255.*

Goesmann, F., Brinckerhoff, W. B., et al. (2017). The Mars Organic Molecule Analyzer (MOMA) instrument: Characterization of organic material in martian sediments. *Astrobiology* 17: 655-686. DOI: 10.1089/ast.2016.1551.*

Hudson, R. L. (2017a). An IR investigation of solid amorphous ethanol - spectra, properties, and phase changes. *Spectrochimica Acta* 187: 82-86. DOI: 0.1016/j.saa.2017.06.027.*

Hudson, R. L. (2017b). Radiation chemistry of solid acetone in the interstellar medium - a new dimension to an old problem. *Physical Chemistry Chemical Physics* 20: 5389-5398. DOI: 10.1039/c7cp06431d.*

Hudson, R. L., Gerakines, P. A., Ferrante, R. F. (2017). IR spectra and properties of solid acetone, an interstellar and cometary molecule. *Spectrochimica Acta* 193: 33-39. DOI: 10.1016/j.saa.2017.11.055.*

Khayat, A. S., Villanueva, G. L., Mumma, M. J., Tokunaga, A. T. (2017). A deep search for the release of volcanic gases on Mars using ground-based high-resolution infrared and submillimeter spectroscopy: Sensitive upper limits for OCS and SO_2. *Icarus* 296: 1-14. DOI: 10.1016/j.icarus.2017.05.014.

Lai, J. C.-Y.i, Cordiner, M. A., Nixon, C. A., Achterberg, R. K., Molter, E. M., Teanby, N. A., Palmer, M. Y., Charnley, S. B., Lindberg, J. E., Kisiel, Z., Mumma, M. J., Irwin, P. G. J. (2017). Mapping Vinyl Cyanide and Other Nitriles in Titan's Atmosphere Using ALMA. *The Astronomical Journal* 154: 206 (10 pp). DOI: 10.3847/1538-3881/aa8eef.

Nuth, Joseph A. III, McCoy, Timothy, Johnson, Natasha M. (2017). Chapter 7: Exploring the possible continuum between comets and asteroids. *In Primitive Meteorites and Asteroids* (ed. N. Abreu). ISBN: 9780128133255.*

Paganini, L., Mumma, M. J., Gibb, E. L., Villanueva, G. L. (2017). Ground-based Detection of Deuterated Water in comet C/2014 Q2 (Lovejoy) at IR wavelengths. *The Astrophysical Journal Letters* 836 (2): L25 (7pp). DOI: 10.3847/2041-8213/aa5cb3.*

Palmer, M. Y., Cordiner, M. A., Nixon, C. A., Charnley, S. B., Teanby, N. A., Kisiel, Z. Irwin, P. G. J., Mumma, M. J. (2017). ALMA detection and astrobiological potential of vinyl cyanide on Titan. *Science Advances* 3:e1700022. DOI: 10.1126/sciadv.1700022.

Roberge, A., Seager, S. (2017). The "Spectral Zoo" of Exoplanet Atmospheres. In *Handbook of Exoplanets* (eds. H. J. Deeg and J. A. Belmonte), Springer Publishing Company. ISBN: 978-3-319-55333-7.

Roth, N. X., Gibb, E. L., Bonev, B. P., DiSanti, M. A., Mumma, M. J., Villanueva, G. L., Paganini, L. (2017). The Composition of Comet C/2012 K1 (PanSTARRS) and the Distribution of Primary Volatile Abundances among Comets. *The Astronomical Journal.* 153: 168 (8pp). DOI: 10.3847/1538-3881/aa5d18.

***NAI supported, but not explicitly acknowledged**

Team Members

Michael Mumma
Neyda Abreu
Jose Aponte
Ricardo Arevalo, Jr.
Geoffrey Blake
Boncho Bonev
William Brinckerhoff
Steven Charnley
Martin Cordiner
Michael DiSanti
Jason Dworkin
Jamie Elsila
Sara Faggi
Frank Ferguson
Perry Gerakines
Erika Gibb
Daniel Glavin
Reggie Hudson
Natasha Johnson
Yi-Jehng Kuan
Manuela Lippi
Karen Meech
Stefanie Milam
Tom Millar
Joseph Nuth
Lucas Paganini
Eric Parker
Anthony Remijan
Mark Sutton
Geronimo Villanueva